Reply to RC3: 'Comment on hess-2022-330'

[Reviewer comments in normal font; *Author replies in italic*]

This manuscript deals with the modelling of shallow groundwater flows and levels in urbanized catchments, and highlights the impact of both the urban geology description and the spatial resolution used in the distributed model. This topic is of high interest, because the interactions between groundwater and underground constructions are important in urban soils whose features are very variable, and we need to improve our ability to simulate these complex hydrological behaviours.

The study is based on an integrated hydrological model using MIKE SHE code and this model allows a detailed representation of groundwater levels and flows. Velocity fields and then travel times may be deduced from the model; this is a real added value of this modelling application : this type of result is quite rare in the field of urban groundwater modelling and it has to be noticed. The impact of urban infrastructures in the shallow groundwater flows and level is proved through this study and this is a step forward in the urban hydrology behaviour knowledge.

The structure of the paper is basic and clear, with a first introduction section presenting the main issues related with this topic and a short state of the art dealing with urban shallow groundwater modelling, and a focus on the importance of the soil and geology description. The second section includes the case study presentation. The Geological models and the main modelling methodology adopted here is presented then and the data- modelling- and evaluation methodology adopted here. The last sections are usual, with results, discussion and conclusion.

Reply: *We thank the reviewer for the overall positive and constructive feedback on our work. Below, We will address the reviewer's comments and how we intend to respond to the issues pointed out by the reviewer.*

General opinion and minor comments

This manuscript is devoted to the sensitivity of an integrated hydrological model to the urban geology, and uses 3 different representations (i.e. 3 geological models) with various consideration of the specific urban soil features. The sensitivity of the model to the spatial resolution is analysed too. For this last factor, I wonder if only two grid sizes is enough for the study of the effect of the spatial resolution.

Reply: *We acknowledge that by only testing two grid sizes for the hydrological model we cannot claim to have done an exhausting analysis of the sensitivity of the model to the spatial resolution. Furthermore, as we have written to the first reviewer, we concede that the manuscript lacks a justification for the choice of discretization of both the geological voxel models and the hydrological models.*

As written in the response to the first reviewer we suggest to add the following lines in the method section:

Text to add after line 160:

The effect of spatial discretization was tested by using a coarse discretization relative to the urban subsurface infrastructure and a finer discretization close to the scale of the urban subsurface infrastructure, e.g., roads and trenches. For both the geological and hydrological modeling tools a discretization in the order of 1-10 m becomes computationally challenging when the size of the model is large, that is millions of grid cells.

Text to add after line 180:

The choice of discretization for the voxel model of urban geology was guided by the experience from the study of Mielby & Henriksen (2020;) and Mielby & Sandersen (2017) and chosen to be a 5 x 5 x 1 m to be able to represent the subsurface cable trenches which are typically 1-3 m wide and 1-2 m in depth for this study area. The horizontal discretization was thus larger than the dimensions of the trenches. This was because a smaller discretization for a model at the city scale would have been too computationally heavy for the hydrological model to handle. Mielby & Sandersen (2017) argued that the discretization of the geological and hydrological model has to meet the required detail, yet not exceed the computational capabilities. The two voxel models each had 22 million voxel grids.

Text to add after line 212:

For the hydrological modeling, multiple grid sizes were initially tested. The two grid sizes of 50 and 10 m were chosen based on a tradeoff between computation time and the number of grid cells for the model size.

Furthermore, we will elaborate on the topic of choice of grid sizes for urban hydrogeological models in the discussion section during the revision of the manuscript.

A suggestion for text to add to the discussion during the revision of the manuscript:

We wanted to test the impact of urban geology for only two discretizations; a coarse discretization relative to the urban subsurface infrastructure and a finer discretization close to the scale of the urban subsurface infrastructure, e.g., roads and trenches.

The two sets of models with different spatial discretization produced the same results on simulated groundwater levels, however, the 50 m resolution models simulated longer residence time than the 10 models. These results illustrate that the computational grid size can affect the simulation of particle transport and residence time.

These results are of importance for future studies of urban hydrogeology since the computational time of the two tested resolutions varies substantially. The 50 m models were 60 times faster in computational time than the 10 m resolution models. A coarser grid resolution is thus only sufficient if the groundwater level dynamics are of interest, while for the simulation of groundwater ages and transport in a complex urban subsurface, a finer grid is required.

