

## Evaluating the hazard of reactivating contaminates by infiltration-based climate adaptation solutions – exemplified with a case study from Denmark

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**ABSTRACT:** By 2050, an estimated 70% of the global population will reside in urban areas, posing significant challenges for urban planners amid expanding cities and impending climate changes. Ensuring stable surface water disposal becomes crucial, prompting the adoption of Sustainable Urban Drainage Systems (SUDS) as an economically viable solution. However, integrating SUDS presents challenges for urban planners as no clear guidelines for assessing contaminants potentially mobilized by SUDS have been conducted in Denmark so far. To address this challenge, an urban 3D geological voxel model with a discretization of 1 m x 1 m x 0.5 m has been developed. The model, spanning 1 km<sup>2</sup>, was conducted in the city of Aarhus, Denmark. The model is based on high-density geophysical data comprising DualEM-421 and ERT profiles, 75 boreholes, and GIS information on anthropogenic structures. The geological model serves as the basis for a groundwater and contaminant transport model, in which the effects of increased infiltration from SUDS on groundwater flow patterns and the fate of contaminants can be quantified. The project successfully evaluated the contamination hazards for the area. In the present case, there was no immediate risk of reactivating surrounding contaminants, as they were located too far away from the SUDS for the rising groundwater, due to the increasing infiltration through the SUDS, to affect them. However, the results shows that cellars in the area may be threatened by the local groundwater rise. Based on the methodology and results from the project, a best practice has been developed, enabling urban planners to integrate SUDS into the urban environment without potentially remobilizing surrounding contaminants. The adopted best practice can be successfully applied in similar situations to reduce the hazards associated with urban development.

**KEYWORDS:** SUDS, Contaminations, Groundwater, Best practice.

### 1 INTRODUCTION

During the last century, a demographic change has occurred as people increasingly move towards urban areas (UN, 2019). The continuous growth of cities, combined with anticipated climate changes, presents significant challenges for urban planners. Climate models predict that the severity of extreme weather events in Denmark, such as more frequent and intense summer precipitation events, will increase, and winters will become wetter (Langen et al., 2019). Since traditional urban sewer systems are designed for the present climate, the new precipitation patterns are expected to cause a higher frequency of flooding in urban areas. Therefore, one of the most significant challenges is to ensure the stable disposal of surface water. An easy and economically feasible solution is to introduce Sustainable Urban Drainage Systems (SUDS) into the urban area (Duffy et al., 2008; Ossa-Moreno et al., 2017; Webber et al., 2019). Due to continuous urbanisation, numerous former industrial sites containing contaminants in urban areas are now being transformed into residential areas. The majority of these contaminants have been mapped and evaluated to determine whether remediation is necessary. In many situations, the contaminants have been considered less acutely dangerous due to their location in the unsaturated zone, and thus, deemed immobile. However, if increased infiltration from SUDS leads to

a general rise in the groundwater table, a reassessment of the numerous known and mapped contaminated sites should be conducted.

However, urban planners face multiple challenges when evaluating whether infiltration from SUDS, in conjunction with insufficient knowledge about the geological and hydrological setting, constitutes a threat to the environment (Cen et al., 2021). In Denmark, there are no clear guidelines on how to assess the impact of contaminants mobilised by SUDS. To address this issue, one urban case site (SPARK) in Aarhus, Denmark, have been selected, Figure 1. Infiltration-based SUDS are one of the means for managing surface water at the SPARK location.

The project has successfully assessed the hazards of reactivating contaminants around the case site based on detailed information on geology and hydrology. The findings have been documented as best practices for urban planners to use when integrating SUDS into the urban environment (Ministry of Environment of Denmark, 2021).

