Preamble to the Editor:

The authors want to make note of the fact that the manner in which the review of our manuscript has been handled HESS is not well aligned with what we have experienced in numerous other contributions to the peer-reviewed literature over our careers.

Our original paper received two reviews that we provided detail response to and that resulted in major changes to the manuscript. Apparently, the Editor could not get these reviewers to comment on the revision, so instead asked two new reviewers to comment. The result was two additional reviews with nearly opposite criticisms to the original reviews. The original reviewers called for more explanation of methods. These new reviewers call for a deletion of all the added explanation. We tried to again strike a balance in the content presented in the new version.

The bottom line is that our study presents "modeling methods development" research. Our focus is Green Infrastructure simulation using the commonly-used SWMM model. In the United States, SWMM is used to make billion-dollar decisions about urban drainage design, particularly in Cities that are under Consent Decree over combined sewer overflow violations. SWMM modelers need a valid approach to GI simulation at larger urban watershed scales. There is very little reporting or direct research on this issue to guide SWMM users toward good modeling practices for GI simulation.

SWMM users that adopt the approach that we develop can use the HESS article as a reference to support its strength for balancing model complexity and output uncertainty. We think this will be the primary utility of the paper over the long term. As such, we wanted to provide enough detail for users to adopt the approach while presenting the results of unique and novel analyses that we conducted to validate the approach in terms of it over all utility at GI simulation for planning purposes. The bulk of the paper was intentionally focused on describing the "why" and "how" of our approach to GI simulation in SWMM. The results/discussion section has been structured to 1) validate the approach that we developed in terms of balancing model complexity and output uncertainty (accuracy) and 2) demonstrate the utility of adopting the approach to watershed-scale GI effectiveness considerations.

We have gone through this second round of completely new responses and made adjustments. These reviews were in some ways more critical of the manuscript than the first. At this point we request that the Editor makes a decision about this manuscript. We will make adjustments as needed for a final version, but the current feedback we have received represents a dichotomy that is difficult to know how to handle.

Sincerely,
The authors.

1st Reviewer:

Summary:

This paper leverages a highly resolved database of urban land cover to evaluate how effectively different SWMM model set-ups capture the hydrologic processes of urban watersheds with GI at a small (I'll call 'hillslope') scale. Once the ideal model set up (ideal in that balances complexity with *perceived* accuracy) is identified, this model set up is used to simulate flows at the watershed scale. The watershed scale simulations are done to evaluate parameter sensitivity and compare source area contributions to hydrographs generated by GI vs. non-GI scenarios.

General comments:

The research questions posed are certainly worth answering. The data used, along with the author's demonstrated modeling skill, is suitable for answering the questions. Specifically, the author's attempts to improve representation of "reality" (i.e., an HRE) of urban surface connectivity to GI within the SWMM framework (i.e., a subwatershed) is valuable. However, the paper is often bogged down by an extensive discussion of the methods used, relative to an exploration of the results generated. Also, conclusions are often made without a reference to a specific metric of evaluation.

Authors' general responses:

⇨ The reviewer had a good grasp of the major themes of our paper as we wanted them to be interpreted. We appreciate the consideration he/she gave to the material. Our general responses to 1) the criticism about extensive methods and 2) conclusions without a reference to a metric for evaluation are as follows:

1) We have moved several paragraphs and 2 sections from the methods section to an appendix, but in our defense in the first round of reviews of this paper, both reviewers asked for more description of the methods. In our revision we tried to include all of the specific details that those reviewers asked for, while also noting that we have published an EPA Report as a "user's guide" that provides methodological detail as well. We moved 2.5 pages of content to a new Appendix. Hopefully that satisfys the opposing criticisims about methodological content that we have received from 4 different reviewers.
2) We think this comments stems from some confusion over the difference between the two primary analyses that we conducted and present in the paper to evaluate GI modeling approaches is SWMM: A) We used a hypothetical approach to assess differences in subcatchment parameterization in SWMM and validate the approach we developed for spatial discretization and parameterizing SWMM for GI modeling. B) We then used the validated approach to subcatchment characterization to parameterize a SWMM model at the watershed scale, and use that model to demonstrate how the effects of GI scenarios can be incorporated and evaluated using the SWMM output at this scale. We decided early on that it would be inappropriate to use the watershed scale and the observed flow data available for this scale to gauge the differences among

the discretization approaches because of potentially confounding effects introduced when the drainage network and groundwater algorithm are included to run the simulation. We now explain this reasoning and try to clarify differences between the analysis in this revision (see first paragraph of section 2.5).

3) We think that if a reader is clear about the relevance of the hypothetical analysis then there should not be any confusion about the metric for evaluating what is approach we determined to be best. It should be clear from Figures 8 and 9 are two of the primary data figures in the paper. Both were meant to depict the relative differences that the approaches to subcatchment parameterization have on SWMM output. We discuss both in detail and we clarify that our primary means of assessing the performance of each option considered is based relative to what we assume is the approach that would provide the least output uncertainty, because it is the most spatially explicit one. But this approach is impractical for SWMM modeling at a watershed scale, so we base our assessment of the 'best' approach among the 5 others considered relative to this most spatially explicit one with the criteria of balancing complexity in model set-up with accuracy. It can be seen in Figure 9. That Option 6 is nearly identical in terms of average flow rate, peak flow rate, and total runoff volume as the most spatially explicit one (Option 1). So is option 2 and 3, but those are harder to implement during parameterization of SWMM. Option 6 is the best. This is explained in detail in the discussion of figures 8 and 9. We make this clear in the 2nd sentence of the conclusion section.

<u>Study Limitations</u>

There are some considerable limitations to the methods used in this manuscript. Specifically:

1. The 6 model set ups are evaluated at the hillslope scale using a design storm approach. Model "accuracy" (as the authors refer to it) seems to be based solely the author's expectations of physical processes in the watersheds. While I'm sure the authors have an excellent understanding of these processes in a historically well-studied watershed - using observed flows to validate the model set-ups would be a far better approach.

⇨ Response: We disagree with the reviewer on this point. We decided early on that it was inappropriate to use the watershed scale and the observed flow data available for this scale to gauge the differences among the discretization approaches because of potentially confounding effects introduced when the drainage network and groundwater algorithm are included to run the simulation. It is most rational to conduct the evaluation at the hillslope scale (as the reviewer calls it), because this is the scale that defines the HRE, i.e., the land area that drains to a storm sewer inlet. We felt it more rational to assume that the most spatially explicit characterization of this area (option 1) would be the most accurate, or have the lowest output uncertainty, and provide references to support that assumption. However, we acknowledge that it would be best to have supporting observational data at this scale to prove this assumption, but obtaining flow data at the point of entry to a storm sewer inlet can be very difficult in practice.

If there is some other way that model accuracy is assessed (i.e., beyond comparing the output to expected behavior) in this portion of the manuscript (Sections 3.2) it needs to be stated explicitly. Are results compared relative to model set-up "Option 1" because this modeling framework is most complicated? Are they compared to the mean? Also - the "MR5subs" metric is not defined. Nor is "Variation from 5 Subs" on the y-axis in Figure 10. Is this how accuracy is assessed? Whatever assumptions are made to compare, they must be stated explicitly (and justified)

- ⇨ Response: Based on the above. Our approach to characterizing the accuracy of the subcatchment parameterization in SWMM using the hypothetical analysis is rational.

To that end: I would not suggest comparing model output to other model output. I would suggest comparing the 6 model set-up options at the **watershed scale** - and see which set-up is best able to represent the **observed flows** in the July 2009 period with and without calibration. Then, the can truly be assessed, and there is potential for a discussion of the complexities associated with the various model set ups and calibrations. Alternatively, the authors could re-frame this entire section of the manuscript as "critical evaluation of model physics" or something – an avoid using the term accuracy. However, the assumptions that go into the "critical evaluation" need to be explicit and justified with literature and/or specific observations at the site.

- ⇨ Response: We appreciate the reviewer giving this issue considerable thought, but as noted above it is more rational to conduct the HRE analysis using the smaller hypothetical area. Just because we have observed flow data for the watershed scale does not mean that it makes best sense to use that data to qualify our modeling approach to parameterizing SWMM subcatchments at the HRE scale.
- ⇨ We think if the reader understands the reasoning behind why we conducted the hypothetical analysis at the scale we did and the chosen evaluation criteria then there should be no concern with how we framed the results/discussion or how we characterize the relevance of the SWMM output. In fact, with any of the 6 options we studied, we could make the watershed level model output align closely with the observed data during the calibration process, but with the option we suggest this calibration effort will be reduced and the amount of model input and output data will be considerably lower.
- ⇨ Finally, it is noteworthy that none of the other Reviewers raised this concern.

2. With regard to the hydrograph separation method: separating the sources of runoff is definitely valuable, and the way the authors do this is clever. However, is SWMM not able to output these variables explicitly? It is a physical model. Why do the authors need to back-calculate these fluxes by adding/subtracting different model scenario output? If either SWMM cannot output these variables directly or if it is too complicated to aggregate the output from all the subwatersheds at the watershed scale: a justification for the "back-calculation" approach should be provided in the introduction.

- ⇨ Response: We appreciate the Reviewer's recognition of the cleverness of our approach to hydrograph separation. While, SWMM provides some (e.g., system-wide surface runoff and groundwater flow) not all the source flow paths that we have presented, there is no provision in SWMM for obtaining the information as the reviewer suggests in the current framework of the model.

- ⇨ As described in the manuscript (after Figure 11 in page 19), the relative contribution of the primary hydrologic components with and without GI implementation can be examined by this hydrograph separation approach, which can provide valuable insights for GI planning.
- ⇨ Hydrograph separation is mentioned in the last paragraph of the Introduction. We think it would be confusing to the reader to add a justification for the hydrograph separation approach before we actually explain how it works. We added a sentence at the end of the Introduction to note that there is currently no provision in SWMM for accomplishing this.

3. I do not see the value in "calibrating" – or even restricting - BPA width. The actual BPA will change with storm size (as the authors point out). Why not just leave the BPA as the total pervious area – which is a better representation of the potential to infiltrate run-on. Then, just change the connectivity to the pervious area in the modelling scenarios and allow the model's infiltration routine calculate how much water is infiltrated vs. how much runs off the surface? This is more realistic. Some specific comments on this can be found in the next section of the review. Additionally, the specific metrics by which different BPA widths were compared is not explicitly mentioned in the text.

- ⇨ Response: We don't understand what the Reviewer is talking about. BPA width actually represents the BPA size. As described in Sections 2.2.3 and 3.1, we estimated three choices of potential BPA with 0.30, 0.61, and 1.52 m buffering widths. The three choices of BPA were compared during the calibration. The results are presented in Section 3.1.
- ⇨ As we argued and proved in this study, that the total pervious area (TPA) should not be treated the same as BPA. Please check out the simulation results from Options 4 and 5 in Figures 8 and 9, which treat TPA as BPA, compared to the other options that clearly identify the BPA, especially when smaller storms were simulated which are key flow capture scenarios for GI implementations.
- ⇨ As described in Section 2.2.3, the entire surface of TPA does not receive runoff from upgradient impervious areas, in general. Actually, this is one of the main areas that we have examined in this study: The relevance of explicitly modeling BPA vs. TPA.

<u>Manuscript Organization</u>

I also have a series of suggestion regarding the organization of the manuscript. The manuscript, as it is, is very, very long. It includes 14 figures. I'm aware of HESS's page limitation, but it seems like this manuscript could be streamlined. Some suggestion I have for removing/reorganizing content are:

- ⇨ Response: Agreed, but much of the detail was added at the request of earlier reviewers. Clearly is difficult to strike a balance that will make all readers happy. Have relocated some of the details on model set-up that are independent of the new approaches we present here to an Appendix.

