Author Response to Referee #1

The potential of green infrastructure in urban pluvial flood mitigation - a scenario-based modelling study in Berlin

Sophia Dobkowitz et al.
HESS, `doi:10.5194/egusphere-2025-5466`

RC: ***Referee Comment***, AR: *Author Response*

Dear Referee,

thank you very much for your positive response, and for taking the time and effort to examine the manuscript.

Your comments are very helpful to clarify certain aspects in the manuscript. Especially your suggestion for additional figures improves its quality. Please find a point-by-point reply below.

Kind regards,

Sophia Dobkowitz (on behalf of the author team)

Comments and responses

General comments:

- **Different levels of detail in the modelling of individual processes**

RC: ***The manuscript uses a detailed, multi-layered, process-based representation of green infrastructure in the SWMM hydrological model, while surface runoff is introduced into the 2D hydrodynamic model via spatially aggregated inflow points rather than distributed precipitation and infiltration. The authors are invited to briefly discuss this trade-off between process complexity and spatial abstraction and to explain why the chosen level of detail of the green infrastructure is appropriate in general, but also in particular given the simplified representation of surface runoff in the 2D model.***

AR: SWMM employs a detailed, multi-layered representation of green infrastructure (GI) through its LID modules, including surface, soil, storage, and drainage layers using the Green-Ampt method. This level of detail is the default in the SWMM LID Module. The primary focus of the study is to assess differences in runoff generation between various GI types at the subcatchment scale.

The resulting runoff is subsequently transferred to TELEMAC-2D via aggregated inflow points. This approach is adopted for two main reasons: (1) SWMM already provides a robust representation of rainfall–runoff processes, and (2) the highly sealed urban environment, characterized by buildings, roads, and inner courtyards, exhibits complex flow pathways (e.g., narrow passages and underground garages) that are not adequately resolved by the available DEM. A fully distributed 2D rainfall–infiltration model would therefore require extensive and uncertain parameterization to represent these features realistically.

The chosen hybrid approach is appropriate because the effects of GI are most critical at the source, particularly in terms of runoff reduction, while the 2D model focuses on the spatial propagation of flooding. This framework ensures a balance between computational efficiency and process relevance and is consistent with established practices in coupled SWMM–2D modelling studies.

- **Justification of different infiltration approaches**

RC: ***Green infrastructure elements are modelled using, among other approaches, the Green–Ampt infiltration model, whereas infiltration from permeable surfaces is represented using the Curve Number method. The authors are encouraged to briefly explain the rationale for applying different levels of process representation within the same hydrological model and to comment on the implications of this choice.***

AR: GI is implemented exclusively with the Green-Ampt approach in SWMM. Furthermore, as Flood mitigation impact of GI is the focus of our study, it seams appropriate to model GI more detailed than the other urban surfaces. Here, SCS-CN method was chosen due to its widespread application for urban environments and due to the lack of soil hydraulic parameters for urban soils. For further details, see answer to question RC1-11.

- **Spatial aggregation and presentation of spatial results**

RC: ***An illustrative figure showing the delineation of subcatchments and the locations of their outflows (corresponding to inflow locations in the 2D hydrodynamic model) would help to better understand the spatial representation within the modelling chain. In addition, an example illustrating the variability of runoff hydrographs among different subcatchments would be informative.***

AR: We will add two new figures, showing the subcatchments with their outflow locations (see answer to question RC1-8) and exemplary runoff hydrographs to illustrate the different temporal runoff distribution among subcatchment types (see answer to question RC1-17).

RC: ***The final results are derived from spatially explicit information (e.g. water depths, affected buildings, and the area exceeding certain water depth thresholds). However, no spatial results such as inundation extent or water depth maps are presented. Including at least one representative map is recommended to support the interpretation and plausibility of the spatial results and to facilitate understanding of the aggregated indicators (see also the specific comment on Figure 3).***

AR: We will add a map showing the inundation extent and water depths for the rain event with a return period of 100 years.

