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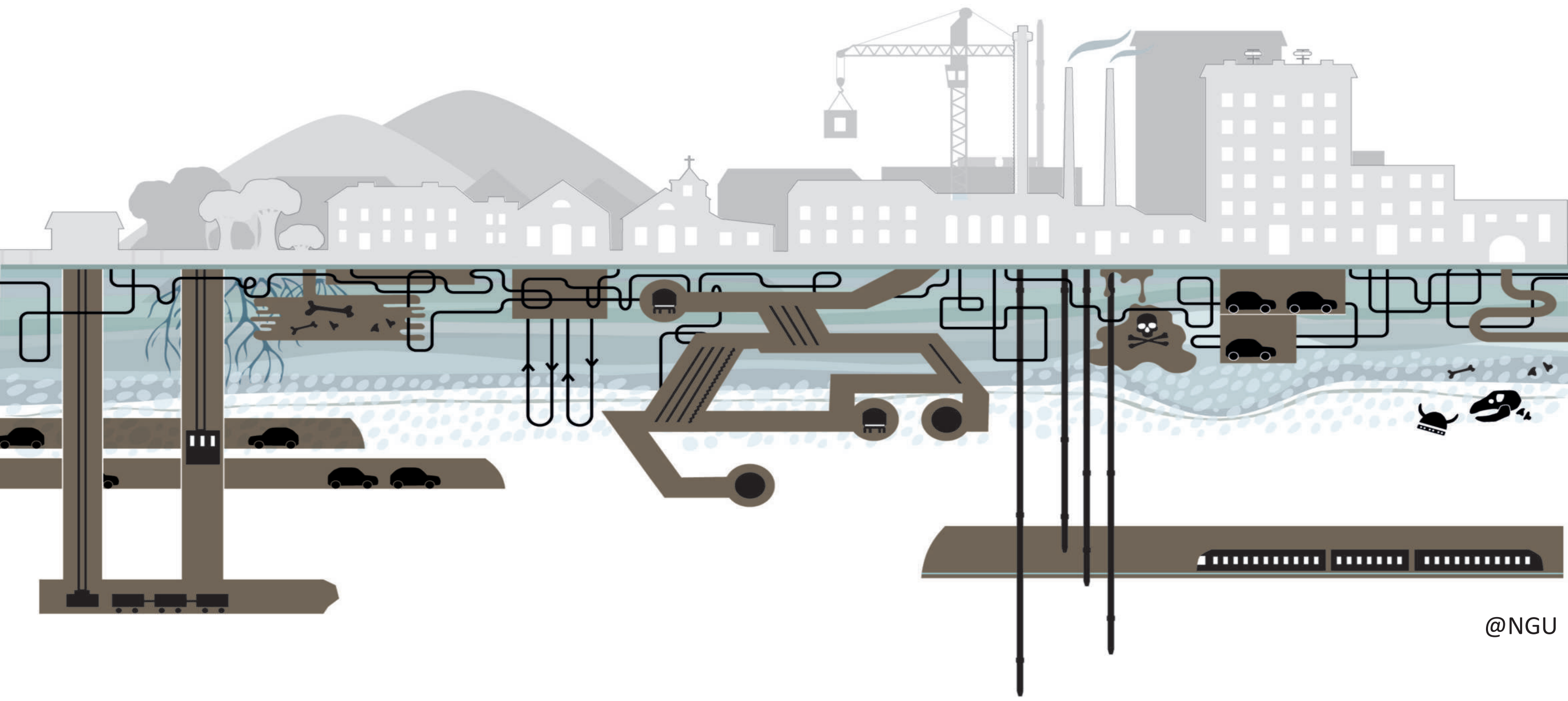

Opening up the subsurface for the cities of tomorrow

Considering access to subsurface knowledge – Evaluation of practices and techniques

TU1206 COST Sub-Urban WG2 Report

Susie Mielby, Ingelöv Eriksson, Diarmad Campbell, Johannes de Beer, Helen Bonsor, Cécile Le Guern, Rob van der Krogt, David Lawrence, Grzegorz Ryżyński, Jeroen Schokker, Carl Watson

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Many participants of the Sub-Urban COST Action have contributed to this report and to the Action as a whole, each with their own experience and expertise. This evaluation would not have been the same without their presentations, comments, and discussions; they are all thanked for their contributions.

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Project website: www.cost.eu/COST_Actions/tud/TU1206/

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Abstract

The subsurface is an important constituent of the physical environment of cities. We live on top of it; building and construction have to deal with the structure and properties of the subsurface, and occasionally with the hazards it presents; and we benefit from, and in some cases are dependent, on many of its ecosystem services. Cities not only expand outward and upward, but also downward. More and more, subsurface space is being used to relieve the increasingly crowded and congested urban surface. The more use we make of subsurface space, the more surface space we free up for the one function that cannot do without daylight and fresh air: living.

COST (European Cooperation in Science and Technology) Action TU1206 Sub-Urban explores sustainable use and management of the urban subsurface, and the use of subsurface information in urban planning and development. The importance of appreciating the importance of the ground beneath cities may seem self-evident, but studies by the Action's Working Group 1 have confirmed that the urban subsurface is in fact still largely 'out of sight, out of mind'. It does not present a daily concern to city planners and managers, and when it does, there is often trouble. The Action has identified a knowledge and communication gap between subsurface experts, urban planners and decision makers. We argue that the only possible way to bridge this gap is to **provide the right type of subsurface information, in the right format, and at the right time** and make sure that the **people receiving the information** (urban planners and decision makers) are able to **understand and use the information to take decisions**. The overall challenge in "Opening up the subsurface for the cities of tomorrow" is to be able to:

- On one side - to understand and identify the city needs in order to develop/provide appropriate knowledge and products/tools for the municipality, city region, water board or other end-user, and
- On the other side – to identify good practice and relevant technologies when mapping and modelling the subsurface of the urban areas to enable improved and sustainable use and management of the urban subsurface.

This report describes the background to, and examples of, good practice, and tools that can realize these challenges. Taking the outputs from Working Group 1 (the 'state of the art') as a starting point, Working Group 2 has evaluated the knowledge needed to characterise and understand the urban subsurface (including the man-made infrastructure, artificial soils, and natural geological features) by means of a variety of good practices and techniques and identified knowledge gaps. This report summarises findings on: Subsurface information and planning; Data acquisition and management; 3D geological modelling of the subsurface; Groundwater and geothermal monitoring and modelling; Geotechnical modelling and hazards; Subsurface geochemistry; and Cultural heritage.

Taking the perspectives both of urban planning and subsurface geoscience, the report identifies urban needs, gives examples of current good practice and best efforts for a wide range of subjects: from identifying city needs; to methods to achieve, store and visualize geological and geotechnical information, and to ways in which sub-surface-related issues can be brought into urban planning. The examples provided describe practices both on municipal and national scales for different geographical settings/typologies. The report also identifies key knowledge gaps in relation to each topic. The good practices and key knowledge gaps are presented in summary tables.

We propose the Geo City Information Modelling (GeoCIM) concept, which expands on Building Information Modelling (BIM) and the City Information Model (CIM), as a tool that can bring together effectively above- and below-ground data and knowledge at scales appropriate to city needs, and also an explicit requirement of sustainable urban planning and management.

Keywords

City; urban planning; urban geology; subsurface; integrated modelling; data acquisition; data management; geotechnical modelling; hazards; 3D geological modelling; groundwater monitoring and modelling; thermal monitoring and modelling; subsurface geochemistry; cultural heritage; Europe

Full reports

This report summarises and analyses the following topics of relevance to planning and management of the ground beneath our cities (available online at www.sub-urban.eu/):

Topic	**Report**
Subsurface information and planning	R. van der Krogt, 2016. PowerPoint presentation. Evaluation framework of city cases for planning with the sub-surface; TU1206-WG2-002.
Data acquisition and management	C. Watson, N.-P. Jensen, M. Hansen, G. Ryżyński & K. Majer, 2016. Data acquisition and management. COST TU1206 Working Group 2, Work package 2.2 report; TU1206-WG2-003.
Geotechnical data and geohazards in city subsurface management	PowerPoint presentation – result from questionnaire on geotechnical data available in this project. G. Ryzynski, K. Majer, B. Mozo, A. Toumazis; TU1206-WG2-004.

3D urban subsurface modelling and visualisation	J. Schokker, P.B.E. Sandersen, H. De Beer, I. Eriksson, H. Kallio, T. Kearsey, S. Pfleiderer & A. Seither, 2016. 3D urban subsurface modelling and visualisation - a review of good practices and techniques to ensure optimal use of geological information in urban planning. COST TU1206 Working Group 2, Work package 2.3 report; TU1206-WG2-005.
Groundwater, geothermal monitoring and modelling	H.C. Bonsor, P. Dahlqvist, L. Moosmann, N. Classen, J. Epting, P. Huggenberger, A. García-Gil, M. Janźa, G. Laursen, R. Stuurman & C.R. Gogu, 2015. Groundwater, Geothermal modelling and monitoring at city-scales – identifying good practice, and effective knowledge exchange. COST TU1206 Working Group 2. Work package 2.4 report; TU1206-WG2-006.
Geotechnical modelling and hazards	G. Ryżyński, B. Mozo, A.Toumazis, I. Vergauwen, G. van Alboom, M. Van Damme, V. Vanwesenbeeck, K. Majer, D. Entwisle, A. Ustun, I. Peshevski, M. Jovanovski & M. S. Serbulea, 2016. Geotechnical data and geohazards in city subsurface management. COST TU1206 Working Group 2. Work package 2.5 report; TU1206-WG2-007.
Subsurface geochemistry	C. Le Guern & B. Sauvaget with contributions from D. Campbell & S. Pfleiderer, 2016. A review of good practice and techniques in sub-urban geochemistry; to ensure optimal information use in urban planning, COST TU1206 Working Group 2. Work package 2.6 report; TU1206-WG2-008.
Cultural heritage	J. de Beer with contributions from F.C. Boogaard, M. Vorenhout & G. Gianighian (2016). A review of good practices in cultural heritage management and the use of subsurface knowledge in urban areas. COST TU1206 Working Group 2, Work package 2.7 report; TU1206-WG2-009.

1. Introduction

Project Sub-Urban

COST[1] Action TU1206 Sub-Urban[2] explores management of the urban subsurface and the use of subsurface information in urban planning, with emphasis on sustainability in general. The main objective of the Action is to provide a long-needed contribution to greater interaction between experts who develop urban subsurface knowledge and those who can benefit most from it - urban decision-makers, urban planners, practitioners (utilities, private consultants and contractors) and the wider research community. It has done so by establishing a network to co-ordinate, integrate and accelerate the world-leading research into modelling the subsurface taking place in European institutions, and by developing a Toolbox to enable the knowledge to be widely disseminated and more easily incorporated in urban policy and planning.

The work has been taken forward through four interacting Working Groups (WGs):

- WG1 Compile inventories of existing methods, practices and case studies
- WG2 Evaluation and integration of techniques
- WG3 Preparation of guidelines and a Toolbox
- WG4 Dissemination and training

This report summarises the results, conclusions and recommendations of Working Group 2. The recommended good practice workflows and techniques for delivering and accessing subsurface information and knowledge form the basis for the development of the Toolbox by Working Group 3.

The general challenge for Working Group 2 in "Opening up the subsurface for the cities of tomorrow" has been to:

- On one side - to understand and identify the city needs in order to develop/provide appropriate knowledge and products/tools for the municipality and others to use, and

- On the other side – to identify good practices and relevant technologies when mapping and modelling the subsurface of the urban areas to enable improved and sustainable use and management of the urban subsurface.

[1] COST is the longest-running European framework supporting transnational cooperation among researchers, engineers and scholars across Europe. It is a unique means for them to jointly develop their own ideas and new initiatives across all fields in science and technology, including social sciences and humanities, through pan-European networking of nationally funded research activities. See http://www.cost.eu/
[2] http://www.cost.eu/COST_Actions/tud/TU1206/

This report describes the background to, and examples of good practice and tools that can realize these challenges. It identifies urban needs, and gives examples of good practice for a wide range of subjects: from identifying city needs, to methods to achieve, store and visualize geological and geotechnical information, and to ways in which sub-surface related issues can be brought into urban planning. The examples describe practices both on municipal and national scales and for different geographies and urban typologies. It also identifies key knowledge gaps for each topic.

State of the art in 12 cities – From Working Group 1 to 2

As the first stage of the project, Working Group 1 assessed the 'state of the art' in terms of urban sub-surface knowledge and use in planning in European cities, and prepared a series of comprehensive city reports for A Coruña, Bergen, Dublin, Glasgow, Hamburg, Helsinki, Ljubljana, Nantes, Novi Sad, Odense, Oslo and Rotterdam. These reports can be accessed via the project website: www.sub-urban.eu .

Working Group 1 summarised these reports, and drew some general conclusions on the subject, and offered a view on the way forward (Van der Meulen et al., 2016). It fittingly describes the importance of the urban subsurface to the life of urban citizens as *Out of sight, Out of mind*. Urban citizens benefit from subsurface ecosystem services that are vital for the quality of their lives; for transport, storage, foundations and for hosting networks for utilities, including electricity, water and sewage. Just take a minute to imagine a city where all these necessary networks were above ground. Although the subsurface hosts such important components of city infrastructure, it is seldom fully understood or indeed recognised at all. The COST Sub-Urban TU1206 Working Group 1 summary report states that *"General awareness of the subsurface below cities typically only exists where either great opportunities are presented, think of boomtowns like Kimberly (diamond mining) and Dawson (Klondike gold rush), or great risks, for example in San Francisco (the San Andreas Fault) and Naples (the Vesuvius volcano). However, for most other towns, beneficial subsurface conditions are taken for granted and the subsurface is only considered when adverse conditions manifest themselves."*

Taking advantage of the opportunities that the subsurface offers is often technically challenging. Unlike space above ground, the subsurface is filled with solid matter; soils and rocks of different qualities are used as the platform for the foundations of buildings, or they need to be removed and displaced to give way for spatial use of the subsurface (basements, tunnels, etc.). Other resources such as groundwater for potable water and ground source heat also use space in the subsurface. However, there are no physical boundaries for these resources, and for the other sub-surface uses, as seen from a planning perspective.

Over time, sophisticated methods have been developed to collect data about the subsurface, and clever solutions have been identified to overcome technical challenges.

There are advanced methods and technologies to drill tunnels, establish foundations for ever-larger buildings, and exploit ground heat resources. There is also a growing awareness of the economic advantages of reusing data and information that have been collected and stored throughout time in many (but certainly not all) European cities.

Subsurface data and information are mainly considered at a project level of use, and reuse is often difficult. Experience from COST Sub-Urban show that there is a lack of consideration of subsurface information in planning stages of projects and programmes. Data are often brought into the process when a decision about spatial use has already been made. The lack of subsurface information in the early planning stages has a knock-on effect on planning and projects at a later stage. Unforeseen ground conditions (a term covering ground conditions encountered during construction) in large projects can cause significant and costly delays. Mass movements and flooding can cause severe damage to property and even loss of life. Long term effects such as the remobilisation of pre-existing contanants, change in groundwater levels, or man-made heating of groundwater aquifers can cause severe problems for human health, ecosystems and property.

COST Sub-Urban was founded on the premis (COST TU1206 Memorandum of Understanding) of the prevalence of a widespread gap between subsurface experts, urban planners and decision makers. The presence of this gap has been confirmed and reinforced by the studies of Working Group 1. We argue that the only possible way to bridge this gap is to **provide the right type of subsurface information** and make sure that the **people receiving the information** (urban planners and decision makers) are able to **understand and use the information to take decisions**. Knowledge and information at the right time, in the right format, and in the right place are key in this process.

Technical experts often speculate or philosophise about the needs of planners and policy makers they wish to serve, who in their turn speculate about or are unaware of technical (im)possibilities. The Sub-Urban COST Action has facilitated interaction between the two groups, allowing all participants to keep to their trade, and to bring in what each does best, so reducing the gap. Even though (potential) providers and users of urban subsurface information do of course consult with each other, Sub-Urban has enabled a level of exposure between the two that is rare, both in duration and depth. The general lesson learnt from the whole exercise is that the interaction achieved in this way is very useful and productive.

Taking the outputs from Working Group 1 assessment of ‘the state of the art’ as a starting point, Working Group 2 has evaluated the knowledge needed to the urban subsurface (including the man-made infrastructure, artificial soils, and the natural geological features) by means of a variety of good practices and techniques, and identified knowledge gaps. The results are presented in a series of comprehensive technical reports and presentations for each of the subjects: Subsurface information and planning; Data acquisition and management; 3D geological subsurface modelling; Groundwater and geothermal monitoring and modelling; Geotechnical modelling and hazards; Subsurface geochemistry; and Cultural heritage.

Each individual report takes both an urban planning and a geoscientific subsurface perspective, and was jointly prepared by planning and geoscience experts organised in eight sub-groups. A ninth subgroup gave special attention to the topic of integrated modelling. The study has been initiated into economic aspects, which will be reported as part of the Working Group 3 output.

Future impacts of climate change and urban growth

Future city growth threatens sustainable development - a pattern of growth in which resource use aims to meet human needs while preserving the environment for present and future generations (Brundtland Commission, 1987). Over the past decades, increased urbanization has created more pressure - not only on the suburban outskirts - but also in the inner core of the cities, putting important environmental issues such as water management and cultural heritage under stress.

Potential economic aspects are assessed in The Global Risks Report (World Economic Forum, 2016). Failure in climate change mitigation and adaptation, and failure in urban planning have both come out with a ranking that emphasizes the importance of what we earlier summarised from Working Group 1 (see Figure 1). The above observations, together with the observed trends in both climate change and urbanization, highlight the necessity to use subsurface information in urban management and planning much more, and in more ways, than at present.

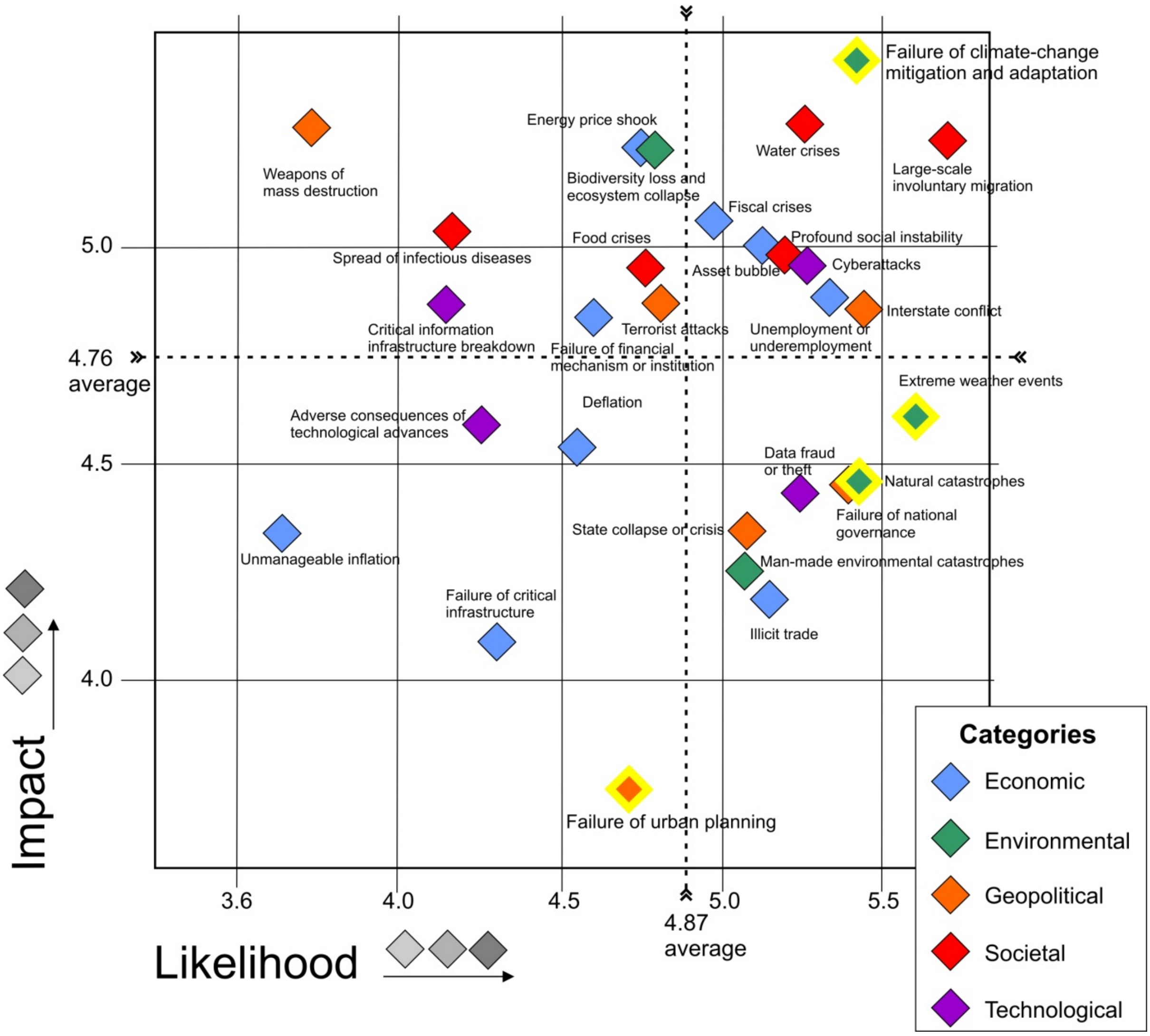

Figure 1. Estimated likelihood and economic impact redrawn after The Global Risk Landscape by The World Economic Forum, 2016. In the figure we have highlighted in yellow: Failure in urban planning, Natural catastrophes, Extreme weather events, and Failure in Climate change adaptation and mitigation that are of particular interest and relevance to urban areas

What is the challenge?

Increased urbanisation will place yet more pressure on urban areas. It is vital therefore to assure sustainable use of urban areas. To achieve this with respect to the sub-surface, we must try to **bridge the gap between the providers and users** of subsurface information and acknowledge interests and knowledge in their different worlds.

The communities of practice relevant here can be categorized as follows:

- Urban planning and management
- Building and constructions
- Environmental analysis and management
- European environmental systems

Urban planning and management; so far these have been largely focused on specific areas and to existing and planned land use – at surface. Spatial planning and management are typically based on map layers describing features related to the surface (2 - 2½-dimensional). Three-dimensional information related to the subsurface is with few exceptions, if collated at all, used mainly to ensure overall planning of occupation and infrastructure.

Building and other man-made construction: these focus on specific projects, i.e. planning, design and construction. Information on geotechnical conditions and on constructions of importance in the urban area is collated in relation to the specific project, and data are often private. Other third party data include those related to roads, sewer pipes, etc. Building Information Modelling (BIM) is used mainly for data exchange within the project, and for the project management process and the design and construction of the specific building/constructions.

Environmental subsurface analysis and management consider issues such as climate adaptation (infiltration, flooding etc.), abstraction of water, and storage of heat; all are related to time and the surrounding land use and geology, and they are complex (3-4 dimensional) by nature and often handled through the use of monitoring and models**.**

Changes in climate, enhanced infiltration, changes in water abstraction, drainage, heat storage etc. all potentially cause environmental impacts. These impacts are related less to a specific area on surface, than to aquifers and related geological formations below surface. There is a need for analysis of the total impact on the entire water cycle.

European environmental systems have been developed by The European Environmental Agency (EEA). The management system is based on indicators in order to - in a simple way - monitor progress with implementation of policy measures and assess their effectiveness.

- This EEA structural thinking on the environment in relation to socio-economic activities is divided into indicators, a reporting chain and an interplay framework (EEA, 2014): The Indicators are a simple set of measures for development, e.g. soil moisture (hydraulic head).
- The reporting chain reflects the phases that link the individual steps of information generation from: Monitoring, Data, Indicators, Assessment to Knowledge (MDIAK).
- The framework reflects the interplay between the environment and socio-economic activities: Driving force, Pressure, State, Impact and Response (DPSIR), see Figure 2.

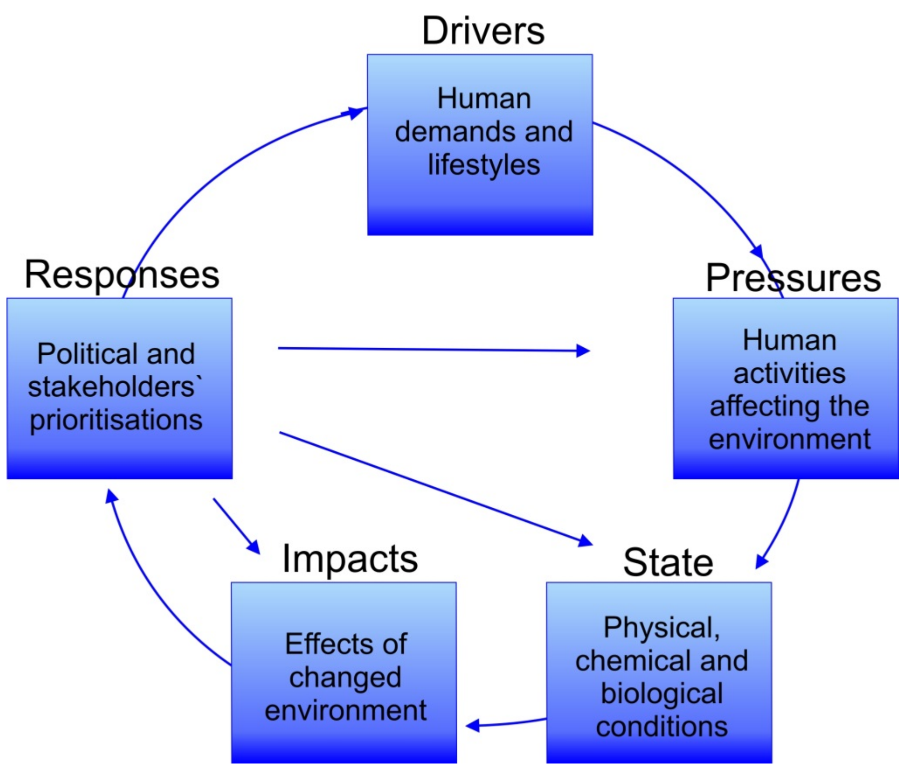

Figure 2. The DPSIR framework has been developed by EEA to accommodate the assessment of environmental impacts and ensure environmental progress of societal challenges

Organisation of Working Group 2

COST Action TU1206 Sub-Urban and its Working Group 2 started in April 2014. A series of meetings and workshops were organised where good practice and good efforts were presented and discussed. The ensuing discussions were important in creating awareness of the challenges that cities are facing, and the solutions they have been developed.