1. Great length is spent regarding the watershed scale model parameterization and set up (i.e. Fig 6 and its paragraphs of discussion). It seems to me like much of the detailed methods discussed are standard practices in SWMM. I would suggest the authors determine which of these steps is novel vs. which are just typical urban hydrologic modeling practices, and focus on just writing up the novel components. Direct the reader to the SWMM user manual, or assume they have some basic understanding of hydrologic modelling. I have some specific suggestions in the "Specific Comments" section of this review.

⇨ Response: Agreed, we kept the novel aspects in, and moved the other more 'standard' SWMM set-up details for the study watershed to an Appendix.

2. The SWMM model and its components (i.e., parameters, use of subwatersheds, etc. – Section 2.5) is introduced AFTER these components have been discussed extensively during the description of the 6 model set-ups (Section 2.4). Perhaps moving this ahead of the set-ups would be a better organizational set up, and allow for the removal of duplicate text from the current Section 2.4.

⇨ Response: Agreed. The order of Sections 2.4 and 2.5 are switched in the revised manuscript.

3. The ratio of methods to results in this paper is extremely large. I understand that the steps presented in the manuscript are meant to be used as a model to future SWMM users modelling GI, but the introduction frames the manuscript are purely evaluating SWMM model set up for evaluating GI. Perhaps some text in the introduction that describes how this manuscript is really a suggested method for modelling GI in SWMM - with some critical evaluation - would be more suitable for the actual contents of the manuscript.

⇨ Response: We added the suggested qualifier to the introduction: 2nd sentence of the last paragraph.

4. Reference the Lee, 2017 report when describing the watershed's land cover instead of documenting it in this manuscript

⇨ Response: As a technical paper, we tried to minimize any duplications or too detailed contents.
⇨ We have referenced the Lee et al. (2017) report.
⇨ We also re-located some of the details to Appendix, which are not completely presented in the referenced report.

5. It is often unclear which spatial scale (i.e., hillslope vs. watershed) specific parts of the manuscript are describing. Clarifications should be added in almost all of the manuscript's sub-sections.

⇨ Response: We're surprised by the confusion. HRE was defined earlier on as our 'small scale' unit of consideration. If this is understood, then whenever we write about HRE the scale of attention would be known. We never used or intended to use 'hillslope vs. watershed' scales for differentiating spatial scale in this study. "An HRE is the drainage area (i.e., a real spatial element of the landscape being modeled) where GI practices may be implemented to control the element's surface runoff prior to discharge to the stormwater collection system." A watershed can consist of a single HRE (which would be very rare) to numerous HREs.

Specific comments:

A note before beginning – continuous line numbers would make completing a future review of this manuscript much easier

⇨ Response: The manuscript was prepared using the HESS-provided MS-Word template, including the way of presenting line numbers.

Abstract

- Pg 1, Ln 17-21: Add clarification on spatial scale: design storms = hillslope; continuous = watersheds

⇨ Response: Amended.

Introduction

- Pg 2, Ln 9-10: What about infiltration as an objective of GI?

⇨ Amended to include infiltration.

- Pg 2, Ln 12: Each installation is relatively less expensive, but also has relative less impact. Should add some detail as to what costs your describing while making this claim

⇨ Response: Some clarification was added.

⇨ Cost-effectiveness of GI application depends on various site-specific conditions. Thus, we used conditional sentences and added "may" in the sentence. We tried to provide a kind of GI potential, rather than a concrete general fact, as we responded to the previous revision. Because this is not so critical part of our study, we can remove these sentences especially if it creates any mis-conceptions or confusion.

- Pg 3, Ln 12: "modeld" >> "modeled"

⇨ Response: Corrected.

- Pg 3, Ln 28: "After the HRE delineation is performed in SWMM, each one undergoes" >> Clarify sentence structure so "one" is clear

⇨ Response: Clarified.

- Pg 3, Ln 34: Clarify "conventional objectives"

⇨ Response: Clarified with fundamental examples.

Methods and Material

- Pg 5, Ln 28: What is a stormwater detention area vs. a dry/wet pond?

⇨ Response: In this watershed the stormwater detention area was created by adding a culvert with an orifice control structure into the existing stream channel to satisfy the 10yr detention requirement. It does not really fit the definition of a dry or wet pond.

- Pg 6, Figure 2: Possibly add some of the shapefile IDs to the map? Generally, though, I'm not sure this figure is needed. The text adequately describes the spatial database.

⇨ Response: We believe some of the readers will benefit from the visual for the spatial representation and the organization of the attribute data.

- Pg 7, Ln 5-10: BPA is variable based on storm size (as the authors point out) – so why try limit yourself to one BPA width? Why not just allow for the entire pervious area to potentially infiltrate? As would be the case in real life. If the run-on is greater than the infiltration capacity at any time, the infiltration model will handle this appropriate and generate surface runoff.

⇨ Response: The entire pervious area can infiltrate. The BPA defines a subset of that pervious area that receives runoff from ICIA. Not all the PA receives the runoff. This is the critical distinction we make and show in the paper why it is important.

⇨ As mentioned earlier, the impervious runoff from the upgradient area physically does not get evenly distributed to the entire surface of TPA. Only a small connected often downgradient part of the pervious area can receive impervious runoff and work like a buffering strip or swale. If we model TPA as BPA, we may end up either over-estimating the onsite infiltration of the impervious runoff or under-estimating the infiltration rate compared to the actual value (depending upon TPA to BPA ratio). This is all explained in the discussion of the results of the hypothetical analysis (Figs 8 and 9).

- Ph 7, Ln 11: Where do these widths come from?

⇨ Response: As mentioned in the manuscript, we arbitrary selected these numbers to use for the calibration. We believe this range of values will work for most urban/suburban areas where GI's are often implemented. In case of where the three suggested options do not work, one can apply linear interpolation/extrapolation between the width and the size of BPA; or conduct additional buffering analysis using ArcGIS to derive more choices for defining and refining BPA widths.

- Pg 7, Figure 3: While it is certainly attractive, this figure is not that valuable (especially considering there are so many in the manuscript already). I think the readers can conceptualize what a 0.3m buffer looks like without the visual aid.

⇨ Response: We disagree. The figure gives a visualization of how the different BPA lengths translate to space and also provide context for the extent of BPA around all of the ICIA.

- Pg 7, Figure 4: Consider adding the inlets to this map

⇨ Response: While adding the inlets would be valuable, we think it would make the figure look too cluttered. The inlets are presented in Figure 7.

- Pg 8, Figure 5: For the subcatchment boxes: do the sub-subcatchment areas (i.e., "TPA" and "TIA" in Option-4) run in series or in parallel? There is discussion of this (somewhat) in the text when discussing the SWMM model connectivity scenarios – but including a set of arrows and/or arranging the sub-subcatchment areas vertically when connected in parallel and horizontally when in series would be of great value to this figure

⇨ Response: We tried to improve this figure to minimize any mis-conceptions and provide better understanding based on the first set of reviews. To describe the internal flow directions, we have added the physical and conceptual representations of HRE including the directions of flow pathways. We think this figure is a reasonable and balanced representation. Furthermore, we write in Section 2.5 "Option 4 configures the single subcatchment with only two subareas, impervious and pervious. The runoff from pervious area discharges through impervious area (i.e., TIA = DCIA)."

- Pg 9, Ln 33: This could be my own lack of understanding – but I'm unclear on what the "cumulative" precipitation values represent. Either way - I'm not sure it adds considerable value to include this in the text and in Table 1. Percentile is likely sufficient.

⇨ Response: Rain event 'Percentiles' are a common way of characterizing the size of an individual event. The Cumulative statistics quantifies the percentage of the annual precipitation that contributed from storms which are smaller than or equal to the considered event. So, if GI is designed to control smaller storm sizes based on the results in this chapter it will control the majority of the total annual precipitation over the long term. We present the information to show the reader what the eight, 24hr events translate to in terms of sizes and percentages of annual rainfall. We added the following to the text of the Table 2. "Note: The Percentile and Cumulative, percentage-based statistics qualify the exceedance probability of each event and the relative contribution of events of similar size or lower to the annual rainfall, respectively."

- Pg 10: As mentioned in the "General Comments" – the SWMM model and its components/parameters should probably be introduced prior to the discussion of the 6 model set-ups

⇨ Response: Thanks for the suggestion. We switched the sections.

- Pg 10: This subwatershed set up was done for the entire watershed – may want to clarify this at some point. Same with the discussion of parameterization on Page 11

⇨ Response: We have added more text to clarify this matter throughout the manuscript.

- Pg 10, Ln 30: Why bother introducing the 16 land cover types at all? Just introduce the 10 the first time, and remove this later clarification.

⇨ Response: The 16 types were important for the original development of the spatial database. Because it is possible to examine other types of generalization or simplification of the land use, we included the original configuration. We did move the description of step to aggregate to 10 types to the Appendix.

- Pg 11, Figure 6: This figure seems too fundamental to the process of modelling to warrant inclusion. As mentioned: unless the paper is reframed as a "new method" for running SWMM with GI – I would remove this. I would actually advocate for this framing because it aligns better with the content (namely, all the nitty-gritty set up and parameterization details included). However, I'm not sure HESS would be the place for such a manuscript

⇨ Response: We somewhat agree, but, again, the figure was prepared in response to the first round of reviews. We think the new approach to GI modeling in SWMM is novel and useful to be beneficial to a more technical audience. We think that the other part of this comment comes from a lack of understanding of the relevance of the hypothetical analysis described above. This analysis supports our approach to SWMM subcatchment characterization, and this type of analysis is never available to SWMM modelers.

⇨ SWMM users that adopt our approach can use the HESS article as a reference to support its strength for balancing model complexity and output uncertainty. We think this will be primary utility of the paper over the long term.

- Pg 11, Ln 15-32 and Pg 12, Ln 1-24: There is far too much SWMM set up 101 in this section. Is it possible to reduce this to a table of parameter values? And just refer the user to the SWMM manual when describing what each parameter is and how it was determined?

⇨ Response: Many of the set-up details are important to fully understand what adjustments need to be made in the parameterization of SWMM for users interested in adopting the approach. For the more standard parameterizations that are not dependent on our new HRE-based approach to subcatchment parameterization, those have been moved to an Appendix. Again, much of the detail was added at the request of the first reviewers.

- Pg 12, Ln 31: Hillslope or watershed scale?

⇨ Response: We never intended to use the term 'hillslope' or present an explicit dichotomy between 'hillslope vs. watershed'. This is the construct that the Reviewer is using to gain context for the content presented. At a general level it works, but it is creating confusing as noted several times previously. We have used HRE, which is a single drainage area that discharges surface runoff to a storm sewer inlet. Because of urban drainage design, this does force HREs to represent a small scale, and it also should imply why we wouldn't want to conduct the analysis of how we translate the HRE concept to the SWMM model at the watershed scale.

- Pg 13, Ln 7: Here is evidence that one BPA width is probably not the best way to model this. Again – I'd advocate allowing all of the BPA to infiltrate water, and let the model physics determine how much of that water makes it to the subsurface – this seems more representative of reality

⇨ Response: The reviewer is confused about BPA. We've tried to make the description as explicit as we can. All the BPA does infiltrate water as does the SPA. BPA is a portion of the TPA. One of our main points is that all the TPA is not working as BPA as the Reviewer seems to want to suggest. Our new approach accommodates this reality in the SWMM model set-up, and, therefore, makes the model more realistic.

- Pg 13, Ln 9-15: Refer to SWMM manual

⇨ Response: We disagree. We used the equation and descriptions to explain GW parameterization, thus it would be helpful for readers to see the related content. However, we have moved the section on groundwater parameterization to an Appendix.

- Pg 13, Ln 27: PCSWMM should be mentioned earlier in the manuscript if it is a critical step to the model set up

⇨ Response: We used PCSWMM just for importing GIS data in this study. This aspect is described in detail in Lee et al. 2017 (EPA Report). Since this is not relevant to the main objectives of this paper we will remove reference to PCSWMM.

