Author's response to the revision of hess-2022-330

Editor Comment

[Editor's comments in normal font; *Author's response in italics*]

Dear authors, thank you for the detailed response to the reviewers' comments. I suggest to proceed with a moderate revision aimed at implementing all points that have been raised, mostly related to modelling assumptions and experimental setup.

I also encourage the authors the fully address the comment raised Referee #2 on the representation of human-water interactions in hydrological/geological models (comment #2). It is true that the Introduction clearly outlines the goals of this study, but it is also true that other parts of the manuscript could be expanded to create a stronger tie with the overarching theme of this special issue ('Representation of water infrastructures in large-scale hydrological and Earth system models'). The Discussion, for instance, does an excellent job in discussing the specific results of this study, but it could be slightly expanded to elaborate on some of the open challenges (e.g., data availability, computational requirements, scalability to even larger domains, model availability) that will be faced when advancing the representation of urban geology in hydrological/geological models. I believe such expanded discussion will be interesting to the readership of this SI.

Author's response:
Thank you for the opportunity to submit a revised manuscript based on the three reviewers' comments. We are very appreciative of the constructive suggestions to improve the manuscript. In the revised manuscript, we have implemented all points that have been raised and corrected typos.
Please note that all page and line numbers mentioned under Author's changes refer to the marked-up manuscript version.

RC1: 'Comment on hess-2022-330'

[Reviewer's comments (RC) in normal font; *Author's response (AR)in italics*; Author's changes (AC) in manuscript]

RC1.1
Overall, this is an interesting manuscript worth being published.
I do see, however, some room for improvement, especially in the use of the terms "resolution" and "spatial discretization". The authors appear to use different spatial resolution (10m and 50m in the horizontal direction), both of which obviously come with a different degree of geological resolution. It is unclear whether the different model results are then attributed to the spatial discretization or to the different geological resolution. To disentangle this, a grid discretization study should be conducted first, and the same grid should then be used to examine the effect of different geological resolution. I think as is, the term spatial discretization is confused with geological resolution. A poor spatial discretization may result in round-off and truncation errors, which are numerical artefacts. A fine enough grid should be free of numerical artefacts, and this grid could indeed be used to test different degrees of geological resolution. Different geological resolution may actually show different results (just like with different spatial discretizations) but the effect of numerical artefacts would be absent.

AR1.1:

We thank the reviewer for the overall positive and constructive feedback that has helped us to improve our work. Please note that all page and line numbers mentioned under Author's changes refer to the marked-up manuscript version.

We acknowledge that the terms "spatial resolution and "spatial discretization" are used inconsistently in the manuscript. One of the objectives was to analyze the effect of spatial discretization on the simulations. As part of the manuscript revision, we have replaced the word "resolution" with "discretization" since discretization is the term that best describes what we did when we chose a grid size of 5 x 5x 1 m for the voxel models and tested different horizontal grid sizes for the hydrological model.

Furthermore, the reviewer's comment also shows that it was unclear which discretization was used in the different geological and hydrological models. Besides a consistent use of terminology, we have included a table of the modeling experiments in the revised version of the manuscript.

The reviewer suggests adding an initial grid discretization analysis to the study. We agree that both the geological resolution and discretization can affect the simulation results. Rather than documenting a full grid analysis in the manuscript, we have added some lines to the method section that justifies our choice of grid discretization.

AC1.1:

The word use of "resolution", "discretization" and "computational grid size" has been streamlined to assure proper use of terminology and consistency, e.g. in the revised manuscript page 1, line 9 "resolution" was replaced with "discretization".

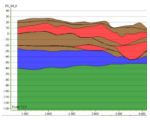
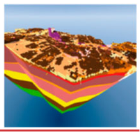
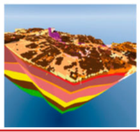
In the material and methods section of the revised manuscript page 7, lines 168-179 the following text has been altered:

The effect of the geological configuration was analyzed by applying three geological models V0, V1, and V2 in otherwise identical ~~integrated~~ hydrological models. ~~The effect of computational grid size on the hydrological simulations was examined by using two different horizontal grid sizes in the hydrological model, respectively 50 m and 10 m resolution.~~ The effect of spatial discretization was tested by using a coarse discretization relative to the urban subsurface infrastructure, with a horizontal grid discretization of 50 m, and a finer discretization close to the scale of the urban subsurface infrastructure, e.g., roads and trenches, with a horizontal grid discretization of 10 m. 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, resulting in e.g., millions of grid cells. 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 and retaining geological detail. ~~Post calibration of t~~The effect of the geological configuration and spatial discretization ~~grid size~~ was analyzed based on the hydrological models' simulation of high-water levels, the 95th percentile, and particle tracking.