The group rapidly expanded to include eight subgroups listed below, together with their respective group leaders, below:

1. Subsurface information and planning – Rob van der Krogt
2. Data acquisition & management – Carl Watson
3. Interactive 3D modelling & visualisation – Jeroen Schokker
4. Groundwater, geothermal modelling & monitoring – Helen Bonsor
5. Geotechnical modelling & hazards – Grzegorz Ryżyński, Igor Peshevski & Beatriz Mozo
6. Geochemistry – Cécile Le Guern
7. Cultural heritage – Johannes de Beer
8. Economy – Tine Compernolle

The most important results from each subgroup (except for the Economy group – whose studies will be incorporated in the Working Group 3 Toolbox) are summarised in this report. The full technical reports from the subgroups are available through the Sub-Urban web page. (www.Sub-Urban.eu)

A ninth, small, subgroup was established to deal with Integrated Modelling (Carl Watson, Jeroen Schokker, Helen Bonsor and Susie Mielby) and that topic is described in Chapter 3 of this report.

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European Environmental Agency, 2014: Digest of EEA indicators 2014. EEA Technical report No 8/2014.

Van der Meulen, M. J., Campbell, S. D. G., Lawrence, D. J., Lois González, R. C., Van Campenhout, I. A. M., 2016. OUT OF SIGHT OUT OF MIND? Considering the subsurface in urban planning - State of the art. *COST TU1206 Sub-Urban Report,* TU1206-WG1-001.

World Economic Forum, 2016: The Global Risks Report, Inside report. 11th Edition. Committed to improving the state of The World. Http://wef.ch/risks2016

2. Evaluation of practices and techniques

Access to subsurface knowledge

The process of subsurface knowledge building starts very often with the identification and use of existing, available data and maps, and continues with capture of data followed by **successive knowledge building** as illustrated in figure 3.

The first step is to investigate what we can gain from already existing maps and data. The next step is to capture essential data, and the third step is to put together this information in a frame/model. The fourth step involves the attribution of physical parameters in order to predict future situations or explain processes, and, finally, the fifth step addresses the use of the subsurface information in decision-making.

The decision-making is highly dependent on collation, modelling, integration and aggregation of subsurface knowledge.

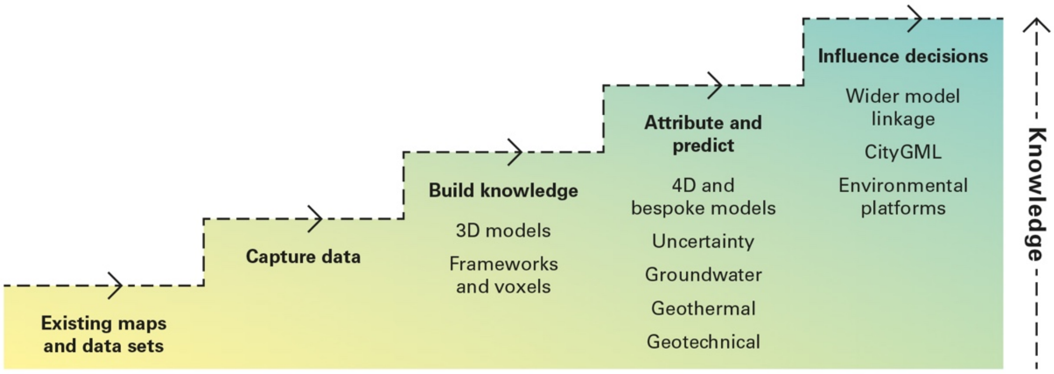

Figure 3. Key information levels in the knowledge building process. Figure developed by Diarmad Campbell, British Geological Survey

The levels and requisite knowledge building are dependent on **the phase of operation** (e.g. an idea that should be investigated, a final masterplan for a municipality or permission to undertake a specific construction in a quarter etc.). Besides the **geological and hydrogeological variations in scale, available data and modelling tools** and **history** all play important roles in the planning and management of the urban areas.

In the Sub-Urban Action, our strategy for the inventory and evaluation of practices and techniques is based on the following table of subsurface topics that were identified at the inception of the Action (see Figure 4).

1	Data management	1.1		1.1.1	Specifications
1		1.1		1.1.2	Online capture, including made ground (anthropogenic)
1		1.1		1.1.3	Data management (on different scales)
1		1.1		1.1.4	Data delivery and update
1		1.1		1.1.5	Data re-use
2	3D Model development	2.1		2.1.1	Workflows for main modelling software and different city scenarios
2		2.1		2.1.2	Deterministic modelling, incl. made ground
2		2.1		2.1.3	Stochastic modelling, incl. made ground
2		2.1		2.1.4	Model uncertainty
3	Knowledge development	3.1	Model attribution	3.1.1	Physical properties e.g. hydraulic conductivity, aquifers
3		3.1		3.1.2	Chemical properties
3		3.2	4D process/time-series modelling	3.2.1	Groundwater, historical and predictive time series models for aquifer protection, sustainable drainage, effects of climate change
4	Knowledge use	4.1		4.1.1	City case-studies
4		4.1		4.1.2	Visualisation
4		4.1		4.1.3	Monitoring
5	Knowledge delivery and integration	5.1	Subsurface/above ground linkage	5.1.1	Building Information modelling (BIM) and CityGML
5		5.1		5.1.2	Buried infrastructure
5		5.1		5.1.3	Archaeological/cultural assets
5		5.2	Incorporation in Decision making tools	5.2.1	Volumetric planning
5		5.2		5.2.1	Ecosystem services stewardship
5		5.2		5.2.2	Aquifer vulnerability/groundwater protection
5		5.2		5.2.3	Thermal and other mineral resource extraction and storage
5		5.2		5.2.4	Ground stability and foundation conditions
5		5.2		5.2.5	Risk management in development/construction
5		5.2		5.2.6	Protection of cultural heritage
5		5.2		5.2.7	Hazard identification and risk management
5		5.2		5.2.8	Burial of services and development of subsurface infrastructure, including underground transport, storage and waste disposal

Figure 4. Subsurface information provided in different knowledge levels. The uppermost level is related to data acquisition and management, and the lowermost is focused towards decision making and planning

As mentioned in the introduction, the evaluation has been undertaken systematically by sub-groups, concentrating on the special need for access to subsurface information in our cities.

The results of these evaluations are reported in the following sections. In each section, the topic is described in an urban context under the following headings:

- Key Topics
- Seen in the urban context
- Urban needs
- Priority datasets
- Examples of good practice
- Key knowledge gaps
- References

Compilations of the selected good practice examples and key knowledge gaps are presented as summary tables in Chapter 5.

2.1 Subsurface information and planning

4.1	**Knowledge use**	4.1.1	City case-studies
4.1		4.1.2	Visualisation
4.1		4.1.3	Monitoring
5.1	**Subsurface/above ground linkage**	5.1.1	Building Information modelling (BIM) and CityGML
5.1		5.1.2	Buried infrastructure
5.1		5.1.3	Archaeological/cultural assets
5.2	**Incorporation in Decision making tools**	5.2.1	Volumetric planning
5.2		5.2.1	Ecosystem services stewardship
5.2		5.2.2	Aquifer vulnerability/groundwater protection
5.2		5.2.3	Thermal and other mineral resource extraction and storage
5.2		5.2.4	Ground stability and foundation conditions
5.2		5.2.5	Risk management in development/construction
5.2		5.2.6	Protection of cultural heritage
5.2		5.2.7	Hazard identification and risk management
5.2		5.2.8	Burial of services and development of subsurface infrastructure, including underground transport, storage and waste disposal

Figure 5. Extract from table of knowledge levels (figure 4) showing main topics of relevance to Subsurface information and planning subgroup

Key Topics:

City information needs, strategic planning, planning and management levels, planning and construction, maintenance, integration of subsurface expertise.

Subsurface planning seen in the urban context

Subsurface planning is especially important in urban areas where the subsurface is frequently used or where geological and/or geotechnical conditions have impact on existing or intended developments. The Sub-Urban WG 1 report *“Out of sight Out of mind, considering the subsurface in urban planning – State of the art”* describes to some extent what urban planning is, and why it is important to plan for the subsurface and use subsurface information in urban planning.

The need for sub-surface information and consultation will vary depending on whether the planning is on a strategic, or a detailed level (project related).

It is recognized that planners and decision makers have limited understanding of the subsurface; likewise, subsurface specialists have little understanding of the type and scale of information relevant to different levels of planning. Consequently, there is a great need to improve communication between the two parties.

Urban planners, as well as subsurface specialists, need to improve their understanding of the different types of information that are needed in strategic and detailed planning processes. As in the above ground planning process both parties need to understand **where in the planning hierarchy** specific types of information are needed and **where in the planning process** the information is needed and to **produce guidelines** for this.

Urban needs

Urban needs can be defined as a need for anyone involved in urban development to understand and use any information relevant to a development within the city. In this context, it means planners, designers, decisonmakers and people affected (the public, such as neighbours and organisations) by the development.

It is of particular interest that those managing the strategic and detailed urban planning processes (planners) have a comprehensive understanding of the assets and challenges of the subsurface.

An urban planner is only as good as the information that is available to him or her. Information that is available in traditionally used formats such as geotechnical reports, geological maps or 3D models need to be translated into formats that are more readily understood by urban planners and decision makers. To facilitate this, cities ought to possess or have easy access to competence of how to use available subsurface information.

To fully succeed in developing clarity and strong communication between urban planners and technical disciplines, the terminology of different users needs to be fully understood by all parties. This also enables an understanding to be developed of how subsurface information can be made relevant and more accessible to other specialists, and a common understanding of future actions can develop.

From the perspective of subsurface data providers and experts, it is important to identify so-called '**city needs**' and '**planners questions**', in order to determine what kind of information could be valuable for all levels of urban planning, and how this information should be exchanged and communicated.

City needs' can be determined from policy frameworks and urban planning tasks which will differ between countries, regions and municipalities. Driving forces that frame city needs and urban planners include:

- Policy framework (legislation, political decisions and directives, etc.)
- Planning level (scale, type of urban planning task)
- Planning phase/stage
- City characteristics (such as economy, physical environment, planning characteristics and data availability).

Such a **"city need analysis"** ought to be based on local subsurface challenges and/or the resources of the city. It should also be adapted to satisfy legislation, expected development of the city and available subsurface information.

Information about the subsurface needs to be: easy to capture; reliable; organized; regularly updated; and possible to integrate into the planning and construction process. The type and amount of information will vary with the planning level/ type of planning task.

Examples of good practice

This section presents a selection of good practices from European cities as well as a summary of a workshop on strategic planning and considerations of the underground, held in Ljubljana 2016.

The best practices focus on how cities have worked to understand and incorporate their specific city needs in urban planning at different planning levels and planning phases.

1. How to identify subsurface information needs - example from Oslo

A broad understanding of the need for sub-surface information is crucial when it comes to implementing and using sub-surface information such as maps, reports and working processes within a municipal organization.

During the current Oslo subsurface project, a subsurface information need analysis was carried out. (Eriksson, Borchgrevink 2016). The following methodology was used:

Step 1: Analyzing geological/sub-surface assets and challenges within the local urban environment. (City, Metropolitan or regional level). Sub surface specialists such as geologists, hydrogeologists and geotechnicians identified the main assets and challenges related to the geology of the urban area under analysis. In Oslo, the results were presented in a simple table and these have helped to understand which geological or geotechnical features should be taken into account in strategic urban planning. Taking too many layers into account, and/or using complicated geological terms, should both be avoided, as these will greatly limited the number of potential end-users that can understand and use the table.

Step 2: Analysing sub-surface information needs within the planning and building process through a series of workshops and working meetings with urban planners at all levels. The information gained through the workshops is presented in a spreadsheet and as well as a report, that contains valuable information that cannot be fitted into the original table. The workshops are more efficient with a skilled facilitator involved. To keep the planning processes at any level efficient, the information to be consulted by the urban planners need to be highly relevant and readily used.

The main value of the exercise **is in raising the awareness of subsurface assets and challenges** that are specific to the city. The tool can be used to analyse subsurface information needs at all planning levels. The spreadsheet was designed so that it was easy to understand which information is needed and at what level. (Eriksson, Borchgrevink et al., 2016).

During the analysis, the diagram shown in Figure 6 was developed; it illustrates the relationship between the planning phases and planning processes in Norway. It also shows where subsurface information is needed.

Step 3: Implementation of the results in the quality management system. This process includes: making maps available through a web-based portal; making checklists and guidelines available to users; training and informing users; and providing regular updates of the information.

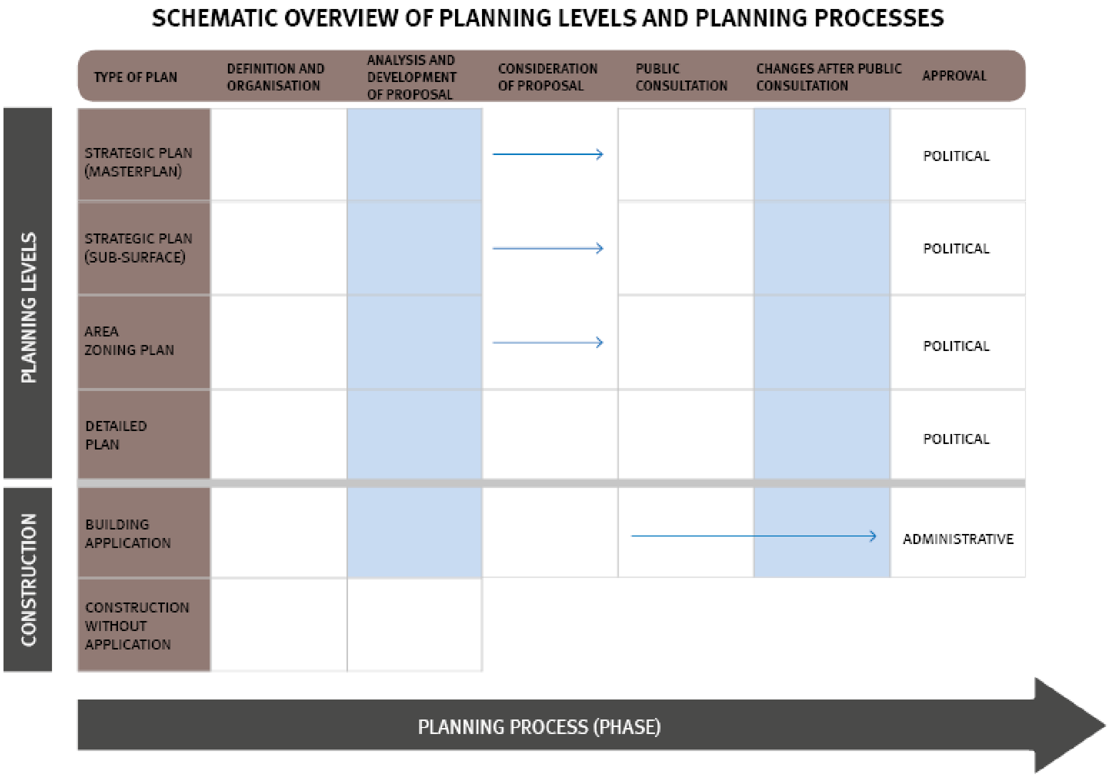

Figure 6. A schematic view over planning levels and planning phases based on the planning regime in Norway. Sub processes in blue represent the need for subsurface information in urban planning. A table that describes what information is needed and at what level was also developed. (Borchgrevink & Eriksson, 2016)

2. How to involve subsurface specialists in urban planning – example from the city of Glasgow.

Developing volumetric development processes, which integrate above ground design with below ground conditions and opportunities, is reliant on new interactions between subsurface specialists (geotechnical engineers, geologists, datasets) and urban planning and design processes. This should take place during not only the design and construction stages of development, but also in early strategic decisions of development processes when planning policy and priorities are outlined, and land use and development priorities mapped out (Bonsor, 2016).

Traditionally, subsurface knowledge is brought into urban development only at project-levels – at planning approval stage, or construction stages – when building design must be approved against ground conditions. Subsurface knowledge and specialists are rarely used to inform earlier strategic decisions about how urban development priorities for improving city resilience, increasing well-being, and lowering carbon growth of cities, should be mapped against land quality and the portfolio of available land and other development within a city. Greater integration of subsurface knowledge and specialists at all stages of the development process, including planning, is essential if cities are to be able to harness below ground opportunities, and realise an integrated above and below volumetric planning process, which can deliver key City Development Plan policy priorities (e.g. unlocking brownfield development; realising lower carbon city; increased city resilience) (Bonsor, 2016).

Developing this new work approach requires transformation of the traditional roles and relationships between institutions, and specialists and decision makers in urban development processes. At a project-level, Business Information Modelling provides one mechanism of doing this, which many cities are now exploring. The inclusion of subsurface data and knowledge within Business Information Models helping to increase the visibility of available subsurface data and knowledge, which above ground project design can utilise. At a city-scale level, the city of Glasgow is examining in detail the knowledge exchange, and new understanding actually required between planning and subsurface specialists, for subsurface data to be appropriately understood and utilised by the strategic development process (Bonsor, 2016). The importance of closing these strategic knowledge gaps and identifying replicable methods for other cities to follow is recognised by the work being funded by a Knowledge Exchange Fellowship by the Natural Environment Research Council, which is seeing a geologist embedded within the Development Plan team of Glasgow city Council for three years. This is enabling very rich and deep understanding of what training, capacity and new knowledge is required to be developed for effective utilisation of subsurface knowledge within the hitherto aboveground development design and planning processes (Bonsor, 2016). Iterative development of understanding through successive pilots of different approaches is being found to be a very successful approach to bridging the knowledge gap.

3. The Swedish Geotechnical Institute's landslide and erosion expertise - an example of national support to strategic and detailed planning

The Swedish Geotechnical Institute (SGI, www.swedgeo.se) is an expert agency that works towards a safe, efficient and sustainable development and sustainable use of land and natural resources.

One way to reduce vulnerability and strengthen societal resilience is to reduce the risk of disaster occurrence and thus mitigate serious consequences. When it comes to disaster risk reduction, the process of physical planning is the most important tool in Sweden to help society avoid placing new developments on ground that may be threatened by natural disasters in the present, or in the future. As a part of this preventive work, The Swedish Geological Institute (SGI) has built up an organization to provide all municipalities and county administrative boards throughout the country with help regarding geotechnical safety issues (e.g. landslides, erosion, mudflows, rock fall and geotechnical issues related to flooding) in the process of physical planning. This includes regular information visits, YouTube seminars (https://www.youtube.com/watch?v=Aldfd98UopU), as well as review of planning documents

4. Communication between urban planners and subsurface specialists – example from Rotterdam municipality

A method has been developed and used in Rotterdam for building projects at different planning levels, as well as for making urban designs and area zoning plans. It has been developed and applied on redevelopment projects in brownfield areas in Rotterdam (the Netherlands), Buggenhout (Belgium) and Gothenburg (Sweden).

Rotterdam municipality started developing the method in 2007. The municipality produced maps in PDF format that transferred sub-surface data into a readily understandable format; so called "2D traffic light maps" that were discussed during workshops between sub-surface specialists and urban planners. According to the municipality, the results depended on initiatives taken by sub-surface specialists instead of a need from urban planners. The method is described in the COST TU1206-WG1-013 report "Rotterdam between cables and Carboniferous" (van Campenhout, 2016).

In 2010, the method was taken a step further in the project *Design with the Subsurface*, with Deltares and TNO. Project teams from the municipality used System Exploration Subsurface and Environment (SEES) to integrate subsurface information into their visions and designs. The methodology was transformed with the Balance 4P project (Norrman et al., 2015) together with Deltares, the Technical University of Delft and Chalmers University of Technology (Sweden). The "methodology" was taken to a higher abstraction level from where various project parts were filled in: GIS; cost/benefit analyses and governance aspects; the 2D approach became 3D; the traffic light maps became 3D seduction maps; and the Subsurface Potential Map was developed. Sketches on how to include the subsurface into area zoning plans were done. Balance 4P suggests a holistic approach to brownfield redevelopment that puts the process in focus.

Results from workshop on strategic planning and considerations of the underground, Ljubljana, 7 September 2016

When planners needs are addressed, focus has mostly been on planning for defined projects (on a level where stakeholders are identified, and cost/benefit analysis can be carried out). Accurate underground information can be of great importance to such plans.

Superior plans (strategic plans) often determine, or at least give guidance to, principles of detailed land use plans. The assumption prior to the workshop was that the use of underground information and consultancy on a strategic planning level is less commonly used than the importance of the outcome of the plan should call for.

To get a deeper understanding of relationships between strategic and detailed planning and the possible shortcomings connected to insufficient considerations of the subsurface when planning on at strategic level, a workshop on strategic planning and the considerations of the underground was organized in September 2016.(Borchgrevink J, Eriksson I. 2016) During the workshop strategic urban planners from Oslo, Gothenburg, Helsinki, Rotterdam, Prague, Vienna and Ljubljana discussed common challenges and solutions.

The main topics discussed were:

- Strategic planning, contents, organization, legislation and decision-making.
- How is underground information currently used on strategic planning levels, and is there potential for improvement?

It was noted that the English terminology used to describe strategic and detailed planning levels varied between countries, and clarification was needed. Though most cities have plans on more than two levels, the discussions were simplified to distinguish between strategic and detailed levels. In some cities (Rotterdam and Vienna), strategic planning is carried out by the province/federal state. Most strategic plans are initiated and approved by politicians.

It was concluded that all information, made available to everybody, at all times, is not the answer. To a great extent the necessary information on various planning levels are questions of scale:

On a strategic planning level, the general need on a rough scale is to be aware of:

- Depth to bedrock (and in some cases nature of bedrock, mining etc.)
- Major soft soil characteristics (landslide, quick clay, contamination)
- Areas where groundwater management can be of importance
- How to include (major) underground constructions

Based on the discussions, the following areas with potential for improvement were discussed and agreed by the participating cities:

- Groundwater management
- Coordination of planned constructions
- Organisation of the shallow subsurface (cables and pipes)
- Clarification of responsibilities
- Economic aspects (private – municipal)
- Improve and coordinate processes
- Create continuity and trust

Helsinki has developed a tool to manage the coordination of planned construction by their Underground Masterplan, established in 2006. The Underground Masterplan stood out as the only successful tool to coordinate management of infrastructure and rock resources among the cities that participated in the workshop. It is described in the Helsinki city study (Ikävalko et al., 2016,TU1206-WG1-007).

Key knowledge gaps

- What is a useful scale for geological and geotechnical information such as landslide hazard maps, depth to bedrock maps, etc. to be used in strategic planning? (Detailed enough to be useful yet easily used and understood by urban planners and decision makers.)
- The role of National Geological Surveys as a support to questions related to strategic planning in the urban sub-surface.
- Experiences from renewals or updates from existing urban subsurface masterplans.
- Examples of financial solutions used to make subsurface information available in strategic planning where guidelines for several unknown projects are set. For example, how the need for digitization, collection of data and production of maps have been financed when there are several unknown stakeholders, both private and public.
- Methods to bring subsurface information into urban planning in cities with little resources such as data, time and/or economical resources.
- The benefit of an extended and intensified usage of geotechnical data for suburban space management. As the interference of new tunnels, metro lines, cultural heritage, underground car parks and buildings sub-levels with existing underground infrastructure is becoming more and more prevalent, collaboration with other users of these data must be investigated.

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Website of the Swedish Geological Institute www.swedgeo.se

2.2 Data acquisition and management

1.1	**Data management**	1.1.1	Specifications
1.1		1.1.2	Online capture, including made ground (anthropogenic)
1.1		1.1.3	Data management (on different scales)
1.1		1.1.4	Data delivery and update
1.1		1.1.5	Data re-use

Figure 7. Extract from table of knowledge levels (Figure 4) showing main topics of relevance to Data acquisition and management subgroup

Key Topics:

Integration of urban datasets, From analogue to digital data, Commercial and public data centre services, Managing permissions and roles

Seen in the urban context

In urban areas, there are many types of subsurface data that are needed during urban planning and during the planning of individual construction projects. The challenges are further complicated by the wide spectrum of stakeholder groups, each with specialist requirements and differing levels of knowledge. Information about the subsurface needs to be made available in ways, which are appropriate to each type of consumer, from a geotechnical engineer carrying out a site investigation, to a member of the public wanting to know if their house is at risk of flooding.

Knowing and understanding the subsurface beneath our cities implies that there is a general need for geological maps and understanding, and locally for very detailed information.

Traditionally, Geological Survey Organizations (GSO's) collect, store, interpret and distribute data and information on the subsurface. They do this typically on a nationwide scale in the context of natural resource exploration, which means that urban areas are often underrepresented in their databases.

City authorities and other stakeholders in urban environments produce and need to access a greater density of geotechnical data than is often the case in lesser populated areas. However, due to lack of organization and non-public data collation - it is often very difficult to collate all relevant information together in ways, which are easy to analyze or communicate.

Due to the densely populated nature of urban environments, there is a **growing need to understand interdisciplinary relationships** between geological properties and human processes. Geological Survey Organisations and other public bodies need to incorporate data from external, sometimes commercial, sources in order to see the whole picture and despite advances in technology, which have resulted in more data being made available in digital formats, there remains a large body of analogue data sources, which are expensive to digitize.

The **increasing volumes and variability of data** generated means that the current labour intensive digitization processes are unsustainable for many cities. In order to **minimize manual processing,** it is necessary for newly acquired data to be captured and communicated between stakeholders using **standardized digital formats** that support automated processing.