- Pg 13, Figure 7: Is it possible to combine Figure 4 and 7?

⇨ Response: While it is possible, we think the resulting figure would be too cluttered we choose to keep the current figures as-is.

- Pg 14, Ln 9: BPA is not in Figure 6

⇨ Response: Corrected. It was supposes to be Figure 3.

- Ph 15, Ln 1: What is the spatial scale these simulations were done at? And what model set-up was used (out of the 6 tested)?

⇨ Response: We think this was clearly described in the manuscript: this is done for the entire watershed modeled by configuring HRE with Option 6. The six options were examined only for a hypothetical HRE.

- Pg 16, Ln1-10: See "General Comment" on including justification for back-calculating these values vs. taking model output directly. A good place to do with would be in the last paragraph of the Introduction on page 4

⇨ Response: As explained earlier, there is no provision in SWMM for acquiring all of the components gained from the hydrograph separation approach we presented in this manuscript.

<u>Results and Discussion</u>

- Pg 16, Ln 19ff: This not a result, it is a description of the watershed. Aren't all of these details in an EPA report somewhere (e.g., Lee, 2017)?

⇨ Response: Yes, 'it is a description of the watershed', but is the "result" of applying the approach that we describe for setting-up the spatial database. While the EPA report includes this description, the spatial information of the study site is critical to the content presented.

- Pg 16, Ln 22: What scale was the BPA calibration performed at? If watershed scale, then I would assume the July 2009 time period was used. What size storm events occurred in this period? If they're all small – I would expect an underestimation of the BPA width. If it occurred at the hillslope scale – what design storms were used?

⇨ Response: As presented in the manuscript, model calibration was conducted for the study watershed using observed data. The actual storm intensities during the modeling period are also presented in Figure 11. We characterize the rainfall during the period in section 3.3 as "There was a total of 164.6 mm of rainfall during the three days of this period; this storm is smaller than the 1 yr return period design storm (61.0 mm/d) but larger than the 6 month storm (48.3 mm/d) based on the storm statistics for the study area (see Table 2)."

- Page 16, Ln 22: These results do not mean "that the runoff from ICIA is discharged to the adjacent 0.61 m of pervious area" – soften the language. E.g.: "a 0.61m buffer width best mimicked hydrologic behavior, evaluated by metric XYZ"
    - Note: what was used to compare these runoff widths? Total runoff? Peak flow? NSE? Include this, it seems important.

⇨ Response: We amended as the reviewer suggests.

⇨ Channel flow is a combined discharge from surface runoff and subsurface flow (GW flow in SWMM) in both modeled and observed values. We compared the whole hydrographs based on R^2 and NSE as shown in Figure 11. By accident, both R^2 and NSE were omitted in the previous revision while those values were presented in the original manuscript. Now both values were included in the figure.

- Pg 17, Ln 1: What spatial scale did this occur at?

⇨ Response: This is based on the entire study watershed. Again, the modeling analysis for a hypothetical urban HRE with synthetic storms was just conducted to determine the most appropriate approach to configure an HRE in SWMM. No additional analysis was applied to the single HRE with design storms in this study.

- Pg 17-18: See General Comment #1 on the use of the word "accuracy" in this section 3.2

⇨ Response: See above. Accuracy is not an incorrect way to present the evaluation. Where appropriate we now use "presumed accuracy" to qualify the fact that we have no means of directly testing the assumptions we made regarding evaluation of the HRE configuration options in SWMM.

- Pg 18, Ln 17: Define MR5subs – it is important

⇨ Response: Defined.

- Pg 19, Ln 3-4: "Fig 10" >> "Fig 11"

⇨ Response: Corrected.

- Pg 19, Ln 1-10: 3% change in total runoff doesn't seem like a lot of sensitivity. This should be noted. How much did total runoff change during calibration?

⇨ Response: The text was amended to include the suggested point.

- Pg 19, Ln 13-24: Move calibration discussion of calibration ahead of discussion of sensitivity analysis. Alternatively, combine and condense these paragraphs.
  ⇨ Response: We made some changes here, but it makes more sense to us to discuss sensitivity before calibration.

- Pg 20, Ln 12: "Fig. 12b and 13" >> "Fig 13b and 14" Conclusions
  ⇨ Response: Corrected.

- Pg 21, Ln 3: "accuracy" is not the best word
  ⇨ Response: We feel otherwise: See above.

2nd Reviewer:

Review of "Drainage area characterization for evaluating green infrastructure using the Storm Water Management Model" for HESS.

This manuscript endeavors to solve a problem in the popular SWMM model, which is how to deal with the disconnection of impervious surfaces that result from green infrastructure (GI) implementation. The existing method is, at best, clunky when a high density of GI is modeled. The approach proposed by the authors seems like an improvement, but the manuscript gets so bogged down in the minutiae of the methodology that the reader is left not quite knowing which of the six options presented is the recommended solution. The manuscript toggles between synthetic storms applied within a small hypothetical area, with no calibration or validation (as everything is hypothetical and synthetic), and a calibrated (but not validated) SWMM model of a 100 ha suburban watershed. The introduction is good, but there is no discussion section to bring the reader back to the big picture questions that motivated the work and to identify remaining challenges and next steps. I expect high quality articles to provide such insights.

- ⇨ Response: We clearly disagree with the criticism about the structure and the quality of the content presented. We've tried to clarify the rationale and relevance of the hypothetical analysis. The goal of the discussion component was to describe the relevance of applying the proposed approach for configuring SWMM for GI modeling through demonstration at the watershed scale using a case study. Our intent was to demonstrate how the output from a SWMM model configured as we suggest could be valuable for GI design considerations. There is very little SWMM GI literature that can be drawn upon to provide context and depth to the discussion. Modelers using SWMM and considering GI effects rarely report the methods used to configure the GI simulation. We think we did the best we could do without overstating the relevance of the results.

In reviewing the previous reviewers' critiques and the authors I responses I note that there are lingering issues. A previous reviewer asked for a better description of the model calibration process, including criteria of performance. However, the only place I saw such a criteria was in the abstract where the Nash-Sutcliffe is reported. The authors response suggests that they view the sensitivity analysis of the synthetic storms in the hypothetical area as a calibration. It is not. The issue of higher peak flows in the watershed-scale GI scenario is still inadequately explained (see later comment). I note that previous reviewers did ask for more methodological detail. I feel that the level of methodological detail in the manuscript is now excessive in places. Perhaps this is a matter of personal preference, but I have made later comments about places where the detail seems (to me) to be more than sufficient.

- ⇨ Response: R^2 and NSE are presented in the main text as well (sentences before Figure 11; within Figure 11; and Conclusions).
- ⇨ We agree that "the level of methodological detail in the manuscript is now excessive in places". As expressed in the responses to the 1st reviewer's comments earlier, the details of the methodology are now presented in the Appendix to the revised manuscript.

Specific Comments

Abstract, line 17. It is unclear how the approach can be validated by comparing synthetic storms without having any reference to the hydrograph that would actually be produced by such events.

⇨ Response: Please see the responses to Reviewer 1 comments above.

Abstract, line 18. Tell the readers what the suggested approach is, because all they know is that six options were evaluated.

⇨ Response: Additional descriptions/clarifications have been added.

Abstract, line 19. I believe this is the only place where model calibration results are reported.

⇨ Response: Actually, we reported the estimated R^2 and NSE between the observed and the modeled in Section 3.3 (see Figure 11 and related contents) and Conclusions, in addition to the Abstract. The values for R^2 and NSE in Figure 11 were accidentally omitted in the previously revised manuscript while those values were presented in the original manuscript. The values have been included again in the figure.

p. 3, 1st paragraph: I think this section could be clearer in describing how SWMM does or does not include stormwater control measures (including GI) in the subcatchments in a typical setup. It's my understanding that runoff is generated from a subcatchment and then routed through one or more stormwater control elements before being added to the pipe or drainage network.

⇨ Response: So, we are supposed to delete content about how a SWMM Model is set-up in general, but here the Reviewer wants additional content on currently standard GI modeling practices in SWMM. In SWMM vernacular, the capture and retention of rainfall/runoff onsite are referred to as low impact development (LID) practices. While SWMM can explicitly model eight different generic types of LID controls, but there are some nuances and limitations to placing LID controls within a subcatchment. We consider an extended discussion of those nuances would distract the main discussion and would be outside the scope of this paper.

⇨ If the reviewer means the 'control elements' as detention/retentions systems before discharging the stormwater flow to the main receiving water (e.g., channels, streams, or rivers), those types of controls would be part of conventional downstream controls, not modern GI practices.

p. 3, line 25: Is homogeneous really what you are trying to say here? Or is it really that each subarea can consist of multiple different landcover components (e.g., DCIA can include paved streets, rooftops, driveways, and sidewalks)?

⇨ Response: We intended to mean the same as the reviewer.

⇨ We have amended the text to remove any potential misunderstandings.

p. 3, line 28: But HRE delineation isn't really done in SWMM in the sense that the drainage area isn't defined by topography or pipe networks. Instead the HRE characteristics are assigned to a particular GI, as you've described.

⇨ Response: We have defined/proposed HRE in this manuscript. The reviewer is limiting the definition of GI as a kind of (small) downstream control practice: a GI system receives runoff from an HRE to control onsite. But GI practices can be part of an HRE.

p. 3, line 32: It's true that the more subcatchments there are the more input and output values are created, but why is this appearing halfway through a discussion of HREs. This paragraph may need some reorganization to help the reader understand the flow/overarching connective concept.

- ⇨ Response: We are unsure what the reviewer is asking us to address here.

p. 4, lines 1-5: I agree with this description of how adding GI to SWMM goes. It gets complicated really quickly!

- ⇨ Response: We appreciate reviewer's recognition on this matter.

p. 5, line 18: Having done this sort of work, it may be overstating the case that storm sewer inlets are often visible from aerial photographs. Image quality, shadows, parked cars, tree canopies, and other obstructions can make them very difficult to locate without on-the-ground verification.

- ⇨ Response: We amended the sentence to include the suggested clarification.

p. 6, line 4: It might be helpful to remind readers what BPA and SPA stand for here, since these acronyms are unique to this manuscript.

- ⇨ Response: That might be helpful, but the copy editors will typically remove any abbreviations that are spelled out again in the same manuscript. Therefore, we have placed a 'List of Abbreviations' at the end of the manuscript.

p. 7: A lot of the information on this page feels overly detailed, more like what I'd expect to find in a technical report or manual than a journal article.
p. 8-9: There is so much detail on the model setup in these pages that the reader who is not trying to replicate this exact experiment does not need to know. The flow of the story is entirely lost as the reader wades through these details. Can some of this detailed be moved to an appendix? Or is it already covered in the published technical report, so that can be referenced instead?
p. 11: The writing through here continues to be overly long and detailed. For example, at line 25, the authors write that characteristic width was estimated using an area-weighted flow length as recommended in Gironás et al. (2009). That would seem to be an adequate description for the purposes of a journal article, yet it continues for a full 10 lines of detail. Again, the risk here is that the reader misses the forest for the trees or loses interest in the paper entirely.
p. 12. The excessive detail just goes on. For example, it's not necessary to tell readers that the area-weighting was doing in Excel.