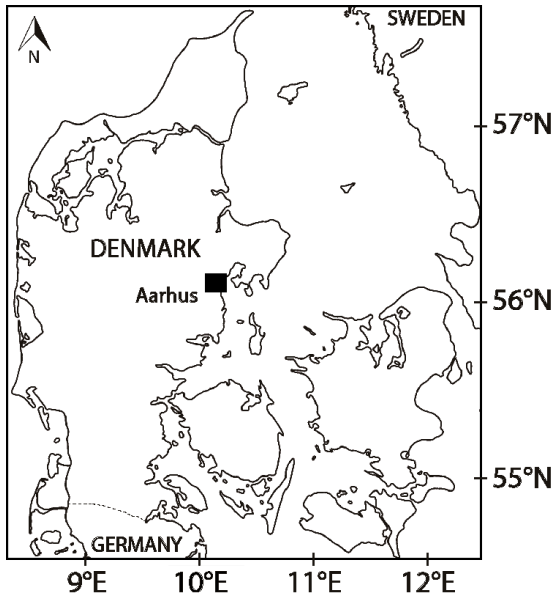


Figure 1. Overview map of the SPARK location

## 2 DATA AND METHODOLOGY

The SPARK site have been mapped using DualEM-421, Electrical Resistivity Tomography (ERT) surveys and boreholes. The groundwater table is located approximately 1 to 3 m below the ground surface (mbgs) based on measured groundwater levels obtained from boreholes. Data included for the interpretation of the hydrogeological model at SPARK is shown in Figure 2.



Figure 2. Overview map showing the position of the geophysical mapping and boreholes at the SPARK site. Mapped contaminations in the near vicinity of the SPARK site are marked with purple and red areas,

ERT profiles with blue lines, DualEM-421 measurements with small dark blue dots, and drillings with purple, red, yellow and green dots.

### 2.1 Geophysical data

The DualEM-421 data were collected using a DualEM-421 ground conductivity meter (DUALEM Inc., Milton, ON, Canada). The DualEM-421 system comprises six receiver coils arranged with three horizontal and vertical coils, positioned at 1, 2 and 4 m and 1.1, 2.1 and 4.1 m, respectively, from the transmitter coil. Data processing and inversion were conducted using the Aarhus Workbench software ([www.hgg.au.dk](http://www.hgg.au.dk)). Approximately 5% of the data were removed due to noise or couplings from buried conductors. Spatially constrained inversion (SCI) was applied to generate a smooth 14-layer model (Auken et al., 2015).

A total of 6 ERT profiles were collected using an ABEM Terrameter LS (see Figure 2). The depth of investigation was approximately 20 to 30 mbgs. ERT processing and inversions were carried out using the Aarhus Workbench software, including AarhusInv (Auken et al., 2015; Auken and Christiansen, 2004). To prevent couplings, the lines were planned in the green areas away from buildings and known buried cables. And 90 degrees on the central path way where coupled data related to lighting up a central pathway were edited away.

### 2.2 Boreholes

35 boreholes were available within the SPARK site, with an additional 50 boreholes in the near vicinity of our investigation (see Figure 2 and 3).



Figure 3. Overview map showing the position of the 10 boreholes within the SPARK site (Bor1 to Bor10) providing recent groundwater levels, the calculated hydraulic heads from the groundwater model (red contours lines) and the model domain for the geological and groundwater model (marked with the white square).

The majority of the boreholes are geotechnical boreholes, with drill depths ranging from 5 to 10 mbgs. The borehole information includes geographical coordinates, depth, borehole sample descriptions, lithological boundaries, groundwater levels and chemical analysis. The quality of the borehole information varies due to differences in borehole age and drilling methods.

### 2.3 SUDS

In Figure 4, the planned SUDS for the SPARK site is illustrated. The area is designed to handle all the rainwater within the site itself. As shown, the SPARK site contains multiple rainwater basins, some with permanent free-standing water (dark blue areas) and others with a fluctuating water table (light blue areas), as well as flooding corridors between the basins to divert surface water to the basins (blue arrows). Infiltration is expected to occur from the three squared basins marked with dotted blue lines and a red circle.