Urban needs

Legislation and urban planning priorities differ significantly across Europe but there are common priorities with regards to the types of datasets and technologies that could be used to enhance our understanding of the urban subsurface.

Priority datasets include:

- Geotechnical properties (geology and borehole analysis)
- Groundwater data (modelled and observed)
- Subsurface buildings and Tunnel locations (in three dimensions)
- Piping (e.g. fresh and waste water piping from utilities)
- Pollution information (location, type, history, geochemical properties)
- Land use (historical, current and in some cases future plans)
- Surface water features

The following datasets are also gaining significance across Europe, and beyond. Therefore, we expect them to become higher **priority in the near future:**

- Live, and near live, environmental monitoring sensor data (helping researches to identify significant events in real time as well as model dynamic processes)
- Detailed information about anthropogenic deposits (ideally categorized using communally agreed standards)
- Geothermal /energy well locations and details
- Integrated 3D building and subsurface models (BIM)

In addition, the following **technological priorities** have been widely reported by city partners in the Sub-Urban network:

- Data discovery, data access and cross network data integration services that support collaborative work across urban stakeholder communities
- Decision Support Systems (DSS) that integrate key, city-focused, datasets and models in a single tool
- Automation of processes to digitize analogue data, traditionally a very expensive, labor intensive, task
- Distributed /federated data architectures to support integration of related datasets from multiple sources, securely managed using appropriate authentication and permissions tools.
- Calculating and communicating uncertainty, inherent in subsurface models, is crucial when specialist knowledge is being shared with non-specialists.
- The so-called challenge of 'BIG data' has been raised many times. Stakeholders are concerned about the large and growing data volumes, data variability and fast data update rates, which are particularly relevant in a modern urban environment.

Examples of good practice

The WG2.2 Data Acquisition and Management Subgroup have investigated and documented four of the high priority topics (Watson et al., 2016, TU1206-WG2-003).

1. Integrating urban datasets

Using the software tool GeoScene3D as an exemplar: How to capture, in a single model, multi scaled data covering the key sub urban datasets such as geology, anthropogenic deposits, and infrastructure. Incorporating comments on the range of data source formats and ways in which the often large amount of data can be structured and displayed.

2. From analogue to digital data

Using examples from the Polish Geological Institute: How to develop a set of procedures and systems that will enable the migration from paper and PDF documents towards well-structured datasets. Covering how the work was planned, systems developed and the quality assurance processes refined.

3. Commercial data and public data centre services

Using the example of the geotechnical data format AGS and how the British Geological Survey are developing workflows and systems to enable data sharing between commercial organisations and public sector data centres for the benefit of the city of Glasgow, UK, and its wider conurbation.

4. Managing permissions and roles

Using the experience of the GEUS distributed database systems; this topic will describe the technical architecture and constraints, which are required to administer a system that involved many users of different roles across a range of organisations throughout Denmark.

Key knowledge gaps

In assessing these examples of good practice, the WG2.2 Data Acquisition and Management Subgroup identified the following key recommendations:

- Clarify unclear legislation related to data acquisition and management policies
- Adopt standard naming conventions and use of controlled glossaries
- Develop data exchange and validation tools which are independent of proprietary software
- Maximize use of open data discovery and data access platforms, with low financial and security costs
- More metadata are needed to improve data discovery, explain how to use the data, and communicate any restrictions on their use.

While these recommendations represent the collective opinion of the Subgroup, there is a lack of hard evidence to support these recommendations; financial cost-benefit analysis of implementing such strategies would almost certainly justify greater investment in the wider adoption of these recommendations.

BIG Data is an emerging topic of interest; greater knowledge is required to identify efficient and affordable techniques for collecting, storing and managing the massive datasets required to model urban cities accurately.

There are increasing tensions between stakeholders who have conflicting needs; many would benefit from the trend towards more open and accessible information whilst others have very real security concerns about valuable data being given away, or falling into the hands of malicious users. There is no real widespread understanding of how cities address these conflicting needs.

References

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2.3 3D geological subsurface modelling

2.1	**3D Model development**	2.1.1	Workflows for main modelling software and different city scenarios
2.1		2.1.2	Deterministic modelling, incl. made ground
2.1		2.1.3	Stochastic modelling, incl. made ground
2.1		2.1.4	Model uncertainty
3.1	**Model attribution**	3.1.1	Physical properties e.g. hydraulic conductivity, aquifers
3.1		3.1.2	Chemical properties
3.2	**4D process/time-series modelling**	3.2.1	Groundwater, historical and predictive time series models for aquifer protection, sustainable drainage, effects of climate change
4.1	**Knowledge use**	4.1.1	City case-studies
4.1		4.1.2	Visualisation
4.1		4.1.3	Monitoring
5.1	**Subsurface/above ground linkage**	5.1.1	Building Information modelling (BIM) and CityGML
5.1		5.1.2	Buried infrastructure
5.1		5.1.3	Archaeological/cultural assets

Figure 8. Extract from table of knowledge levels (Figure 4) showing main topics of relevance to the 3D geological subsurface modelling subgroup

Key Topics:

Subsurface modelling, modelling man-made ground, model integration, model maintenance

Seen in the urban context

In many cities across the world, both the challenges and potential uses of the subsurface are gradually becoming an integral part of 3D urban planning. Depending on the planning theme and stage, adequate information is required on the 3D geometry and properties of natural sediments / rocks and man-made deposits at the appropriate level of detail. Both subsurface geometry and properties originate from geological processes, but especially in the urban context, the results of past natural forces have often been subsequently altered by the actions of man. On top of that, the uppermost meters of the subsurface may consist of made ground, in which a range of man-made structures, such as basements, cables and subsurface infrastructure reside.

Today, in more and more countries, geological subsurface modelling is gradually replacing traditional mapping (e.g. Van der Meulen et al., 2013). Most often however, the information needed to create a reliable and useful urban subsurface model is not available within the relevant Geological Survey Organisation, let alone a single database. Different data types have to be combined to construct the model, data density is typically very variable and the data come in an array of different formats and are therefore not readily interoperable. Furthermore, data requirements vary at different stages within the planning process and with the planning issue and scale at stake. Due to the dynamic nature of the urban subsurface, after model delivery regular maintenance is required to prevent the model from quickly being outdated.

Typically, 3D geological subsurface modelling output is not used directly in the urban planning process, but forms the basis for applied models, for example, a geohydrological schematisation to model the effects of groundwater extraction or a geotechnical calculation connected to a building project (see Figure 9). Consequently, the direct user of geological data is typically another subsurface specialist, rather than an urban planner. Ultimately, however, geological property models form a common ground to make sure that all applied models can interact.

Policy theme	Belfast / Londonderry	Bergen	Brno / Olomouc	Dublin / Cork	Glasgow	Helsinki	London	Manchester	Melhus	Nantes	Odense	Oslo	Prague	Rotterdam	Svendborg	Vienna
Hazard management & safety	X	-	X	-	X	X	X	X	X	-	-	-	X	-	-	-
Sustainable development	X	X	-	-	X	X	X	X	X	X	-	X	-	X	-	-
Sustainable energy	-	-	-	-	-	-	-	-	X	-	-	-	-	X	-	X
Climate change (adaptation & mitigation)	-	-	-	X	-	-	X	-	-	-	X	-	-	-	-	-
Ecology & natural protection	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Archaeology / cultural heritage	-	X	X	-	-	-	-	-	-	-	-	-	X	X	-	-
Water management (quality & quantity)	X	X	-	-	X	-	X	X	X	-	X	-	-	-	X	X
Soil management & pollution	-	-	-	X	-	-	-	-	-	X	-	-	X	-	X	X
Underground storage	-	-	X	-	-	-	-	-	-	-	-	-	-	X	-	-
Integral planning (e.g. urban development plans)	-	-	X	X	X	X	X	X	-	X	-	X	X	X	-	-

Figure 9. Relationships of existing European 3D urban subsurface models to policy themes, as based on an inventory of 3D urban subsurface models within the framework of the COST Action Sub-Urban (Schokker et al., 2016). Black crosses indicate a possible link; red crosses indicate a strong relationship

Urban needs

For a city, constructing a 3D geological model is hardly ever a goal in itself. However, a 3D urban-scale model of the geological units and their lithological properties forms a common base for specialised 3D models that contain information on e.g. groundwater, geotechnical or geochemical aspects of the subsurface. Figure 10 shows an example from the city of Vienna. Underlying city needs are very diverse and can be related to any of the policy themes mentioned in Figure 9 and are listed in the remaining Chapters of this report.

Whatever the planner's question or the exact field of application, the urban context demands that a geological subsurface model:

- Can incorporate multiple types of input data from multiple sources and or parties;
- Can cope with huge differences in data density in all three dimensions;
- Can be used at different scale levels;
- Contains information on the extent and properties of man-made deposits;
- Can be combined with above-ground information;
- Has an output format that is understandable by a non-specialist;
- Can be regularly updated; and
- Is being maintained.

We therefore focus on good practices that are related to the construction and maintenance of 3D urban geological models and the modelling of man-made ground.

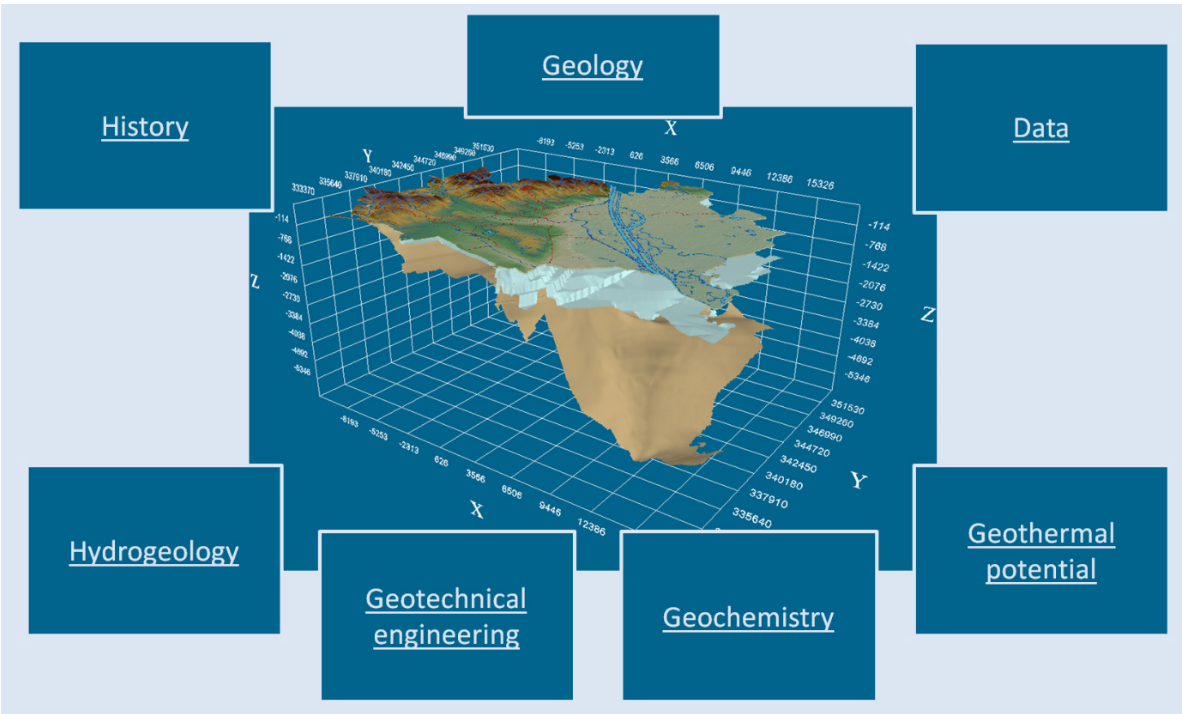

Figure 10. The 3D geological model of Vienna forms the common base for hydrogeological, geotechnical, geochemical and geothermal models of (parts of) the city (modified from Pfleiderer & Hofmann, 2004).

Examples of good practice (Schokker et al., 2016; TU1206-WG2-005)

1. Application of a phased approach in the construction of the 3D geological model

3D geological subsurface modelling is typically complicated and very time-consuming. It is therefore advised to apply a phased approach (Figure 11):

1	**Initial model consideration phase**	• Which types of problems/challenges are related to the man-made ground? • What is the 3D/4D model intended to be used for (overview, urban planning, construction, remediation etc.)? • Who is the end user of the model? • What types of questions should the model be able to answer? • Are data from boreholes, CPTs, excavations, etc. going to be merged with modelling of infrastructure data (modelling of possible infill of excavations around conduits, cables, etc.)? • Do we include man-made subsurface structures (basements, etc.?) as man-made ground? • Which model scale is needed? • Can we accept a model with varying detail? • What is the expected model output for the end-users?
2	**Data evaluation phase**	• Evaluation of data density (existing hard data). Do we have an adequate number of data points and a fair distribution within the model area? • Evaluation of data detail (existing hard data). Does the data detail meet our requirements? • Do we have enough infrastructure data to model the excavation infill? • Do we have enough descriptions of the city development in the past (e.g. historic sources and maps) and enough descriptions on the planned future city development? • Can detailed Digital Elevation Models (DEMs) contribute to the modelling of the man-made ground? • Can geophysical methods be applied in the urban areas (electromagnetic and electric methods, georadar, seismics, etc.)? • Evaluation of data quality. Does the data quality meet our requirements? Are the data from old surveys still usable today? • Are the data sets present in a format that can be used directly or do we need one or more data conversion phases? • Decision on data focus. Use of existing hard data (boreholes, excavations, CPTs, etc.) alone, or in combination with modelling of subsurface/above ground infrastructure data (character of infill)?
3	**Data collection phase**	• Field data acquisition.

		• Conversion of old data to suitable formats. • Collection of third party data (e.g. by buying borehole data from private sources, etc.).
4	**Modelling phase**	• Decision on model type (3D/4D, layer model, voxel/volumetric cells model, use of statistics, etc.). • Decision on model scale. • Combination/merging with existing geological models? • Parameterization of the man-made ground.
5	**Model delivery phase**	• Decisions on how and which parts of the model/data should be accessible to the end-users. • Is tailoring of specific types of output needed? • Teaching the end-user how to use (and not use) the model. • Appropriate communication of model uncertainty.
6	**Update phase**	• Decisions on update cycles and procedures. • Decisions on organizing the ongoing data collection and modelling to keep the model up-to-date (data availability, scientific staff, planners, stakeholders, funding, etc.). • Continuous focus on adding relevant data from new (and maybe unconventional) sources.

Figure 11. Phased approach as applied in the construction of the 3D geological model for the city of Odense (Schokker et al., 2016; TU1206-WG2-005)

2. Constructing and maintaining 3D urban geological models

The 3D geological subsurface model of **Vienna** (Austria) was originally constructed as part of a study to improve existing maps of surface geology as well as to create structural maps of underground geological formations (Pfleiderer & Hofmann, 2004). The Geological Survey of Austria (GBA) carried out the study for the Vienna City Administration, with the objective of extracting the geological information inherent in tens of thousands of borehole logs. Almost as a byproduct, GBA combined all raw data and derived subsurface information to construct a 3D geological model. The city later commissioned GBA to complement the geological model with hydrogeological and geotechnical data and after that to characterize geological modelling units and groundwater with respect to geochemical baseline values. Thus, the geological model became a multi-purpose application in the fields of urban geology, geotechnical engineering, hydrogeology and geochemistry. Recently another aspect has been added to the applications of the Vienna City model by investigating the potential of shallow surface geothermal energy usage within Vienna both for closed-loop systems and for groundwater heat pumps. This study benefitted significantly from the existing 3D model and especially from the knowledge of geological structures, depth to water table and hydrological properties. As such, all applications of the Vienna City model are based on the same geological information and the results can be readily combined. The multi-purpose model is being maintained for the city by GBA.

Glasgow (UK) has been identified by the Scottish Government as a major area of regeneration. Critical in this regeneration is understanding how geology controls issues that affect new developments. The main reason for the construction of the Glasgow model is to understand issues associated with: the siting of buildings in relation to shallow mining and the potential for instability; the thickness and composition of glacial units; and other hazards, such as the movement of industrial contaminants through the subsurface, associated with urban regeneration in a post-industrial city (Campbell et al., 2010). The Glasgow 3D model comprises both bedrock units, and unconsolidated sediments and anthropogenic deposits. Anthropogenic deposits (made ground) represent a combination of made and worked ground, including filled and partially back-filled pits and quarries. As such, anthropogenic and natural subsurface layers are both present, and have been modelled in considerable detail. The Glasgow Conurbation geological model was designed for use by a range of end-users, including practitioners, and has been released through the ASK (Accessing Subsurface Knowledge) Network, which was developed by the British Geological Survey (BGS) and Glasgow City Council (GCC), with support from other partners in the public and private sectors. Its main aim is to make geological data more readily available to consultants, contractors, local and regulatory authorities, and researchers, to help reduce the cost of ground investigation when delivering successful construction and regeneration projects, and to encourage further innovation and research. Higher resolution versions of some parts of the model have been prepared, where a specific need has been highlighted (e.g. regeneration and development areas, and linear transport and other infrastructure corridors). A lower resolution catchment-scale model of the River Clyde, which passes through the centre of Glasgow, has also been developed for groundwater modelling, etc.. The 3D model is also designed to fit within the British Geological Survey's National Geological Model, which is a multi-scalar, geospatial model of the subsurface arrangement of the rocks and sediments of the UK.

3. Modelling man-made ground

Climate change and man-induced changes in the water cycle will create increasing stress on existing urban run-off systems. The municipality of **Odense** (Denmark) therefore needed a tool to be able to handle the water cycle of the city in the future and to calculate probable scenarios and be able to address the changes in due time. A vital part of this tool is the physical framework - a 3D geological model of the subsurface that visualises the aquifers and aquitards. This model of the physical framework had to be constructed before the hydrological modelling was initiated. As large volumes of the city's subsurface have been and are being reworked and altered as part of urban activities, the man-made parts of the subsurface play a vital role in the hydrological cycle. In realising this, mapping and modelling of the subsurface of Odense needed to include mapping and modelling of the man-made component of the subsurface. The approach adopted was to: identify the series of main events that have affected the upper part of the subsurface (e.g. digging and infilling of trenches for sewers, water pipes and power cables); order these chronologically; decide which ones to include in the mapping and use the events as proxies for the extent and physical properties of the man-made layers. The Municipality of Odense, VCS Denmark waterworks, private companies and the Geological Survey of Denmark and Greenland (GEUS) collaborated to construct the 3D geological/hydrogeological model. The results of the Odense project are a hydro stratigraphic model that can be used at different scales, and a tool targeted at mapping and modelling of the man-made layers. The final off-the-shelf product is a standard hydro stratigraphic model with surfaces in a 100 m grid (Mielby et al., 2015).

Anthropogenic processes and deposits include a wide ranging from archaeological activities to modern urban development. The city of **Bergen** (Norway) is an example where both buried heritage and standing monuments are of prime significance. The subsurface in the whole city centre is characterised by significant thicknesses of anthropogenic deposits up to 1000 years old with high archaeological value. These so-called archaeological deposits are "sandwiched" between the natural geological deposits below, and the modern man-made deposits of various compositions above. Deterioration of organic material often occurs as a consequence of lowering of the groundwater level, which make archaeological deposits such as those in Bergen particularly vulnerable. A main goal for the medieval centre of Bergen is therefore to establish a stable hydrological environment. A 3D geological model provides a framework for the integration of other spatial and process models to help assess the preservation potential for Bergen's buried heritage. At the World Heritage Site of Bryggen, the Geological Survey of Norway (NGU) constructed such a 3D geological model in conjunction with a numerical groundwater flow model (De Beer et al., 2012).

Key knowledge gaps

- The complexity of the urban subsurface, including man-made ground, combined with the level of detail of information asked for in many urban planning issues, and the difficulties involved in collecting new data in a city environment, demand that geologists look beyond their traditional data sources (e.g. borehole descriptions, shallow geophysics) and use data from third parties. However, the integration and "translation" of all of the different data sources into one model workflow is currently very time-consuming and case-specific.
- Combined 3D property modelling of the small-scale heterogeneity of man-made deposits and natural deposits requires new modelling approaches. The combined approach used in Odense looks promising, but has yet to be tested in other cities.
- The properties and functions of the urban subsurface are subject to frequent alterations, making models quickly out-of-date. Management of the shallow urban subsurface requires model tools that can be frequently updated to reflect the current situation (e.g. in conjunction with hazard management) or can quickly incorporate additional information. Currently, there are no general workflows available that enable quick model update.
- There is a need for dynamic (4D) urban subsurface models that can be used for real-time monitoring and incorporation of time-series data on subsurface properties, e.g. in conjunction with cultural heritage management or monitoring building activities.
- At the present time, shallow subsurface models are largely constructed on an *ad hoc* basis when a subsurface-related problem occurs. It would be much more cost-effective if one geological framework model were available, that formed a common basis for the various kinds of dedicated models of parts of the city. Apart from being actively maintained, a framework model would have to be scalable (5D), in order to be of real use.
- To give subsurface information a firm position in urban planning and management, geological information will have to be presented in the right format, and at the right time. It should also possible to incorporate the subsurface infrastructure and to combine the model with aboveground information. At present, there are no good examples of a truly integrated modelling approach that extends both above and below the surface.

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2.4a Groundwater monitoring and modelling

3.1	**Model attribution**	3.1.1	Physical properties e.g. hydraulic conductivity, aquifers
3.1		3.1.2	Chemical properties
3.2	**4D process/time-series modelling**	3.2.1	Groundwater, historical and predictive time series models for aquifer protection, sustainable drainage, effects of climate change
4.1	**Knowledge use**	4.1.1	City case-studies
4.1		4.1.2	Visualisation
4.1		4.1.3	Monitoring
5.1	**Subsurface/above ground linkage**	5.1.1	Building Information modelling (BIM) and CityGML
5.1		5.1.2	Buried infrastructure
5.1		5.1.3	Archaeological/cultural assets
5.2	**Incorporation in Decision making tools**	5.2.1	Volumetric planning
5.2		5.2.1	Ecosystem services stewardship
5.2		5.2.2	Aquifer vulnerability/groundwater protection

Figure 12. Extract from table of knowledge levels (Figure 4) showing the main topics of relevance to the groundwater monitoring and modelling subgroup

Key Topics:

Soil moisture/groundwater level as environmental indicator, Design of monitoring, Design of modelling of urban scenarios

Seen in the urban context

For subsurface opportunities such as groundwater to be realized and utilized to greatest effect to support future cities, subsurface resources must be understood appropriately by city planners (GCC, 2012). To supply this understanding to city municipalities and their stakeholders in urban development, geological survey organisations and/or research institutes/researchers must have robust datasets of groundwater resources at city-scale, from which they can develop relevant, appropriate knowledge and derived understanding for city municipalities and their stakeholders, and for informed strategic decisions within city planning. 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, and are essential to ensure that robust data and knowledge are generated of the key urban resources of groundwater and heat.

This chapter provides an initial review of existing examples of good practice in Europe with respect to groundwater monitoring and modelling, so that other cities may build and develop on these across Europe. In reality, there is a broad range of good practice that has been/is being achieved in cities across Europe. Some cities have very good groundwater datasets and monitoring, and these data are transferred and utilized 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. In some cities, however, there are few subsurface environmental data available, and planning processes often largely omit consideration of the subsurface.

Urban needs

Cities must be able to understand their underlying groundwater resource not only to be able to utilize and manage the resource, but also to understand how the groundwater resource is changing through time in response to pressures of climate and increased urbanization. There is also the vital need to understand how the resource is one the one hand impacted on, and also what it in turn impacts on, and particularly subsurface urban infrastructure (sewers, pavements and buildings).

Climatic variability and extreme weather events are predicted to increase in both magnitude and frequency over the coming decades. At the same time, urban growth is projected to increase significantly, adding pressures on: drainage and the likelihood of flooding, including the role of groundwater flooding; opportunities to use resources (water supply, shallow geothermal energy). Further important considerations for all cities, and not only those dependent on groundwater for public water supply or industry, include: mitigating against the flooding of basements of houses; understanding where infiltration sustainable drainage schemes are appropriate to alleviate pressure on drainage infrastructure; and understanding the interaction of competing uses of the groundwater resource (e.g. increasing the density of ground source heat schemes). All of these have a cumulative downstream effect. Monitoring of water-table changes in response to climatic events, and also interaction with subsurface infrastructure are essential to provide relevant knowledge and understanding for city planning.

Under these broad needs for understanding urban groundwater resources, there is a large range of specific drivers for groundwater monitoring, at city-scales. These include, but are not restricted, to the needs 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 previously used, or managed the groundwater resource (e.g. cities which do not have issues with flooding or shallow groundwater-levels, and cities which have not historically used groundwater for drinking water supply)
- protect the groundwater resource from over-abstraction, stop abstraction and contamination – especially if used for public water supply
- manage flooding (including flooding of basements)

- manage and redevelop contaminated soil and land in general
- manage and regulate increasing use of shallow geothermal heat resources – both for heating and cooling.

Understanding the depth to the water-table in a city is a key dataset required to inform these strategic decisions. Without these data and knowledge, building foundation design, appropriate use of infiltration schemes, and utilization and management of shallow geothermal energy schemes and private and public water supplies in an urban conurbation are very difficult, and unnecessarily costly. Monitoring groundwater-levels within urban areas is also essential if city managers are to be aware of, and able to mitigate, the downstream impacts of the uses of these subsurface resources in other parts of the city.

Cities, which have historically relied on groundwater abstraction for industry or public water supply generally, have a large amount of this groundwater monitoring data and monitoring infrastructure at the city-scale. In these cities, monitoring networks must be systemized and revised to ensure they are of an appropriate design and spatial distribution for current monitoring drivers (e.g. Water Framework Directive), rather than the historical ones.

In cities, which have had traditionally, very little historical use of the urban groundwater, there are typically very few monitoring data or associated monitoring infrastructure. Here, monitoring must be focused, and cost-effective, in order to provide regulators and city authorities a general and basic understanding of the main characteristics of the groundwater resource – e.g. the depth to groundwater across the city.