Furthermore, on page 7, lines 182-186 a new table has been added to the revised manuscript.:

Sandersen and Kallesøe (2017). The geological models V1 and V2 were developed as part of this study. An overview of the geological models and their differences is presented in Table 1.

Table 1. Overview of models and their differences in discretization and geological model type

Hydrological model name	Horizontal discretization of the hydrological model (m)	Geological model name	Geological model type		Discretization of the geological model
V0_50 V0_10	50 10	V0		Layer model	Layers and lenses with varying thickness
V1_50 V1_10	50 10	V1		Combined voxel and layer model with urban infrastructure	5x5x1 m in the voxel model (the top 15 mbgl). Layers and lenses with varying thicknesses
V2_50 V2_10	50 10	V2		Combined voxel and layer model with urban infrastructure and soil material	5x5x1 m in the voxel model (the top 15 mbgl). Layers and lenses with varying thicknesses.

In the revised manuscript page 8, line 222-209 the following text has been added:

anthropogenic structures in the uppermost subsurface and computational constraints. The choice of discretization for the voxel models with urban geology was guided by the experience from the study of Mielby & Henriksen (2020) and Mielby & Sandersen (2017) and chosen to be 5x5x1 m to be able to represent the subsurface infrastructure trenches which are typically 1-3 m wide and 1-2 m in depth for this study area, while the Road trenches are around 10 m wide +/- and therefore 5 m is a good intermediate size. The horizontal discretization was thus larger than the dimensions of the trenches. A smaller discretization for a model at the city scale would have been computationally expensive in the hydrological model. Mielby & Sandersen (2017) argued that the discretization of the geological and hydrological model must meet the required detail, yet not exceed the computational capabilities. The two voxel models each had 22 million voxel grids.

RC1.2:

Maybe the authors could also re-think the title. It is unclear whether groundwater quantity is meant, or quality, or level, or availability? This should perhaps be clarified.

AR1.2:

Concerning the title, we agree that the title should be more specific and suggest the following title: 'Impact of urban geology on model simulations of shallow groundwater levels and flow paths'

AC1.2:

Page 1, lines 1-2 the title has been changed to:

Impact of urban geology on model simulations of shallow groundwater levels and flow paths

RC2: 'Comment on hess-2022-330'

[Reviewer's comments (RC) in normal font; *Author's response (AR)in italics*; Author's changes (AC) in manuscript]

RC2.1:

This paper examines the impact of representation of anthropogenic urban geology and spatial resolution on the simulation of shallow groundwater levels and flows. The authors developed two geological models from an existing hydrostratigraphical model by accounting for urban subsurface infrastructure and soil material and integrated them with hydrological models of 50m and 10m resolution. The effect of geologic configuration and spatial resolution are then analyzed in terms of high-water levels and particle tracking using a case study of the city of Odense in Denmark. Overall, I find the paper well written and comprehensive. It is worthy of publication.

AR2.1:

We thank the reviewer for the overall positive and constructive feedback on our work. Below, We will address the reviewer's comments and what we have changed due to the issues pointed out by the reviewer. Please note that all page and line numbers mentioned under Author's changes refer to the marked-up manuscript version.

RC2.2:

The methods and results are well-explained, and I have no comments on them. Since this paper is submitted as part of a special issue ('Representation of water infrastructures in large-scale hydrological and Earth system models'), I would suggest that the authors revise the introduction, discussion, and/or conclusions to bring out the broader implications of advancing representations of human-water interactions in hydrological/geological models due to increased impacts of anthropogenic interventions.

AR2.2:

The main motivation of the study was to test a method of representing urban geology at the city scale and to simulate the impact of anthropogenic interventions on the interactions between the hydrological system and the engineered water infrastructures. We have slightly adjusted the introduction and expanded the discussion and conclusions in the revised manuscript to highlight and elaborate this even further as required.

AC2.2:

In the revised manuscript page 2, lines 29-37, we have adjusted the opening paragraph to address the theme of the special issue.

As more than half of the world's population lives in urban areas and urbanization globally continues to increase (United Nations, 2018), urban water resources receive increasing attention (McGrane, 2016; Lundy and Wade, 2011; Mitchell, 2006; Farr et al., 2017; Birks et al., 2013). ~~The main factors which impact the urban hydrological system are the impervious land cover, upper soil alterations, subsurface infrastructure, and groundwater abstraction. These factors alter the natural set of flow paths and create artificial supply and sewer pathways (Salvadore et al., 2015; Schirmer et al., 2013; McGrane, 2016).~~ Cities are hydrologically complex, because of interactions between ~~urban~~ built structures, ~~piped water networks~~ water infrastructures, such as pumps, drainage, sewers and water pipes, and the natural hydrological system, where ~~with~~ surface and subsurface processes ~~occurring~~ occur at various spatial and temporal scales (Salvadore et al., 2015; Han et al., 2017; Kidmose et al., 2015; Fletcher et al., 2013; Tubau et al., 2017; Vázquez-Suñé et al., 2016).