Minor comments

The overall manuscript, including methods and results, is relevant and well-prepared and written. However, I have a few minor comments that could be into account in order to improve the quality of the manuscript and help the reader.

First of all, I noticed a lack of justification, especially in the Methods section. The authors did not always argue their assumptions :

- p5 l 118 : "… concrete pavement , which have an imperviousness of 75%" . How was this value estimated? Traditionally, this kind of surface is considered as totally impervious. But I acknowledge that it may be partially pervious. But that should be explained.

Reply: *The quoted sentence says above 75% in the manuscript. The sentence is a description of the map in Figure 1b, which shows the imperviousness in percentage in 10 m grids. The data on imperviousness is from a raster map from the Danish Geodata Agency (2019).*

Buildings and pavements are as the reviewer points out normally considered 100% impervious. Yet, the map contains areas where the imperviousness is 75%. This can be places where a little area with vegetation is placed next to a building or a road.

As suggested by the reviewer, we will specify this in the manuscript during revision.

In the manuscript, in lines 116-118 the text says:

"Approximately 50 % of the total land cover in the model domain is impermeable or semi-permeable such as buildings, asphalt, and concrete pavement, which have an imperviousness above 75 %."

We propose to add the following lines after this sentence:

Buildings and pavements are normally considered 100% impervious. Yet, the map contains areas where the imperviousness is 75%. This can be places where a little area with vegetation is placed next to a building or a road.

-p7 l 183 : " … and additional data on soil material in the top 5 meters". As the modelling application is quite sensitive to the soil configuration, especially in the first meters, one can wonder where this "additional data" comes from! What kind of additional data? From drilling data? From infiltration tests?

Reply: *As suggested by the reviewer, we will specify what data was used on soil material during the manuscript revision.*

In the sentence that follows the cited line 183, we refer to table S1 which presents an overview of the data for the geological models: "The different data and sources utilized for the geological models are presented in the supplementary material (Table S1). ".

Table S*1*. Overview of data for the geological models

Category	Data type	Source	The geological model that utilized the data
Hydrostratigraphical model (V0)	3D layer model in GeoScene	Sandersen and Kallesøe (2017)	V0, V1, V2
Urban infrastructure	Sewer network	Vandcenter Syd A/S (2019a)	V1, V2
	Water supply pipes	Vandcenter Syd A/S (2019b)	V1, V2
	District heating pipes	Fjernvarme Fyn (2019)	V1, V2
	Gas pipes	Danish Gas Distribution (2019)	V1, V2
	Roads and railways	Danish Geodata Agency (2019)	V1, V2
	Road build-up material	Vejdirektiratet (2019)	V1, V2
	Railway build-up material	Nielsen (2016)	V1, V2
	Buildings and basements	Odense Kommune (2019)	V1, V2
Soil material	Soil mail	Jakobsen et al. (2022)	V2
	Shallow geotechnical boreholes	Geological surveys of Denmark and Greenland (GEUS) (2019)	V2

We propose to add the following lines to the manuscript after the reference to the table in the supplementary material:

The additional data on soil material in V2 voxel model is a soil map (Jacobsen et al. 2022) and soil descriptions from shallow geotechnical boreholes (GEUS, 2019). The soil map by Jacobsen et al. (2022) is in 1:25000 resolution and is based on samples of soils every 200 m at 1 m depth. The soil descriptions from shallow geotechnical boreholes were derived by looking through non-digitalized documents in the Danish National well database.

-P8 l 207-209 " the location of roads and pipes (…) were used as proxies for the presence of excavations and trenches" What is the relevance of this assumption? Did you assess this assumption? Did you compare this proxies methodology to real data? Is it valuable only in this study case or could it be transposed in any urban catchment?

Reply: *We acknowledge that the quoted sentence is a vague formulation of the methodology of defining the extent of infrastructure in the geological voxel models. We propose to add the following lines to the manuscript in line 208 after the quoted sentence:*

The location of the roads and the pipes were retrieved from the road directory and the pipe owners, see table S1 for data sources. The extent of the excavations and trenches was based on national standards for profiles of road design and pipe trenches, see table S1 for sources. It was assumed that the design of the roads, railways, and trenches followed these standards.