Examples of good practice

Whilst different data and monitoring network designs are required for different monitoring objectives, there are guiding principles of good practice.

In **designing urban groundwater monitoring networks,** one must start at the back of the process: what kind of information is needed, and how often should it be updated? Different drivers and requirements for groundwater monitoring, demand different resolutions of data – Figure 13.

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 – Figure 14.

Often, a single monitoring network cannot capture all of the required data, and several different dedicated monitoring networks need to be designed individually for each monitoring objective – e.g. a high resolution network (spatially and temporally) is required for monitoring groundwater-levels for flood risk, and a separate lower resolution network is required to understand and characterize the resource to meet the requirements of Water Framework Legislation. Different networks can, though, be combined into an integrated groundwater monitoring network.

Re-design and systemization 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). Prior to the review of the city monitoring, the network consisted of over 2000 monitoring points. An agreed groundwater model, a conceptual understanding of the urban groundwater resource, was used by the city municipality, the State Geological Survey (BSU) and the public water supply utility company Hamburg Wasser) to identify where higher/lower monitoring density was required according to: the location of public supply well fields, known competing uses; 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 stakeholders' groundwater data (often held in different formats) having to be systemized and collated before the city analysis and review could be undertaken. Monitoring points of highest construction quality, known age, operation performance and location in the aquifer – were retained – boreholes which gave lower quality data, or which had costly operation costs, and poor performance were de-commissioned.

The revised monitoring network now contains only 650 monitoring points, of which 45 are required to meet the needs of the Water Framework Directive (WFD).

Municipality	Main monitoring objective	Number of wells	outreach
dam	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

Figure 13. Different drivers and requirements for groundwater monitoring, demand different resolutions of data; monitoring objectives; and density in a number of Dutch cities and municipalities

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.

↓

Analyze 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, flooding 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.

Figure 14. Key elements of good practice in the design of groundwater monitoring networks

Very similar guiding principles exist for **construction and execution of groundwater modelling** as for observational monitoring networks:

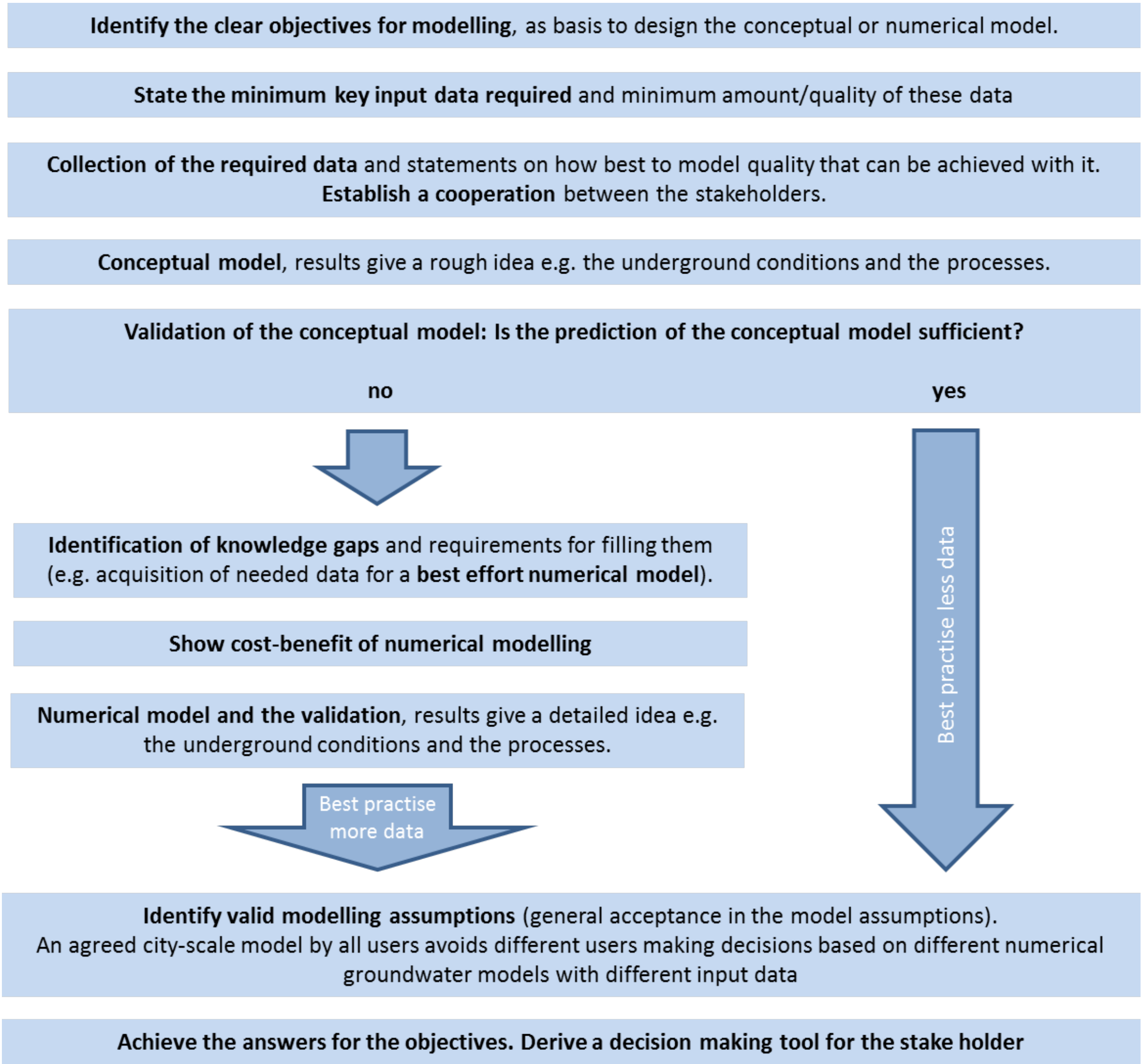

Figure 15. Generalised good practice workflows for development of groundwater models in urban areas with differing data availability

Some city case studies of good practice are (Bonsor et al., 2015, TU1206-WG2-006):

1. Groundwater modelling used to support city planning and management of subsurface resources

The groundwater model was developed by the city's public Water Supply Company (**Hamburg** Wasser, Germany) in collaboration with the State Geological Survey (BSU) in the city municipality. The BSU 3D geological model was used to inform the geometry and stratigraphy of the aquifer. The BSU model is based on approximately 200 000 coded boreholes. The 3D numerical groundwater model was developed with SPRING (delta-h) software to parameterize this geological framework with the city's extensive groundwater monitoring data (Bricker et al, 2013). Essential to this was the integration of both public and private datasets available within the city. This was used 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 management of groundwater catchment protection areas.

2. Integrating subsurface infrastructure to city-scale groundwater recharge and flow modelling – to better understand the impacts and interaction of the infrastructure to the urban groundwater resource

The city of **Bucharest** (Romania)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 on and altered by subsurface infrastructure (Boukhemacha et al, 2015). This model incorporates the available monitoring network data in the city, and as such, Bucharest also provides an example of good practice in using and translating groundwater monitoring to support decision-making and management of the city's groundwater resource.

3. 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 (Janža, 2015). This DSS integrates groundwater monitoring data with geological and hydrogeological data, to inform the water utility company and regulators when appropriate remediation actions are needed to protect the city's groundwater-sourced public water supply in the event of a contamination event. The groundwater model is based on the MIKE SHE/MIKE 11 modelling 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.

Key knowledge gaps

Critical knowledge gaps, which limit modelling capabilities and the capacity to implement best practices in groundwater monitoring network design and use – include:

- In many cities/countries there is no formal legislation or regulation on specification of monitoring infrastructure
- Significantly difficulty in designing appropriate and representative groundwater monitoring networks, in cities which have very little historical groundwater data or understanding of the urban groundwater resource, and no existing network infrastructure
- Urban groundwater monitoring systems have been developed over time and are ad-hoc, and do not capture appropriate data for current monitoring needs
- Lack of understanding of aquifer properties of man-made (artificial) deposits and subsurface infrastructure, and how these should be appropriately modelled in 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

The value of good practice to develop robust, systematic, groundwater 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. Fundamental knowledge and communication gaps between subsurface environmental specialists and city planners, generally leads to the subsurface being overlooked in urban planning processes (Lavoie et al., 2013). Geological Survey Organisations have a key role to play in providing appropriate data and knowledge to underpin appropriate management of groundwater resources within city planning to ensure the resource can be utilised effectively, and sustainably, to support future cities, and bridge the current and fundamental knowledge gap.

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2.4b Geothermal monitoring and modelling

2.1	3D Model development	2.1.4	Model uncertainty
3.1	Model attribution	3.1.1	Physical properties e.g. hydraulic conductivity, aquifers
3.1		3.1.2	Chemical properties
3.2	4D process/time-series modelling	3.2.1	Groundwater, historical and predictive time series models for aquifer protection, sustainable drainage, effects of climate change
4.1	Knowledge use	4.1.1	City case-studies
4.1		4.1.2	Visualisation
4.1		4.1.3	Monitoring
5.1	Subsurface/above ground linkage	5.1.1	Building Information modelling (BIM) and CityGML
5.1		5.1.2	Buried infrastructure
5.1		5.1.3	Archaeological/cultural assets
5.2	Incorporation in Decision making tools	5.2.1	Volumetric planning
5.2		5.2.1	Ecosystem services stewardship
5.2		5.2.2	Aquifer vulnerability/groundwater protection
5.2		5.2.3	Thermal and other mineral resource extraction and storage

Figure 16. Extract from table of knowledge levels (Figure 4) showing the main topics of relevance to Geothermal monitoring and modelling subgroup

Key Topics:

Temperature level as an environmental indicator, Design of monitoring, Design of modelling of urban scenarios

Seen in the urban context

The use of Shallow Geothermal Energy (SGE) provides a major opportunity for urban areas to meet their 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 (for both heating and cooling) can, however, place significant pressure on urban aquifers if exploitation of the resource is not effectively planned, and particularly if there are competing uses of the groundwater resource. If inadequately managed, SGE use can lead to changes in both groundwater levels, temperature and groundwater quality. These have wider implications, and the utilization of the SGE resource in urban areas must be integrated with above ground spatial planning priorities if the resource is to be utilized sustainably and to greatest benefit. A classic example of this can be seen from the Netherlands, where increased use of SGE schemes in urban areas led to rises in groundwater temperature and subsequent increases in microbial populations in groundwater in some cities have led to significant decay of wooden building piles in heritage areas, leading to building subsidence and damage.

This review focuses on SGE, where 'shallow' is defined as < 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), Borehole Thermal Energy Storage (BTES) and open systems Aquifer Thermal Energy Storage (ATES). Whilst single closed loop systems are the most prevalent system used to exploit SGE in many cities within Europe, other systems may become increasingly important in the future, as cities increasingly look to use SGE for much larger district-heating schemes. This review therefore does not focus on any one technology as such, and the key elements of good practice in SGE monitoring and regulation reviewed are independent of the choice of technology.

Europe is a wide area with large differences in geology, groundwater, and SGE resources contained within these geological environments. Cities underlain by consolidated sedimentary bedrock geology offer the greatest SGE potential, but Crystalline Basement geological environments, and unconsolidated Quaternary geology also offer SGE potential – in these environments the saturated thickness and presence of fracture zones, become very important. Cities underlain by layered geology, in which different horizons are separated by sealing clay horizons, present excellent opportunities for multiple uses of the different groundwater resources. If appropriately developed, 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 that the separating aquitard should not be penetrated more than necessary with drilling to ensure the two aquifers remain isolated.

Urban needs

There is a clear need for good practice in the use and management of SGE to ensure that the SGE resource is managed sustainably alongside the many other competing uses of the subsurface in urban areas. In the future, a higher density of geothermal use will lead to unavoidable conflicts between neighboring sites and other uses 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 of "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).

Key planning needs for monitoring and modelling of SGE resources in cities, are to improve understanding of the resource – its opportunities and risks in relation to the following points:

- 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 the 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 such as buildings and tunnels, ecosystems)?
- How many, and what density of SGE heat schemes can be sustainable in an area?
- Potential interference of SGE schemes with existing subsurface infrastructure (tunnels, sewage networks) and heritage buildings.

Drivers and barriers to SGE use in urban areas - Whilst SGE offers a significant potential resource to cities 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. Common drivers for SGE use are:

- government subsidies and financial profit incentives
- national renewable energy targets which the 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 (Ground Source Heat Pumps)
- strict regulation of SGE use – time and cost, and the high level of site investigation required

Having a clear and appropriate level of SGE regulation and legislation is seen to be 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.

Examples of good practice

Key elements of good practice for SGE use and management in urban areas center on the: 1) planning of SGE use in urban areas; 2) monitoring and operation of SGE; 3) regulation; and 4) thermal waste management. At a generic level, to assess the influence of SGE systems on urban groundwater flow and thermal regimes, Ground Water Bodies should include each of the work steps in Figure 17. This builds on work to develop good practice of shallow geothermal assessment in the cities of Basel and Zaragoza (Epting et al., 2013; Epting and Huggenberger, 2013; García Gil et al., 2014).

This highlights that planning of SGE use, or the continued monitoring and operation of SGE need to be based on a significant knowledge base of the urban groundwater and SGE resource.

Regulation of SGE schemes can be done at national, regional, or local levels; and detailed requirements depend on the geological and urban settings, conflicting interests and the SGE opportunities in the area.

There is a large disparity in legislation and regulation with regard to SGE use in Europe. In almost all countries, legislation only extends to open system/loop SGE; closed system/loop SGE are regulated to varying amounts but non-legislatively. Generally closed loop systems are regulated only by separation distance. The Netherlands is one of only a few countries to regulate closed SGE, using both separation distance and 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 the basis of 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, planning permission has been required since 2012, even for single loop closed systems in urban areas. This is to try to ensure authorities and city municipalities are aware of the number and proximity of SGE schemes operating within urban areas, so that any negative impacts of rising groundwater temperatures, changes to groundwater ecology and subsurface heritage can be mitigated.

1	At a ***planning*** *stage* for SGE	• 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
2	For appropriate level of ***monitoring*** of SGE operation and impacts	• groundwater levels • groundwater temperature (from top to bottom to get temperature profiles – and also upstream and downstream of the GSHP point) • abstraction and re-injection temperatures • pumping rates and volumes (extraction and reinjection sites)
3	For good practice in ***regulation*** of individual SGE schemes, to minimise neighbouring, and collective, impacts of the schemes	• 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, se RE-GEOCITIES Database Handbook)

Figure 17. Data and good practice required to support management of SGE

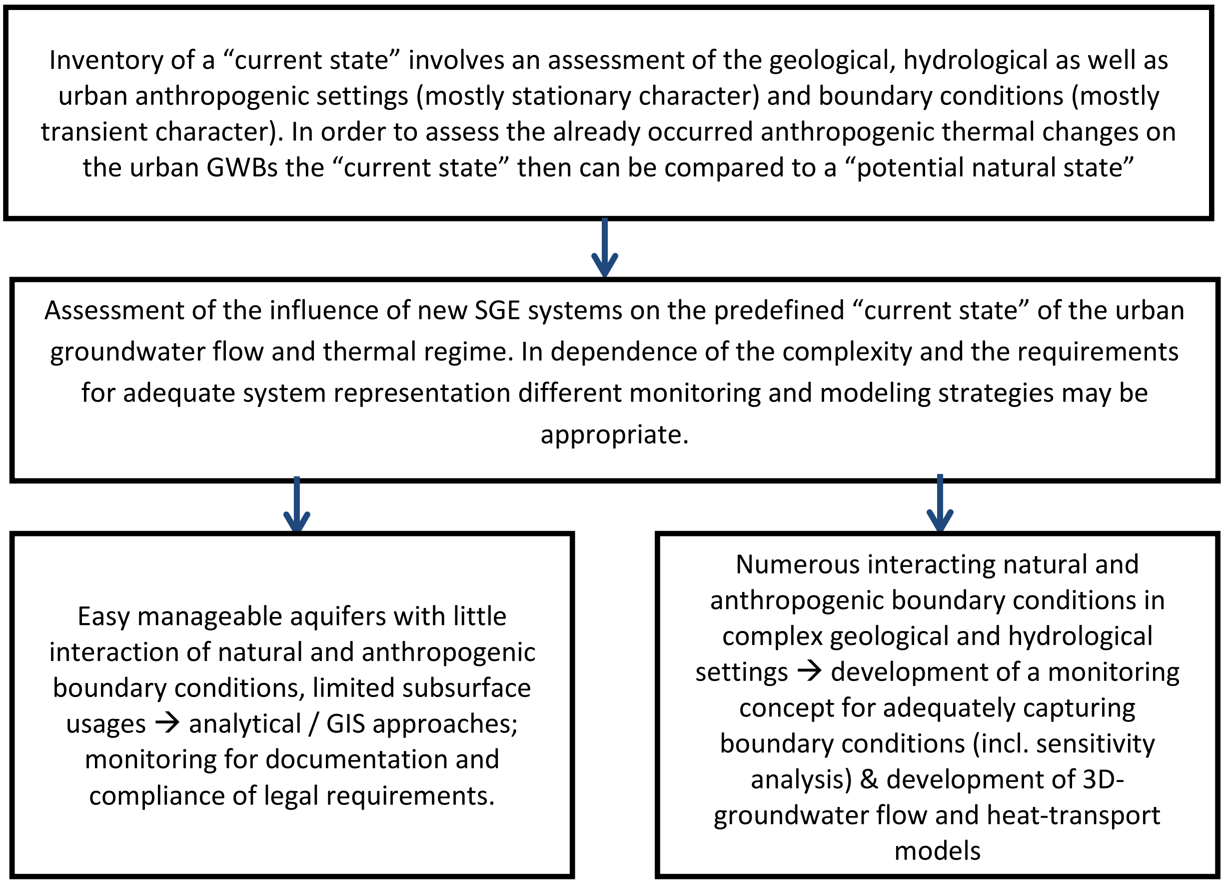

Figure 18. Work steps in good practice to assess the influence of SGE systems on urban groundwater flow and thermal regimes, using groundwater model or water balance approaches.

Some city examples of good practice include (Bonsor et al., 2015, TU1206-WG2-006):

1. Monitoring and modelling

Groundwater monitoring data, from a high-resolution monitoring network in the city of **Zaragoza** (Spain) 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 there is increasing concern over the collective impact on raising the groundwater resource temperature in the urban area, and therefore the need to regulate and manage the thermal resource.

Modelling work, using the high-resolution monitoring data, has enabled the strength of the hydraulic connectivity between the river and the groundwater resource to be better understood, alongside what thermal impact seasonal flood events have on the groundwater resource. As a result, "cold" winter floods and the interaction with geothermal installations can now be utilised by the regulators to enable enhanced thermal management of the aquifer. This management is essential to enable increasing use of geothermal energy in the city, without negative impact.

Zaragoza also forms an example of a potential first approach to standardize the concession of new geothermal exploitation installations (García-Gil et al, 2015). 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.

2. Anthropogenic influence and monitoring

The city of **Basel** (Switzerland) 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 affected the aquifer and groundwater resource. The work has placed specific emphasis on 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 groundwater body that was investigated enabled guidelines to be provided, as well as a suitability map to be developed for the relevant authorities for geothermal subsurface use 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 occurred, and without thermal groundwater use.

Key knowledge gaps

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

- How can a series of 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)?
- How can these complexities be communicated and included in city planning?
- To what degree can 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?

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2.5 Geotechnical modelling and hazards

3.1	**Model attribution**	3.1.1	Physical properties e.g. hydraulic conductivity, aquifers
3.1		3.1.2	Chemical properties
5.1	**Subsurface/above ground linkage**	5.1.1	Building Information modelling (BIM) and CityGML
5.1		5.1.2	Buried infrastructure
5.1		5.1.3	Archaeological/cultural assets
5.2	**Incorporation in Decision making tools**	5.2.1	Volumetric planning
5.2		5.2.1	Ecosystem services stewardship
5.2		5.2.2	Aquifer vulnerability/groundwater protection
5.2		5.2.3	Thermal and other mineral resource extraction and storage
5.2		5.2.4	Ground stability and foundation conditions
5.2		5.2.5	Risk management in development/construction
5.2		5.2.6	Protection of cultural heritage
5.2		5.2.7	Hazard identification and risk management
5.2		5.2.8	Burial of services and development of subsurface infrastructure, including underground transport, storage and waste disposal

Figure 19. Extract from table of knowledge levels (Figure 4) showing main topics of relevance to the Geotechnical modelling and hazards subgroup

Key Topics:

Increased use of existing subsurface knowledge, geotechnical data, geotechnical modelling, Landslide monitoring and Subsidence

Seen in the urban context

Geotechnical modelling is very important for managing construction and other uses of the subsurface of our cities. Geotechnical data are essential for this, and they include not only borehole profiles, but also a large number of geotechnical field investigation results and laboratory test data. The huge array of geotechnical testing methods (including most common field tests such as: CPT, DMT, SPT, DP, PMT, FVT as well as specific laboratory tests: for example, TXT, OED, BET, permeability and organic content) make up the number of parameters necessary to fully characterize the city subsurface.

The data from geotechnical investigations improve and extend the basic geological interpretations, based on lithology and stratigraphy, and enable more advanced modelling of urban subsoils for construction purposes. Geotechnical boreholes and cone penetration tests (CPT,being one of the most popular geotechnical field test methods) are mostly shallow, down to an average of 30 m below surface. Therefore, they characterise geotechnical only the uppermost layers of the geological profile. However, in association with associated data including in situ and laboratory parameters, they are very valuable for parametric 2D and 3D modelling of the urban subsurface that is/has been affected by construction activities and soil-structure interaction.

The rapid growth of urban areas, and the constant development of city infrastructure, necessitates better understanding of underground space. Across Europe, the urban subsurface is usually taken into consideration in the planning process, but awareness of the importance of knowledge about the subsurface and geohazards among city planners and stakeholders still needs to be increased. This includes the need for greater consideration of subsurface information in City Master plans, if geological and geotechnical problems are to be anticipated, and more realistic construction timeframes and budgets are to be developed.

Main sources of information about the city subsurface are the databases, maps and geological models maintained by Geological Survey Organisations in the main. Such databases also contain information and maps of geohazards. Other sources of relevant information include archives held by municipalities, some of which have their own own borehole records, maps and databases. In city areas, there is also a considerable volume of data about underground space held in form of geotechnical data. The geotechnical data are typically “site specific”, and are gathered for specific construction projects. This kind of subsurface data is collected mostly by commercial companies, is generally not readily available to meet the needs of municipalities (e.g. for master planning, cultural heritage, road- and railway building) and/or Geological Survey Organisations (e.g. for the development of maps and geological models). Efficient use of geotechnical data for city scale modelling is often prevented by its restricted availability.

City spatial planning must also take into account areas of **existing and potential geohazards**. Areas with geological instability have a tendency to reveal themselves during the construction process or during ground investigation. Overlooking the potential for geohazards during spatial planning may lead to serious repercussions (e.g. large material losses, damage to city infrastructure and even injuries and death). The destructive force of geohazards can be extremely very high, although their occurrence is local and often periodic.

There is often considerable information and knowledge about geohazards available in the databases and inventories of national Geological Survey Organisations, and this should be taken into account during spatial planning. However, the awareness of the potential impact of geological hazards amongst planners and stakeholders is often relatively low, so that city plans often fail to take account of this issue or cover it only in a limited way.

Therefore, incorporating geohazards into mapping and 3D modelling is one of the most important issues to address if safe and effective urban development/planning are to be achieved. Since there are already existing recommendations, methodologies and tools for dealing with landslide hazards, it is rather the intention of this report to bring to the attention of urban planners, the importance of geohazards during urban spatial planning.

Urban needs

There is a great need to extend and intensify the use of geotechnical data for modelling and management of suburban space. The impingement of new on existing city infrastructure (tunnels, metro lines, underground car parks, and high-rise buildings sub levels) is becoming more and more commonplace, and therefore, the use of geotechnical data and consideration of geohazards on a city scale geological modelling is increasingly necessary.

Geotechnical data are collected mostly during commercial/private projects, so they are often not readily available for use by the municipality, unless there is legislation in place to require the data to be made available (e.g. in relation to the National Key Register (BRO) in the Netherlands, and in national/state legislation in Germany) or there is a prevailing culture of data sharing (e.g. the ASK network in the Glasgow area (UK)). Also, as geotechnical databases are often hosted by widely differing entities (public bodies such as Geological Survey Organisations, or private sector construction, industry and infrastructure companies) the data are likely to be kept in many different locations (archives, repositories and local databases) and in formats which are not interoperable. Another barrier towards greater use of geotechnical data for modelling purposes is the basis of ownership and legal status of the geotechnical data. Hence, many important geotechnical data are not available for wider use/re-use.

Effective use of geotechnical data and geotechnical models will require robust solutions for enabling data exchange between the data providers (private companies), and those who need access to the data (e.g. municipalities and geological surveys). Such solutions must bring mutual benefits to all interested parties, as geotechnical laboratory and in situ tests are expensive and their results represent valuable intellectual property of the companies. Companies must therefore see the benefit of sharing their data.

Geotechnical models and databases can be of significant use for:

- Preliminary investigation of the subsoil/soil prior to in situ testing (desk studies, geological risk analysis)
- Planning and interpretation of in situ tests (and subsequent lab tests)
- Reporting of raw data (for modelling and implementation in GIS and BIM systems)
- Advanced use of data and policy making (by experts and city planners)
- Communication and increased understanding of the importance of city subsurface.

Another key issue to assure safe and smart city development is to identify **the full scope of geohazards** and consider them in city planning and geological modelling, to increase public awareness.

A natural hazard is a natural process or phenomenon that may cause loss of life, injury or other impacts, property damage, lost livelihoods and services, social and economic disruption, or environmental damage. The Council of the European Union – Commission Staff Working Paper – Risk Assessment and Mapping Guidelines for Disaster Management defines two basic terms:

- Geohazard (Geological hazard) - A geological process with the potential to cause harm.
- Risk - The likelihood that the harm from a particular hazard will be realised.