In the revised manuscript page 29, lines 647-701, we have added the following to the discussion section in order to elaborate on the implications of advancing the representation of human-water interactions in hydrological models.

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 and very different residence times than the 10 models. This illustrates that the computational discretization affects the simulation of particle transport and travel time. The results suggest that a coarser spatial discretization is sufficient if it is only the groundwater level that is of interest, while for the simulation of groundwater ages and transport in a complex urban subsurface, a finer grid is required. These results are of importance for future studies of urban hydrogeology since the computational time of the two tested discretizations varied substantially. The 50 m models were 60 times faster in computational time than when the models had a 10 m horizontal discretization.

Mielby and Sandersen (2017) have made some suggestions on which resolution and discretization to use for different-sized urban models. They suggest that the spatial discretization of the model should be coarser when the size of the model increase and wise versa, which is a common approach to overcome the time and computational burden of hydrological models. Yet, if one wants to look into flow paths and to travel time of compounds moving between the surface water, groundwater, and water infrastructures in urban areas, such as water extraction and leaking sewers and water pipes, the spatial resolution of the model input and the model discretization need to reflex the urban geology, such as pipes and trenches by keeping the discretization at a scale that does not smear out the heterogeneity of anthropogenic layer.

Moreover, as Salvadore et al. (2015) illustrate, the processes of sewer and mains leakage occur at a time scale of minutes to hours and at the resolution of cm to a few meters, whilst the surface water processes occur at 1 m to 1 km at a time scale of seconds to hours. The groundwater processes occur at scales from less than one meter to kilometers and at many different timescales from an hour to years. Thus, this challenges the models' flexibility to integrate the dynamic processes at various spatial and temporal scales to produce realistic urban hydrological simulations of the groundwater level and flow paths in urban areas.

Solutions for the spatial discretization could be to have a regional model that can be updated and refined for a smaller area, as done in this study and suggested by Mielby and Sandersen (2017). A drawback of constructing a model for a small aerial extent is that it neglects the impact that local alterations can have on larger scales as documented in Attard et al. (2016a, c). Secondly, an alternative to the refinement method of this study could be to use a model where the spatial discretization can vary within the model domain (e.g., MODFLOW6), and thus have a finer discretization in the vicinity of the water infrastructure to capture the exchange that occurs in these places at short temporal intervals. Thirdly, one could use machine learning as an alternative to or as an addition to a physical-based model. Koch et al. (2021) used simulation results from a coarse physically based model to guide a machine-learning model for the prediction of extreme groundwater levels at a finer scale. Meanwhile, Schneider et al. (2022) used a coarse physical-based regional hydrological model and ran smaller submodels at a finer scale to downscale the hydrological model outputs of climate change impact on the groundwater level for the regional model area to the finer scale. None of the studies were specifically focused on cities, yet the methods could potentially be adapted to urban areas. The second and third suggestions are approaches that can be used for large-scale urban areas, and still have a fine spatial discretization near the urban anthropogenic elements.

Regarding the challenges of the different temporal resolutions of the processes, this study applied the MIKE She code, where it is possible to apply different computational timesteps for the three main components: surface, unsaturated zone, and saturated zone. This is also possible with other model codes such as PARFLOW.CLM as in Bhaskar et al. (2015) or MODFLOW 6 (Langevin et al., 2017).

Ultimately, models are a reflection of the knowledge one has about the system and the data that is available for input, calibration and validation ((Madsen et al., 2010; Refsgaard et al., 2022). For urban studies, it is not only knowledge and data on climate, geography, geology, and hydrological data that is essential, but also data on the subsurface constructions, the backfill surrounding these constructions, utility trenches, water infrastructures, and human–water interactions. For instance, one of the important model assumptions for this study is that leaky sewers will drain the shallow groundwater. Here, the study is limited because measured groundwater inflow to the sewers is not available. Measurements of sewer- flow and separation of the different inputs to the sewer system could qualify and verify this model- assumption.

Since aging and leaking sewers and water pipes cause an impact on the water flow in urban areas it is relevant to document both new and existing subsurface infrastructure as the cities develop and to maintain these water infrastructures to ensure the cities' resilience to both extreme weather conditions and slower, yet, progressively altering climate conditions (Hibbs and Sharp, 2012). This study had quite detailed information on the location, age, the extent of the subsurface constructions, and water infrastructure that will not always be available. Yet, as more and more constructions become digitally documented this data can be fed into the urban hydrological models, which can be updated with the new information. This study used GIS data, with properties of the pipes assigned in an attribute table and standard guidelines for dimensions of the trenches that the pipes are placed in and the back material surrounding them. 3D building information modeling (BIM) is increasingly used for the design and documentation of buildings and can potentially more easily be combined with urban hydrological models. Nonetheless, reuse and updates of urban hydrological models are highly relevant since urban areas are frequently changing and since it requires many man-hours to build detailed integrated models.