- ⇨ Response: We agree with these comments. As mentioned previously and noted by Reviewer 1 as well, we were asked to provide more detailed descriptions on the methods by the previous reviewers. We tried to respond to the request even though we felt this might be too much (or unnecessary). Unfortunately, the previous reviewers did not respond to our update and they were left in the manuscript.
- ⇨ Many of the details of the methods are now re-located under an Appendix.

p. 13, line 9. I am bothered by the use of the term interflow interchangeably with groundwater flow. In the usage with which I am familiar, interflow originates from the unsaturated or transiently saturated zone and is not synonymous with groundwater movement. We would not expect to adequately model interflow with the simple equation shown in equation 3. I suggest that the authors clearly define what they are attempting to model and then use the correct term throughout the manuscript

- ⇨ Response: In the revised manuscript, 'interflow' is entirely replaced with 'subsurface flow'.

p. 14, line 31. What was the metric used to quantify the modeling result in the calibration process? This is an important piece of missing information.

⇨ Response: The used metric is added. It is based on flow volume.

p. 15-16, Section 2.8. Here interflow and groundwater flow are used interchangeably in the context of hydrograph separation. In my experience, interflow would be considered part of stormflow while groundwater would contribute to baseflow. I suggest the authors revise their terminology to reduce confusion.

⇨ Response: Again, 'interflow' is replaced with 'subsurface flow' throughout the revised manuscript.

p. 16, bottom. Somewhere in here it seems important to explain what the model calibration results looked like and how the model parameters were judged to be sufficiently calibrated.

⇨ Response: The R^2 and NSE between the modeled and the observed are presented in Figure 11.

p. 18, line 9. Since the authors are comparing model results from simulated storms, I am curious how they concluded that some options produced "inaccurate" results, since there is no correct or observed results that can be tested against. (See also page 17, line 21.) At line 12 on page 18, the authors propose that Option 1 is the most accurate because it is the least spatially lumped. If that is the criteria for accuracy, that should be explained somewhere earlier in the paper (e.g., move this paragraph closer to the beginning of section 3.2). However, the problem with arguing that least spatially lumped is most accurate is that there are lots of parameters to be calibrated and we really don't know whether those parameters are correct or not.

⇨ Response: We explain more exactly the accuracy is gauged relative to the most spatially explicit option (See responses to Reviewer 1).

⇨ We added some clarification on this matter using literature citations as well.

p. 19, line 10. Less sensitive than what?

⇨ Response: Amended.

p. 20, line 22. An explanation of the physical or modeled processes that could generate higher peak flows as a result of downspout disconnection is required. I understand that the pervious area is saturated and producing runoff, but wouldn't that runoff end up in the same place as water from the connected downspouts would have? And wouldn't the connected downspout runoff, which travels continuously through pipes arrive at the stream faster or in a more concentrated fashion than runoff generated by overland flow through vegetation? I'm struggling to understand the mechanism here.

⇨ Response: We are assuming that there is a typo in the line and page reference for this comment (i.e., p. 20, line 22). As a description for the mechanism: Assume all downspouts from a rooftop are disconnected from the direct pipeline to the storm sewer (i.e., DCIA is converted into ICIA). If there is a rain storm with low intensities but an extended period, the pervious area that receives rooftop runoff (i.e., BPA) will be saturated earlier than the other pervious area (i.e., SPA) because of the extra run on from the rooftop. After saturation, the saturated pervious area hydrologically responds more like impervious area (i.e., minimal loss by the saturated infiltration rate). Under this condition, the rooftop runoff cannot be hydrologically controlled by the BPA. However, if the downspouts are not disconnected (i.e., the rooftop is still DCIA), the pervious area, where possibly receives runoff from the rooftop if the downspouts are disconnected, can be maintained a hydrologically unsaturated status longer than BPA. If the pervious area is not saturated yet, the area can control the low intensity rain directly fallen onto the area (i.e., This area is part of SPA). Under this physical situation, the surface runoff rate with downspout disconnection can be higher than that with downspout connection because less stormwater can be controlled onsite with downspout disconnection. If this physical situation occurs at the peak rainfall intensity during a storm event, the peak surface runoff rate with downspout disconnection can be higher than that with downspout connection (i.e., the area of rooftop and the BPA may respond like impervious area increasing the peak flow). This would be a very special but possible case. Of course, the overall event-based surface runoff volume will be decreased with downspout disconnection in any cases.

Figure 1. The main portion of Figure 1 is not at the optimal scale to see either the study watershed's distribution of land uses or to understand its context relative to a major city. It seems like the scale of the map should aim to communicate at least one of those objectives.

⇨ Response: The closest major city, Cincinnati, is placed on the map with an additional description in the title of the figure.

Figure 5. It would be helpful to define "Trpt" and "Bldg" in the figure caption so that readers do not need to find this information in the manuscript text.

⇨ Response: "Trpt" and "Bldg" are defined at the bottom of the figure. Both are also presented in 'List of Abbreviations' at the end of the manuscript.

Drainage area characterization for evaluating green infrastructure using the Storm Water Management Model

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Abstract. Urban stormwater runoff quantity and quality are strongly dependent upon catchment properties. Models are used to simulate the runoff characteristics, but the output from a stormwater management model is dependent on how the catchment area is subdivided and represented as spatial elements. For green infrastructure modeling, we suggest a discretization method that distinguishes directly connected impervious area from the total impervious area. Pervious buffers, which receive runoff from upgradient impervious areas should also be identified as a separate subset of the entire pervious area. This separation provides an improved model representation of the runoff process. With these criteria in mind, an approach to spatial discretization for projects using the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) is demonstrated for the Shayler Crossing watershed, a well–monitored, residential suburban area occupying 100 ha, east of Cincinnati, Ohio. The model relies on a highly resolved spatial database of urban land cover, stormwater drainage features, and topography. To verify~~validate~~ the spatial discretization approach, a hypothetical analysis was conducted. S~~s~~ix different representations of a common urbanscape that discharges runoff to a single storm inlet were evaluated with eight 24 h synthetic storms. This analysis allowed us to select a discretization scheme that balances complexity in model set-up with presumed accuracy of the output with respect to the most complex discretization option considered. The balanced approach delineates directly and indirectly connected impervious areas, buffering pervious area receiving impervious runoff, and the other pervious area within a SWMM subcatchment. ~~With minimal calibration effort, the suggested approach out~~ It performed well at the watershed scale with minimal calibration effort~~other options and was highly correlated with the observed values for a two month continuous simulation period~~ (Nash–Sutcliffe coefficient = 0.852; R^2 = 0.871). The approach accommodates the distribution of runoff contributions from different spatial components and flow pathways that would impact green infrastructure performance. ~~The~~A developed SWMM model using the discretization approach is calibrated by adjusting parameters per land cover component, instead of per subcatchment, and, therefore, ~~. This approach~~ can be applied to relatively large watersheds if the land cover components are relatively homogeneous and/or categorized appropriately ~~throughout~~in the GIS that supports the model parameterization. ~~This land cover component based approach reduces the number of modeled parameters for consideration during calibration.~~ Finally, with a few model adjustments, we show how the simulated stream

hydrograph can be separated into the relative contributions from different land cover types and subsurface sources, adding insight to the potential effectiveness of the planned green infrastructure scenarios at the watershed scale.

1 Introduction

Conventional stormwater modeling has focused on the design of urban drainage systems and flood control practices that achieve fast drainage and reduce risk of flooding (NRC, 2009; WEF–ASCE, 2012). These objectives focus attention on larger storms, such as 2 to 10 yr return period storms for designing drainage systems and 25 to 100 yr storms for designing flood control practices (WEF–ASCE, 2012). Conversely, nearly 95 % of pollutant runoff from urban areas is produced from events smaller than a 2 yr storm (Guo and Urbonas, 1996; Pitt, 1999; NRC, 2009). It is well recognized that the best way to resolve this pollution problem is to implement controls as close to the source of runoff generation as possible (Debo and Reese, 2003; WEF–ASCE, 2012).

Green infrastructure (GI) practices were developed to correct this water pollution problem and restore the natural hydrologic cycle (WEF–ASCE, 2012; USEPA, 2014). GI includes structures like green roofs, rain barrels, bioretention areas, buffer strips, vegetated swales, permeable pavements, and infiltration trenches, or practices, such as, disconnecting downspouts. The specific design objectives for GI include minimizing the impervious areas directly connected to the storm sewer, increasing surface flow path lengths or time of concentration, and maximizing onsite depression storage and infiltration at the lot–level (WEF–ASCE, 2012). This translates operationally to individual stormwater management practices that are relatively small but densely distributed in space (USEPA, 2009). Although GI is distributed at higher spatial densities, each unit is relatively inexpensive if the unit can be considered as part of landscaping, and in total, may provide a cost–effective alternative to more traditional larger centralized practices, like detention ponds especially in cases where land is not available or very expensive.

There is a great deal of interest in modeling GI effects at watershed scales to help inform regional stormwater management planning and design decisions. However, from a stormwater modeling perspective, the approach taken for model representations of GI requires different methodological considerations compared to the traditional large–size, low spatial density of the more centralized and regional control features (Fletcher et al., 2013; USEPA, 2012; Guo, 2008). While conventional stormwater management practices have focused on end–of–pipe controls at the downstream end of the drainage area (i.e., centralized systems), GI practices focus on on–site controls at the upstream side (i.e., distributed systems). The surface hydrologic properties (e.g., land cover, slope, overland flow path, etc.) remain the same before or after applying centralized systems, but they are altered with on–site GI systems. GI practices actually aim to amend the landscape hydrologic properties to reduce the negative impacts of stormwater (USEPA, 2007). Hence, modeling approaches for evaluating GI should be able to account for the changing surface hydrologic properties that come with GI implementation.

The Storm Water Management Model (SWMM) of the United States Environmental Protection Agency (USEPA) is one tool that has a large user–base and a broad application history for informing stormwater management projects around the world (Niazi et al., 2017). In the current version of the model, GI effects are simulated using low impact development (LID) algorithms. LID is largely synonymous with GI in SWMM vernacular. The LID modeling options were added in 2010 (Rossman 2015; Rossman and Huber, 2016). Since then, while numerous LID/GI modeling studies have been introduced, best modeling practices for simulating GI in SWMM have received comparatively little attention in the literature (Niazi et al., 2017).

~~With this in mind, this~~This study was intent on evaluating approaches to modeling GI effects at a watershed scale using SWMM. In the set–up of a SWMM model, the urban area of interest is divided into smaller spatial units, referred to as subcatchments. To implement a traditional stormwater control feature like a retention pond, it is usually acceptable to provide minimal detail of the drainage area (Rossman and Huber, 2016). This leads to spatial aggregation which tends to produce larger subcatchment areas that aggregate land cover types and simplify the existing storm sewer system to realize a more cost–effective model set–up and output data management. ~~As long as~~If the simulated hydrographs are matched with the observed data during model calibration, the model is considered a sound representation of the drainage processes important for designing the retention pond. The trade–off is that coarser schematization requires more decisions on how to aggregate catchment properties (Rossman and Huber, 2016). In contrast, for simulation of GI, the construction reality is that GI is built as part of building and landscape arrangements all upgradient of the drainage network (Dietz, 2007; Montalto et al., 2007; USEPA, 2009; Zhou, 2014). Therefore, ~~in order~~ to accurately examine GI alternatives, a drainage area for modeling should be defined as an area that drains runoff to a storm sewer inlet with no or minimal spatial aggregation of landscape features affecting hydrologic properties. In SWMM, this drainage area is modeled as single or multiple subcatchments. Since SWMM version 4.4H, overland flow routing is allowed from one subcatchment to another (Huber, 2001; Huber and Cannon, 2002). To minimize confusion between real and modeled drainage areas, we coin the term hydrologic response element (HRE) in this study. An HRE is the drainage area (i.e., a real spatial element of the landscape being modeled) where GI practices may be implemented to control the element's surface runoff prior to discharge to the stormwater collection system. There are many alternatives for configuring the HRE for GI modeling in SWMM. We evaluate six different options in this study.