To allow practical implementation of geohazard risk assessment and mapping on a city scale, a multi-hazard and multi-risk approach is necessary. All types of natural hazards should be analysed and identified. The comprehensive list of geohazards (according to PanGeo Project 7FP, 2013) is shown in Figure 20. Also, geohazards such as flash flood and groundwater flooding areas should be taken into consideration.

City planners can utilize this information to properly manage city infrastructure development. Spatial plans concerning geohazard areas can give citizens and investors valuable information on their occurrence. This information could be of considerable value to developers at very early stages in their planning of developments for example, but it could also affect the value of land, and existing houses. Such information would though enable more informed choice of design methods and monitoring systems for construction activities.

Considerable opportunities for geohazards identification are provided by remote sensing methods, including satellite imagery (Landsat, Iconos, etc.) and satellite interferometry (e.g. InSAR – interferometry satellite aperture radar).

1	**Deep Ground Motions**	1.1	Earthquake (seismic hazard)
		1.2	Tectonic Movement
		1.3	Salt Tectonics
		1.4	Volcanic Inflation / Deflation
2	**Natural Ground Instability**	2.1	Land Slide
		2.2	Soil Creep
		2.3	Ground Dissolution
		2.4	Collapsible Ground
		2.5	Running Sand / Liquefaction
3	**Natural Ground Movement**	3.1	Shrink-Swell Clays
		3.2	Compressible Ground
4	**Man Made (Anthropogenic) Ground Instability**	4.1	Ground Water Management Shallow Compaction
		4.2	Ground Water Management Peat Oxidation
		4.3	Groundwater Abstraction
		4.4	Mining
		4.5	Underground Construction
		4.6	Made Ground
		4.7	Oil and Gas Production

Figure 20. Geohazards inventory according to the PanGeo Project, http://www.pangeoproject.eu (PanGeo 7FP 2013)

Eventually, geohazard identification will lead to better management of the hazard and risk and planners/decision makers will be able to decide whether to block developments in selected areas, to mitigate the risk, which will enable safe construction, or to prepare early warning systems for specific situations, where higher level of risk can be accepted.

Examples of good practice

To present examples of good practice in the use of the geotechnical models, databases and geohazard inventories in relation to city subsurface management, three examples have been chosen. More case studies and description of this topic are presented in the detailed subgroup report (WG2.5) available on the COST Sub-Urban website (www.Sub-Urban.eu).

1. Geotechnical databases

The mission of DOV is to structure and manage all data and information concerning the soil and subsoil of Flanders and make them widely available. DOV is a geotechnical database (see DOV), intended as a platform to foster for cooperation between partners. The data and information concerning the soil and subsoil of Flanders are made available in an integrated way, and are supported by controls and reporting on their quality.

The data in DOV originate from the activities of DOV's private sector partners. The data relate to geology, geotechnics, groundwater and soil. Since 2013, geothermal data have been added to DOV.

The geological information in the database include drillings, lab tests, geological interpretations (Quaternary, Neogene-Paleogene (Tertiary), Cretaceous, faults), 3D mapping (see Figure 21), related drill logs and lab test data, etc. The geotechnical information in the database include drilling data, cone penetration tests, geotechnical laboratory tests, and other geotechnical interpretations, thematic maps, etc.

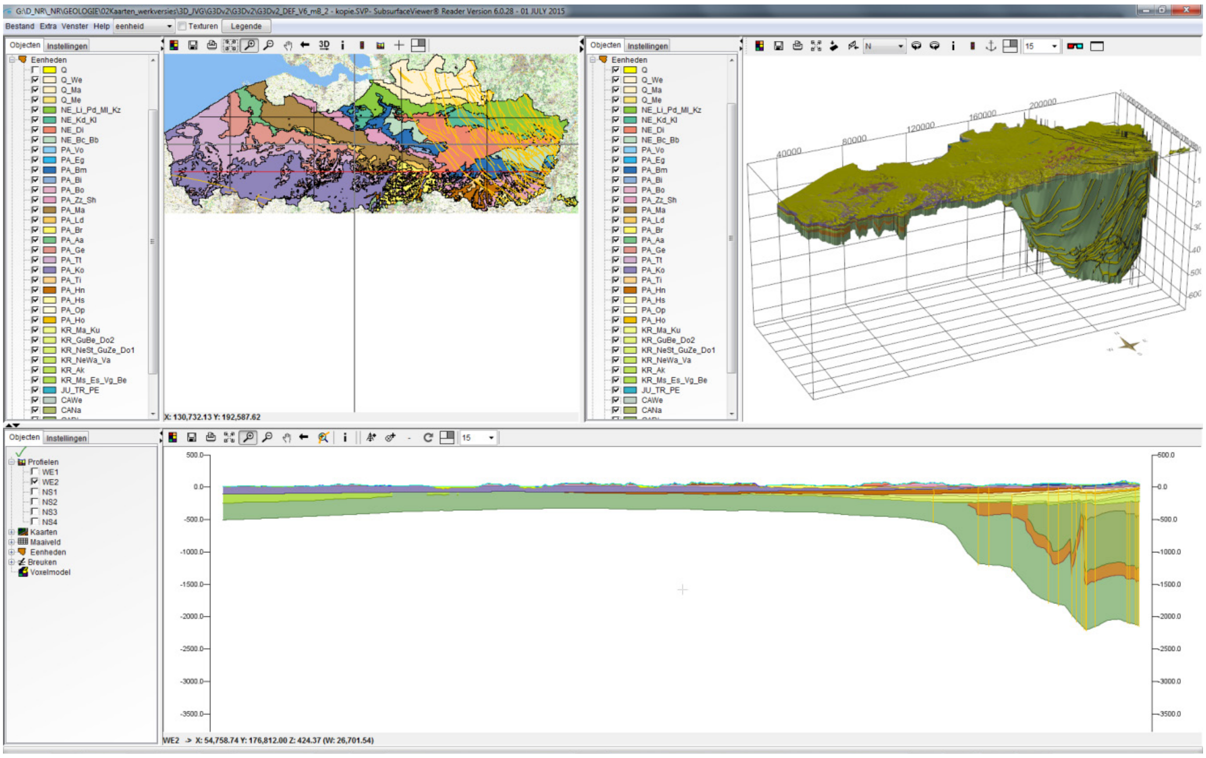

Figure 21. Impression of geological 3D model in the 3D SubsurfaceViewer® with a) 2D map, b) 3D view, c) cross section generated from the model. Geological 3D Model (Matthijs et al., 2013) published at http://dov.vlaanderen.be

The main advantage of bringing all the data from the different sources together in DOV is that they can be consulted and re-used by DOV's partners and other interested parties. The reuse of these data is not without problems. The data are not a substitute for ground investigation on current projects, and data should only be used as reference data in a geotechnical setting, mainly because of the inaccuracy, particularly in older data, of the location of observations, drill sites, and in situ tests.

DOV is multidisciplinary, and offers subsoil/soil information for a wide range of applications: geotechnical design, environmental studies, geological mapping, groundwater modelling, groundwater policy, and scientific research. Therefore, users of DOV can be found within a wide range of organizations, such as governmental institutions, universities, consultancy firms, the wider private sector, municipalities and even the public.

DOV database applications are divided into internal and external applications. Internal applications are available only to DOV partners; more than 300 partners can log into DOV to use these. The external applications are available on the internet (http://dov.vlaanderen.be) and can be used by anyone free of charge. The daily monitoring of the applications indicates an average of 250 users per day.

Among several other geotechnical databases, with similarities to DOV are the Geological Survey of Ireland's (GSI) National Geotechnical Borehole Database (see http://www.gsi.ie/Mapping.htm) and Polish Geological Institutes (PGI) Engineering-Geological Database (see http://atlasy.pgi.gov.pl).

Geotechnical databases can be used to generate a wide range of 2D and 3D outputs that can be applied directly to urban needs. Examples of such outputs include the foundation conditions map (1:10 000 scale) prepared directly for city spatial planning in the city of Łódź in Poland, and a 3D model of Quaternary cover for the city of Dublin (Ireland) presented in figures 22 and 23 respectively.

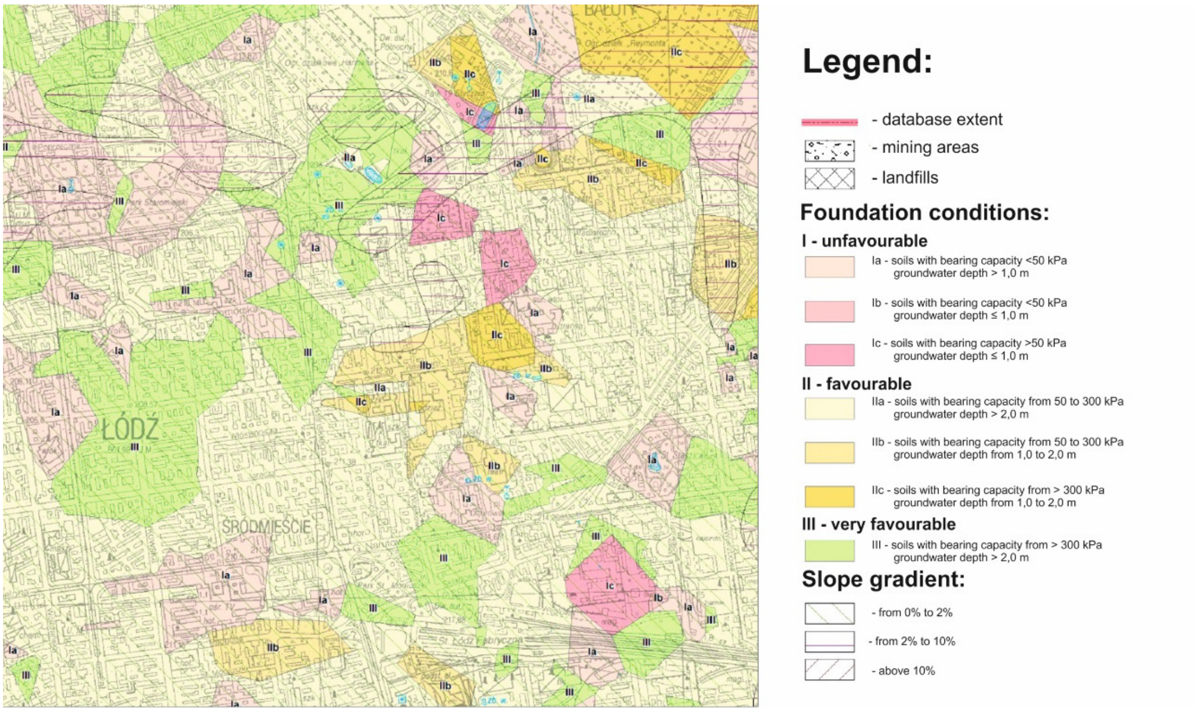

Figure 22. “Traffic-light” map with foundation conditions (based on soil type and ground water depth) at the 2,0 meters below ground level. An example of geotechnical database processing 2D product oriented for city master planning (for the city of Łódź in Poland)

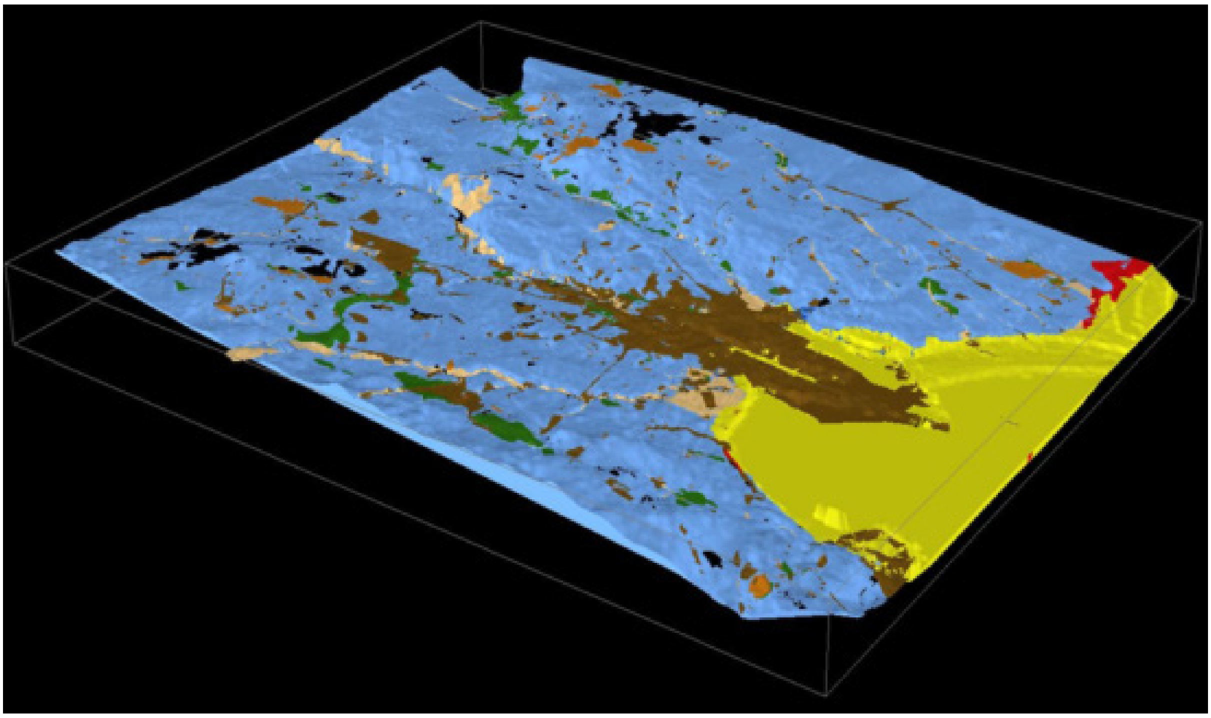

Figure 23. 3D model of the Quaternary Geology in Dublin City, Ireland (blue is glacial till, red is estuarine sediments, yellow is marine sediments, green is glaciofluvial sand and gravels, brown is made ground, orange is top soil and light cream is alluvium)

2. Framework of geotechnical data exchange

Establishing a framework for geotechnical data exchange between private companies, geological surveys and municipalities is a vital step in improving knowledge of the urban subsurface. Such a task has been undertaken in Glasgow (UK). The primary objective was to develop a network – ASK (Accessing Subsurface Knowledge) – to change the culture of subsurface (geoscience) data and knowledge exchange in the Glasgow conurbation, and beyond. Greatly increasing the impact of geological 3D data and knowledge will be a key result. Also incorporating the clients, consultants and contractors (the private sector) into the data exchange network, and sharing with them the benefit of access to the geological/geotechnical database and related 3D geological models, is an essential step in convincing them, that they can derive a direct benefit from sharing their data with a geological survey organization and local municipality.

The generalized information flow in ASK network is shown in Figure 24. A key aim of ASK is to improve the basis for decision-making, as well as lowering development and regeneration costs, within the Glasgow area, and possibly through expansion of the ASK approach, to other UK cities and city-regions. The ASK network partnership is a mechanism to provide data and exchange knowledge between the public and private sectors. It was initiated by the British Geological Survey (BGS) and Glasgow City Council (GCC), with support from other partners in the public and private sectors (ASK Network). The ASK network website provides further information: http://www.bgs.ac.uk/research/engineeringGeology/urbanGeoscience/Clyde/askNetwork/home.html.

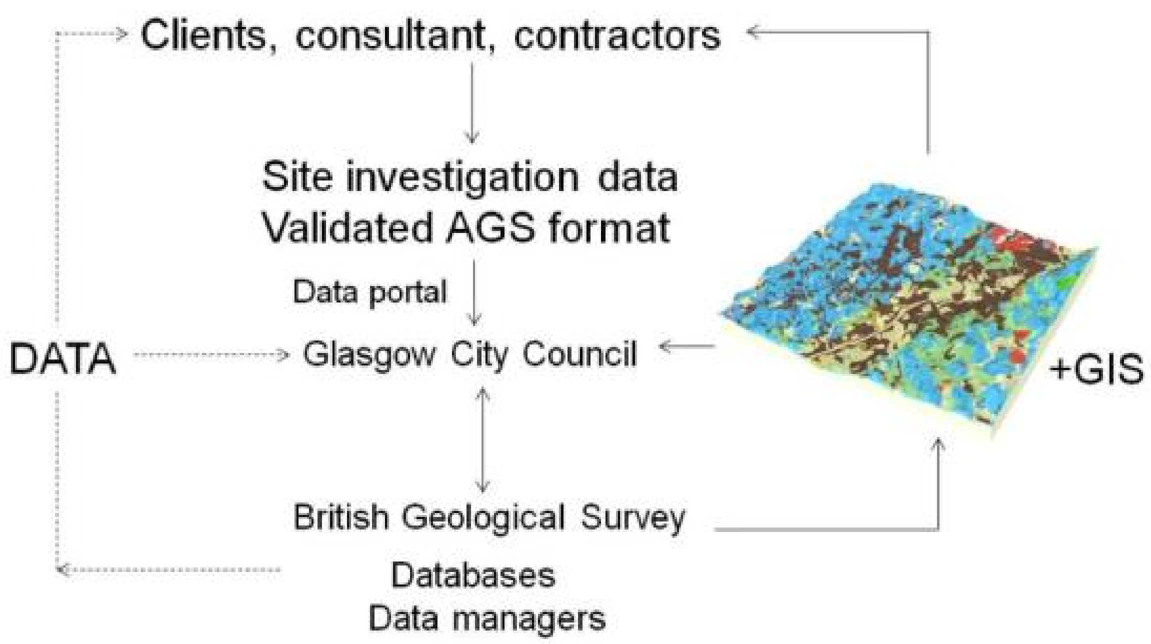

Figure 24. Geotechnical data and information flow in ASK Network

3. Geohazards – Landslide inventories

With regard to landslide data (database, inventory, susceptibility, hazard and risk maps), most countries in Europe have some type of landslide database (in paper or digital format). The quality of data they hold, and the frequency of update varies greatly however, as does their ability to present data in a GIS (e.g. the SOPO Landslide Database of the Polish Geological Institute - http://geoportal.pgi.gov.pl/portal/page/portal/SOPO/Wyszukaj3).

Landslide databases are established and maintained, mainly on a national or regional basis by Governmental institutions and in some cases by local authorities. In other instances, the databases are linked to specific Projects (for example the IFFI project developed by ISPRA, the Italian National Institute for Environmental Protection and Research). However, existing data are often restricted in access; access may require cooperation with specialists in the field.

Working group 2.5 has estimated that there are at least 800.000 registered landslides in databases and thematic maps across Europe. This may be a significant under-estimate, however. Those countries most susceptible to landslides are typically those with the extreme topography (e.g. Switzerland, Italy, France, Austria, Spain, France, Slovenia, Poland, Slovakia, Bulgaria, Romania, Bosnia and Herzegovina, and Macedonia) and therefore those with the most landslide data.

As one of the most affected countries, Italy has one of the most advanced databases of landslides in Europe. It was prepared within the framework of the IFII project (Inventory of Landslide Phenomena in Italy - http://193.206.192.136/cartanetiffi/). This consists of an inventory of all registered landslides in Italy, with clear distinction of the landslide mechanism, demarcation of zones through which a landslide is likely to travel, and site-specific information from landslide investigations. It is a web-based and easy to use service.

Figure 25. SOPO (Landslide Conteraction System) Polish Geological Survey web browser application. An example of landslide inventory. Map presents identified landslides with relation to their Landslide Registration Forms. (http://geoportal.pgi.gov.pl/portal/page/portal/SOPO/Wyszukaj3).

Key knowledge gaps

The main knowledge gaps limiting more widespread use of geotechnical models and geohazard inventories in relation to urban planning and management of the urban subsurface include:

- How to increase the awareness among city planners and stakeholders of the importance of geotechnical modelling and geohazards inventories?
- How to incorporate geotechnical modelling and geohazards data into the early stages of spatial planning?
- How to encourage private companies to share their geotechnical data with geological surveys, municipalities, and each other? Legal enforcement may be one option, but cooperation may be equally effective or even preferable (cf. ASK Network)?
- What should the optimal framework/standard be for integration of 2D/3D geotechnical models (site specific) with city-scale 3D models?

Geotechnical data are key to effective parametrizing of 3D models. Geological 3D models contain mostly basic geological information on lithology and stratigraphy. More pertinent parametrization is needed in order to influence construction-related decision-making. This requires access to a range of geotechnical data. Both physical and mechanical parameters from geotechnical databases can be used for 3D model parameterization. Key parameters include: bulk density, moisture content, grains size distribution, friction angle and cohesion, oedometric modulus, etc.. Such parameterized models can help to fill the gap between city scale data (1:10 000), which provides the geotechnical context to sites, and site-specific data (1:500). Spatial planning and feasibility studies for new large construction projects should use such parameterized 3D models as a starting point in their geological risk assessment and planning of site investigation.

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2.6 Subsurface geochemistry

2.1	3D Model development	2.1.1	Workflows for main modelling software and different city scenarios
2.1		2.1.2	Deterministic modelling, incl. made ground
2.1		2.1.3	Stochastic modelling, incl. made ground
2.1		2.1.4	Model uncertainty
3.1	Model attribution	3.1.1	Physical properties e.g. hydraulic conductivity, aquifers
3.1		3.1.2	Chemical properties

Figure 26. Extract from table of knowledge levels (figure4) showing main topics of relevance to Subsurface geochemistry subgroup

Key Topics:

Subsurface geochemical levels as Environmental indicators, Databases, Visualization, Use of geochemical information

Seen in the urban context

Within the last few centuries, cities have developed in size and nature of occupancy, from small historic cities to larger industrial communities, and more recently to modern city with an environmental focus. Recently, European cities have faced several major changes, and especially de-industrialization and population increase. Reconstruction and redevelopment of cities implies that much of the available space is brownfield in nature and often includes areas formerly used for industrial or mining. Although former industrial areas can be attractive potential for housing due to their location (in proximity to the city centre or to a riverside), their soils and subsoils are often contaminated, potentially harmful for human health and the environment, and potentially costly to remediate. As well as contamination from industry and mining, many other sources of contamination of soils and subsoils linked to human activities must be taken into account: service activities, agriculture, traffic, leakage from sewers, leakage from individual domestic fuel tanks, waste deposits etc. The use of pesticides in paved areas, gardens, football fields, golf courses etc. are all further source of contamination (point source or diffuse). So are some anthropogenic deposits used as fill materials, such as demolition waste (e.g. resulting from paint, plaster, PCBs in transformer oils). In particular, industrial or mining waste has frequently been used in construction or civil works in the neighbourhood of the industry, or even elsewhere in the city. However, there is often little or no traceability of the use of industrial or mining (or even demolition) waste, although these may represent important sources of diffuse pollution.

2D mapping of topsoil geochemistry, generally health driven, appears generally well documented (Johnson et al, 2011; Demetriades and Birke, 2015). However, 3D representation of subsoil geochemistry is rarely infrequent. This may explain some unexpected contamination problems during space reconversion, and subsequently unexpected costs, delays and unfavourable public image.

Urban needs

The main need of city planners in relation to the geochemical quality of soils and subsoils is to have reasonable and representative visualisation of the data in a form, which enables them to be used effectively, and in an integrated way with other datasets (socio-economic, health, etc.).

The current state of knowledge in relation to soil geochemistry (when available) is overwhelmingly based on surface (topsoil) and very near surface sampling of subsoils. This is expressed in the form of 2D mapping, based on interpolation between sample sites.

Running in part concurrently with the activities of the Sub-Urban Working Group 2 subgroups, Alecos Demetriades and Manfred Birke, with contributions from the EuroGeoSurveys Geochemical Expert Group, have reviewed the state-of-the-art in relation to geochemical surveying of urban soils, building on the earlier thematic volume of case studies contained in the thematic volume "Mapping the Chemical Environment" (Johnson et al., 2011), and including the overview of those case studies by Johnson and Demetriades (2011). As a result, a comprehensive Urban Geochemical Mapping Manual has been produced (Demetriades and Birke, 2015b). This compliments the manual that was written for the second URban GEochemistry topsoil mapping project in Europe (URGE II), to be carried out by the EuroGeoSurveys Geochemistry Expert Group in different European towns and cities (Demetriades and Birke, 2015a). The task of the Sub-Urban Geochemistry Subgroup (WG 2.6) has been greatly eased as a result. Rather than attempting to duplicate the efforts of Demetriades and Birke, and of EuroGeoSurveys colleagues in any way, Sub-Urban has been fully supportive of their efforts. The Manual therefore represents a substantial contribution by the EuroGeoSurveys Geochemistry Expert Group's to the COST Sub-Urban Action, and its Geochemistry Sub-group in particular, and is gratefully acknowledged.

The current surface soil sampling campaigns in urban (and other areas) - while ideally suited, and much needed in urban areas, to address health issues in particular - suffer similar limitations to surface mapping of geology, when used in relation to urban (re)development, and construction work, and remediation of contamination in particular, due to the limited state of geochemical knowledge in the third dimension (depth). In practice, such geochemical data rarely exist in any quantity. City needs should, ideally, include therefore better knowledge of soils and subsoils at depth, much in the same way as discussed in relation to geological knowledge previously in this report (see 3D geological modelling section 2.3). Associated knowledge of the geochemical quality of soils/subsoils can be linked to their improved geological knowledge in 3D. It should also take into account both of the natural baseline and anomalies, and diffuse and point source anthropogenic contamination. If and when available, especially during the early stages of urban planning, this 3D geochemical knowledge could be very useful in optimizing urban redevelopment projects, anticipating contamination problems, and managing excavated materials (e.g. local reuse possibilities, disposal costs etc.). All of these aspects can have important economic, environmental and social consequences. They are considered here to be essential for urban sustainable development.

To meet these more ambitious needs, improved development of data acquisition, management, visualisation and use of these are crucial steps.