In the revised manuscript page 32, lines 733-743, we have added the following to the conclusion section in order to elaborate on the implications of advancing the representation of human-water interactions in hydrological models.

To simulate the water fluxes and flow paths in cities, the results from this study suggest that urban hydrological models need to include ~~and groundwater~~ overland and subsurface drainage, as well as the water's interactions with water infrastructure, such as pumping, drainage, and leaking sewers. Moreover, the results showed that the properties of the anthropogenic layer and the horizontal discretization of the shallow urban geology that represents the presence of infrastructure trenches, water infrastructure, and subsurface constructions, need to be chosen carefully since these factors impact the model results as well as the computational time. To meet this computational and time-consuming challenge we propose that urban hydrological modeling consider the reuse of a large-scale regional model for setting up a refined urban hydrological model for a smaller area, as in this study. Alternatively, for larger urban areas, we propose to vary the spatial discretization within the model domain, such that a smaller discretization is applied in the areas where infrastructure trenches, water infrastructure, and subsurface constructions are present, and potentially to make use of coupling machine-learning with an integrated physically based hydrological model.

Minor comments

RC2.3

Line 260: Missing reference

AR2.3: The missing reference in line 260 (original manuscript) is Table 2. This has been corrected during the revision of the manuscript, yet as one more table have been added to the manuscript the correct reference is now Table 3..

AC2.3: In the revised manuscript the reference has been corrected on page 13, line 323.:

layers and their outer boundary conditions is specified in **Error! Reference source not found.**, and even though the geological models were altered the

RC2.4:

Line 301-302: Consider revising to "and another set of parameters selected to be tied to…"

AR2.4:This has been revised as required.

AC2.4: In the revised manuscript page 15, lines 364-366 the text has been changed to:

The sensitivity analysis was based on composite sensitivities as described in Doherty (2015) ~~was~~ and conducted for all 96 model parameters. Based on the analyses across all models a set of free parameters was selected subject to calibration and another set of parameters to be tied to the free parameters.

RC2.5:
Line 302: "and" instead of "sand"
AR2.5: We have changed the text "sand" to "and" as suggested by the reviewer.

AC2.5: In the revised manuscript (page 15, line 366) the text has been changed to:

One parameter set was selected for the V0 model ~~s~~and one

RC2.6:
Line 315: "Eq" instead of "Ep"
AR2.6: We have changed the text as suggested by the reviewer.

AC2.6: In the revised manuscript (page 16, line 379) "Ep" has been changed to "Eq"

RC2.7:

Line 317: "Eq. 2" instead of "Eq. 3.2"

AR2.7: We have changed the text as suggested by the reviewer.

AC2.7: In the revised manuscript (page 16, line 381) "Eq. 3.2" has been replaced by "Eq.(2)"

RC2.8:

Eq. 2 and Line 325: Why do the weights have subscript hi, dj, and hk? Do they change according to indices i, j, k? Perhaps it will be clearer to specify the weights in Line 325 (e.g. state "w_{hi} = 0.45")

AR2.8:

First, we would like to correct a mistake in the notation of the mathematical expression of the measurement objective function, Eq. 2. During the revision of the manuscript, we have corrected the mistake in Eq. (2) and specified the group weight more clearly in the text as suggested by the reviewer.

AR2.8: In the revised manuscript the (page 16, lines 385-392) have been changed to:

$$\Phi_m = \alpha_h * \sum_{i=1}^{h}(\omega_{h,i}(h_{obs,i} - h_{sim,i}))^2 + \alpha_{ampl} * \sum_{j=1}^{ampl}(\omega_{ampl,j}(ampl_{obs,j} - ampl_{sim,j}))^2 + \alpha_d * \sum_{k=1}^{d}(\omega_{d,k}(d_{obs,k} - d_{sim,k}))^2 \quad (2)$$

where α is the group weight. The group weight was assigned as follows: α_h=0.45, α_ampl=0.45, and α_d=0.10. ω_is the weight of i'th, j'th or k'th observation. As a standard, all observations had a weight of 1, yet after initial calibration runs some of the head and amplitude observations located near the west boundary were assigned a value of 0.

RC2.9:

Fig. 4: Refrain from using a rainbow colour scale as it could misrepresent data due to its non-linear change in hue.

AR2.9: We have changed the color scale to be both a perceptually uniform scale and color-blind friendly.