To answer the reviewer's questions we find that this method of proxies for the presence of excavations and trenches is the best possible way unless the extent of the trenches is documented and stored in a central and digitalized archive. This is not the practice for this study area and we suspect it is rarely the case for other cities. Moreover, to answer the last question from the reviewer, the presented methodology can be transposed to other urban catchments.

- P8 214-220 – Why the SHE model was chosen here? We can understand that it is the model used by the research team, but could the authors argue why this model is appropriate to do this study? Are there any equivalent modelling tools/methods that could have been considered for this type of modelling study? Is SHE model the only one that allows to achieve the objectives of this study?

Reply: *We acknowledge that the manuscript lacks an argumentation for the choice of model code. We propose to add the following to the manuscript in the beginning of the method section 3.2 Hydrological models (line 212):*

THE MIKE SHE model was chosen for the hydrological simulation because the model can simulate the surface and subsurface processes in an integrated and dynamic manner, as well as it is possible to include surface and sewer drainage. An advantage of MIKE SHE is that it can describe the water flow between different types of surfaces, the root zone, the unsaturated zone, and the saturated zone. Moreover, with this model code, the properties, surfaces, and layers can be spatially distributed in both the horizontal and vertical planes. Other integrated models such as PARFLOW.CLM, MODFLOW 6, and HydroGeoSphere offer similar capabilities, however, given our experience with MIKE SHE we selected this model.

- p9 l 245. What is this surface-subsurface leakage coefficient? A parameter of the SHE model? Does it take into account the leakage in pipes, or only the leakage from surface-subsurface? How could it be estimated?

Reply: *The surface-subsurface leakage coefficient is a model parameter in MIKE SHE. It reduces the infiltration from the surface to the subsurface at paved surfaces as well as the seepage from the subsurface to the surface. In the model, it is applied to the areas where the imperviousness is above 50%.*

Surface-subsurface leakage coefficient does not account for leakage in pipes. Leakage in the pipes was modeled separately and it was assumed that leakage only occurs to the sewer pipes. The leakage was modeled by representing the sewer network as subsurface drainpipes and assuming that the parameter was spatially uniform across the pipe network.

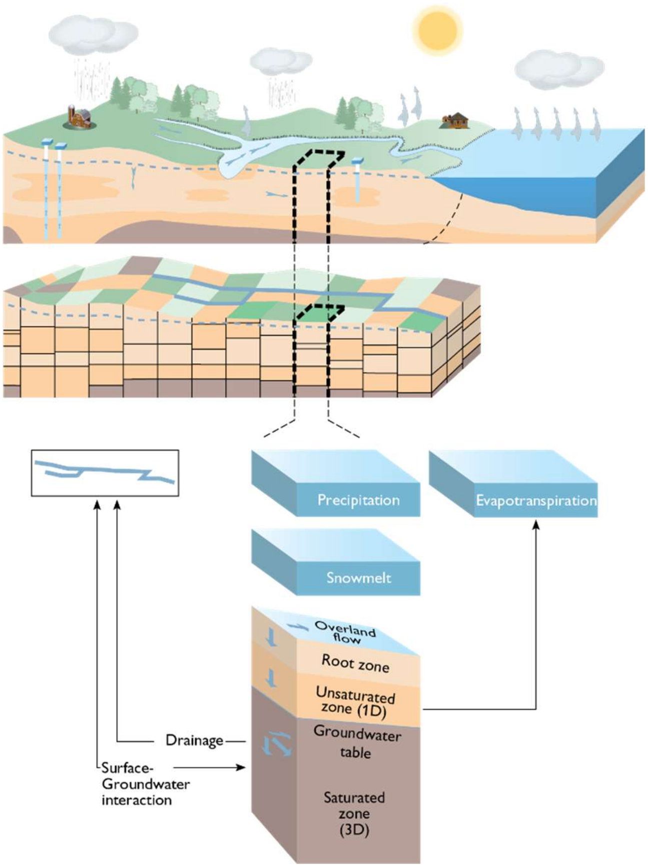
We will make this clear in the revised manuscript.