In SWMM, the subcatchment representation of the HRE is comprised of one or more homogeneous subareas, such as impervious or pervious area, impervious area with or without depression storage, directly connected impervious area (DCIA) or indirectly connected impervious area (ICIA), or LID area (Rossman, 2015; Rossman and Huber, 2016). In urban landscapes, DCIA discharges runoff to the existing storm sewer system without any control, while ICIA discharges to adjacent pervious area (PA). The PA that receives runoff from ICIA works like a buffer strip or swale, therefore acting like an existing GI practice albeit not intentionally designed as such. This is a real characteristic of urban areas that is termed buffering pervious area (BPA) in this study. The other pervious area is called standalone pervious area (SPA) that does not receive or control any runoff from impervious area. An HRE may consist~~s~~ of all or part of these subareas – DCIA, ICIA, BPA and SPA – and implementing GI practices can change subarea ratios and properties, surface runoff processes, and flow pathways within the HRE. Each subarea may also consist of ~~even more homogeneous~~different land cover components. For example, DCIA may include ~~, such as~~ paved streets, building rooftops, driveways, or sidewalks, ~~lawn, or landscaped areas~~. In this study, we questioned how these spatial and hydrologic realities should be modeled using SWMM.

After the HRE delineation is performed in SWMM, each ~~one~~ HRE undergoes a model parametrization procedure that defines the relative proportions of impervious and pervious subareas, how they interact in terms of surface flow pathways, and their hydrologic properties (Rossman, 2015). The subcatchment/subarea configuration of each HRE ultimately specifies the physical conditions used by the model's mathematical algorithms to simulate the dynamics of hydrologic loading to the drainage network. The more subcatchments there are, the more input and output values there are to be managed by the modeler. When setting up a SWMM model using the conventional objectives, such as deriving hydrographs for designing storm collection systems and/or detention/retention systems, the subcatchment parameterization remains the same before and after simulation of the management practice; however, for GI simulation, the internal properties of a subcatchment change, as mentioned earlier. Pending the type of GI, changes may need to be made to the hydrologic properties of subareas or individual land cover components, the proportions of impervious and pervious area, the specification for the routing of runoff between them, the flow path length, and infiltration or the depression storage properties. Adequately rationalizing and tracking these changes can become a problem for the modeler when the total area being modeled is relatively large and aggregated, the GI scenarios are not the same among HREs, or the internal properties among HREs are heterogeneous. A systematic approach to characterizing HREs would help make SWMM GI simulation projects more efficient.

The question of how to best parameterize SWMM is not new especially when it comes to spatial resolution and scaling, but as mentioned, GI modeling, in particular, requires special considerations. This paper describes a suggested method for modelling GI in SWMM and provides critical evaluation. Primary objectives of this study are to (1) examine how to configure HREs for GI modeling and (2) develop a methodology for parameterizing a SWMM model that reflects this configuration with the goal of demonstrating an urban watershed spatial discretization approach that optimizes model performance in terms of tracking model input values and presumed accuracy of the results. We hypothesized that conventional modeling approaches to subcatchment delineation are likely aggregating at too coarse resolution in space and hydrologic response to be appropriate for highly spatially distributed modern GI. We also questioned how the SWMM setup could not only allow for modeling the effects of various GI scenarios, but also facilitate the scaling of GI scenarios from a small HRE, representing the parcel or lot–level, to a watershed level. ~~In order to~~To answer these questions, we examine several acceptable approaches to representing spatial reality in SWMM when the modeling objective is to inform decisions about GI implementation. We use a hypothetical HRE based analysis of spatial discretization alternatives to test our hypothesis related to the appropriateness of spatial and hydrologic response resolution. The hypothetical HRE represents a typical residential area that drains to a storm sewer inlet. The hypothetical HRE is modeled in SWMM by combining six conceivable options in spatial representation and eight design storms that represent the full spectrum of runoff events. From this analysis, an appropriate option is selected for GI modeling in SWMM, and a baseline SWMM model is developed using it for representing the existing condition of a well–characterized 100 ha urban watershed in a headwater area east of Cincinnati, Ohio. To examine the proposed approach, another SWMM model is developed for simulating a GI implementation scenario at the study watershed. Also, an approach for hydrograph separation is presented using the developed SWMM models, which can provide insight for arranging GI implementation scenarios. Currently, there is no provision for accomplishing this in SWMM.

2 Materials and methods

2.1 Study area

An experimental urban watershed drained by a natural headwater stream that does not have any surface stormwater inflows from outside its topographic boundaries was used for this study (Fig. 1). The Shayler Crossing watershed (SHC) is located east of Cincinnati, Ohio and occupies approximately 100 ha that is characterized as 62.6 % urban or developed, 25.6 % agriculture, and 11.8 % forested based on the 2011 National Land Cover Database (Homer et al., 2015). The native soils of the watershed are characterized with high silty clay loam content and therefore are naturally poorly infiltrating. ~~This area is part of the East Fork of the Little Miami River Watershed (EFW) where long–term extensive monitoring and modeling effort is supported by a partnership among the Clermont County Office of Environmental Quality, the Clermont County Soil and Water Conservation District, the Clermont County Stormwater Division, the Ohio EPA and the USEPA, Office of Research and Development. As part of this partnership, the selected urban watershed has been monitored since 2006 by the USEPA.~~

Figure 1. Location of the Shayler Crossing watershed. I-275 is an interstate highway around the Cincinnati metropolitan area.

2.2 The baseline spatial database

2.2.1 Data from the County GIS

Spatial data for the study area was provided by the Clermont County Office of Environmental Quality, which included a detailed GIS of the existing stormwater drainage system and surface topography. The drainage system consists of storm sewer inlets (or catch basins), manholes, pipes, wet/dry detention ponds, and channel network. The County GIS contains the location of the drainage system, invert elevations for inlets and manholes, and pipe sizes. Two types of surface topography data were also available; 0.76 m (2.5 feet) LiDAR (Light Detection and Ranging) data and 0.3 m contours. High–resolution aerial orthophotographs were also provided by the County. Existing databases that include the details for the stormwater infrastructure like in this watershed are not always ~~readily~~ available to the modeler. In these cases, to adopt the subsequently described approach to GI scenario modeling in SWMM could require considerable ground–truthing and site surveying. In lieu of onsite visits, and as will become apparent from the descriptions below, what would be most important is determining the spatial location of storm sewer inlets. These are often visible from readily available aerial photographs, note that the visibility depends on the underlying image quality and the presence of obstacles such as trees or cars. When elevation data for the storm sewer network is unavailable, much can be inferred using surface elevation data and assuming local construction codes for stormwater infrastructures were applied, such as catch basin depths and conveyance pipe diameters and slopes. Such approximations would suffice for GI scenario analysis considerations and where storm sewer design is not the primary focus.

2.2.2 Detailed land cover and subarea categorization

In order toTo obtain a high resolution digital characterization of spatial reality in the study watershed, 16 unique land cover types were identified and digitized using ArcGIS 10.2 (ESRI, 2013) spatial analysis tools on the aerial orthophotographs of the study area. These 16 types are later aggregated to 10 for setting-up the watershed SWMM model (See Appendix). The resulting baseline spatial database included individual records of the watershed surface that could be used to access the location, pattern, and extent of the following sixteen land cover types: streets, parking areas, sidewalks, driveways, main buildings, miscellaneous buildings, paved walking paths, patios, other miscellaneous impervious areas, landscaped or lawn areas, agriculture, forest, dry ponds, stormwater detention areas (in SHC this is created by the addition of a control structure to the stream channel itself), swimming pools, and wet ponds. Each spatial record has its own attributes (i.e., fields in the database) representing the current conditions (e.g., area, land cover) and was characterized based on its future potential for GI implementation (e.g., to evaluate the potential of downspout disconnection for a main building). The initial parameterization and GI modeling approaches described below for the SWMM model are based on content extracted from this land cover database created using ArcGIS tools. This database is often reused to perform model adjustments during calibration and GI scenario analysis. The developed land cover database for SHC contains a total of 3682 records and the median area of each record is 23.5 m^2.

Each surface record in the database is further classified into four types based on its hydrologic characteristics including 1) DCIA, 2) ICIA, 3) Pervious area (PA), or 4) Water. The PA is subsequently split into two subcategories called BPA and SPA after the HRE delineation procedure for SWMM modeling is completed (see below). All main buildings are DCIA because the rooftop downspouts in the existing condition are plumbed to directly discharge to the storm water collection system through buried pipes or street gutters. All the miscellaneous buildings (e.g. storage sheds) are considered ICIA. Streets with curb–and–gutter drainage systems are identified as DCIA. Any directly connected upgradient impervious areas to these streets are initially considered as DCIA. These areas include directly connected driveways, parking areas, and sidewalks. However, if both sides of a sidewalk are surrounded by pervious area, the sidewalk is categorized as ICIA. Streets without curb–and–gutter drainage are ICIA. The remaining miscellaneous impervious areas are ICIA.

Figure 2 contains a sample GIS representation of the 16 previously defined land cover types along with a corresponding attribute table, which indicates hydrologic characteristics representing the baseline classification and a GI scenario–related classification. In the attribute table shown in Fig. 2, the first column contains the record identifier, the second column defines the land cover type, the third column defines how it was classified for modeling the baseline condition, the fourth column defines how it was classified or re–classified for modeling a specific GI scenario, and the fifth column specifies the contributing area. For example, the record ID 36 contained in the table is initially classified as DCIA, but after the rooftop drains were disconnected in the modeled GI scenario, the unit was reclassified as ICIA (in the fourth column). This methodology allows for GI–related hydrology evaluation to be performed without impacting the overall SWMM model structure and setup. A companion USEPA report (Lee et al., 2017) has been prepared to provide the relevant details on the applied spatial analysis techniques such as clip, intersect, union, buffer, and manipulating attribute data.

Figure 2. Sample GIS classified representation of the land cover and hydrologic characteristics.

2.2.3 Configuring the BPA and SPA

BPA is not considered explicitly in a traditional urban stormwater modeling analysis using SWMM. Instead the modeler usually sets up PA within a subcatchment to receive a certain percentage of runoff from impervious areas; this is how ICIA is distinguished from DCIA. However, in reality, not all of the PA receives runoff from ICIA, rather just the part of the PA that is immediately adjacent to the ICIA. When evaluating GI scenarios, one strategy might be to enlarge the size of the buffering area adjacent to ICIA, or engineer GI structures (e.g., cascading filtering or bioretention systems) around this buffering area (a.k.a. BPA) to reduce the direct runoff from impervious surfaces by routing them over grassy areas to slow down runoff and promote soil infiltration. Draining paved areas onto porous areas can reduce runoff volumes, rates, pollutants, and cost for drainage infrastructure (NRC, 2009; WEF–ASCE, 2012). Therefore, because of the nuanced, yet important differences in the geospatial relationship of PA in different GI scenarios, we rationalized the need for retaining the ability to model this aspect while evaluating GI scenarios by splitting the PA into BPA and SPA for GI modeling in SWMM.

Characterizing the precise "physical" extent of BPA ~~in reality~~ is a complicated process that would have to be defined from highly resolved surface topography around ICIA and an understanding of the unsaturated zone processes such as how infiltration and depression storage interact across the pervious surface types to influence flow path length. The physical extent of BPA is also affected by storm intensity, with higher intensity storms creating a larger spread of water across the surface and thereby increasing the extent of available adjacent buffering areas. Lacking the ability to infer flow path length without extensive physical measurements, we instead treat the width of the BPA from ICIA as a calibration parameter. In preparation for this, BPA based on different buffer widths was established during the development of the spatial database. This was done in ArcGIS using the geoprocessing tools "Buffer" and "Intersect". The "Buffer" tool established separate BPA area around all existing ICIA based on arbitrarily chosen distances that serve as equivalent "buffer widths" of 0.30, 0.61, and 1.52 m (Fig. 3). The "Intersect" tool establishes the area for the BPA and adjusts the area of the original pervious area from which it was subtracted, which is now SPA (Lee et al., 2017). Using this spatial information, we arranged three SWMM models that represent three different sizes of BPA. We determined which one among the three cases of BPA sizes provided the more accurate simulation compared to the observed flow data, and as part of model calibration. In this way the BPA width was treated as a calibration parameter in this study.