AC2.9:

The color of the figure (page 18, lines 438-440) has been changed as shown below. Due to a new figure in the manuscript the figure number has been changed from figure 4 to figure 5:

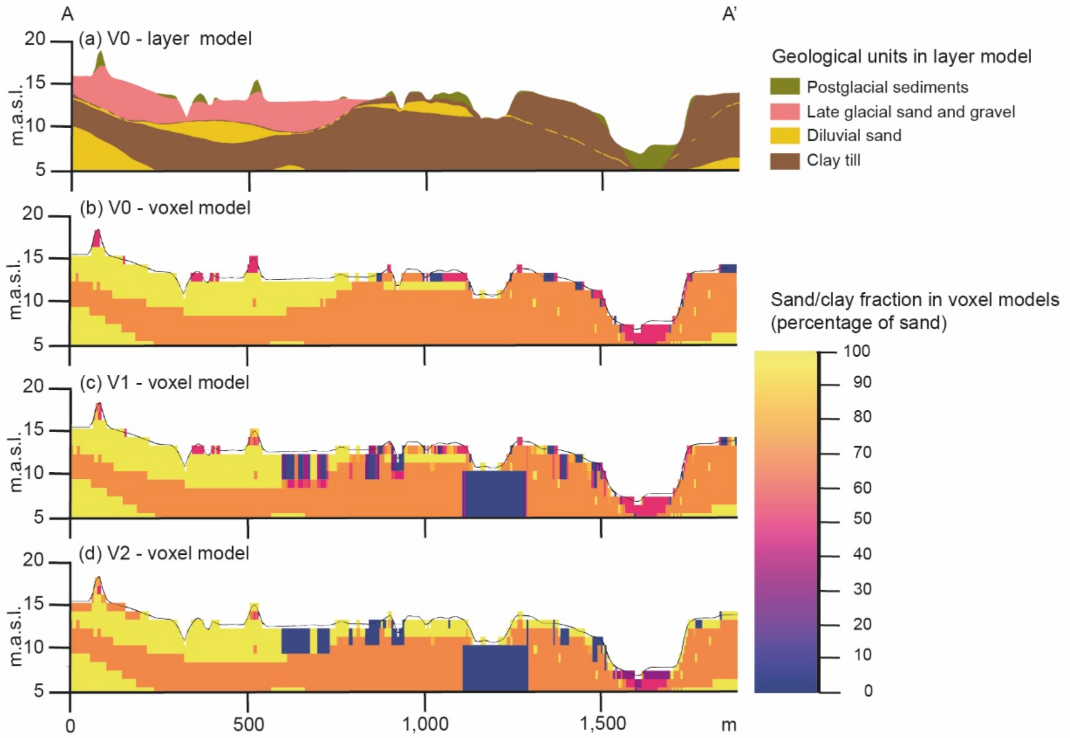


Figure 1. Profile A-A' from the geological models V0 – layer model (a), V0 – voxel model, (b) V1 – voxel model (c), and V2 – voxel model (d).

RC2.10:

Fig 5: "56%" instead of "57%" in the bar plot

AR2.10: Thank you for pointing out the inconsistency in the text and the numbers in Fig. 5. The value has been corrected in the figure.

AC2.9:

The figure (page 19, line 441-444) has been changed as shown below. Due to a new figure in manuscript the figure number have been changed from figure 5 to figure 6:

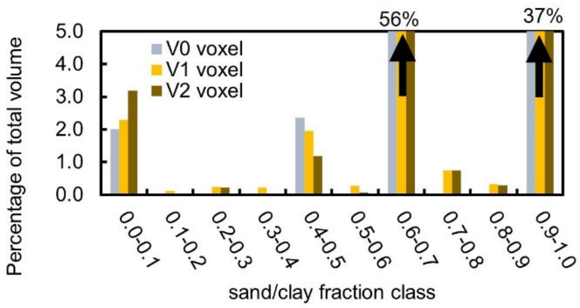


Figure 2. Percentage of the sand/clay fractions of the total volume of the geological voxel models V0, V1, and V2. Note that the sand/clay fractions 0.6-0.7 and 0.9-1.0, respectively take up about 37 % and 56 % in all models, and plot beyond the range of the y-axis.

RC2.11:

Line 438 – Line 441: Please check the subscripts of the model parameters. Some capitalisations are inconsistent with those in Fig. 10

AR2.11: The errors in the abbreviation for the parameters has been corrected as suggested by the reviewer during the revision of the manuscript.

AC2.11: The parameter abbreviations in the manuscript has been correct throughout the results, see e.g page 23, line 506-507:

conductivities $K_{qbv2,h}$ and $K_{Qc,v}$ are well informed by measurements since they are dominated by red-yellow colors. For V0_50 the parameters dominated by blue-green colors are $K_{ct,h}$ and $D_{r,grass}$, while for V0_10 it is $K_{ct,h}$ and C_{riv}.