Examples of good practice (Le Guern & Sauvaget, 2016c; TU1206-WG2-6; Demetriades and Birke, 2015b)

1. Good practice of 2D data acquisition of topsoil

The Urban Geochemical Mapping Manual of Demetriades and Birke (2015b) covers all aspects needed to establish the baseline of concentrations of chemical elements and compounds in urban environments and describes “tried and tested” urban geochemical methodologies for sampling, sample preparation, laboratory analysis, quality control, data conditioning, processing and map plotting. As such, the Manual represents the basis for standardisation of urban geochemical sampling across Europe and globally. The Manual is readily available online (http://www.eurogeosurveys.org/wp-content/uploads/2015/10/Urban_Geochemical_Mapping_Manual.pdf). Therefore, only a brief overview of its scope and content, in terms of good practice, is given here.

Given the potential importance of geochemical data in relation to a wide range of uses, and major issues such as planning, health and well-being, the Manual emphasises the need for high quality, integrity, and legal defensibility of the data. The geochemical baseline can then serve as a basis: for assessing previous anthropogenic impacts (urbanisation, industrialisation etc.), and for the timeline for future change.

The Manual places greatest emphasis on sampling, as any errors at this stage are very difficult to identify, and to rectify, and have knock-on effects throughout the “mapping” process.

Soil is the most widely used sample medium, in urban areas, and especially so for citywide campaigns (Johnson and Ander, 2008). The emphasis of the Manual is therefore on sampling topsoil, and subsoil to a limited depth. Topsoil is the sample medium most likely to be in direct contact to humans, and child health criteria is of particular importance in this regard (Demetriades and Birke (2015b).

Drainage sediments are less widely used than in non-urban studies, in part because of the greater difficulties in their sampling in urban areas culverts etc.). However, drainage sediments (e.g., Fordyce et al., 2004) are better suited than soils for tracking the passage of contaminants through the urban environment.

Urban topsoil, especially in older city areas, is geochemically (and lithologically and structurally) complex and heterogeneous because of anthropogenic influences. This, the cultural layer of Blume (1989) and others, varies from a few centimetres to more than 10 metres and is a significant sink for the legacy of, and any continuing, urban contaminants.

Of most direct relevance to this summary is the guidance by Demetriades and Birke (2015b) on sampling: single spot (rather than composite); systematic (grid-based) rather than random; nominal density of 4 samples per km^2 (but can be any density) typically using a 500 x 500 m grid for central city areas up to 1000 x 1000 m grid for suburbs.

Topsoil is the medium of most direct contact to humans and the principal sample type. From a range of 0-10 cm depth from undisturbed (or least-disturbed) and preferably bare near grid node. Other depth ranges (e.g. 50-60 cm) may be more appropriate, depending on survey objectives. The optimum depth range should be determined by an orientation survey. If topsoil and subsoil samples are collected at all sample sites, both should be from the same depth ranges. Duplicate field samples should be collected at every 20th sample site for projects with >400 samples, and every 10th sample site if <400 samples, with emphasis placed on: preparation of a reference sample or samples, before the project starts; and the need for all analysis to be in one laboratory, for the same suite of elements/compound, using a reproducible methodology, and with strict quality control.

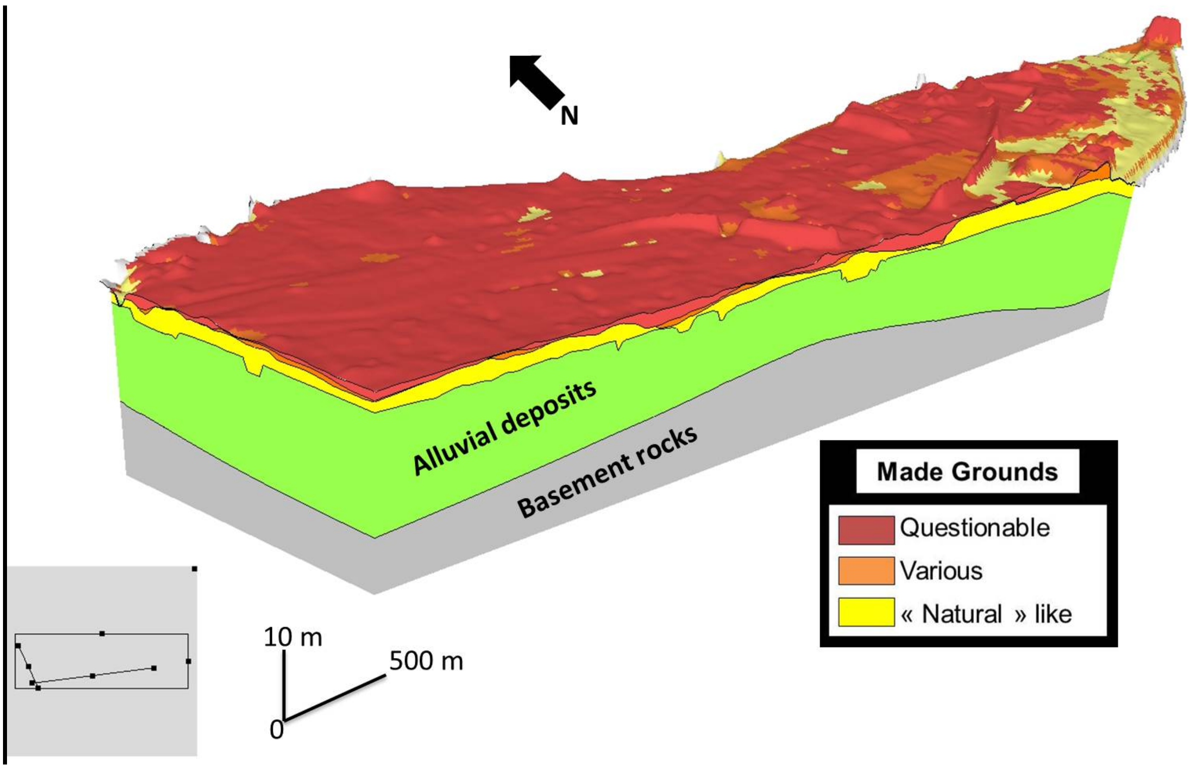
Further procedural guidance on sampling collection, bagging, numbering, avoidance of contamination etc., and including sampling for analysis of organic compounds, is also given by Demetriades and Birke (2015b).

2. Le Guern (**WG2.6 Subgroup Report**) contains detailed case studies of good practice in urban geochemical sampling surveys carried out for Vienna (Austria), and of Glasgow (UK), the latter including in addition to a survey of the urban soils, surveys

of sediments and waters from stream/rivers/estuary within and in the vicinity of the city.

3. The depth extent of urban geochemical surveys (soil and subsoil) is typically very limited. **Deeper geochemical mapping** is less commonly addressed, in part because of its less direct impact on human health, but also because of its cost, and the challenges of addressing its 3D and 4D complexities. This practice might be used for 3D data acquisition on subsoils, with some additional recommendations such as dry drilling and sampling according to lithology rather than depth. However, there are until now few practical examples of good practice with respect to 3D geochemical databases for European cities. The example of the geochemical database of Nantes, and of the French BDSolU (Base de données sur les Sols Urbains - French national database on urban soils) may be referred in this frame as good efforts.

4. **The use of 3D urban geochemical data** is mainly used in relation to issues of contamination management at the site scale. There are only a few examples where this has been carried out at a larger scale (Rotterdam, Nantes, Oslo), and where the data have been published. It is difficult therefore in this context to identify good practices. The same is true for 3D urban geochemical modelling and visualisation. The example of Nantes is suggested as an example of best effort however (see figures 27 and 28).



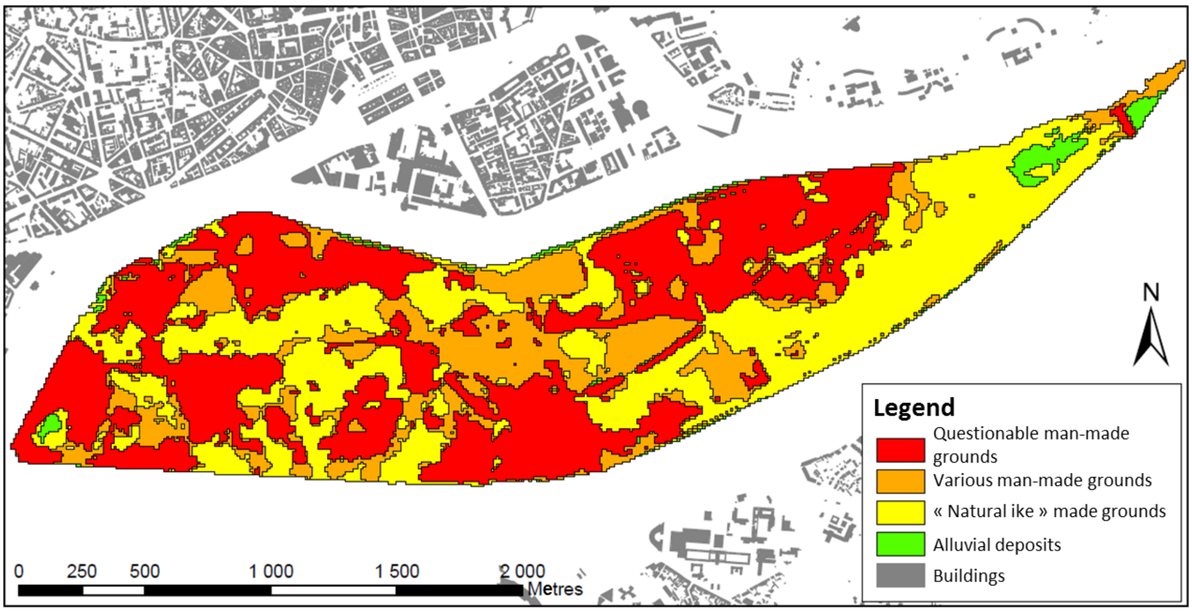


Figure 27. Presentation of geochemical subsoil quality of Nantes Island, France. Above) 3D model integrating several classes of made ground, defined according to their intrinsic potential for contamination (from high for questionable made grounds containing industrial residues to low for more natural made ground present on the island); Below) 2D representation of made ground at 1 m depth, according to their intrinsic potential for contamination, extracted from the 3D model – Ile de Nantes, France (Le Guern et al, 2016a,b).

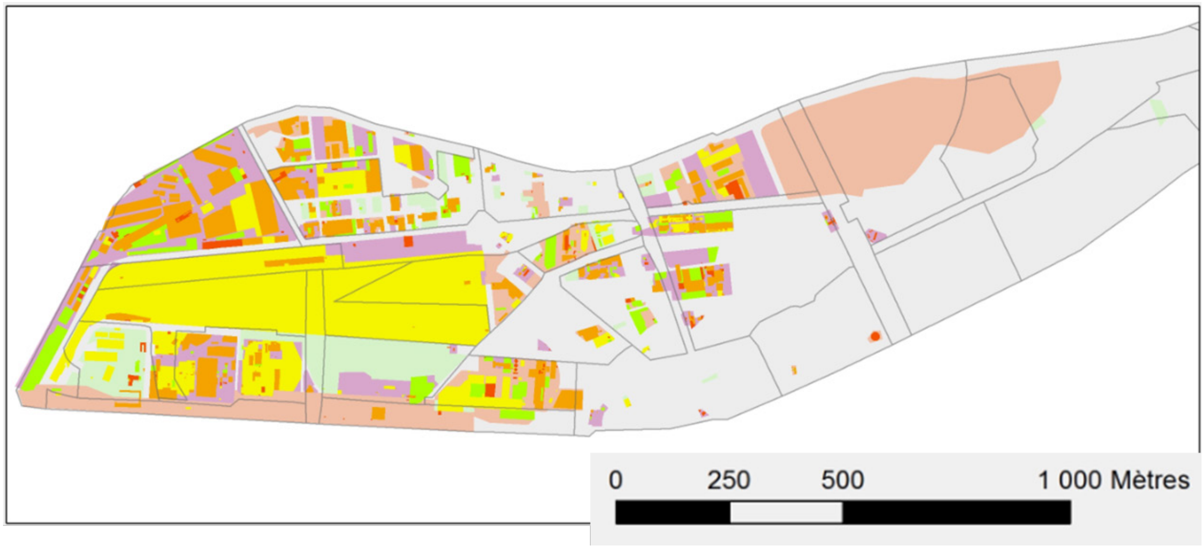


Figure 28. Indicator of potential historical contamination of subsoils by lead linked to former industrial and service activities (from very low to absent in green to very high in purple) – Ile de Nantes, France (Le Guern et al., 2016b)

Key knowledge gaps

1. Development of 3D and 4D mapping technology

The "geological" structure of soils and subsoils in the urban environment is very hard to characterise, and represent in 3D. This reflects to a large extent of the inherent lithological heterogeneity of anthropogenic deposits (made, worked, filled and landscaped ground), and their often extreme lateral and vertical variability as a result of their complex histories.

Urban soils and subsoils constantly evolve: while some are removed or modified (e.g. as a result of decontamination), others are introduced. This may happen rapidly and on a large scale, particularly in major (re)development areas. This may alter important properties of the soils and subsoils (e.g. geotechnical, permeability, geochemistry, organic carbon …). It would be worthwhile, therefore to establish soil and subsoil dynamics by recording time series data recording their current and future changes (removal, importation, transformation). Such information would provide the basis of a 4D representation of urban soils and subsoils.

2. Geochemical data acquisition and management

There is a need to build a general knowledge database of urban soils and subsoils. It should incorporate the following:

- Collation of existing geochemical data in local and/or national databases, taking into account: 3D to 4D data, database structure, management-verification, validation, and updating… In this context, the following key question arises: How to develop and establish national databases? What would be the best solution for public and private data respectively: contractual, legislation, policing…?

- Protocols need to be established for acquiring all forms of geochemical data to ensure their comparability. Protocols are already well established, and thoroughly described for the 2D geochemistry of near-surface soils (Demetriades and Birke, 2015). Similar protocols are needed and need to be tested, for 3D data also (e.g. drilling, sampling according to lithology rather than depth, etc.). The protocols should be flexible enough to take account of site-specific characteristics. Standardisation of descriptions is also essential.

- Improved methods are needed to enable more reliable and robust comparisons and reuse of existing data acquired under different protocols (different extraction methods and/or detection limits).

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3. 3D representation and use of geochemical data

Geostatistics are valuable for: identifying gaps in data; selecting data for interpolation; identifying best methods of interpolation of data; and interpolating data when their spatial correlation is confirmed.

Extensive research is needed to developing geostatistics for 3D subsoil geochemistry, e.g. on the following aspects: interpolation methods (linear, non-linear, voxel - cf. Schokker et al., 2016), management of heterogeneity, and analysis and management of uncertainty. It would be also useful to develop integrated spatial or even spatio-temporal representations (cf. GeoCIM, see below, Chapter 3).

Further work is needed in developing better representations of the data for end-users, In this regard, indicators of geochemical quality versus potential use of soils and subsoils, and cost/benefit analyses would be particularly useful.

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2.7 Cultural Heritage

5.1	**Subsurface/above ground linkage**	5.1.3	Archaeological/cultural assets
5.2	**Incorporation in Decision making tools**	5.2.1	Volumetric planning
5.2		5.2.1	Ecosystem services stewardship
5.2		5.2.2	Aquifer vulnerability/groundwater protection
5.2		5.2.3	Thermal and other mineral resource extraction and storage
5.2		5.2.4	Ground stability and foundation conditions
5.2		5.2.5	Risk management in development/construction
5.2		5.2.6	Protection of cultural heritage

Figure 29. Extract from table of knowledge levels (Figure 4) showing the main topics of relevance to the Cultural Heritage subgroup

Key Topics:

Protection of cultural heritage, urban planning, surface and groundwater management

Seen in the urban context

Cultural heritage, whether building and other standing monuments, or subsurface archaeological remains, is internationally recognized as a valuable legacy and record of our past history. The European Convention on the Protection of the Archaeological Heritage (CETS 143, 1992) establishes European policy and incorporates concepts and ideas that have now become accepted practice in Europe. Conservation and enhancement of the archaeological heritage is one of the key goals of urban planning policies. One of the key objectives of European policy is to protect, preferably in situ, archaeological remains buried in the soil, or under the seabed, and to incorporate archaeological heritage into spatial planning policies.

Historic cities need to face up to the challenge of new developments. Typically, (re)development is typically part of a planned renewal, and attention must be paid as to how historic buildings and archaeological deposits in the inner city should be managed. Every city has a subsurface legacy, which reflects the development of the city over time (see Figure 30).

In terms of ecosystem services, the subsurface environment acts either as a carrier of archaeological heritage in situ (stewardship) or it provides the support for above ground cultural heritage. Often, it is not enough to protect the heritage site or monument itself: for example, new developments outside a specific protected area can cause changes in groundwater level, and serious damage to heritage buildings and archaeological deposits. Conflicting subsurface uses, and unappreciated impacts on subsurface resources, threaten the "stewardship" of the subsurface for archaeological heritage, as well as the bearing capacity for above ground monuments. Safeguarding the subsurface ecosystem services that support archaeological heritage currently lacks robustness and conflicting uses of the subsurface are often largely unaddressed.

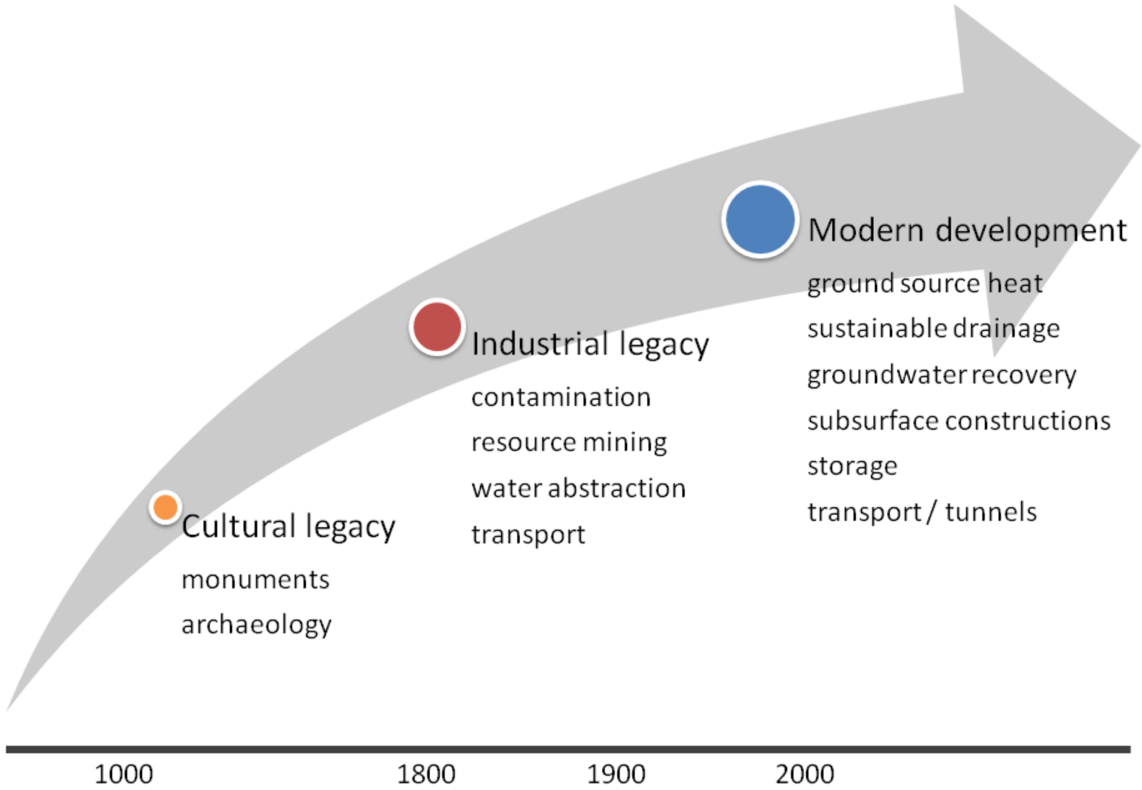

Figure 30. Every city has a subsurface legacy, which reflects development of the city development over time (De Beer et al., 2016, TU1206-WG2-007)

Management of cultural heritage is often related to surface -and groundwater management. Dewatering is one of the greatest concerns for those managing waterlogged archaeological sites, as well as a great threat for the wooden foundations of aboveground monuments. To ensure their long-term survival, waterlogged organic material needs to remain waterlogged all year round, as this significantly reduces the diffusion of oxygen required for most bacterial decay and aerobic corrosion reactions. Within the urban context, urbanisation can alter the city's water balance considerably, causing lowering of groundwater levels and potential desiccation of archaeological material. In the event of excess precipitation, most rainwater in cities is currently rapidly discharged through the storm water and sewerage system. Therefore, even are a relatively short spell of dry weather, or water shortage, lowering of groundwater levels soil moisture loss need to be reversed. This vulnerable and artificial balance of the urban water cycle is increasingly threatened by climate change and growing urbanization.

Over the past few years, the "traditional" practice of rapidly discharging storm water to the surface water system has been changed. The aim is now to buffer, infiltrate and delay rainwater runoff on-site, using sustainable (urban) drainage systems (SuDS). This paradigm provides a unique opportunity to improve protection of cultural heritage, and particularly archaeological heritage. However, implementation of more sustainable water management practice has in many countries only been carried out on a relatively small scale, in newly built districts or some renovated districts, and with the main focus on storm water management, and flood and contaminant control. Archaeological heritage and above ground cultural heritage assets are however often located in historic city centres.

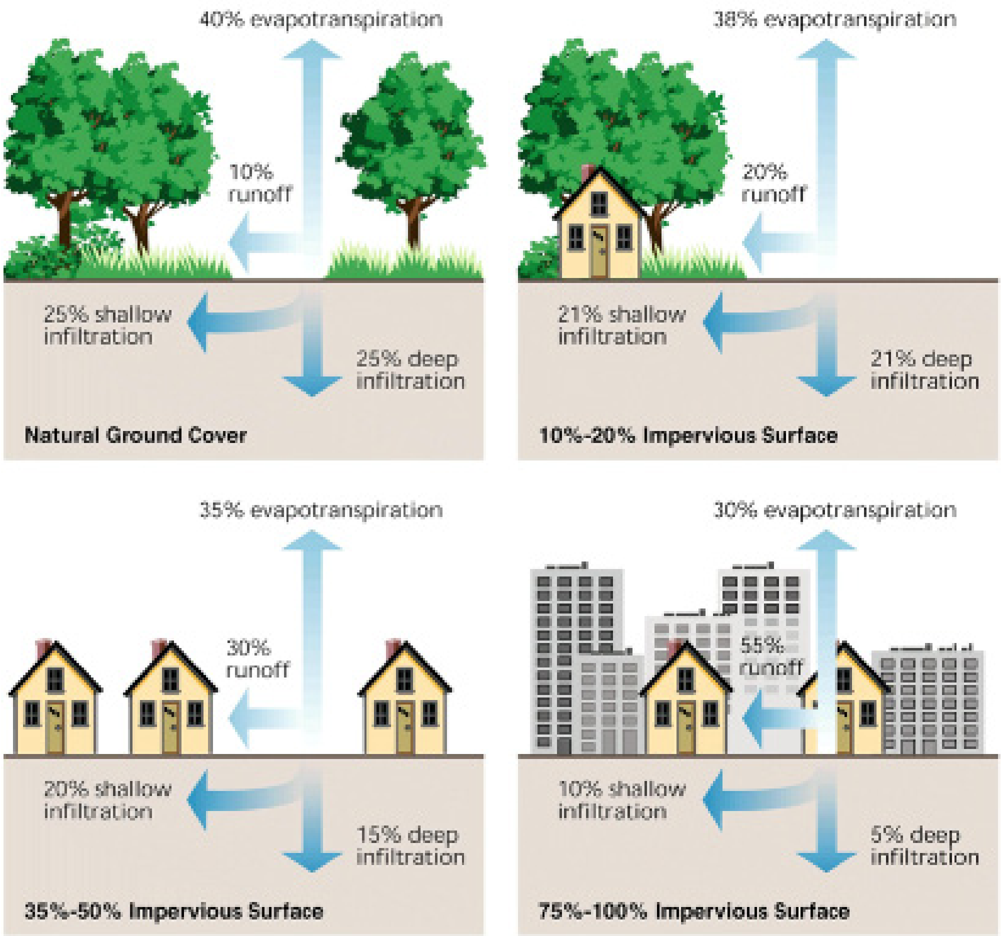

Figure 31. The effect of urbanization on the natural water balance, Source: FISRWG (1998)

Urban needs

In recent years, the field of cultural heritage preservation, and particularly archaeological heritage preservation, has seen significant progress towards a more holistic approach, involving a range of different disciplines. This progress has also been triggered by some alarming international examples of environmental changes caused by urban developments have resulted in accelerated decay of archaeological deposits, as well as damage to above ground heritage buildings. As mentioned before, the European Convention for Archaeological Heritage (Council of Europe, 1992) states, that archaeological heritage should preferably be preserved in situ, within the subsurface environment. In order to do so, there is a need for a proper understanding of the related natural and man-made subsurface environment. Only then can in situ preservation be feasible, and design of mitigation, as well as management of heritage sites, be successful.

In autumn 2015, under the Horizon 2020 work programme for 2016-2017, the European Commission launched new calls for large-scale demonstration projects in cities as living-labs for nature-based solutions for climate and water resilience, and cultural heritage as a driver for sustainable development. The fact that both topics are considered together in new calls, also confirms that the European Union envisages the need for a more holistic approach in research and development on cultural heritage management at a European level.

The topic "cultural heritage" is limited here to physical heritage, i.e. buildings, monuments, archaeological remains and artefacts. Other types of cultural heritage, such as traditions, are not considered. For clarity, physical cultural heritage is divided into 1) standing cultural heritage, such as monuments and historic buildings and sites, and 2) subsurface cultural heritage, such as archaeological deposits and artefacts in situ. In addition, focus is put on water as the most important agent that directly affects the preservation conditions of physical cultural heritage in either a positive or negative way. In urban areas, there is a need for improved hydrological and hydrogeological data and understanding, to protect and preserve physical cultural heritage. Water management is also of significant cultural heritage value in its own right in many historic cities across Europe and beyond. Since ancient times, the urban subsurface has provided ecosystem services for water management, such as a source for drinking water and space for wells, cisterns and other infrastructure. Physical remains of these systems and their functions, both below and above ground, are an important cultural legacy of cities, contributing to their identity and also providing lessons for current water management practices. In modern urban planning practice, there is a need to map and embed the historic elements and understand their relationship within their wider natural and man-made urban environment.

