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Development of a 3D geological/hydrogeological model targeted at sustainable management of the urban water cycle in Odense City, Denmark

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Abstract

Many urban areas in Denmark are facing rising groundwater levels due to decreasing groundwater abstraction, greater rainfall and rising sea level due to climate change. Therefore, solutions for handling excess surface water and groundwater in urban areas are needed. To ensure a good background for a continued and sustainable handling of the urban water cycle, special attention has to be paid to the development of geological/hydrogeological models of the subsurface as a basis for management and planning.

A 3D geological/hydrogeological modelling tool for handling the urban water cycle within Odense City has been setup in a collaborative effort involving authorities and private stakeholders. With Odense City as a pilot area the developed tools and the gained experience has been made available for other cities facing similar challenges. This paper introduces the Odense Model, presents the major project considerations during the construction, and briefly presents the model results, the developed tools for urban planning/management and the project considerations concerning the continued use and maintenance of the model.

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1. Introduction

Odense City is located in the middle of Odense Municipality in the south-central part of Denmark (Fig. 1). The main part of the city has developed over the past 200 years, and only a minor part in the city centre is older. Odense City is situated close to a river (Odense Å), near the coast and at the low end of the catchment, as is the case of many other cities in Denmark. The location implies that the city is exposed from all sides in relation to climate changes (e.g. excess surface water run-off, raised groundwater levels, raised sea level).

![Fig. 1. Study area: Odense Municipality](image)

The near-surface geology within Odense Municipality consists of a Quaternary succession dominated by clayey till deposits with local sand layers and lenses. The terrain and the sediment distribution in the city is affected by erosional and depositional events in the Late Glacial and the Holocene [1]. Like many other cities in Denmark, no systematic geological mapping has taken place in Odense since the seventies [2]. The Quaternary sediments beneath Odense City have variable hydraulic conductivities, and due to the mainly clayey subsurface, infiltration of water is impeded in many areas. Facing rising groundwater levels due to decreasing groundwater abstraction, greater rainfall and rising sea level in the future, solutions for handling excess surface water and groundwater are needed.

In 2012, The Municipality of Odense, the water utility (VCS Denmark) and the Geological Survey of Denmark and Greenland (GEUS), decided to join forces and to develop a 3D geological/hydrogeological modelling tool as basis for handling the urban water cycle. With Odense City as a pilot area the developed tools and the gained experience would be available for other cities facing similar challenges. The Danish Water Technology Foundation granted funding for a two-year project. The pilot project finished in 2015 [3], and in 2016, the tools and modelling procedures were evaluated as a good practice example for several topics in the EU COST TU1206 Sub-Urban Action [4, 5].

During recent years, local hydrogeological modelling in urban areas has been carried out in connection with remediation of contaminated sites, handling of surface water and groundwater levels at construction sites, geothermal energy plants, projects concerning protection of cultural heritage etc. Traditionally, little or only sporadic re-use of the models has taken place and new modelling often begins from scratch. In this way the individual models were short-lived and only made for specific local purposes. This also implies that the individual models have been based on different data with different focus and consequently the model results cannot be compared.

This practise conflicts with the purpose of urban planning and management, because ideally reliable and uniform information about the urban subsurface are required. The urban subsurface develops over time and therefore a follow-up on consequences of impacts - whether artificial or natural - is important. Therefore, the main philosophy behind the Odense project was to obtain a technical basis for obtaining the best possible and (closest to) reproducible results...
for the planning and management of the entire water cycle. To that end, it is imperative to put all effort into constructing and maintaining only one model of the subsurface.

2. Detailed analysis of urban modeling requirements

2.1 Working strategy

From the very beginning of the pilot project, comprehensive effort was put into analysing different typical urban cases in order to find a balance between the available data, and the models capability and requirements [5, 6].

2.2 Modelling in a changing hydrogeological environment

Handling of rain in urban areas often implies a desire to use of SUDS (Sustainable Urban Drainage System) based on surface infiltration. In Denmark, there have been several examples where this implementation has not been possible due to low infiltration and generally poor drainage conditions. Besides, the establishment of these SUDS should not result in flooding on e.g. neighbor’s parcels or other sensitive places within the catchment. SUDS solutions therefore require a thorough knowledge of the geology and hydrogeology.

It is necessary to incorporate knowledge of city development over time (increase/change in build-up areas, pavements, water abstraction etc.), impacts from industry (water consumption, pollution); former drainage related to agriculture etc. and in addition the impacts of future climate changes. An evaluation of the individual and accumulated effects is important to ensure a sustainable urban environment and to protect the city against unwanted impacts. Urban modelling reveals a need for handling the different impacts on the water cycle at different scales and a need for inclusion of relevant man-made (anthropogenic) layers. A prerequisite for this is near-surface mapping with systematic use of existing and new data. The modelling requires knowledge of not only surface hydrology, drainage systems, geology, but also accurate information on buildings, infrastructure elements (e.g. constructions, pipes) within urban areas.