RC2.12:
Line 446-447: delete "4.3 Simulation of high-water levels."

AR2.12: Thank you for pointing out this typo error. We will delete this during the revision of the manuscript.

AC2.12: In the revised manuscript the typo have been deleted at the end of the paragraph on page 23, line 517-518:

the regularized calibration were considered realistic and well-defined and were accepted for further analysis. ~~4.3 Simulation of high-water levels~~

RC2.13:
Line 452: "V2_50" instead of "V2_5"
AR2.13: We have changed the text as suggested by the reviewer.

AC2.13:In the revised manuscript (page 24, line 525) "V2_5" has been replaced with "V2_50"

RC2.14:
Line 477: add "models" after "V2"
AR2.14:We have changed the text as suggested by the reviewer.

AC2.14: In the revised manuscript (page 25, line 523) "models" has been added after "V2"

RC2.15:

Line 509, 517: Check capitalization and subscript of parameter "Dr,grass" and "KQs2,h"

AR2.15 This will be corrected during the revision of the manuscript as suggested by the reviewer.

AC2.15: In the revised manuscript page 27, line 583 the parameter abbreviation has been corrected from $d_{r,grass}$ to $D_{r,grass,}$ and on page 28, line 591 from $K_{qs2,h}$ to $K_{Qs2,h,}$.

RC3: 'Comment on hess-2022-330'

[Reviewer's comments (RC) in normal font; *Author's response (AR)in italics*; Author's changes (AC) in manuscript]

RC3.1:

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.

AR3.1:

We thank the reviewer for the overall positive and constructive feedback on our work. Below, we respond to the reviewer's comments and specify what changes there have been made in the revised manuscript based on the reviewer's comments. Please note that all page and line numbers mentioned under Author's changes refer to the marked-up manuscript version.

General opinion and minor comments

RC3.2:

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.

AR3.2:

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. As we have written to the first reviewer (RC1), we concede that the manuscript lacks a justification for the choice of discretization of both the geological voxel models and the hydrological models. We have added additional text to the method section to justify our approach and choices.

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

AC3.2:

In the material and methods section of the revised manuscript page 7, lines 169-179 the following text has been altered:

The effect of the geological configuration was analyzed by applying three geological models V0, V1, and V2 in otherwise identical ~~integrated~~ hydrological models. ~~The effect of computational grid size on the hydrological simulations was examined by using two different horizontal grid sizes in the hydrological model, respectively 50 m and 10 m resolution.~~ The effect of spatial discretization was tested by using a coarse discretization relative to the urban subsurface infrastructure, with a horizontal grid discretization of 50 m, and a finer discretization close to the scale of the urban subsurface infrastructure, e.g., roads and trenches, with a horizontal grid discretization of 10 m. 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, resulting in e.g., millions of grid cells. 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 and retaining geological detail. ~~Post calibration of t~~The effect of the geological configuration and spatial discretization ~~grid size~~ was analyzed based on the hydrological models' simulation of high-water levels, the 95th percentile, and particle tracking.

In the revised manuscript page 8, lines 222-209 the following text has been added:

anthropogenic structures in the uppermost subsurface and computational constraints. The choice of discretization for the voxel models with urban geology was guided by the experience from the study of Mielby & Henriksen (2020) and Mielby &

Sandersen (2017) and chosen to be 5x5x1 m to be able to represent the subsurface infrastructure trenches which are typically 1-3 m wide and 1-2 m in depth for this study area, while the Road trenches are around 10 m wide +/- and therefore 5 m is a good intermediate size. The horizontal discretization was thus larger than the dimensions of the trenches. A smaller discretization for a model at the city scale would have been computationally expensive in the hydrological model. Mielby & Sandersen (2017) argued that the discretization of the geological and hydrological model must meet the required detail, yet not exceed the computational capabilities. The two voxel models each had 22 million voxel grids.

In the revised manuscript page 27, line 566, the following sentences have been added to the beginning of the discussion section:

We tested the impact of urban geology for two discretizations; a coarse discretization and a finer discretization close to the scale of the urban subsurface infrastructure.

RC3.3:

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.

AR3.3:

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 have specified this in the revised manuscript.

AC3.3:

In the revised manuscript page 5, lines 126-128 the following text has been added:

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

RC3.4:

-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?

AR3.4:

As suggested by the reviewer, we have specified which data was used on soil material during the manuscript revision.

AC3.4:

In the revised manuscript pages 8-9, lines 213-217, the following text has been added in the method section:

sources utilized for the geological models are presented in the supplementary material (Table S1). The additional data on soil material in V2 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.