Examples of good practice

1. Standing monuments and sites

Many historic cities in Europe and beyond contain important monuments, historic buildings and other standing remains of human activity. Depending on the historic development of the city, the legacy will range from the infancy of the city, through evidence of trade, to industrial and pre-modern development. The protective management of standing monuments and historic sites depends on knowledge of geological and man-made subsurface conditions and processes affecting the stability and degradation of this cultural legacy.

The Vondelpark case in **Amsterdam City**, the Netherlands, illustrates this dependency and how subsurface knowledge contributes to improved protection of standing monuments and sites (Verhoog, 2007; De Beer et al., 2016, TU1206-WG2-007). Subsidence of the Vondelpark, a national monument, has averaged 1 cm per year during the last 150 years, resulting in a cumulative subsidence of 1.5 meters. Subsidence causes serious problems not only for maintenance and water management within the park itself, but particularly along the borders of the park, where historic houses founded on wooden piles are located. The wooden foundations are threatened by the lowering groundwater levels needed to keep the park dry.

A series of geotechnical and hydrogeological investigations have been carried out to develop effective solutions. A combined system with a dry swale with soil passage, constructed wetland, drainage, infiltration and a hydrological barrier now secures improved groundwater conditions and a supply of clean surface water that is circulated over a constructed wetland to improve the water quality. This has resulted in more durable paths and lawns, trees are growing older and wooden pile foundations are no longer threatened by low groundwater levels.

Figure 32. The Vondelpark case illustrates how subsurface knowledge contributes to improved protection of standing monuments and sites. Subsidence causes serious problems not only for maintenance and water management within the park itself, but particularly along the borders of the park (source: project.waag.org/parq/vondelparkmap)

2. Archaeological heritage and artefacts in situ

There are good examples of how archaeological heritage depends on subsurface conditions and processes, particularly related to hydrological conditions. Probably one of the best-documented cases in the world is the World Heritage Site of Bryggen in **Bergen** (Seither et al., 2015, TU1206-WG1-003). In the thematic report on cultural heritage (de Beer et al., 2016, TU1206-WG2-007) , two cases are given on how archaeological heritage and earth sciences disciplines can interact and benefit from each other's techniques and competence. The first case - **the Nantwich case** (Malim et al., 2015) - is a technical study on mapping, leading to guidance to planners. The second case is a good example from the planning perspective, and discusses the interaction of different stakeholders in the process of redevelopment of the city centre of **Tønsberg**, Norway's oldest city (Harvold et al., 2015).

3. Sustainable urban water management and cultural heritage

Water management and cultural heritage are strongly intertwined; either where historic water management has achieved heritage value, or where current water management practices contribute actively to protect and preserve standing cultural heritage and archaeological heritage. The thematic report on cultural heritage (de Beer et al. 2016, TU1206-WG2-007) illustrates this by using two cases: the historic development of the City of **Venice** in Italy (Gianighian and Pavanini, 2010) and the preservation of the highest man-made hill in the Netherlands, the **Motte Motherland** (Boogaard et al, 2016). An example of historic sustainable water management is provided by the use subsurface cisterns in Venice (Gianighian and Pavanini, 2010) and many other cities in southern Europe. Venice had about

6,000 subsurface sand cisterns, a dense collection of small fresh water aquifers, situated in a salt-water lagoon (see Figure 33 below).

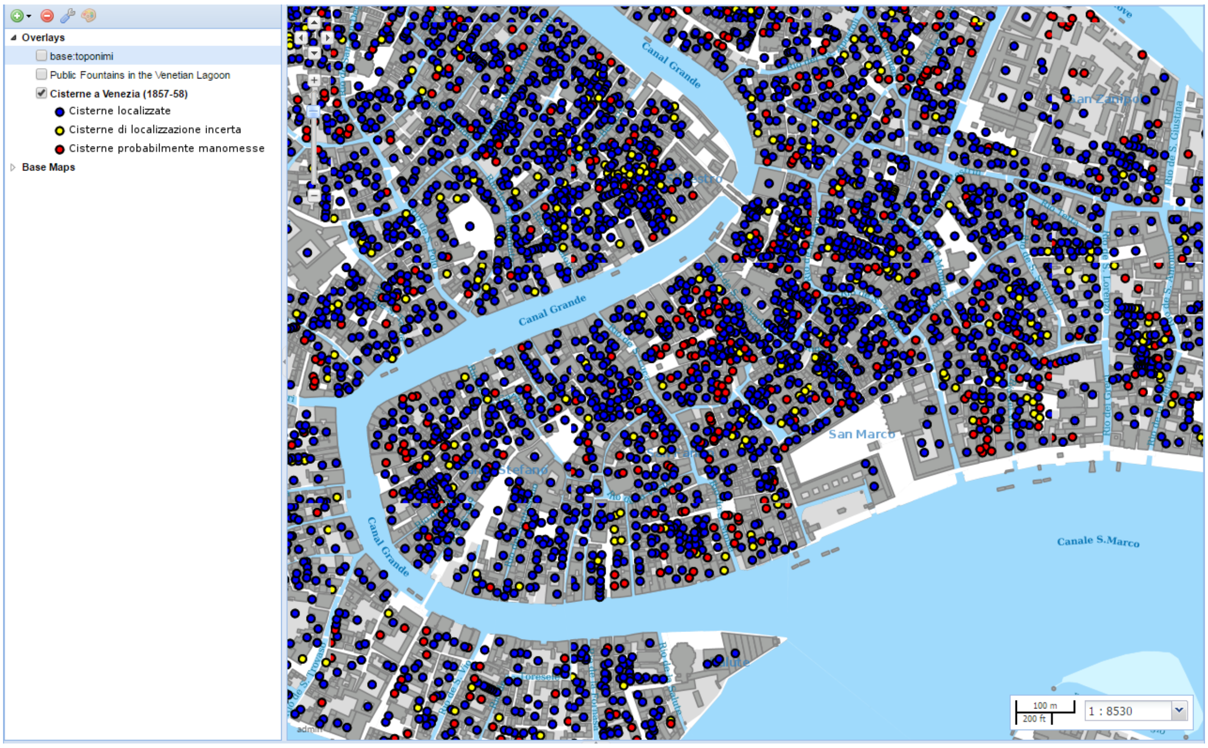

Figure 33. Overview of mapped cisterns in Venice, Italy (source: http:\\cigno.atlantedellalaguna.it, 2016)

Key knowledge gaps

Cities have commonly developed from a small historical core into a larger (unsustainable) industrial city with extensive subsurface resource exploitation, and finally to a modern development. The challenge today is to consider all aspects of this growth, from preservation of historical heritage, to industrial pollution and the further need for space. Cultural heritage protection is often related to surface- and groundwater management. This poses a threat, certainly in view of climate change and the current need for adaptation of urban water systems.

There is a large risk of heritage deterioration due to unforeseen circumstances. There are many factors to consider; natural, political or management decisions, characteristics of the soil, historical activities, (ground) water circulation, human activities, or simply the wrong location. Significant progress has been made in recent years towards a more holistic approach, involving a range of different disciplines (Holden et al., 2006). This progress has been triggered by developments where environmental changes caused by urban development have resulted in decay of archaeological deposits and damage to historic buildings (e.g. Rytter & Schonhowd, 2015). **A proper understanding of the natural and man-**

made environment and the processes affecting heritage is essential for in situ preservation, design of mitigation measures, as well as management of heritage sites. Cultural heritage resources have to be considered as an integral element in urban planning processes if they are to be preserved for future generations.

In general, the **current status in urban planning shows a lack of coordinated policy with respect to the subsurface**. In urban developments, conflicts as a result of prior uses of, and unappreciated impacts on, suburban resources. Amongst these, archaeological heritage is either unaddressed or taken care of too late in the planning process. This makes the use of underground space in cities suboptimal. In terms of ecosystem services, the subsurface environment either acts as a carrier for archaeological heritage (stewardship) or supports above ground heritage. Often it is not enough to protect the heritage site or monument itself; new developments outside a specific protected area can lead to changes in groundwater level, and cause serious damage to heritage buildings and archaeological deposits.

The multiple benefits that modern sustainable water management systems may provide, including support for heritage preservation, are not yet fully recognized by those who can benefit most from it; heritage managers, water managers as well as urban planners and decision makers. A knowledge gap exists in terms of awareness of the option to include (retrofit) modern climate adaption measures in historic cities. Similarly, it is necessary to further develop technical modifications to established sustainable water management systems if they are to be applied in areas with vulnerable cultural heritage. Implementing new infrastructure for sustainable water management in archaeologically important areas can be challenging (de Beer et al., 2012b). Any local structure used to manage surface - and groundwater flow can potentially damage archaeology (de Beer et al., 2012a). Most of these structures require groundworks, and some are placed completely under the surface. This trade-off requires special attention and experience (Rytter and Schonhowd, 2015).

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3. Integrated urban and sub-urban information modelling

Time for GeoCIM

Urban development strategy and policy is increasingly centred on developing cities as high-quality places of economic growth, increased sustainability and quality of the natural environment, and improved social equality, health and well-being of their populations. The overall strategic goal is to foster improved city resilience to future change and shocks. Realisation of this development approach and goals requires local governments to have an appropriate city knowledge base (Bonsor 2016; Mielby et al. 2015).

A wide array of strategic data is relevant – ranging from demographic trends, business development, community mobility, health indices, deprivation indices, energy demands, ground conditions, land assets and land use, quality of place, to accessibility of services, planned service infrastructure, infrastructure investment and demand, and quality and connectivity of space (Bonsor 2016).

Large-scale screening data are required to inform early strategic decisions on how the quality of the city's land and the available portfolio of land assets are best mapped to housing delivery, infrastructure planning and other development priorities. Many of these datasets are interrelated but have traditionally been viewed in isolation. To maximise their relevance, it is necessary to combine them into a holistic, above and below ground, view. In later stages of the development process, more site-specific data are required to assess the viability of development proposals, understand what mitigation might be required to realise development of some land assets, and to realise opportunities and risks to the construction process, in an integrated urban design approach (Bonsor 2016; Mielby et al. 2015).

Initiatives such as Building Information Modelling (BIM), aim at developing more integrated uses of different relevant data in major development projects, but have, to date, almost ubiquitously been focused on the design, construction and management phases of individual project development. However, the BIM approach is as relevant – if not more so – to earlier stages of the development process to improve visibility and utilisation of relevant data to strategic development decisions.

BIM systems are shared knowledge resources for information about a facility, forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition (Nationalbimstandard.org., Retrieved 24 March 2016). BIMs tend to lack representation of the subsurface, although it is possible to include anthropogenic and natural subsurface features. BIMs also tend to be created for a single building or relatively small-scale sites, but there is no restriction on the size of project to which BIM can be applied. In order to support volumetric decision-making about an urban space, it is necessary to integrate information about much larger proportions of a city. The integration of surface and subsurface information is considered especially relevant when planning and making decisions at an urban quarter to metropolitan scale (van der Krogt, R. 2016).

To address the challenges of sustainable urban development, and the proliferation of unconnected BIMs, the concept of a City Information Model (CIM) has recently gained support amongst urban planning researchers (Gil et al., 2011).

Confusingly, there is a similarly named concept - Civil Information Model (CIM), which appears to be the term civil engineers and civil infrastructure professionals apply to the BIM process, i.e. BIM processes and BIM models used to design, construct and manage infrastructure (horizontal) rather than building (vertical) projects. The use of the terms horizontal and vertical to differentiate between buildings and infrastructure suggests an almost 2D–2.5D view of the world by both of these communities (Guo et al., 2014) as opposed to a more complete 3D-4D view that integrates above- and below-surface features of a city.

Although the BIM and CIM concepts could be used to manage urban environments sustainably, both lack explicit reference to ground surface or underground properties, which affect, and are affected by, buildings and infrastructure designs. In order to address this shortcoming, we propose the Geo City Information Modelling (GeoCIM) concept (Figure 34); expanding on the BIM and CIM principles by making the above- and below-surface data at scales appropriate to a city an explicit requirement of a sustainable urban planning and management. The prefix "geo" is used to mean ground or land and can be seen to represent geology, geotechnics, geolocation, geophysics, etc.

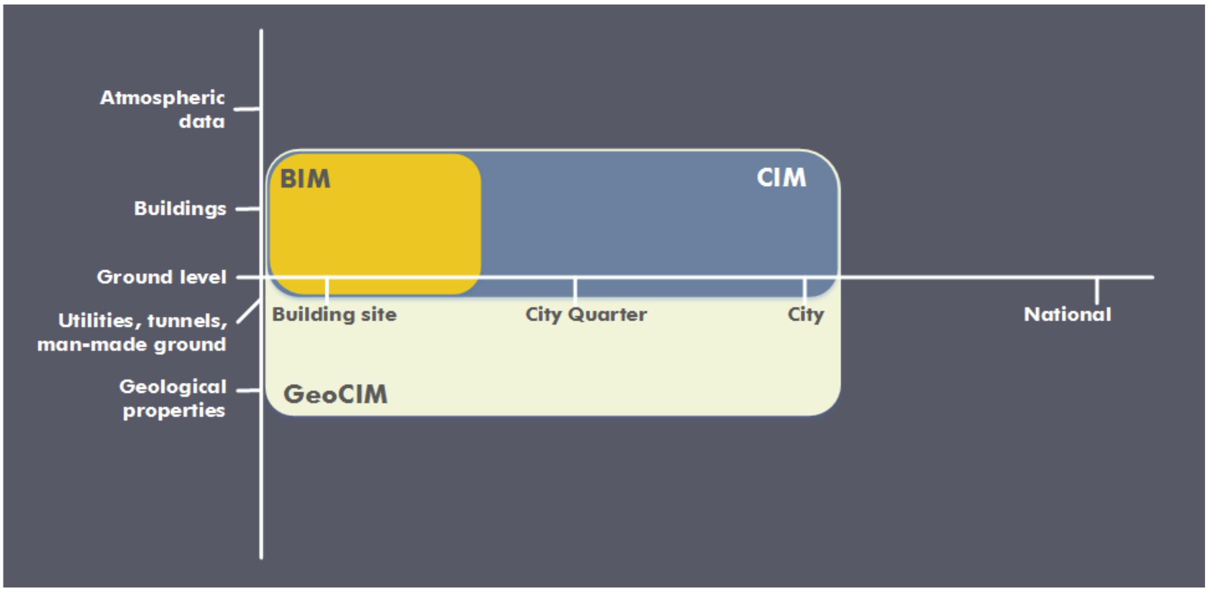

Figure 34. BIM, CIM and GeoCIM relationships by geographical scale of interest (x-axis) and data themes above and below ground (y-axis)

Geo City Information Modelling (GeoCIM) is a process involving the generation, sharing, integration and management of digital representations of physical and functional characteristics of at least the following urban environment layers:

- Surface layer: natural and man-made on-surface features
- Anthropogenic subsurface layer: man-made ground, buried infrastructure, foundations
- Natural subsurface layer: geological units, hazards and processes

Geo City Information Models (GeoCIMs) are 3D or 4D digital representations, which can be exchanged or networked to support volumetric decision-making about an urban space. GeoCIMs handle the very different scale, update needs in their different layers, and have a flexible output scale depending on the user and usage. GeoCIMs can be used by individuals, businesses, government agencies and researchers to sustainably plan, design, construct, operate and maintain diverse physical infrastructures and urban resources, such as water, heat, ecosystems, power utilities, communication utilities, transport networks and buildings.

The lifespan of GeoCIM's are more directly linked to the life span of City Development planning policy (typically 5-10 years). In contrast, the life span and application of BIM's are shorter and linked directly to individual development projects.

GeoCIMs do not have to take the form of a single software tool. Specialist data and models may exist in specialist tools with the communally relevant elements being exposed at an appropriate scale and in a way that enables integration with information from other key stakeholders.

GeoCIM users and their needs

The primary users of GeoCIM can be categorised as follows:

- Subsurface specialists
- Urban planners
- Decision makers
- General public and others

Subsurface specialists will be able to use GeoCIMs to share crucial information about geological structures, processes and hazards through a tool that is accessible to a wider audience than has traditionally been the case. These specialists will also benefit by being able to identify the location of man-made structures that influence subsurface processes such as groundwater flow or ground stability.

Urban planners will use GeoCIMs in the planning process as a single point of information for all key urban datasets in three or four dimensions. It should also be possible to incorporate environmental indicators such as water table data, air quality and soil quality into GeoCIMs; this would support the integration of environmental assessments and planning if considered relevant.

Decision makers will be able to visualise and quantify the impacts of high-level strategic decisions without the need to delve into specialist interrelated domains of geoscience, construction and city planning.

The general public would have greater access to information about their environment and if the GeoCIM is developed using an open web service there is a real possibility that new applications would be developed by interested amateurs and commercial ventures, maximising information re-use.

All stakeholders will be able to use GeoCIMs to identify knowledge gaps and prioritise future data collection activities. GeoCIMs can also be used as an index to key stakeholders and data sources, identifying points of contacts and resources where users can find more detail on a model component that cannot be easily communicated in such a multi-purpose knowledge-exchange tool.

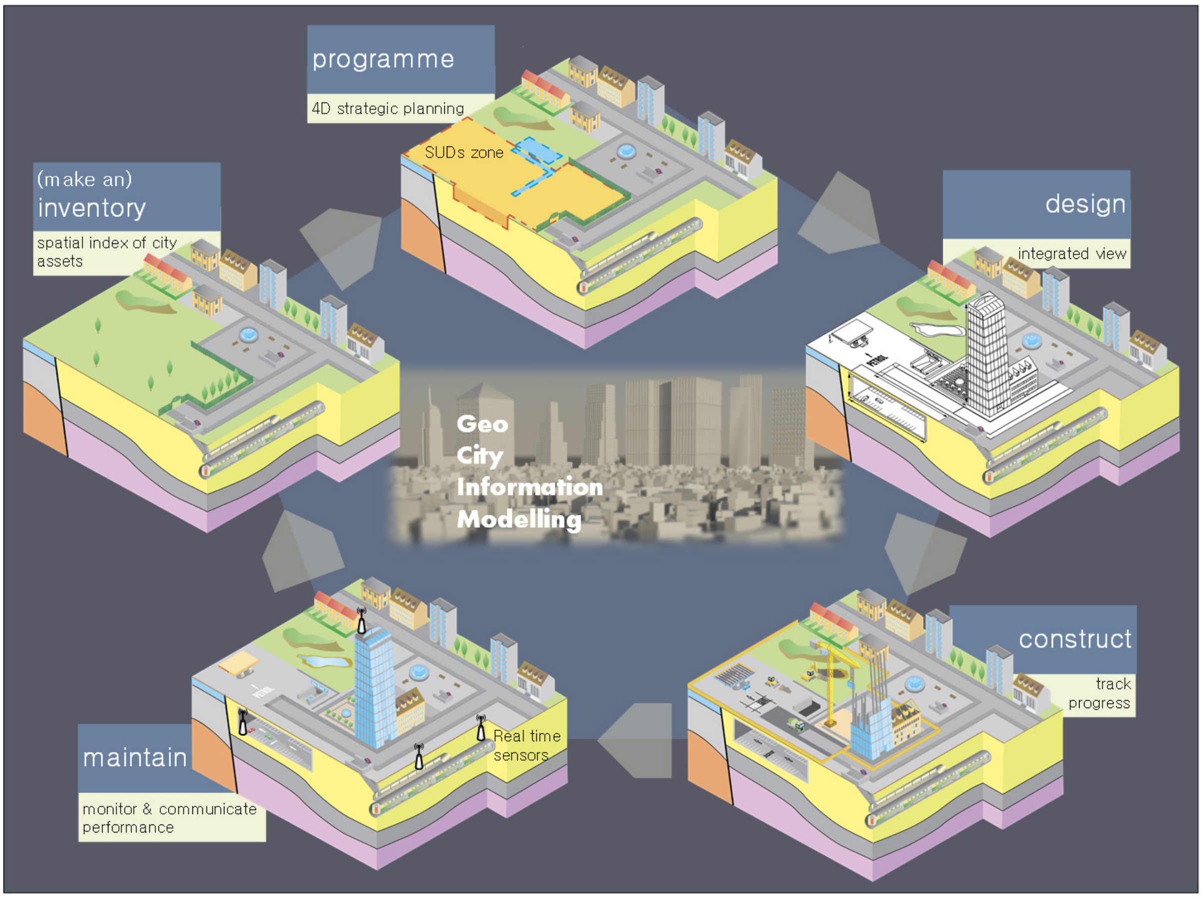

Figure 35. GeoCIM lifecycle, making all spatial data relevant to planning decisions available in a common data environment, supporting strategic planning and effective delivery of infrastructure projects by providing easy access to all related information at each stage of the process

Examples of good practice

At the time of writing this report there are no examples of GeoCIMs that fully satisfy the definition given earlier. The following examples demonstrate how certain aspects of the GeoCIM definition have been met in various urban planning projects throughout Europe.

1. Integrating above and below-ground GeoCIM layers

In the Danish city of **Odense,** the integrated surface and subsurface groundwater management project has resulted in the creation of a 3D model for the whole city that contains many of the aspects desired in a GeoCIM (Mielby et. al., 2015; Schokker et al., 2016). The Odense Municipality Model contains information on all three GeoCIM layers: natural & man-made on-surface, anthropogenic subsurface and natural subsurface features. However, only the natural subsurface layer is available throughout the municipality, while anthropogenic and natural subsurface features are recorded in two sub-areas of the model and detailed information about all three layers is only available for a test area affected by the development of the new road Thomas B. Thrigesgade. There are other examples in cities like **Helsinki** (Ikävalko et. al., 2016) and **Oslo** (Eriksson et. al., 2016), which focus more on the integration of the two uppermost GeoCIM layers, while **Bergen** (Schokker et al., 2016; Seither et. al., 2016; De Beer; 2016, Bergen City report) and **Hamburg** (Taugs et al., 2016; Bricker, 2013) focus on the integration of anthropogenic and natural subsurface features. Each of these cities has concentrated on the integration of data that is readily available and most relevant to immediate development priorities. These partial implementations of the GeoCIM concept are actively used by subsurface specialists and city authorities to plan developments despite the lack of coverage or detail in some datasets.

2. Optimising an existing groundwater monitoring network

In the city state of **Hamburg** (Germany), the State Geological Survey (BSU) and public water authorities have efficiently re-designed and optimised the existing city-scale groundwater monitoring network (Bricker, 2013; Bonsor et al., 2015). They have done so by combining the city's 3D geological and groundwater models with information on the construction quality of monitoring wells, thus integrating two out of three of the desired components of a GeoCIM (anthropogenic and natural subsurface features). As such, the number of monitoring wells could be greatly reduced without quality loss of the monitoring network. Detailed information on buildings, their basements and foundations is currently missing from this example. Adding this information would not only enable the identification of areas that are critical to high groundwater levels, but also individual buildings that are at risk. Eventually, this could lead to informed decisions on mitigating costs to minimise flooding risks.

3. Embraced future use of 3D models for all three GeoCIM layers

In Scotland, **Glasgow** City Council (GCC) has embraced the use of 3D models for all three GeoCIM layers. They have commissioned 3D geological models from BGS geologists incorporating geotechnical site-specific data submitted to the council by the construction industry (Watson et al., 2016). GCC have made an Urban Model available to the public in two formats, a block model and a more detailed photorealistic 3D model with façade textures, accurate to 20 cm. GCC encourage the use of the block model for the early pre-application stage of development plans and the photorealistic model for submitted proposals (Glasgow.gov.ukl, Retrieved 14 June 2016).

The Urban Model is being used to inform commercial building development projects and test flooding scenarios, whilst the BGS (natural subsurface) model is used by the construction industry to de-risk development and reduce costs associated with early-stage site investigations. GCC have ambitions to combine the Urban and BGS models to provide a more holistic single reference tool for all stakeholders.

Implementation

The examples mentioned earlier show how even partial implementations of the GeoCIM concept have provided significant benefits.

Successful implementation of a new GeoCIM is likely to be affected by the following technical issues:

- **Public availability of data and models**

  Intellectual property rights and proprietary data formats are just two examples of factors, which limit the availability of data, and models that should be included in GeoCIMs. Although technical limitations can be extremely frustrating, they are often easier to overcome than political or commercial concerns about sensitive and valuable information.

- **Development of common data exchange formats**

  Many potential GeoCIM stakeholders' store and exchange data in a wide range of bespoke and proprietary formats. There are exceptions, such as the geotechnical investigators who use AGS (Association of Geotechnical and Geoenvironmental Specialsts digital data exchange formats; AGS.org.uk, Retrieved 20 June 2016), but many are used to working in relative isolation and have traditionally seen little need for integration with other disciplines. In some cases new technologies, such as 3D city modelling or real time sensors, come along, which require harmonisation to support effective data integration. In addition to standardising exchange formats, it is also necessary to define controlled vocabularies of common terms to reduce ambiguity and misunderstandings between stakeholders.

- **Model maintenance and update**

  Many of the 3D models that have been created for the urban environment have been the result of one-off projects and the need to maintain the model state has been secondary to satisfying immediate project-based requirements. 3D model storage and exchange systems are starting to gain traction (Gabriel et. al., 2015; Wood et. al., 2014) but more work is required to make these processes more automated and user-friendly.

- **Use of GeoCIMs across planning-stage boundaries**

  As with the model maintenance issue, there is a need to develop recommendations on how to transfer information, and perhaps model ownership, from one planning stage to the next.

Key knowledge gaps

The largest knowledge gap in this subject area is how to initiate the GeoCIM process. However, it is not necessary to commit, up front, to creating the perfect, fully-featured GeoCIM from scratch.

The biggest impacts of a GeoCIM are likely to come in the earliest phases of the decision-making and planning process, when a holistic overview of all relevant information can result in design changes that minimise cost and hazard risks. There needs to be greater recognition of this potential impact and benefits of GeoCIMs within this early stage of the decision-making and development process – as well as the knowledge benefits of integrating above- and below-ground city information to these early strategic decisions. This is something that city municipalities and other government bodies, as well as geological survey organisations and other research organisations are only just beginning to realise and fully explore.