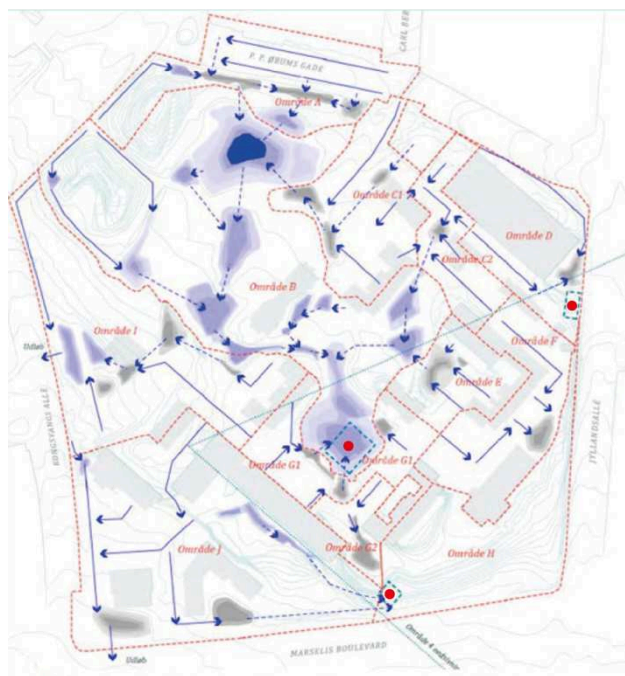


Figure 4. Planned handling of the surface waters at the SPARK site. Credit: Aarhus Vand, NIRAS, MarselisborgCentret.

### 2.4 Methodology and model inputs

Based on lithology information from boreholes and geophysical data, a geological voxel model was created with cell sizes of 1x1m along the horizontal axes and 0.5m in the vertical direction, see Figure 3 for areal extent of the model. Pipes and buildings were added to the voxel model using GIS data. The methodology

principles can be found in Andersen et al., (2020) and Andersen, (2020). Based on the geological model, a groundwater model was constructed using the FEFLOW software using the same voxel size and the same areal extent as the geological model. As there wasn't any detailed information on the water balance for the SPARK area, general considerations for precipitation, evaporation, and surface water flow in the Aarhus area are used as input (Jensen, 2020 and Ministry of Environment of Denmark, 2021). For the boundary conditions along the model domain, an overall regional groundwater model of Denmark was used (Ministry of Environment of Denmark, 2021). The hydraulic conductivities of the various lithologies was obtained from Schwartz & Zhang, (2002). Finally, the groundwater model was calibrated by comparing observed and calculated hydraulic heads in the upper sand aquifer. After the completion of the groundwater model, FEFLOW was also used to model the transport of contaminants based on the hydrological model and estimated extents and concentrations of contaminants.

## 3 RESULTS

### 3.1 Geological and groundwater models

In Figure 5, a south to north profile from the SPARK site illustrates how geophysical data and boreholes are interpreted into a hydrogeological model.

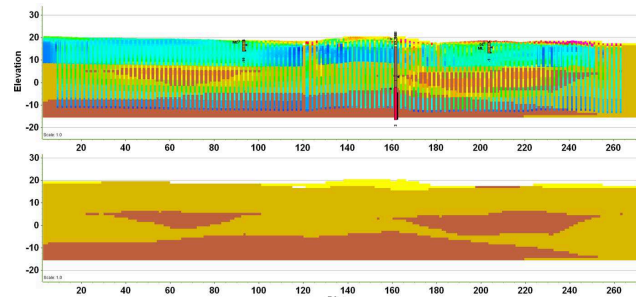


Figure 5. Top: Geophysical data and boreholes shown. Blue and green colours represent clay dominated sediments. Yellow and red colours represent sand dominated sediments. Bottom: the interpreted geology. The position of the profile can be observed on Figure 2.

The geology at SPARK is interpreted to consist of 1 to 5 m of sandy fill at the surface (yellow layers in Figure 5). Underlying the fill, a layer of moraine clay up to 30 m thick is interpreted (light brown colours on Figure 5). Interbedded within the moraine clay, sand lenses are observed, exhibiting changes in areal extent and thickness (red colours on Figure 5). Below the moraine clay layer at 30 mbgs, a sand layer is observed. Since moraine clay, with a low hydraulic conductivity of around  $10^{-9}$  m/s, dominates the upper 30 m, infiltration is restrained and large fluctuations in the near-surface groundwater are observed. This can be observed in the results from the groundwater model, as shown in Figure 6 where a contour map showing the changes in groundwater levels due to the construction of SUDS has been compiled based on a current precipitation scenario (situation a on Figure 6) and a future precipitation scenario (situation b on Figure 6). It can also be observed that the increased infiltration, and consequently the rise in the near-surface groundwater, does not interfere with the

contaminations nearby (green and purple areas on Figure 5) and therefore does not reactivate them in this case. This is primarily attributed to the geological setting, where the fillings within the SPARK site constrain the extent of the rise in groundwater. However, it is acknowledged that if more surface water were to be infiltrated in the future, remobilisation cannot be ruled out.