RC3.5:
-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?

AR3.5:
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 have strived to make this clear in the revised manuscript.
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.

AC3.5:
In the revised manuscript page 10, lines 239-243, the following alterations have been made:
~~When defining the infrastructure settings, the locations of roads or pipes available as GIS overlays were used as proxies for the presence of excavations and trenches.~~ The location of the roads and the pipes were retrieved from the national road directory and the pipe owners as GIS files, 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.

RC3.6:
- 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?

AR3.6:
We acknowledge that the manuscript lacks an argumentation for the choice of model code. In the revised version of the manuscript, we have elaborated on this at the beginning of section 3.2 Hydrological models. Generally, the section has been modified substantially after receiving the comments given to us by reviewer RC3. We have added an argumentation for the choice of model and a schematic figure of the hydrological model.

AC3.6:

In the revised manuscript page 10-12, lines 250-288 the following text in section 3.2 Hydrological models have been altered a new figure have been added:

The study includes six hydrological models. The differences between the models were, as presented in Table 1, the application of two different horizontal discretizations and the three geological models used for the simulation of the subsurface processes. The hydrological models were based on the MIKE SHE code (Abbott et al., 1986 a,b). THE MIKE SHE code was chosen because of its ability to integrate the surface and subsurface processes dynamically, as well as its ability to include both overland and sewer drainage. Moreover, with this model code, the properties of the subsurface and the computational layers can be spatially distributed in both the horizontal and vertical planes. Other integrated hydrological models such as PARFLOW.CLM, MODFLOW 6, and HydroGeoSphere offer similar capabilities.

Error! Reference source not found. illustrates the common setup of the six hydrological models. The model components were overland flow, unsaturated zone flow, and saturated zone flow. The MIKE SHE models were coupled to a MIKE HYDRO model (DHI, 2017) for the simulation of groundwater seepage to the river bed and river discharge in the two creeks within the model domain.

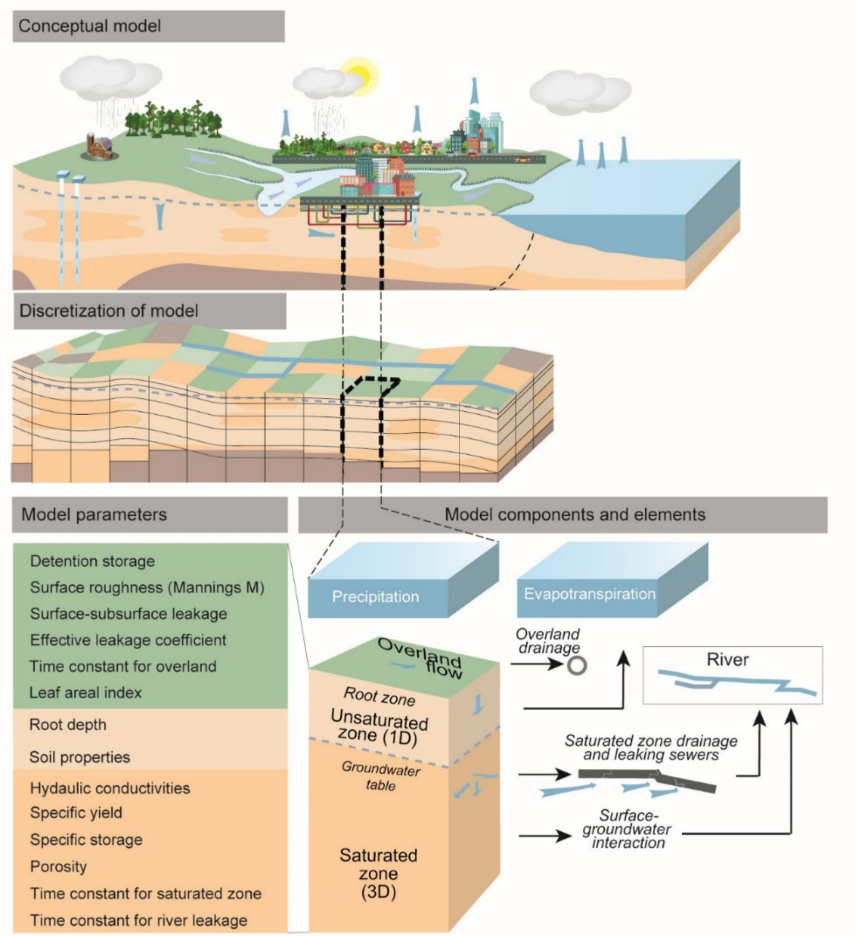


Figure 3. Illustration of the model setup for the hydrological models

The overland flow was described by a finite difference approximation of the 2D Saint Venant equations for diffusive flow. The unsaturated zone flow was described by a simplified two-layer water balance approach assuming vertical flow and a conceptual formulation for actual evapotranspiration. This approach is primarily applicable to areas where the groundwater table is shallow and the actual evaporation rate is close to the potential rate (Butts and Graham, 2005), which is the case for the study site. The saturated zone flow was described by the governing equation for 3D saturated flow based on Darcy's law. Subsurface drainage was included as a sink term and depended on the groundwater level, depth of the drains, and a time constant. Detailed descriptions of the components can be found in DHI (2017, 2020). ~~The integrated hydrological model was~~