2.3 The anthropogenic layer and its use

Mapping of the anthropogenic deposits in the urban areas is important because:

- Knowledge of the subsurface at construction sites is crucial (good fill/bad fill)
- Planners need to know about all parts of the subsurface of the existing city and to be able to plan beyond, as urban growth implies a battle for space both above and below the surface
- Knowledge of the anthropogenic deposits is needed to forecast consequences of land-use changes/abstraction/infiltration – affecting the urban water cycle. This is equally important when forecasting consequences of a changed climate

Modelling the urban infrastructure implies use of many new datatypes, new data sources and a data amount much bigger, more detailed and more dynamically changing than seen in traditional hydrogeological modelling.

The anthropogenic layer resulting from a complex series of events forms a layer on top of the geological sequence; see Fig. 2. Usually, the geological deposits are older than the anthropogenic layer and therefore constitute the layers underneath the man made deposits. The anthropogenic layer is the result of a historical sequence of events that through the years have changed the uppermost layer of the subsurface. This means that it is important to have knowledge of the city history in order to model the uppermost layers. The age of the different data used in the mapping and modelling is important as later urban activities can change the validity of the information about former deposits. Geological deposits identified in a boring can for instance be substituted by later buildings or constructions, and will therefore no longer be present.
Fig. 2. Illustration of infill around different buried infrastructure (fill, buildings, pipes, boreholes etc.) contributing to the anthropogenic urban layer (shown in yellow) on top of the original geology (layers shown in green, brown and red).

2.4 The 3D geological/hydrogeological modelling tool

In order to construct a model that can handle the required tasks in order to be able to function as basis for the urban water cycle, the following fundamental elements should be included:

- Aquifers and aquitards
- Information of both geological and anthropogenic deposits and objects (man-made fill and infrastructure)
- Data/knowledge about the groundwater table/hydraulic head

Modelling in a variable scale is important, in order to be able to make detailed interpretations of urban areas and their catchments with use of the largest possible amount of information.

2.5 Maintenance strategy for the modelling

The continuous maintenance and update of the model is important to ensure that the model continues to be functional and up to date. Therefore, a strategy for model update has been an important part of the project. From the very beginning of the project, it was important to ensure that the hydrogeological model with its aquifers are referenced to the already established hydrogeological units; to ensure that the model will fit the structure of surrounding hydrogeological models and to make future updates possible. For many years, there has been a tradition for groundwater modelling in Denmark to re-use the structure of the national DK-model. A continuation and refinement of this praxis would make it possible for others to use the Odense Model.

For the modelling of the anthropogenic layer, it was important to use the original data formats of the cadastral and infrastructure data, in order to make future updates easier to perform. As the update frequency of some of the delivered data sets is rather high, it was relevant to work out standards and tools for handling the delivered data.
3. Results of the Pilot project

3.1 Data – Concepts for data evaluation, quality and use

The success of urban planning and management relies on fast and easy access to information of good quality. The data handling in hydrogeological modelling projects is commonly very costly, and in urban areas, the amount of data implies a workload that may be even more time consuming. Therefore, in order to optimize time spent on the relevant datasets, the available data were analysed and data management procedures (e.g. quality classification and usability of the individual datasets) were described [7].

Special data models were constructed to account for excavations with potential local importance for groundwater flow beneath houses and along pipelines. Data models such as these were needed because of a general lack of detailed data describing the anthropogenic layers. This type of modelling implies a possibility to use other types of knowledge, e.g. varying construction procedures for applying infill under new buildings and around pipelines [7].

Special attention was paid to geotechnical borehole data because they generally cover the uppermost part of the subsurface and contain a high degree of detail beneath the cities. However, large parts of these data are not in the public databases and many are considered private property of the geotechnical companies and therefore are not publicly available [8]. Access to this type of data would require payment and due to financial circumstances, this was unfortunately not possible in the scope of the project.

The evaluation of the geotechnical data also revealed a potential for open access for several other users of geotechnical data in the urban areas (building administration, remediation, road- and railway building, cultural heritage, utilities etc.), that is not fulfilled today [8].

3.2 Handling anthropogenic data

For the handling of the anthropogenic data and mapping the anthropogenic layer, applications in the software-modelling tool, GeoScene3D, were developed [9]. These applications made it possible to handle the large amount of anthropogenic data and to map different kinds of structures (e.g. the sequence of excavations mentioned above; see Fig. 3).