Figure 3. Depiction of the different distances applied for the estimation of BPA in the baseline condition using ArcGIS.

2.3 HRE delineation

Urban HREs were delineated manually within the GIS using the surface topography (0.76 m LiDAR) and the layout of the storm sewer system (Rossman and Huber, 2016). Because GI is designed to capture and control stormwater runoff before it discharges to the storm sewer system, the HRE for GI analysis should be delineated as the area that drains runoff to an actual storm sewer inlet. With GI implementation, some inlets can be removed or combined for economic benefits because the peak and volume of stormwater discharge will be decreased after implementing GI practices (Sample et al., 2003; Braden and Johnston, 2004; USEPA, 2012). Based on this, two HREs are combined into one HRE if the two HREs were located side–by–side at one street location, and one of the two HREs was smaller than 2023.4 m^2 (0.5 acre). For undeveloped or agricultural areas in the study watershed, the HRE boundaries were generally selected with an intent to keep all HREs a similar size to help maintain hydrologic continuity among them. The result of the HRE delineation for the entire SHC watershed is shown in Fig. 4.

Figure 4. Detailed spatial representation of the Shayler Crossing watershed.

2.45 SWMM parameterization

Commented [JGL1]: Followed by the 1st reviewer's suggestion, the order of the previous sections 2.4 and 2.5 are switched in the revised manuscript.

SWMM developed by the USEPA, is a comprehensive mathematical model for analyzing hydraulics, hydrology, and water quality process dynamics in the urban environment (Huber and Dickinson, 1988; Gironás et al., 2009; Rossman, 2015; Rossman and Huber, 2016, Niazi et al., 2017). Here version 5.1.007 of SWMM was used. SWMM generates runoff when rainfall depth exceeds surface depression storage and infiltration capacity at the subcatchment scale. SWMM has extensive routing capability that can simulate the runoff through a conveyance system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM can also estimate the quality of runoff discharging from subcatchments and route it through the conveyance system. The model can be used within a continuous or event–based framework.
Unique to our application of the SWMM model is the set-up of the BPA. This process is described in detail in Appendix. Because the natural stream draining the study area receives lateral inflow through subsurface soil media (a.k.a., subsurface flow), SWMM's groundwater modeling options were implemented. The groundwater component of the SHC SWMM set-up is also described in Appendix.

2.5.1 Subcatchment/subarea parameterization

A subcatchment is a fundamental hydrologic component of a SWMM application, and can be defined as an area that drains runoff to a storm sewer inlet, open channel, or another subcatchment. The SWMM subcatchments in this study will represent the HREs that were delineated during the development of the spatial database described above. Each SWMM subcatchment is configured with a specific drainage area, % imperviousness, width, and slope. Subareas divide each subcatchment into impervious, pervious, and/or LID areas that are used to account for internal heterogeneity. These areas are modeled in the abstract based on the relative percentage of the subcatchment each occupies, i.e., subareas have no real spatial reference.

Therefore, all pervious areas within one subcatchment, for example, are lumped and modeled as one contributing hydrologic entity no matter how disconnected or patchy the actual physical reality may be. This establishes a relationship between the subcatchment size and the spatial resolution of the model. The larger the subcatchment area, especially in the urban environment, the more spatial lumping that results, and the more abstracted from reality the model becomes. The size of the subcatchment and the heterogeneity among land covers and their organization within each subcatchment or subareas interact to effect model complexity as well as accuracy. In most cases, modelers try to strike a balance between these when configuring a SWMM project. Subareas are parameterized by setting values characteristic of each, such as *n* and *DS* for both IA and PA. The Green–Ampt option for infiltration modeling was used in this study, and this requires three parameters per subcatchment's PA including, the saturated hydraulic conductivity (K_{sat}), capillary suction head (*Suct*), and initial soil moisture deficit (*IMD*). Internal flow between the subareas can be routed from pervious to impervious, impervious to pervious, or directly to the outlet. LID areas have their own set of parameters.

The spatial database that included land cover digitization and HRE delineations was used to parameterize the SWMM model. ~~To reduce model complexity, the original 16 land cover types (mentioned in Sect. 2.2.2) were reduced to 10 by merging the paved walking paths, patios and miscellaneous impervious areas with other impervious areas, the dry ponds were merged with lawn areas, the detention area was merged with forest, and the surface areas for wet ponds and pools were modeled as IA without *DS*. The structures of the dry ponds, detention areas, and wet ponds were modeled as SWMM storage units. The final 10 land cover classifications used for the parameterization include: main buildings, miscellaneous buildings, streets, driveways, parking, sidewalks, other impervious areas, lawn, forest, and agriculture.~~ ~~This~~With the land cover data ~~was~~ spatially overlaid with ~~the data layer from~~ the HRE delineation in~~using~~ ArcGIS (Fig. 4)~~. With this overlay~~, the characteristics of each SWMM subcatchment could be defined using the detailed land cover status per subcatchment and unique hydrologic parameters per land cover component presented in Table 1~~2~~. Each land cover type is either all impervious or all pervious. "Length" represents a typical distance for overland flow before it turns into a concentrated flow path, which is controlled by the hydrologic design features of the land cover type. For example, overland flow at a rooftop is maintained only from the roof crest to the gutter because flow through a gutter is considered concentrated. The same regime change in flow (i.e., from overland flow to concentrated flow) may happen at any place where more than one instance of impervious land cover converge hydrologically, e.g., at a street gutter where overland flows from streets and driveways intersect. Using ArcGIS, the initial values for "Length" were determined by averaging multiple field measurements of perceived overland flow lengths for each land cover type. More detailed procedures for the SWMM modeling methods used in this study are presented in Appendix.

Table 1~~2~~. Initial and calibrated modeling parameters for the Shayler Crossing watershed.

~~2.5.2 Setting up the BPA~~

~~The baseline BPA (that controls runoff from ICIA) was modeled by parameterizing the subcatchment LID Controls of SWMM. The LID process 'vegetated swale' was selected among the LID control options in SWMM as the most appropriate option to~~

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represent the actual BPA. The BPA area estimated from the geoprocessing steps described above was added as well as values for the width, initial saturation, and % of subcatchment imperviousness draining to the BPA. The width was set to 18.3 m (60 feet), was equal across all subcatchments, and was based on the average linear footage of BPA around the existing ICIA from distance measurements made using the GIS on a number of common ICIA features in the watershed, e.g., driveways, sidewalks, and miscellaneous outbuildings. Individual BPAs within a subcatchment are assumed to be parallelly aggregated in setting-up the vegetated swale. The initial saturation was also equal across all subcatchments; set at 25 % (this value self–equilibrates after the model warm–up period, see Sect. 2.6). The berm height of the vegetated swale was set at 2.54 mm (0.1 inch) to minimize any storage effect within the berm, which is the case for real BPA, and vegetation volume fraction was set to be 0. The percentage of subcatchment imperviousness contributing to the BPA (i.e., the ICIA) is obtained by dividing the ICIA by the total IA. Since the total pervious area (TPA) remains identical for each HRE, the sizes of SPA for individual HREs can be determined as SPA = TPA – BPA for the three different sizes of BPA, which were derived by applying three different distances for the proximity analysis in GIS. When we calibrated the model, we checked which one, among the three cases of BPA sizes established above would calibrate the best for various storm sizes.

2.5.3 The groundwater component

Because the natural stream draining the study area receives lateral inflow through subsurface soil media (a.k.a., interflow), SWMM's groundwater modeling options were implemented. In SWMM groundwater flow is estimated by the following equation (Rossman, 2015):

$$Q_{gw} = A_1 (H_{gw} - H^*)^{B_1} - A_2 (H_{sw} - H^*)^{B_2} + A_3 H_{gw} H_{sw} \qquad (3)$$

Where, Q_{gw} = groundwater flow rate [L^3T^{-1}]; H_{gw} = height of saturated zone above the bottom of aquifer [L]; H_{sw} = height of surface water above the bottom of the aquifer [L]; H^* = threshold groundwater height [L]; and A_1, A_2, A_3, B_1, and B_2 = empirically derived coefficients.

The top of the saturated zone is placed somewhere between the soil surface and the bottom of the aquifer. The H^* is identical to the height of the streambed above the bottom of the aquifer (Rossman, 2015). No measurement data were available for relative elevations of the saturated zone or the bottom of the aquifer for the study area, but even with these values the groundwater parameterization in SWMM cannot be explicitly configured given the five coefficients that need specification (Eq. 3). Therefore, as is typical, we based the groundwater simulation on the elevation difference between individual subcatchment surface and its nearest stream bottom, which affects H_{gw}. Groundwater modeling parameters were defined using the SWMM Reference Manual (Rossman and Huber, 2016) and SWMM users' group knowledge base (e.g., https://www.openswmm.org/Topic/1465/groundwater-parameters; https://www.openswmm.org/Topic/4840/groundwater-values). As part of simulating soil moisture content, evaporation is modeled by localized average daily rates for individual months obtained from an existing report (NOAA, 1982). The rates were taken directly based on the location of the study site without adjustment. A depiction of the baseline SWMM project file with 191delineated subcatchments for the SHC watershed

~~is shown in Fig. 7. In order to import the GIS data for SHC, PCSWMM Professional (CHI, 2015) was used initially in this study because the current version of EPA SWMM does not have a GIS interface (Fig. 6).~~

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2.54 Model set–up options for a hypothetical HRE in SWMM

Commented [JGL4]: Followed by the 1st reviewer's suggestion, the order of the previous sections 2.4 and 2.5 are switched in the revised manuscript.

As mentioned earlier, an HRE can be modeled as a single subcatchment or multiple subcatchments in SWMM. In the SWMM model set-up just described we used a single subcatchment set-up that was based on the results of an analysis done with the goal of determining which among a series of plausible HRE configuration options strikes a balance among the degree of spatial and hydrologic aggregation, output uncertainty, and computational effort. The most spatially refined approach to a SWMM set–up (Option 1 in this study as presented below) would be to discretize every piece of impervious and pervious surface as an independent subcatchment. This promises a decrease in model output uncertainty (Krebs et al., 2014; Sun et al., 2014), but requires specifying all ~~of~~ the modeling parameters and unique flow directions among all subcatchments, results in longer computational times, and produces data management burdens that are typically not practical. The opposite extreme would be a highly generalized subcatchment characterization where the entire area is modeled as one subcatchment with just two subareas, lumping all ~~of~~ the spatial heterogeneity into a fictional space that has no basis in physical reality. Within this continuum, we chose to consider six plausible options for representing urban spatial constructs that are constrained by the SWMM subcatchment/subarea paradigm were examined (Fig. 5). As shown in the legend of Fig. 5, each rectangle represents a subcatchment in SWMM, and the dotted line divides subareas within the subcatchment. A rectangle without a dotted line means the subcatchment consists of a single (homogeneous) subarea, either 100% impervious or pervious. The arrows represent flow routing directions. Conducting this assessment at the watershed scale would not only be tedious and time consuming to configure, but could be inappropriate because of potentially confounding effects introduced when the drainage network and groundwater algorithm are included in the simulation. We felt it more rational to base our assessment of HRE set-up options at the scale of an HRE, i.e., the area that drains to a storm sewer inlet, and judge the results in comparison to the most spatially explicit option. Note, we do not have supporting observational data at this scale to prove this assumption. This would require flow data at the point of entry to a storm sewer inlet, which is very difficult to obtain in practice.~~The intention was to determine which among the plausible options strikes a balance among the degree of spatial and hydrologic aggregation, output uncertainty, and computational effort.~~

Instead~~ of conducting this analysis using the entire study watershed, which would be tedious and time consuming to configure~~, a hypothetical representationve of a typical urbanscape ~~drainage area~~ was defined as the HRE and used to model eight synthetic single storm events for each of the six set–up options (Fig. 5). The hypothetical HRE is meant to represent a typical 4041 m^2 (1 acre) residential area consisting of 809.4 m^2 (0.2 acre) DCIA, 1214.1 m^2 (0.3 acre) ICIA, and 2023.4 m^2 (0.5 acre) PA. The DCIA consists of 607.0 m^2 (0.15 acre) transportation–related surfaces (e.g., streets, driveways) and 202.3 m^2 (0.05 acre) building rooftops. The runoff from ICIA discharges through 404.7 m^2 (0.1 acre) BPA, thus the SPA of the area is 1618.7 m^2 (0.4 acre).