based on the MIKE SHE code (Abbott et al., 1986 a,b). The model components applied for the MIKE SHE setup were as illustrated in Figure 4: (1) Overland flow, described by a finite difference approximation ofto the 2D Saint Venant equations for diffusive flow. Overland flow is generated when precipitation is higher than the infiltration capacity due to either high groundwater levels or ponding at the surface. Reduced infiltration capacity was specified in paved areas, and drainage of ponded water was specified by the imperviousness of the land cover. (2) Unsaturated flow, described by a simplified two-layer water balance approach assuming vertical flow and a conceptual formulation for actual evapotranspiration. This approach is primarily applicable to areas where the groundwater table is shallow and the actual evaporation rate is close to the potential rate (Butts and Graham, 2005), which is the case for the study site. (3) Saturated flow, described by the governing equation for 3D saturated flow based on Darcy's law. Subsurface drainage is included as a sink term in the equation and depends on the groundwater level, depth of the drain, and a time constant. Detailed descriptions of the components can be found in DHI (2020).

The computational The three hydrologic components were run with independent time steps wereand automatically controlled to secure accurate water balances. The maximum time steps for the three components were: 0.5 hours for overland flow, 6 hours for unsaturated flow, and 12 hours for groundwater flow. MIKE SHE was coupled to MIKE HYDRO (DHI, 2017) for the simulation of stream flow in the two creeks in the model domain. The MIKE HYDRO models used T the kinematic wave approximation was used with a fixed time step of 10 minutes.

RC3.7:

- 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?

AR3.7:

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 in 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 have strived to make this clear in the revised manuscript.

AC3.7:

In the revised manuscript page 13, lines 305-310 the text has been changed to:

detention storage. Moreover, it was used as a linear scaling fraction for the surface-subsurface leakage coefficient, which reduces infiltration in paved areas. . The surface-subsurface leakage coefficient 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 paved area fraction is above 0.5 and it was given the value 6x10-7 s-1 in all cells and then scaled by the paved area fraction. The scaling of the surface-subsurface leakage coefficient by the paved area fraction isThis is referred to as the effective leakage coefficient (DHI, 2020). The surface-subsurface leakage coefficient was given the value 6x10-7 s-1 in all cells. Surface-subsurface leakage was considered for areas with a paved area fraction larger than 0.5

RC3.8:

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.

AR3.8:

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 have added a graphical scheme of the hydrological model set up for the six hydrological models.

AC3.8:

Please see the changes present under AC3.6.

RC3.9:

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.

AR3.9:

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 have rephrased this section of the discussion in the revised manuscript.

AC3.9: In the revised manuscript pages 28-29, lines 616-625 the text has been changed:

~~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 cases where such sewers are renovated, the water table may raise and trigger water seeping into basements or a periodical groundwater table above the terrain. The six model simulations would most likely be different if the sewer system was not leaking. The preferential flow paths would still be present, but the water in those locations would not be drained.~~

It was assumed that the entire sewer system was leaky and thus acted as a drainage system as well. A consequence of this was that the drains in the saturated zone were by far is the most dominant sink to the shallow groundwater, see Figure 12 and Figure 13. Although this assumption about leaky sewers may not be correct in all areas of the model, groundwater seeping into the sewers is a common problem and leads to treatment of excessive quantities of water in areas with shallow groundwater (Bhaskar et al., 2015; Rasmussen et al., 2022). If the pipe network in the model area is partly renovated, the water table may rise and reach unrenovated household drains that feed into the central storm or sewer network.

References

RC3.10:

Several mistakes should be corrected :

- l57 Boukhemacha et al (2051) and Epting et al. (2008) are missing in the list of references
- l115 / l 633 : Danish Geodata Agency ?
- l197 Kristensen et al (2015) is missing in the list of references
- l 227 DHI 2017 is missing
- l 260 is specified in Fejl ! ... Like fundet / to be corrected

AR3.10:

Thank you for pointing out these mistakes. We have corrected these mistakes in the revised manuscript.

AC3.9: In the revised manuscript references have been corrected to:

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.

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

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.

DHI: MIKE HYDRO River User guide, 2017.

Table 3