![Fig. 3. Modelling of subsurface infrastructure. The figure shows an example of a detailed voxel modelling of sewers with permeable infill around the pipeline excavations). Tubes are shown in grey lines and sand/gravel inffills around are shown as yellow voxels. From [9].](image-url)
3.3 Modelling

The pilot project resulted in a municipality model for Odense consisting of a geological and a hydrostratigraphical model [1] supplemented with descriptions of procedures for construction of a detailed anthropogenic voxel model in the selected local areas [9].

A subsurface model that has focus on the uppermost parts of the subsurface will have to include both the geological succession and the anthropogenic layers. However, due to the different nature of the two, different mapping and modelling approaches were needed. The mapping of the original geology used a standard framework-model approach with mapping of layer boundaries, based on primarily borehole data, geophysical data and high-resolution digital elevation models. The anthropogenic layer was mapped by using information of the thickness and character of the manmade in-fill layers from boreholes added with information about the infill of excavations around subsurface infrastructure. The latter required not only detailed data of the age, character and spatial extent of the individual parts of the infrastructure but also specific knowledge of standards for back-fill of the excavations.

The anthropogenic layer and the original geology were finally merged, replacing parts of the original geological layers with the anthropogenic layers (Fig. 2). In this way, the two separate mapping efforts were combined in one final 3D voxel model. However, as the geological/hydrostratigraphical model and the anthropogenic model are constructed differently, it is important to choose a common discretization to enable the final merging. Even more important, it is necessary to decide on a discretisation that meets the required detail, but does not exceed the computational capabilities. Fig. 4 shows the workflow for merging the geological/hydrostratigraphical model with the anthropogenic layer model. This workflow can be used whenever a new local model is constructed.

3.4 Tools and recommendations

A number of general tools and recommendations were established in order to make the results and experiences from the pilot project available for other projects in the region and for other cities [3]:

- A description of the main influences on the water cycle in the urban subsurface
- An analysis of working procedures in connection with the data management of the water cycle
- A systematic collection and assessment of existing available data
- An assessment of the potential for an improved procedure concerning geotechnical data
- Workflows for the use of scale-independent 3D hydrogeological models
- Workflows and tools for 3D modelling of anthropogenic deposits
- Workflows for merging geological and anthropogenic models
- New storage capabilities for geotechnical information in the National Borehole Database (Jupiter (http://www.geus.dk/DK/data-maps/jupiter); hosted by GEUS)

4. The model used for decision support

4.1 Evaluation of the model as a decision-support tool

The developed 3D geological/hydrogeological model was at the time of completion the best basis for strategic planning and management of the subsurface in the Municipality of Odense in 2015. In spite of that, the case studies performed in different urban areas showed that the detail of the model very often turned out to be insufficient when working on a cadastral plot level [3]. Therefore, it is recommendable at the earliest possible stage of the decision processes to evaluate if the available data detail can match the scope of the planning and management. It is important that the sufficient knowledge for making decisions and impact assessments is present.

In Odense City, as well as many other cities, new data are normally collated in connection with new construction projects but not systematically at city scale [10]. In order to have the best model and data available at all times, the municipality 3D model needs continuous updating and improvement with new data to permanently function as a basis for detailed administration of the urban water cycle in the Municipality of Odense [6].
Fig. 4. Workflow for merging a hydrostratigraphical model with an anthropogenic model [6] at chosen scale and extent.

4.2 Future improvements

Because it is important to continuously elaborate and improve the 3D model in order to constitute the continued basis for administration and planning, it is recommended:

- That new data henceforward are collected as basis for the planning and management
- That the authorities require reporting of new geological and geotechnical data from private contractors (both at municipal and national scale)
- That geotechnical data are used in the 3D model
- That the 3D model is continuously re-evaluated according to new data and new requirements
A coordinated data handling and modelling is a necessity to keep track of the consequences of man-made activities for the urban water cycle. The starting point of the procedures for handling the urban hydrological cycle is the planning needs and the current technical and scientific crafts. It requires a systematic and firm data handling that is not developed now, as the SMART City era has just been initiated in Odense. There is a need for leadership, collaboration, (re-)organization and structure that must also include areas outside the cities.

A praxis/system/legislation on municipality/city level assuring the (open) access to data, handling of data and maintenance of a subsurface 3D model is required in order to currently have the right type of information prepared and available for future planning and management.

5. Conclusion

After finishing the 3D hydrogeological municipality model for Odense in 2015 it has been used for different purposes in several other projects and as such the pilot project can be considered a success. In 2017, a new and more detailed geological/hydrogeological model in the western part of Odense has been constructed using the instructions recommended in the present project [11]. Therefore, the new local model can be used to update the Odense model and thus add more detail.

However, a praxis/system/legislation is still required to ensure the organization of a continued collation of data and maintenance of the modelling of the subsurface beneath Odense, including the anthropogenic part.

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