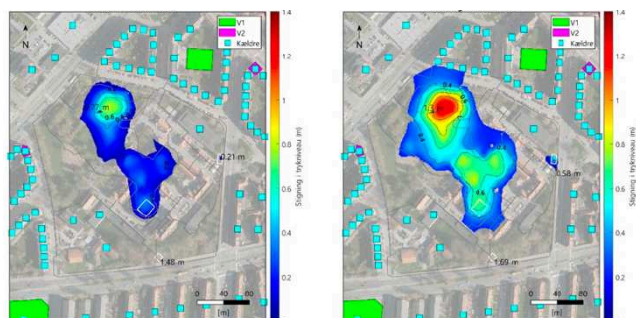


Figure 6. Left: modelled groundwater level with present precipitation pattern. Right: modelled groundwater level with future precipitation pattern. The cyan colour boxes represents building with cellars. The green areas in the northeast and southwest as well as the purple areas in the northeast and west represents contaminated sites.

### 3.2 Best practice

Based on the results and methodology of this project, we have constructed a best practice to be used by municipalities when evaluating whether a permit involving infiltrate-based SUDS in urban areas should be granted or not. The best practice presents the recommended workflow for granting infiltration permits in urban areas where contaminated grounds are often present nearby (see Figure 7).

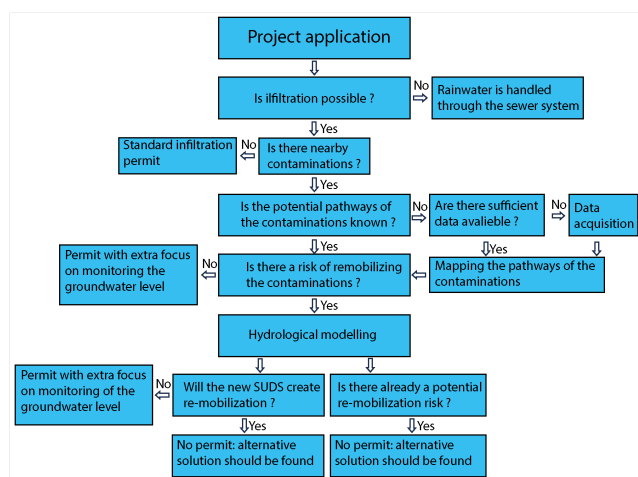


Figure 7. Best practice to evaluate whether a permit involving infiltrate-based SUDS in urban areas should be granted or not

## 4 CONCLUSIONS

This study proposes that a combination of high-density geophysical mapping, in conjunction with boreholes and GIS data, can provide a solid foundation for the development of reliable geological, groundwater and contamination transport models. The models can help city planners understand how contaminations will be affected when there is a change in infiltration patterns in an area e.g. due to the construction of SUDS. This capability potentially enables the identification of remediation measures and an assessment of what should be addressed in the process or as a consequence of the alterations. The employed methodology and findings serve as the groundwork for creating a best practice guide that urban planners can follow when evaluating upcoming applications related to SUDS in urban environments.

It has been revealed that high groundwater near buildings and structures is an immediate and significant risk. For the SPARK site, there does not seem to be an increase in groundwater levels at the contaminated sites, which are fortunately located outside the area affected by the additional infiltration. However, the project results also showed that cellars in the area may be threatened by the local groundwater rise. In this context, it is emphasised that testing for issues with high groundwater can also be addressed using the developed ‘best practice’ by shifting the focus from whether pollutants are affected by rising groundwater to whether buildings and structures are affected by the rising groundwater. Thus, in this case a permit was not given enabling the surface water at the SPARK to be handled using SUDS.

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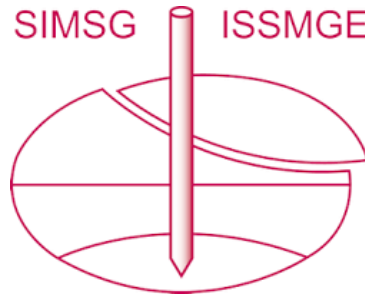
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