Specific comments:

RC: ***1. p. 4, l. 94-96: Where are the locations of the inflow hydrographs in the 2D model?***

AR: We will clarify that the hydrographs are located at the centroids of the subcatchments used in SWMM

RC: ***2. p. 5, l. 113: Please briefly specify what is meant with "simplified hydraulic methodology"***

AR: We will add the information that the BKG approach ignores the runoff reduction from the drainage system and infiltration

RC: ***3. p. 7, l. 126: Please indicate which duration for the 5-year precipitation event was chosen.***

AR: We will indicate that a duration of 15 minutes was chosen, according to the recommendations of DIN EN 752-2

RC: ***4. p. 7, l. 127: Does this mean, a capacity of 16 mm every 15 minutes (i.e. 1.07 mm/min) or only during the first 15 minutes?***

AR: We will clarify that the capacity of 16 mm (corresponding to a precipitation event with a return period of 5 years and a duration of 15 minutes) was applied only once at the beginning of the event.

RC: ***5. p. 7, l. 142: BR on 10 % of the area subtracted by the area covered by buildings: Has this been distributed over all residential subcatchments only or also road subcatchments?***

AR: Yes, BR was place in the overall catchment, including residential and road subcatchments, we will add this information.

RC: ***6. p. 7, l. 151: "we deduced the soil hydraulic parameters from this soil type": Please give the source from which the parameter values have been taken.***

AR: Most of the parameter values were defined based on the information in the EPA SWMM 5.2 User Guide (EPA 2023). We will specify in Table 3 from which source each parameter was deduced.

- EPA SWMM 5.2 User Guide (EPA 2023): *Vegetation volume fraction, Surface roughness, Field capacity, permanent wilting point, Conductivity slope: equation to calculate conductivity slope from soil type (80 % sand, 5 % clay, 15 % silt), Suction head, Storage layer void ratio, Drainage mat void fraction and roughness*
- Dobkowitz et al (2025): *Berm height, Layer thickness, Pavement void ratio and permeability*
- Rossman and Bernagros (2018): *Soil porosity*
- Schaap et al (2001): *Conductivity*

Additionally, we will modify the paragraph about the GI parameters as follows:

The GI types BR, GR and PP are implemented in SWMM as "LID Controls", i.e., "Bio-Retention Cell", "Green Roof" and "Permeable Pavement". For the required input parameters, we extracted typical design parameters and soil hydraulic parameters from Dobkowitz et al. (2025); EPA (2023); Rossman and Bernagros (2018); Schaap et al. (2001). As loamy sand is common in Berlin, we used the soil hydraulic parameters from this soil type. Table 3 shows the resulting set of parameters.

RC: ***7. p. 8, Table 2: Are all GI scenarios without gullies?***

AR: Exactly. For clarification, we will add this information to table 2.

RC: ***8. p. 8, l. 162: A map that shows the subcatchments (and outlet points, i.e. inflow locations for 2D model) would be helpful.***

AR: we will add a map showing the subcatchments with the attributed SCS-Curve Numbers and the outlet points used in SWMM and as input for the hydrodynamic model.

Figure 1: Example building block within the study area.

RC: ***9. p. 8, l. 164: Did topography also play a role in subcatchment delineation?***

AR: Topography did not play a primary role in subcatchment delineation. Subcatchments were defined based on building blocks (including courtyards/Innenhöfe, see Figure 1), which are functionally coherent hydrologic units where flow pathways to streets are difficult to represent — water typically exits only through narrow entrances or garages, which are not resolved in the DEM. Each building block was therefore aggregated into a single residential subcatchment to ensure realistic runoff estimates. Roads were delineated separately, as they are highly impervious subcatchments. While average slope was derived from the DEM, the flat topography (32–45 m a.s.l.) shows minimal elevation variability, making land-use/functional boundaries more relevant than contour-based delineation. This approach aligns with standard SWMM urban practice (Rossman et al., 2010) and supports accurate GI implementation at the block scale.