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4. Analysis and discussion

So far in this report, we have dealt with user needs, evaluated techniques to meet these needs, and identified good practices and knowledge gaps. In this chapter, we propose the next step towards the improved provision and uptake of the requisite subsurface knowledge and of ensuring its accuracy.

The right type of urban subsurface information

We have argued that the only possible way to bridge the gap between providers and users of subsurface information is to **provide the right type of subsurface information** and make sure that the **people receiving the information** (urban planners and decision makers) **understand and use the information to take decisions**.

In chapter 2, it is argued that urban planners, as well as subsurface specialists, need to improve their understanding of what information is needed in the urban planning process. As in any other above ground planning process – there is a need to understand **where in the planning hierarchy (strategic or detailed planning)** which type of information is needed, and **where in the process** the information is needed (see Figure 6). The information about the subsurface needs to be easy to capture, reliable, organized, regularly updated, and possible to integrate in the planning and construction process.

Knowledge and information at the right time and in right place are keywords in this process. For planning purposes, there is a need for information to be simple and easy to understand. Technical subsurface information required in detailed planning or design phases within individual projects needs to be presented simply, straight to the point, and in order.

This is challenging, as everyone that has read the previous chapters would know that incorporating geoscience in urban planning is complicated, and the information to be presented is not simple at all.

The need for a systematic approach

In chapters 2 and 3, we have identified, from both an urban planning and geoscience technology standpoint, a large number of excellent techniques that have been applied to the collection and delivery of subsurface information, and have described good practices adopted by cities in various (but not all) parts of Europe. However, our studies have confirmed that, almost without exception, the techniques and good practices have been applied on a case specific basis.

When, however, one wants to extend subsurface knowledge to the city in its entirety, and go deeper, Working Group 1 confirmed that use of a **systematic, rather than a project-based, approach is essential** (Van der Meulen et al., 2016, TU1206-WG1-001)**.** This conclusion is very much confirmed by Working Group 2, as we have experienced that the identified techniques and good practices are case specific, and that not one-solution, but rather various solutions exist.

How to get a systematic urban approach?

Awareness of the information needed, how that information is delivered, and its background provide a very good starting point for a systematic approach. Therefore, in the following consideration, we will focus on how "the right type of subsurface information" can be identified and delivered.

5.1.3	Archaeological/cultural assets
5.2.1	Volumetric planning
5.2.1	Ecosystem services stewardship
5.2.2	Aquifer vulnerability/groundwater protection
5.2.3	Thermal and other mineral resource extraction and storage
5.2.4	Ground stability and foundation conditions
5.2.5	Risk management in development/construction
5.2.6	Protection of cultural heritage
5.2.7	Hazard identification and risk management
5.2.8	Burial of services and development of subsurface infrastructure, including underground transport, storage and waste disposal

Figure 36. Extract from table of knowledge levels (Figure 4) showing examples of different subsurface information and knowledge issues of potential relevance for urban planning

Urban planners, as well as subsurface specialists, need to define for themselves where **in the planning hierarchy** which type of information is needed and **where in the planning process** the information is.

A systematic approach must be based on all the crafts and traditions that planners and geoscientists have developed over time. In many cases, there are multiple processes and the planning situation varies with drivers and pressures, which implies that delivering "Knowledge and information at the right time and in right place" does not have a single solution, but depends on the particular situation. To ensure that everything is 'remembered', for each planning hierarchy and process a systematic handling of the following key issues is important:

1. The planning hierarchy and process

This requires identification of information of importance in urban planning, at/in/for the:

- Planning stage (From idea to Masterplan)
- Working scale (From quarter to metropole)
- Time frame (From inventory to construction)
- Societal themes (Drinking water, Ecology, Culture, Human health etc.)
- Economy

2. Nature based geographical elements (physical state)

This requires inclusion of various types of subsurface information in relation to:

- Type of geological environment (sedimentary basins, hard rock etc.)
- On-going expectation of geological processes (hazards etc.)
- Scale and depth
- Various Sources of data available for the mapping (boreholes, geophysics, logs, …)

In addition, to include relevant information on climate and surroundings that can affect the entire urban water cycle and thus the groundwater management and the environment:

- Type of Climate
- Water in catchment (flooding and rise in groundwater level)
- Rise in Sea-level
- Expected changes in climate

3. Urban infrastructure and environment (information on human drivers and pressures)

This requires identification of the various types of information of importance to the city, including:

- urban history and development
- issues relevant to support infrastructural development
- natural risk assessment

- environmental risk assessment
- To monitor, identify, and assess relevant indicators

Mutual agreements about the content, common terminology, language, timing and the above-mentioned basic information for all needed themes will facilitate communication between the demand side (planner) and the provider (geoscientist).

How to get access to urban data and updated knowledge?

Providing the right type of information is also a matter of accessibility to all relevant databases, in order to access current updated data, mapping and model results.

If there is insufficient subsurface knowledge available at the start of a building project, building costs risk escalating. In the worst case, legal claims can result from miscalculating costs or risks.

The optimal solution for urban use is when different **data sources are available for all** types of users. If this is not the case, transfer of knowledge, data and models between private and public sector must be considered (political decisions (laws) and tendering contracts can influence this). These considerations must include benefits for society, how to demonstrate and encourage this benefit when money is paid by one stakeholder and gained by another, and how the public and private sectors work together.

The right type of subsurface information at the right time also involves available data finding their way to the database, and ensuring that **the database is updated** with the newest data, as these are the foundation for optimal use of mapping tools, decision support tools and integrated models.

For environmental purposes, it is important initially to assess the sufficiency of the data, and where this is not adequate, **to acquire and collate the relevant data**; for example, indicator analysis and modelling. As for time series data, it is important to have historical data in databases, i.e. that a monitoring network is designed to support the planning authorities from an early stage. Figure 37 shows how The DPSIR framework and The MDIAK report chain (se Chapter 1) is used to help design assessments, communicate results, and support monitoring and collection of information.

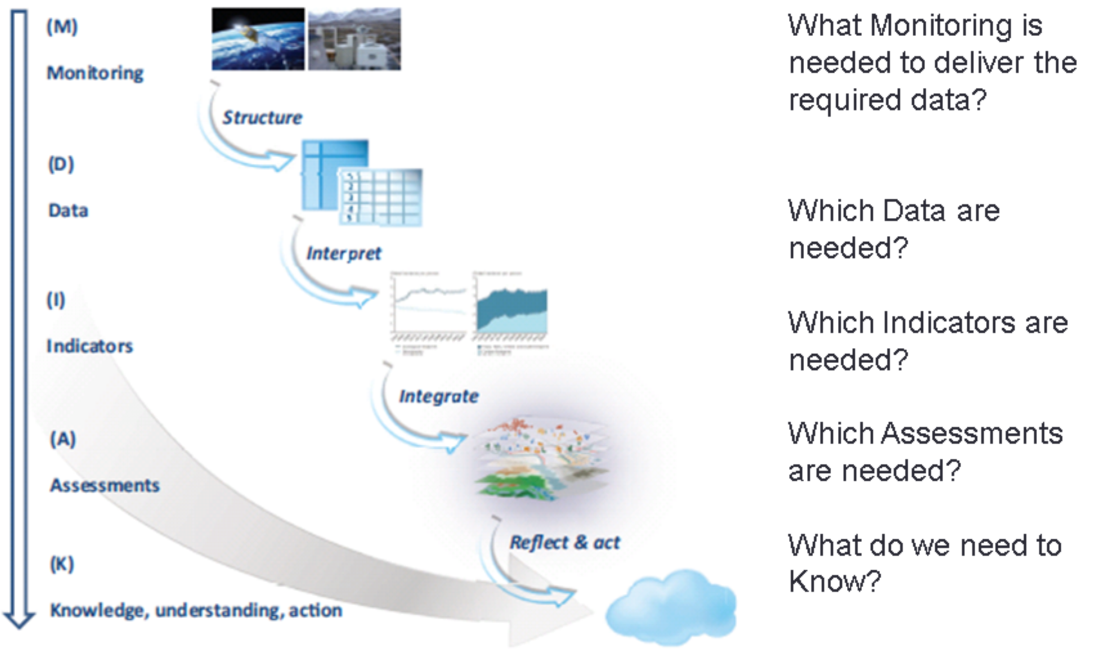

Figure 37. To the left (read top down), how the MDIAK reporting chain leads to knowledge, understanding and action (EEA, 2014). To the right, the DPSIR framework (read bottom up) is used to help design assessments, communicate results, and support monitoring and collection of information

How can we manage collaboration between planners and geoscientists?

Getting the right type of information is a previously unrecognized challenge in relation to integrated urban planning management in urban areas. This is, because the current practice in many cities and GSO´s is for work with subsurface information to be spread out, involving **many stakeholders/ experts** on many levels.

Besides, subsurface data are often collected and used on a project-specific basis, and regardless of whether the project is publically or privately funded, there is a **need for regular updating**, especially of mapping and models.

In order to assure that the correct type of subsurface information (regularly updated) is used, it is recommended that an organisation is established, with an experienced project management, with shared roles and responsibilities, and regular **coordination between the parties involved**.

National **guidelines** would be beneficial, and would help cities with limited resources to produce their own local guidelines. Furthermore, help in performing a city needs analysis by geological and or geotechnical experts from a national body could also help cities to understand the opportunities that exist, and the issues that need to be managed, and conflicts to be resolved within their urban subsurface. This type of analysis would lead to greater collective knowledge and awareness.

References

The Environmental Agency, 2014: Digest of EEA indicators 2014. EEA Technical report No 8/2014.

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5. Conclusions

What does this evaluation of access to subsurface knowledge add up to?

Addressing the findings and conclusions of Working Group 2, as illustrated more generally in Figure 38, would undoubtedly enhance the recognition by decision makers, and their consideration of the urban subsurface within the context of urban planning, policy and development.

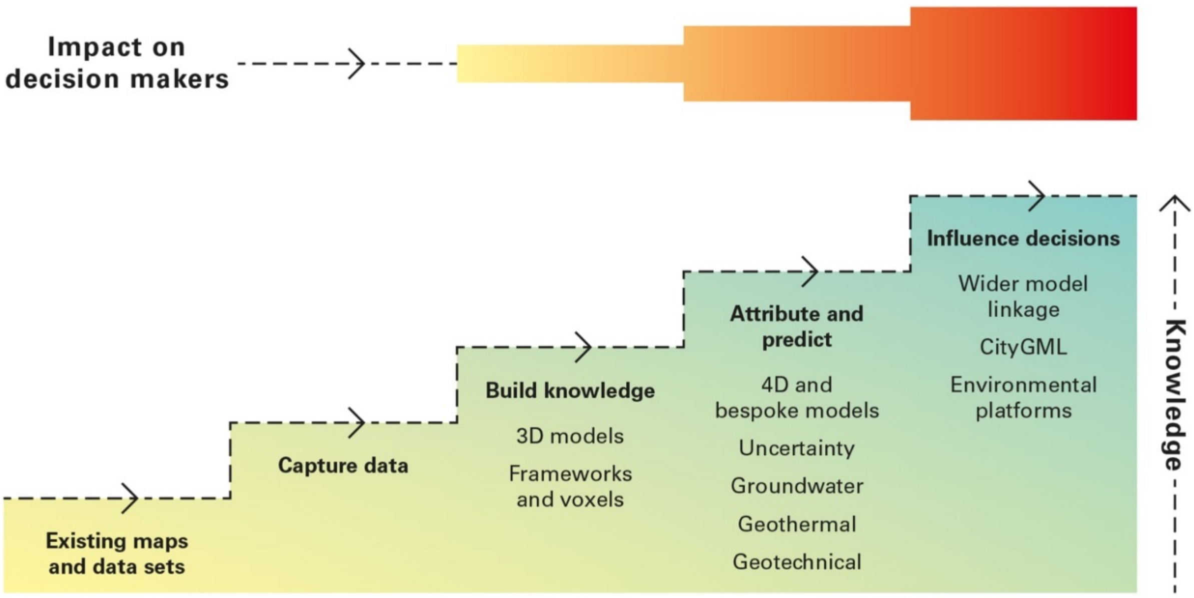

Figure 38. Important information levels in the knowledge building process and potential impact on decision makers. Figure developed by Diarmad Campbell, British Geological Survey

The evaluation described in this Summary Report allows us to draw various conclusions on the following topics:

1. Subsurface information and planning

Systematic consideration of the subsurface in city planning, and urban development as a whole, has the potential to **improve risk management and reduce costly delays in delivering projects, improve mitigation and adaption (e.g. to climate change), and to prevent failures**.

Greater collaboration and mutual understanding between subsurface specialists, and end-users of sub-surface knowledge can not only reduce risk but also **enhance benefits**:

- Address hazards
- Make better and more informed decisions for above ground urban planning
- Maximise opportunities for underground development (basements etc.) and infrastructure (transport, sewerage, Sustainable Drainage, etc.)
- Identify potential heat and water resources, and limitations on their use (abstraction, drainage, water level, unsustainable rise and fall in groundwater, temperature, etc.)
- Inspire new ways of working, and greater freeflow of data and knowledge, which many will lead to improvements in sustainability, resilience, and the environment as a whole.

The development of more holisitic **environmental thinking, to include the surbsurface in urban planning and management** – and especially at an earlier stage in the process than is the case currently, requires that:

- Urban planners are given the necessary resources (knowledge and information) to adapt their current assessments and decision-making

- Geoscientists consider how better to develop/provide the right subsurface information, at the right time, to support urban planning and management

- There is improved communication between urban planners and decision-makers, and geoscientists at all levels.

It is, however, a challenge to bridge the gap between subsurface experts with a range of different technical backgrounds and urban planners and decision-makers - and **collaboration takes time**. An effort from everyone involved is needed to achieve a point where actual understanding and constructive communication is reached. To achieve constructive communication between disciplines, it is essential that all parties understand the terminology that is being used. The onus for translating their knowledge into understandable forms and formats is very much on the shoulders of the subsurface experts.

2. Results of the evaluation of practices and techniques

A systematic approach is needed, for which well-established practices and techniques are important. Working Group 2 has evaluated a number of such techniques and practices and the results are summarized in this report (see Chapter 2).

In many cases, several different techniques are needed, because solutions will depend on local circumstances: geology, land use, climate, history, available data etc. As such, there is no “one size fits all”. Instead, several workflows are presented, and many examples of good practice have been described. Key knowledge gaps have also been identified.

3. Access to subsurface data

In urban areas, data acquisition and management include data from geological/geotechnical boreholes, monitoring (e.g. groundwater and heat), in situ and lab testing, geochemical surveys, mapping and infrastructure development. The considerable amounts of data, especially of geotechnical data, and the extent of modelling, are characteristic for these areas.

Open, and efficient access to, data are particularly important.

In urban areas, most data generally derive from third parties (developers, consultants and contractors). Many of these, and many older data held in archives, are non-digitital, or at least only available in non-idigital formats. **Handling non-digital data** is very time consuming. Although the issue of dealing with non-digital legacy time is inevitably time and resource consuming, for acquisition of new data from third parties, efficient and effective digital data transfer, using standardised formats should be a priority.

For planning and management, subsurface information needs to be presented clearly and simply. Systematic workflows are needed to achieve this (see Chapters 3 and 4), to ensure timely **delivery of fit-for-purpose data and knowledge** that meet the specific requirements of end-users.

4. Modelling and mapping of the urban area

Mapping and modelling of the surface/sub-surface in urban areas addresses themes such as archaeological deposits, infrastructure (tunnels, pipes), buildings, fill and the underlying in situ geology. The method used to map **depends to varying degrees on history, geology, datatype, -amount and –quality, and the scale and uncertainty needed**.

There is yet no full-scale example of implementation of **an integrated model** that includes information on all facets of the above ground, anthropogenic deposits and the in situ natural subsurface. To cover all of these facets, and more, the concept of a GeoCIM has been developed here for this purpose. GeoCIM is based on the BIM concept, but is expanded to contain much greater emphasis on the subsurface.

Summary of Examples of Good practice

Figure 39 presents on a topic basis all of the examples of good practice described above. For further details, see the text in Chapter 2 and 3 and the detailed Subgroup Reports.

Topic	Good practice examples
2.1 Subsurface information and planning	How to identify subsurface information needs
	How to involve subsurface specialists into urban planning
	The Sweedish Geotechnical Institute´s landslide and erosion expertise – an example of national support to strategic and detailed planning
	Communication between urban planners and subsurface specialists
2.2 Data acquisition and management	Integrating urban datasets
	From analogue to digital data
	Commercial data and public data centre services
	Managing permissions and roles
2.3 3D geological subsurface modelling	Application of a phased approach in the construction of the 3D geological model
	Constructing and maintaining 3D urban geological models
	Modelling man-made ground
2.4a Groundwater monitoring and modelling	Key elements of good practice in the design of urban groundwater monitoring networks
	Generalised good practice workflows for development of groundwater models in urban areas where available data are of differing availability
	Groundwater modelling used to support city planning and management of subsurface resources
	Integrating subsurface infrastructure in city-scale groundwater recharge and flow modelling - to better understand the impacts and interactions of the infrastructure to the urban groundwater resource

	Developing decision support tools (DSS), incorporating time series monitoring data of key resources
2.4b Geothermal monitoring and modelling	Key data in the support of different management stages of Shallow Geothermal Energy (SGE)
	Work steps in good practice to assess the influence of SGE systems on urban groundwater flow and thermal regimes, using groundwater model or water balance approaches
	Monitoring and modelling
	Anthropogenic influence and monitoring

2.5 Geotechnical modelling and hazards	Geotechnical databases
	Framework of geotechnical data exchange
	Geohazards – Landslide inventories
2.6 Subsurface geochemistry	2D geochemical data acquisition for the topsoil and shallow subsurface
	The use of 3D urban geochemical data
2.7 Cultural Heritage	Standing monuments and sites
	Archaeological heritage and artefacts in situ
	Sustainable urban water management and cultural heritage
Integrated urban and sub-urban information modelling	Integrating above- and below-ground GeoCIM layers
	Optimising an existing groundwater monitoring network
	Embracing future uses of 3D models for all three GeoCIM layers

Figure 39. Summary list of selected good practice examples

Summary of Key knowledge gaps

In Figure 40, key knowledge gaps are listed for every topic. For further details, see the text in chapters 2 and 3 and the detailed Subgroup reports.

Topic	Key knowledge Gaps
2.1 Subsurface information and planning	What is a useful scale for geological and geotechnical information such as landslide hazard maps, depth to bedrock maps, etc. to be used in strategic planning? (Detailed enough to be useful yet easily used and understood by urban planners and decisionmakers.)
	The role of National Geological Surveys as a support to questions related to strategic planning in the urban sub-surface
	Experiences from renewals or updates from existing urban subsurface masterplans
	Examples of financial solutions used to make subsurface information available in strategic planning where guidelines for several unknown projects are set. For example, how the need for digitization, collection of data and production of maps have been financed when there are several unknown stakeholders, both private and public
	Methods to bring subsurface information into urban planning in cities with limite resources as data, time and/or economic resources
	The benefit of an extended and intensified usage of geotechnical data for suburban space management. As the impact of new tunnels, metro lines, cultural heritage, underground car-parks and buildings sub-levels with existing underground infrastructure is becoming more and more prevalent, collaboration with other users of these data must be investigated
2.2 Data acquisition and management	Clarify unclear legislation related to data acquisition and management policies
	Adopt standard naming conventions and use of controlled glossaries
	Develop data exchange and validation tools which are independent of proprietary software
	Maximize use of open data discovery and data access platforms, with low financial and security costs
	More metadata are needed to improve data discovery, explain how to use the data, and communicate any restrictions on their use

2.3 **3D geological subsurface modelling**	The complexity of the urban subsurface, including man-made ground, combined with the level of detail of information asked for in many urban planning issues, and the difficulties involved in collecting new data in a city environment, demand that geologists look beyond their traditional data sources (e.g. borehole descriptions, shallow geophysics) and use data from third parties. However, the integration and "translation" of all of the different data sources into one model workflow is currently very time-consuming and case-specific
	Combined 3D property modelling of the small-scale heterogeneity of man-made deposits and natural deposits requires new modelling approaches. The combined approach used in Odense looks promising, but has yet to be tested in other cities
	The properties and functions of the urban subsurface are frequently altered, making models quickly out-of-date. Management of the shallow urban subsurface requires model tools that can be frequently updated for a new situation (e.g. in conjunction with hazard management) or can quickly incorporate additional information. At present, there are no general workflows, other than for stochastic modelling of properties, that enable quick model update
	There is a need for dynamic (4D) urban subsurface models that can be used for real-time monitoring and incorporation of time-series data on subsurface properties, e.g. in conjunction with cultural heritage management or monitoring building activities.
	At present, shallow subsurface models are largely constructed on an *ad hoc* basis when a subsurface-related problem occurs. It would be much more cost-effective if one geological framework model would be available, that formed a common basis for the various kinds of dedicated models of parts of the city. Apart from being actively maintained, a framework model would have to be scalable (5D), in order to be of much use
	To give subsurface information a firm position in urban planning and management, geological information will have to be presented in the right format, at the right time. It should also be possible to include subsurface infrastructure and aboveground information. At current, there are no good examples of a truly integrated modelling approach that extends both above and below the surface

2.4a Groundwater monitoring and modelling	In many cities/countries there is no formal legislation or regulation on specification of monitoring infrastructure
	There is significantly difficulty in designing appropriate representative groundwater monitoring networks, in cities which have very little historical groundwater data or understanding of the urban groundwater resource, and no existing network infrastructure
	Urban groundwater monitoring systems have generally been developed over time and are ad-hoc, and do not capture appropriate data for current monitoring needs
	Lack of understanding of aquifer properties of man-made (artificial) deposits and subsurface infrastructure, and how these should be appropriately modelled in 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
2.4b Geothermal monitoring and modelling	How can a series of 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)?
	How can these complexities be communicated and included in city planning?
	To what degree can 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?

2.5 Geotechnical modelling and hazards	How to increase the awareness among city planners and stakeholders of the importance of geotechnical modelling and geohazards inventories?
	How to incorporate geotechnical modelling and geohazards data into the early stages of spatial planning?
	How to encourage private companies to share their geotechnical data with geological survey organisations and municipalities? This may be by enforcement of regulations requiringdata to be sent to geological survey archives, or by cooperation for mutual benefit (like ASK Network)?
	What should be an optimal framework/standard for integration of 2D/3D geotechnical models (site specific) with city scale 3D models?
2.6 Subsurface geochemistry	Development of 3D and 4D mapping technology
	Geochemical data acquisition and management
	3D representation and use of geochemical data
2.7 Cultural Heritage	There is a large risk of heritage deterioration as a result of unforeseen circumstances. The reasons for these are plenty; natural, political or management decisions, characteristics of the soil, historical activities, (ground) water circulation, human action or just the wrong location. Significant progress has been made in recent years towards a more holistic approach, including a range of different disciplines. This progress has been triggered by examples of developments where environmental changes caused by urban development have resulted in decay of archaeological deposits and damage to historic buildings. **A proper understanding of the natural and man-made environment and processes** affecting heritage is essential for in situ preservation, mitigation design, as well as management of heritage sites. Cultural heritage resources have to be considered as an integral element in urban planning processes if they are to be preserved for future generations

	In general, the **current status in urban planning shows a lack of coordinated policy on the subsurface**. In urban development processes, conflicts with prior uses and unappreciated impacts on suburban resources, amongst them archaeological heritage, are either unaddressed or taken care of too late in the planning process. This makes the use of underground space in cities suboptimal. In terms of ecosystem services, the subsurface environment either acts as a carrier for archaeological heritage (stewardship) or supports above ground heritage. Often it is not enough to protect the heritage site or monument itself; new developments outside a specific protected area can lead to changes in groundwater level, and cause serious damage to heritage buildings and archaeological deposits
	The multiple benefits that modern sustainable water management systems may provide, including heritage preservation support, are not yet fully recognized by those who can benefit most from it; heritage managers, water managers as well as urban planners and decision makers. A knowledge gap exists in terms of awareness of the option to include (retrofit) modern climate adaption measures in historic cities. Similarly, it is necessary to further develop technical modifications to established sustainable water management systems if they are to be applied in areas with vulnerable cultural heritage. Implementing new infrastructure for sustainable water management in archaeologically important areas can be challenging Any local structure used to manage surface - and groundwater flow can potentially damage archaeology Most of these structures require groundworks, and some are placed completely under the surface. This trade-off requires special attention and experience

Integrated urban and sub-urban information modelling	The largest knowledge gap in this subject area is how to initiate the GeoCIM process. However, it is not necessary to commit, up front, to creating the perfect, fully-featured GeoCIM from scratch
	The biggest impacts of a GeoCIM are likely to come in the earliest phases of the decision-making and planning process, when a holistic overview of all relevant information can result in design changes that minimise cost and hazard risks. There needs to be greater recognition of this potential impact and benefits of GeoCIMs within this early stage of the decision-making and development process – as well as the knowledge benefits of integrating above- and below-ground city information to these early strategic decisions. This is something that city municipalities and other government bodies, as well as geological surveys and other research organisations are only just beginning to realise and fully explore

Figure 40. Summary list of key knowledge gaps identified

6. General conclusions

Working Group 2 has, besides this summary report and a number of detailed reports, provided the essential framework for the Toolbox being developed by the COST Sub-Urban Action's Working Group 3.

In addition to the concrete results, COST Action Sub-Urban has been successful in creating a community of practice between the geoscience and planning communities, involving cities, universities and institutes.

To some extent, the project is already improving conditions for urban subsurface planning, especially where communication, mutual understanding and awareness raising are concerned. For better impact, however, this will have to be extended to decision makers and the general public.

Assessments of cost- and time-benefits of the rationale behind the systematic inclusion of the subsurface within planning and other decision making (requiring data, databases, modelling, decision support systems, monitoring etc.) has not been undertaken here, but needs to be explored.