Figure 5. A conceptual representation of the hypothetical HRE (20% DCIA, 30% ICIA, 10% BPA and 40% SPA) and the 6 options considered for representing this area in the set–up of a SWMM model.

Referring to Fig. 5, in Option 1, five subcatchments are arranged for modeling the hypothetical HRE, separately modeling transportation DCIA (Trpt) and building DCIA (Bldg) along with ICIA, BPA, and SPA. DCIA is modeled with two sub–groups because buildings have slanted rooftops while paved areas for transportation are basically flat in a typical residential area. This is the lowest level of spatial aggregation among the six options. This option would result in the highest number of subcatchments, and, therefore, number of~~modeled~~ data requirements~~input/output for a given watershed area~~. Option 2 combines the two DCIA subcatchments in Option 1, resulting~~ed~~ in four subcatchments set–up for one~~the~~ HRE. In Option 3, the four subcachments in Option 2 are aggregated into two subcatchments, and each subcatchment is configured with two subareas~~ as shown in Fig. 5~~. The imperviousness and the flow direction between subareas per subcatchment need to be specified in SWMM with "% Imperv", "Subarea Routing", and "Percent Routed". "Impervious" option for "Subarea Routing" means runoff from pervious area flows to impervious area whereas "Pervious" does the opposite ~~direction~~ (Rossman, 2015). "Percent Routed" should be specified as 100 for both subcatchments. In Options 4 through 6, the areas are further aggregated to a single subcatchment representation for an HRE in SWMM~~–set–ups~~. Option 4 configures the single subcatchment with only two subareas, impervious and pervious areas. The runoff from pervious area discharges through impervious area ~~at the subcatchment~~ (i.e., TIA = DCIA). In Option 5, DCIA and ICIA are independently modeled by specifying the "Subarea Routing" option as "Pervious" and the "Percent Routed" as the ratio of ICIA/TIA. This option may be considered an unrealistic~~,~~ 'green' development condition where runoff from ICIA is evenly distributed throughout the entire pervious area, which means the entire pervious area works like a buffer (i.e., TPA = BPA). Finally, in Option 6, LID controls in SWMM are used for modeling BPA and ICIA. BPA is modeled as a vegetated swale with a very small berm height, 2.54–mm (0.1–inch). In the "LID Usage Editor", the "Area of Each Unit" specifies the size of BPA and the "% of Impervious Area Treated" is~~does~~ the fraction ~~of ICIA (i.e., % of~~ ICIA/TIA~~)~~. With this configuration, the ~~single subcatchment can configure the HRE with~~ four hydrologically homogenous subareas – DCIA, ICIA, BPA, and SPA – are accounted for.

Lengths for overland flow (or sheet flow) were assumed to be 4.57 m (15 feet), 9.14 m (30 feet), 12.19 m (40 feet), and 15.24 m (50 feet) for transportation related DCIA, building rooftops as DCIA, ICIA, and pervious area, respectively. The surface slopes of these were assumed to be 3 %, 11 %, 5 %, and 2 %, respectively. Surface dimensions and slopes of typical urban land cover components are based on construction codes or were inferred based on the GIS. The values selected are meant to represent typical residential areas in the Unitedd~~s~~ States. For example, the assumed values were derived using overland flow from the center of the street to the curb in a crowned 9.14 m (30 feet) wide neighbourhood street with 3 % cross–sectional slope for the crown, 18.29 m (60 feet) wide gable houses with 11 % cross–sectional slope for the rooftops, and pervious surfaces with 2 % slope on average. Every IA is modeled with 0.01 for Manning's roughness coefficient (*n)* and 2.54 mm (0.1 inch) for depression storage (*DS)*. Pervious area is modeled with 0.1 for *n* and 5.08 mm (0.2 inch) for *DS*. Identical infiltration parameters were applied to all the options. In this hypothetical HRE model set–up analysis, all of the six options were arranged using the same spatial and hydrologic characteristics. However, the ways DCIA, ICIA, BPA, and SPA were parametrized in SWMM were different among the options (Fig. 5).

Table 2~~1~~. Profile of the selected eight 24 h single storm statistics.

Rainfall–runoff response is also affected by storm size, so we applied eight different 24 h single storms (Table 2~~1~~) selected from a regional rainfall frequency report produced by the National Oceanic and Atmospheric Administration (NOAA) and the Illinois State Water Survey (Huff and Angel, 1992). Another data set was used to estimate the “Percentile” and “Cumulative” rainfall depths per year, i.e., annual statistics per 24 h storm. This data set covered about 35 years of hourly precipitation records from a local weather station in Milford, Ohio. A certain percentile rainfall event represents a precipitation amount that the same percent of all rainfall events for the period of record do not exceed (USEPA, 2009). The percentile values in Table 2~~1~~ were estimated using the method presented in the same report (USEPA, 2009). For example, the 90th percentile rainfall event is defined as the measured precipitation depth accumulated over a 24 h period for the period of record that ranks as the 90th percentile rainfall depth based on the range of all daily event occurrences during this period. Values in the “Cumulative” column of Table 2~~1~~ represent the percentage of annual cumulative precipitation depth, which are less than or equal to the specific rainfall depth during a 24 h period. In SWMM, the selected storms were distributed with 5 min intervals by applying the Natural Resources Conservation Service (NRCS) Type–II distribution (USDA, 1986).

2.6 ~~Model calibration~~Calibration of the SHC watershed SWMM model

Stream flows were measured at the outlet from a rating curve using water depth recorded at 10 min intervals. A tipping bucket rain gauge measured rainfall depths at 10 min intervals, with a minimum detectable rainfall depth of 0.254 mm (0.01 inch). The SWMM model for SHC (Fig. 6~~7~~) was run for a six–month period (01 April 2009 to 31 August 2009) where the first four months of this period were used to stabilize the continuous simulation, in particular for the groundwater simulation. This is defined as the model ‘warm–up’ period, which is the time period required to achieve a stable condition wherein the groundwater level ceases to increase or decrease by a specified initial parameter threshold value. After the warm–up period, the last two months, from July to August 2009, were used for model calibration. Model calibration was done manually by adjusting the initial values for the 10 land cover types, and using the different sets of BPA (see Fig. ~~6~~3.). Changes were integrated one at a time into every subcatchment using the area–weighting approach in an Excel spreadsheet. The calibrated modeling parameters for individual land cover types are given in Table 1~~2~~ alongside their initial values. An Excel worksheet was created with embedded look–up and averaging functions so that changes made to the original values in Table 1~~2~~ or switches between BPA sets configured using the different buffer distances could be easily propagated to changes in the related parameter values used in the SWMM model using the SWMM Excel Editor function. With this approach, the calibration effort is evenly applied to the urban land cover types, which in turn are propagated to the parameterization of all subcatchments, instead of calibrating parameters individually for each subcatchment. This methodology assumes that urban land cover components are generalizable, and independent from scale even though the subcatchments themselves are not generalizable or easily scalable. Also, notable about this approach, the parameter calibration domain remains the same even if the total number of subcatchments is increased and/or the size of watershed area is increased. If a land cover type does not maintain athe sufficient level of homogeneity across the watershed under study, we would need to divide the land cover into sub–categories and use more than one set of parameters for the land cover type in each category. For example, flat rooftops in commercial areas may need to be differentiated from slanted rooftops in residential areas, high and low sloped hillslope categories may need to be characterized in watersheds with a large range in topographic relief, or categories to account for different hydrologic soil types with different infiltration properties. This can be handled by spatial analysis in GIS by overlaying land use, topography, or soil property data with the land cover layer. On the other hand, urban sewer collection systems are zoned in a manner accounting for local variation in topography. Even land use generally follows topography, therefore, land cover is a reasonable surrogate.

Figure 67. Diagram of the developed SWMM model for the Shayler Crossing watershed.

Sensitivity analysis was conducted for the modeling parameters width, slope, *n* and *DS* for IA and PA respectively, K_{sat}, and the size of BPA. Each parameter was decreased and increased 5, 10, and 20 %, respectively, one at a time, and in separate model runs. The sensitivity of each parameter was estimated as:

$$Sensitivity = (\Delta MR/MR)/(\Delta p/p) \qquad (14)$$

Where, *MR* = modeling result in units of flow volume from the SWMM run; Δ*MR* = change in SWMM modeling result based on change in parameter value; *p* = parameter value; and Δ*p* = change in parameter value.

2.7 Modeling GI scenarios

GI scenarios are added to the model using the land cover database, soils, storm sewer systems, GIS techniques to derive relevant BPA, and may require some field investigation to ground truth the options. The general workflow for GI modeling are presented in bottom half of Fig. A-16, bottom diagram. Implementing GI can be achieved by adjusting the hydrologic properties of individual land cover components, such as converting lawn area to shrub or forest (Lee et al., 2005). This sort of GI implementation can reduce the volume, peak, and speed of surface runoff and be modeled by adjusting *DS*, slope, *n*, or overland flow length for the converted land cover component. The one scenario we examined specifically was to decreasinge DCIA by disconnecting the directly connected rooftop downspouts that directly routed flow from the main buildings to the sewer system. This effectively reclassifies main buildings as ICIA. After the downspouts are disconnected, the PA that receives stormwater runoff from the disconnected rooftop now works as additional BPA, and this additional buffering functionality acts as implemented GI in the subcatchment. To model this additional buffering capacity, the size of BPA is re–estimated and the percent of IA routed to BPA is changed in SWMM. The increase in size of the BPA under this GI scenario was estimated again by using the spatial analysis tools in ArcGIS spatial tools by changing the buffering distance value from the calibrated baseline value of 0.61 m (2 feet) to 3.1 m (10 feet) around ICIA, including the disconnected main buildings. As a result, the modeled

GI scenario includes two types model changes~~of GI implementations~~: One that reflects the ~~—~~downspout disconnection and another the buffering area extension.

The characteristic width per subcatchment is a computed value that is usually treated as a calibration parameter in SWMM (see Appendix~~Sect. 2.5.1~~). Under conventional stormwater management modeling approaches, once the width value is set, it is not adjusted during management scenario analysis. ~~This, h~~However, ~~is not the case for GI implementation.~~ GI, by design, changes the flow paths lengths and therefore the computed value of the "width" parameter as represented in SWMM should also change. The methodology we present here provides a systematic way of changing the width parameter in a rational and objective manner to account for the modeled GI scenario. Unfortunately~~However~~, the suitability~~accuracy~~ of this modeling approach cannot be determined until a high density of GI has been implemented at a watershed scale with before and after field observations.

2.8 Hydrograph separation

With the approach taken for the SWMM set–up for both the baseline and GI scenario analysis adjustments can be made to apportion the simulated storm hydrologic loading from the watershed among the dominant sources: DCIA, ICIA+BPA, SPA, and Subsurface ~~Inter~~flow. This can provide further insight into the effects of GI on watershed hydrology. For this purpose, the output from four SHC–SWMM runs were generated:

Run 1) Every subcatchment is specified as described under Option 6 (as conceptually represented in Fig. 7~~8~~a) with groundwater options parameterized to represent the base SWMM model.