Then, the methods section could have been improved with a graphical scheme helping the reader to understand the chosen parametrizations. This is especially needed in the 3.2.2 paragraph, because the list of the presentation of the parametrization and boundary conditions is quite long, and a scheme would be more efficient and more easy for the reader.

Reply: *The parameterization is indeed complicated. Some parameters are defined from data, some were specified from past model experience and some were subject to calibration as described in section 3.3.*

To enhance the readability of the parameterization we suggest to expand the revised manuscript with either an additional table or a figure.

A figure could be an illustration of the model setup such as below with an additional description of the reduced infiltration (the surface-subsurface leakage coefficient), the overland drainage component, and leaking sewers:



Finally, I have a short comment about one element of discussion : l 535-543. The sewers renovation could be a way to reduce the soil-sewer interactions and the infiltration of groundwater in sewers. As discussed by the authors, the preferential flow paths would still be present in the pipe trenches. However, I wonder if having a full renovated sewer system is not an utopy… To my opinion, there will still be some defects in the sewer system and then, as the preferential flow in the trenches remains present, the water will always find a way to penetrate in the sewers. I have the impression that this type of sewer renovation (or "non leaking pipes assumption") is only a "modelling dream"; I am not sure it would be feasible in reality.. (especially in a economical point of view). I would appreciate that the authors re-consider this paragraph.

Reply: *We agree that it is probably not realistic to install a leakage-free pipe network. As the reviewer correctly states, the preferential flow in the trenches remains present, and the water will always find a way to the leaking sewers. In the discussion of the revised manuscript, we speculate* *on the possible impact of the renovation of sewers and we will expand on this topic in the revised manuscript.*

We propose to rephrase lines 535-543 in the discussion to:

It was assumed that the entire sewer system was leaky and thus acted as a drainage system as well. In consequence, drains in the saturated zone were by far the most dominant sink to the shallow groundwater, Figure 12 and Figure 13. Although this assumption may be on the extreme side, groundwater seeping into the sewers is a common problem and leads to excessive water treatment in areas with shallow groundwater. On the other hand, in an idealized case where sewers have been renovated, the water table may raise and trigger water seeping into basements or a periodical groundwater table above the terrain. Yet, a fully renovated pipe network across an urban area is unrealistic. The groundwater will even if parts of the network were renovated still flow along the preferential flow paths and the water will just find another leak in the pipe network. Say e.g a part of the central pipe network was renovated, the water table may rise and reach the unrenovated household drains that feed into the central storm or sewer network.

References
Several mistakes should be corrected :

Reply: *Thank you for pointing out these mistakes. We will correct these in the revised manuscript.*

- l57 Boukhemacha et al (2051) and Epting et al. (2008) are missing in the list of references

Reply:

Boukhemacha, M. A., Gogu, C. R., Serpescu, I., Gaitanaru, D., and Bica, I.: A hydrogeological conceptual approach to study urban groundwater flow in Bucharest city, Romania, Hydrogeol. J., 23, 437–450, https://doi.org/10.1007/s10040-014-1220-3, 2015.

Epting, J., Huggenberger, P., and Rauber, M.: Integrated methods and scenario development for urban groundwater management and protection during tunnel road construction: A case study of urban hydrogeology in the city of Basel, Switzerland, Hydrogeol. J., 16, 575–591, https://doi.org/10.1007/s10040-007-0242-5, 2008.

- l115 / l 633 : Danish Geodata Agency ?

Reply: *Danish Geodata Agency: FOT data, www.gst.dk, 2019.*

- l197 Kristensen et al (2015) is missing in the list of references

Reply:

Sandersen, P. B. E., Kristensen, M., and Mielby, S.: Udvikling af en 3D geologisk/hydrogeologisk model som basis for det urbane vandkredsløb. Delrapport 4 - 3D geologisk/hydrostratigrafisk modellering (Særudgivelse)., De Nationale Geologiske Undersøgelser for Danmark og Grønland, Denmark, 2015.

- l 227 DHI 2017 is missing

Reply:

DHI: MIKE HYDRO River User guide, 2017.

- l 260 is specified in Fejl ! ... Like fundet / to be corrected

Reply:

Table 2: Conditions for the computational layers in the hydrological models