RC: ***10. p. 8, l. 167: "residential subcatchments as pervious except area covered by buildings": Is this rather an overestimation of perviousness?***

AR: You are right, it sounds like that. We will delete the sentence "The roads are defined as impervious, residential subcatchments as pervious, except the area covered by buildings.", as it was misleading. The Curve Numbers were assigned by combining landuse and soil types, as explained in line 169.

RC: ***11. p. 8, l. 168: Is the SCS-CN method suitable here? Detailed multi-layer GI representation incl. Green-Ampt vs. simplified runoff generation using SCS-CN method for other areas; why was this combination chosen? Why not using Green-Ampt also for infiltration from pervious surfaces? (see also general comment 2).***

AR: The SCS-CN method was selected for non-GI surfaces due to its widespread application in urban catchments, its empirical calibration for land use and soil combinations, and its computational efficiency for event-based simulations (Yao et al., 2018).

The Green-Ampt approach is implemented exclusively within the SWMM LID modules (i.e., without user-selectable alternatives) and provides a more physically based representation of multi-layer soil hydraulics, which is critical for modelling GI processes (Stovin and Peng, 2017).

This hybrid modelling approach—combining SCS-CN for conventional surfaces and Green-Ampt for GI elements—is well-established in the literature (Baiamonte 2019).

Green-Ampt was not applied to pervious non-GI surfaces because reliable calibration data are lacking for heterogeneous urban areas (e.g., courtyards and parks), where soil properties can vary. For further details on the selection of the GI parameters, see answer to question RC1-7.

RC: ***12. p. 9, Table 3: Please briefly explain the surface slope for BR and GR was set to 1. The values for conductivity slope and conductivity are the same, please briefly explain what that physically means.***

AR:

- Surface slope: Regarding BR, surface slope is set to 0 % automatically within the model, so we will correct the value to 0 in table 3 for BR (as recommended by EPA, 2023). For GR we used a slope of 1 % as the majority of the roofs in our study area are flat roofs with inclinations of 0-1.14° (Belz 2010).
- Conductivity slope and conductivity: This is a coincidence. Conductivity = 43 mm/h is the value for loamy sand from Schaap et al. (2001), while conductivity slope was calculated from the soil type loamy sand using the equation specified by EPA (2023):

  conductivity slope = 0.48 * sand [%] + 0.85 * clay [%] = 0.48 * 80 + 0.85 * 5 = 43

RC: ***13. p. 10, l. 184-185: Do the output hydrographs strongly differ between the subcatchments? As suggested already before, it would be good to show the inflow locations in the 2D hydrodynamic model. (Furthermore, "point source" sounds more like a pollution source; possibly "inflow hydrograph" or "inflow boundary condition" would be more suitable?)***

AR:

- We will show the inflow locations in a new figure, see answer to question RC1-8.
- We will replace the term point source in the manuscript by "single nodal inflow"
- We will add a figure to illustrate how the subcatchment hydrographs differ between the two categories "Road" and "Residential". Looking at the summarized runoff hydrographs per subcatchment type helps to understand the behaviour of the different scenarios throughout the model chain (see answer to question RC1-17).

RC: ***14. p. 10, l. 207: "calibration performed well": Please clarify if the calibration has been carried out particularly for this study area or if a more general calibration has been carried out in advance and for another study area. Please explain briefly what "relative building damage" (corresponding to the given RMSE values) mean.***

AR: Calibration was done with the survey data from past urban pluvial events between 2010 and 2016 in Germany (Line 199), using cross validation from the same dataset.

We will add the following information to the paragraph:

- The survey data were split for training and testing
- The survey has no datapoints from within this manuscripts study area
- "Relative building damage" is the ratio between repair or replacement costs and the building value, 0.06 means a 6 % relative damage.

RC: ***15. p. 11, l. 209, 210: "In the application the model needs the maximum water depth and velocity from the hydraulic model (from which flood intensity is derived": Maximum water depth and maximum flow velocity do not necessarily occur at the same time, how is the flood intensity defined?***

AR: Flood Intensity is based on a practical information for the stability of people in the flood waters. Based on DEFRA (2006), the „Hazard Rating" = Depth * (Velocity + 0.5), shows a robust relationship to hazard levels for people. The survey data used for calibration depends on people observations, which impedes the acquisition of actual velocity values (in m/s), but instead records a qualitative „intensity". Therefore, we adapt the two different data sources (survey data from model training and hydraulic model for the application) by transforming them into hazard levels, or „flood intensity" using the given equation and defined thresholds. Flood Intensity is fed to the model not as m²/s but as classes.

We will modify this paragraph as follows:

In the application the model needs the maximum water depth and velocity from the hydraulic model (from which flood intensity is derived) and building information from cadastral data (either authoritative or OpenStreetMap data). Maximum water depth and velocity do not necessarily occur at the same time, and this is a potential bias in our approach, in which we potentially overestimate the hazard. We do so for a compatibility of approaches with other data sources, namely (official) flood hazard maps, which often provide solely the max depth and max velocity of a scenario. The same occurs in the survey data used for training, where only maximum depth and maximum „intensity" are reported.

RC: ***16. p. 11, l. 232 ff: Flow velocities were not used for the damage calculation in this study, but are indicated in the flow chart in Figure 1 - this is a bit misleading; do the authors assume no effect of the flow velocity at all for this study area? What are critical thresholds of flow velocities having an impact and which (maximum) flow velocities occur in the scenarios?***

AR: This sentence was misleading. As explained in the comment above, flood velocity is used in the damage modelling, not explicitly but as component of the „flood intensity". It is, therefore, relevant for damage estimation.

We only decided not to discuss and plot flow velocity separately in the flood mitigation analysis, as the occurring flow velocities are very small due to the flat topography. Hence, the flow velocities only become relevant when combined with water depth to estimate the damage.

To clarify this, we will modify the indicated paragraph as follows:

Flow velocity in combination with water depth is crucial for damage modelling. However, due to the flat topography of the study area, flow velocities are rather low. Hence, flow velocity was not discussed separately in the flood mitigation analysis.

RC: ***17. p. 13, Figure 3: The results indicate that, in medium scenarios, PP reduces total runoff less than BR but leads to greater reductions in flooded area and damaged buildings. Since only runoff from the hydrological model is used as input to the hydrodynamic model, this discrepancy may be due to the spatial variability of inflow hydrographs from different subcatchments. An illustrative figure showing this spatial variability would help to clarify and interpret these effects.***

AR: We appreciate your very detailed observation. We will add a figure to illustrate for some example rain events how the hydrographs differ between the different GI scenarios and subcatchment types.

Within the results section, we will amend the respective paragraph as follows:

Among the single GI scenarios, BR produces the lowest runoff with medium and maximum extent. Regarding the flooded area and damaged buildings, BR is also the strongest among the single GI scenarios with maximum extent, however, at the medium scenarios, PP outperforms BR in most events. This can be explained by a look at the temporal distribution of runoff. Figure xx (new figure) shows the runoff hydrographs for the base and single GI scenarios for two exemplary events. In the first column, all subcatchments are included, in the second column only runoff from residential subcatchments and in the third column only runoff from road subcatchments is summarized. It shows clearly how much higher the peak runoff and shorter the runoff duration is for road subcatchments without GI measures compared to the residential subcatchments. In both represented scenarios, the overall peak runoff for BR_{med} *is more than twice as the overall peak runoff for* PP_{med}*. This results in a larger flooded area and more damaged buildings for* BR_{med}*, although the runoff volume is lower compared to* PP_{med}*.*

RC: ***18. p. 16, l. 294-295: I assume a realization on streets is more challenging, and since Knoche et al. indicated only 4.5 % on streets, the PP max scenario might be very ambitious.***

AR: We agree that in the case of retrofitting GI, as in our study area, unsealing the already built street is a very ambitious plan. Hence, we will adapt the corresponding sentences as follows: This means that $\mathrm{GR_{med}}$ is realistic within the next 30 years. The scenarios $\mathrm{PP_{med}}$ and $\mathrm{PP_{max}}$, however, require with 25 and 50 % a much higher unsealing of streets. Besides, the 3 scenarios with the largest conversion to GI ($\mathrm{GR_{max}}$, $\mathrm{GR_{max}}$+$\mathrm{PP_{med}}$ and $\mathrm{BR_{max}}$+$\mathrm{GR_{max}}$) require reductions of the total impervious area beyond those elaborated by Knoche et al. (2024) for a timeframe of 30 years. Hence, their realisation within the next decades seems unrealistic.

RC: ***19. p. 19, l . 374ff: The discrepancy between reductions in total flood volume (from other studies) and in the percentage of area exceeding a water depth of 10 cm could be attributed to strong reductions at localized hotspots with very high water depths, which have a disproportionate influence on total flood volume compared to area-based indicators using a fixed depth threshold.***

AR: This is also a valuable explanation. We will add the following paragraph at the end of the indicated section:

Furthermore, the discrepancy in the flood mitigation impact between the compared studies can be explained by the use of different measures of flood volume itself. Strong reductions at localized hotspots with very high maximum water depth could result in a disproportionate decrease of total flood volume compared to the area-based indicator used in this study.

RC: ***20. p. 19, l. 381: The run time of 1D drainage models is usually relatively small compared to that of 2D models, so the overall runtime is not necessarily much higher. However, the effort required for model setup can be considerably higher, particularly if no drainage model exists in advance that can be coupled to the 2D model.***

AR: Ok, we will omit the run-time argument.

RC: ***21. p. 21, Appendix A: Please clarify how the building damage categories ("low" to "very high") are defined and how they correspond to hydraulic variables such as maximum water depth.***

AR: Thank you for pointing out, we have not defined the damage categories in the manuscript. The damage categories are a split of the relative damage (see answer to question RC1-14).

A direct relationship between damage and each predictor variable is hard to plot or define, as the model is by nature non-linear. All predictors interplay in estimating the relative damage and thus the damage categories.

We will add the following explanation of damage classes to the table heading:

Building damage classes, based on the relative building damage: Low: 0–5 %. Medium: 5–10 %. High: 10–15 %. Very High: 15–100 %.

References

Baiamonte, G.: SCS curve number and green-Ampt infiltration models. Journal of Hydrologic Engineering, 24(10), 04019034, 2019.

Belz C.: Methodenentwicklung für den Aufbau eines Gründachkatasters von Berlin am Beispiel des Bezirkes Friedrichshain-Kreuzberg. Hochschule Neubrandenburg, urn:nbn:de:gbv:519-thesis2010-0500-2, 2010.

DEFRA, Department for Environment, Food and Rural Affairs: Flood Risks to People - Phase 2 - FD2321/TR1, The Flood Risks to People Methodology, 2006.

Dobkowitz, S., Bronstert, A., and Heistermann, M.: Water retention by green infrastructure to mitigate urban flooding: a meta-analysis, Urban Water Journal, pp. 1–16, 2025.

EPA, U.: Storm Water Management Model (SWMM), https://www.epa.gov/water-research/storm-water-management-model-swmm, 2023.

Peng, Z., and Stovin, V.: Independent validation of the SWMM green roof module. Journal of Hydrologic Engineering, 22(9), 04017037, 2017.

Rossman, L. A. and Bernagros, J. T.: National Stormwater Calculator User's Guide—Version 1.2. 0.1, Office of Research and Developemnt, USEPA, Ohio, USA, 2018.

Rossman, L. A. et al.: Storm water management model user's manual, version 5.0, National Risk Management Research Laboratory, Office of Research and . . . , 2010.

Schaap, M. G., Leij, F. J., and Van Genuchten, M. T.: Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions, Journal of hydrology, 251, 163–176, 2001.

Yao, L., Wei, W. E. I., Yu, Y., Xiao, J., and Chen, L.: Rainfall-runoff risk characteristics of urban function zones in Beijing using the SCS-CN model. Journal of Geographical Sciences, 28(5), 656-668, 2018.