Run 2) Groundwater options were excluded from the base model set–up to remove any subsurface flow contributions to the stream flow hydrographs. The difference between 1) and 2) represents the stormwater contributions to the stream as subsurface flow from the watershed.

Run 3) To estimate surface runoff from all impervious areas (i.e., runoff from DCIA, plus ICIA through BPA) in the models without the groundwater, the SPA was also omitted from every subcatchment (Fig. 7~~8~~b).

Run 4) To estimate surface runoff from DCIA, only DCIA was modeled in this run (Fig. 7~~8~~c).

An example result of the hydrograph flow pathway separation is presented in Fig. 7~~8~~d, and the process is summarized mathematically as follows:

$$Q_{total} = Q_{DCIA} + Q_{ICIA+BPA} + Q_{SPA} + Q_{interflow} \qquad (2\text{~~5~~})$$

$$Q_{surface} = Q_{DCIA} + Q_{ICIA+BPA} + Q_{SPA} \qquad (3\text{~~6~~})$$

$$Q_{interflow} = Q_{total} - Q_{surface} \qquad (4\text{~~7~~})$$

$$Q_{SPA} = Q_{surface} - Q_{imperv} \qquad (5\text{~~8~~})$$

$$Q_{ICIA+BPA} = Q_{imperv} - Q_{DCIA} \qquad (6\text{~~9~~})$$

Where, Q_{total} = total runoff with groundwater flow in SWMM; $Q_{surface}$ = surface runoff without groundwater flow; Q_{imperv} = runoff from impervious area (DCIA and ICIA through BPA); Q_{DCIA} = runoff from DCIA only; $Q_{ICIA+BPA}$ = runoff from ICIA and BPA; Q_{SPA} = runoff from SPA only; and $Q_{interflowsubsurface}$ = runoff through groundwater ~~inter~~flow (i.e., subsurface or lateral flow).

Figure 7~~8~~. Conceptual representations of discrete SWMM models for hydrograph separation.

3. Results and discussion

The SHC watershed model~~ed~~ parameter values pre– and post–calibration are presented in Table 1~~2~~.

3.1 Spatial analysis

Table 3 reveals the results of the detailed spatial analysis conducted using the described GIS techniques. The fractional DCIA for buildings, streets, driveways, parking areas, and sidewalks are 96.1 %, 79.5 %, 94.2 %, 42.8 %, and 14.2 %, respectively. Overall, the study watershed is covered by 18.8 % DCIA, and three sets of BPA were derived for 0.30, 0.61, and 1.52 m buffer lengths. After calibration, the 0.61 m buffer around ICIA was selected for SHC. This means that the runoff from ICIA is discharged to the adjacent ~~0.61 m of~~ pervious area with 0.61 m buffer width best mimicked hydrologic behaviour, based on runoff volume and timing in hydrographs (see Fig. 10 and Fig. 11). This existing buffer covers 22683.5 m^2 of pervious area, which is 2.3 % of the entire watershed and 3.0 % of the pervious area. As the baseline, the SHC watershed consists of 18.8 % DCIA, 5.2 % ICIA, 2.3 % BPA, 73.1 % SPA, and 0.6 % Water. Under the modeled GI scenario of disconnecting rooftop drains and extended BPA, the DCIA is reduced to 9.6 %, the ICIA increases to 14.4 %, the BPA increases to 17.2 %, and the SPA is reduced to 58.2 % of the total area, respectively.

Table 3. Land cover status of Shayler Crossing watershed.

3.2 The hypothetical HRE modeling analysis

The eight single storm–hypothetical HRE modeling analysis with the six discretization options resulted in 48 SWMM runs. As explained earlier, this was done to determine which HRE configuration option best balances model complexity and presumed accuracy. Each simulated storm was assumed to last from midnight to midnight. Results are presented as hydrographs between 11:00 and 13:00 hours where most concentrated rainfall occurs in the NRCS–Type II distribution (USDA, 1986) (Fig. 8~~9~~). In large storms, larger than a 5 yr storm in particular, all six types of spatial discretization produce very similar hydrographs as shown in (g) and (h) of Fig. 8~~9~~. The modeled flow rates and total runoff volumes are almost identical.

Figure 8~~9~~. Hypothetical HRE SWMM modeling results

In the large storm situation, all of the PAs are saturated in the early stage of the storm. Once saturated, the PAs are not able to provide any additional onsite hydrologic control, and behave as IA. In view of this, any of the spatial discretization options would be suitable for analyzing flood controls and in designing a drainage system based on a 10 yr storm. However, this is not the relevant case for evaluating GI implementation, which focuses on controlling smaller storms. For storms smaller than a 2 yr event, considerable differences were found among the simulated hydrographs (Fig. 8~~9~~a through e).

In the smallest storm situation (Fig. 8~~9~~a) the options for spatial discretization result in almost identical hydrographs except Option 4, where only DCIA discharges runoff, as TIA is modeled as DCIA. Rainfall onto PA is completely captured by *DS* and/or infiltrated to the soils. Because Option 4 ignores the difference between DCIA and ICIA, the entire impervious area (subarea IA) is ~~actually~~ modeled the same as DCIA, which means all of the runoff is discharged to the storm drainage system directly with no abatement. Under a small storm (like < 1 month storm), runoff occurs only from IA, more specifically, only from DCIA. For small storms, runoff from ICIA is completely controlled by BPA (if ICIA exists), but no ICIA is modeled under Option 4. Because of this, modeled runoff from this option is higher than any of the other options under the small storms. DCIA is modeled explicitly in the other five options. The relative difference~~inaccuracy~~ in runoff estimates caused by modeling TIA as DCIA contribution diminished as larger storms are modeled, Fig. 8~~9~~a to c. Option 4 is not suitable to modeling GI alternatives because it ignores the significance of characterizing DCIA and ICIA within an HRE. Option 5 shows the most significant variation among the simulated hydrographs. This option estimates lower flow rates than the others for smaller storms, but higher peaks in medium–size storms (as 6 month to 2 yr return period storms; Fig. 8~~9~~d through f). Option 5 is configured to simulate the "ideal" green implementation scenario of surface grading for stormwater discharge, in which the entire pervious area works like BPA. The expanded onsite pervious buffer can thoroughly control runoff from ICIA until the *DS* and infiltration capacity of BPA are fully saturated. Once the hydrologic capacities for onsite controls are fully saturated, the entire PA hydrologically responds more or less like IA. Once a subcatchment *DS* fills and exceeds infiltration capacity, this unrealistic 'green' development condition~~the "ideal" green implementation scenario~~ may result in higher peak discharges than the other options.

From th~~eis~~ hypothetical modeling analysis, it can be surmised that an extensive onsite green infrastructure implementation could result in more frequent local flooding, e.g., water intrusion into basements. This may be especially the case when evaluating scenarios for locations where medium–size storms have a long duration, like during the wet season of the Pacific Northwest of the United States. The comparatively high runoff estimated for Option 5 (Fig. 8~~9~~d through f) would be maintained until all PA is saturated by increased rainfall intensity. If a smaller portion of PA is modeled as BPA, while all the other conditions are kept the same, the BPA reaches the saturated condition under a smaller storm. Once the BPA is saturated the area hydrologically responds like IA. However, SPA (i.e., non–buffering pervious area) can still control rainfall within the area. This analysis suggests that it is important to properly~~accurately~~ define the area of BPA especially when analyzing GI alternatives for onsite stormwater controls, as we surmised originally. Therefore, Option 5 is not suitable for modeling a GI scenario because it ignores the actual significance of variance in BPA~~, which controls runoff from ICIA within a subcatchment~~. ~~In common SWMM modeling,~~It is a common modeling practice in SWMM to treat all pervious area ~~is treated~~ the same (as in

Options 4 or 5 in Fig. 5), even though only the BPA can receive water from ICIA. As shown in Fig. 8~~9~~, simulated runoff by Options 4 or 5 would presumably be inaccurate, especially for the <1 year small storms.

Figure 9~~10~~ contains graphs ~~depicting another way of~~ comparing the results among the six options (Fig. 5), showing the relative difference for peak flow, average flow, and total runoff volume for each of the five other Options compared to Option 1, presumably the most accurate one, in terms of output uncertainty~~. Modeling results from Option 1, with five subcatchments discretization is the most accurate~~ because the level of spatial lumping is the lowest.~~ However, that approach also leads to the largest number of calibration parameters, and, therefore, is not easily scalable, but serves as a benchmark for comparing results from the other five options.~~

Figure 9~~10~~. Comparison of the hypothetical HRE modeling results.

The relative differences reported in Fig. 9~~10~~ ('Variation from the result of 5-subs' in Y-axis) were estimated as $(MR_j^k - MR_{5subs}^k)/MR_{5subs}^k$, where MR_j^k represents a modeling result from the k^{th} synthetic storm with the j^{th} discretization option and 5*subs* means the discretization with five subcatments (i.e., Option 6). Options 1, 2, and 3 types of multi–subcatchment discretization present similar hydrologic responses for all storm sizes. In comparison, both Options 4 and 5 result in significantly different hydrologic outcomes, particularly for smaller storms. Again, this is due to the unresolved spatial delineation of DCIA from TIA, and BPA from TPA, respectively. Whereas Option 6 is based on a single–subcatchment approach, but produces similar results to the multi–subcatchment discretization approaches under Options 1, 2 and 3, for all storm classes tested. The difference between Option 6 and Option 1, though worth noting, are marginal for the three important hydrologic characteristics (Fig. 9~~10~~). This ~~modeling~~ outcome of the hypothetical analysis~~again~~ supports our original rationale for the relevance of characterizing the BPA. Under Option 6, the four critical hydrologic components (i.e., DCIA, ICIA, BPA, and SPA) are distinctly modeled in SWMM within a single–subcatchment that is delineated based on the actual drainage area to a storm sewer inlet (termed an HRE in this study). Based on the results, Option 6 balances the combination of discretization criteria, especially in terms of the level of effort required in model set–up, configuring parameter values and output uncertainty.~~in tracking the relative accuracy of the modeling results.~~

3.3 SHC watershed-scale modeling results

Option 6 (Fig. 5) was used to set up the SWMM model for the SHC watershed as described above. The SHC model consists of 191 subcatchments and 269 junctions and conduits (Fig. 6~~7~~). The model also includes two wet ponds, two dry ponds, and a 10 yr detention area modeled as storage structures with orifice–type hydrologic controls. The results of the model sensitivity analysis were summarized for the period 22 to 24 July 2009, using the total runoff volume as the endpoint being assessed with Eq. (2~~4~~) (Fig. 10~~9~~). There was a total of 164.6 mm rainfall during the three days of this period; this storm is smaller than the 1 yr return period design storm (61.0 mm/d) but larger than the 6 month storm (48.3 mm/d) based on the storm statistics for the study area (see Table 2~~1~~). While 3% change in total runoff is not significant in sensitivity, ~~T~~the most sensitive parameter was K_{sat}, followed by BPA and *DS*. Whereas the changes in K_{sat} affect the entire PA (75.4 % of SHC), the changes in BPA affect a much smaller area (2.3 % of SHC for the baseline condition) than PA. The other parameters (i.e., width, slope, and n) were found not to be as sensitive, with negligible changes in results ≤ ±0.15 % even for ±20 % change in the individual parameter value. When land cover status is represented accurately in a SWMM model, certain parameters will be less sensitive because of the underlying hydraulic and spatial realities are well represented. For example, the parameters representing the impervious land cover types in this modeling analysis were found to be less sensitive than pervious area parameters.

Figure 10~~1~~. Sensitivity analysis of the SWMM parameters at SHC.

Model calibration was conducted by adjusting the land cover–based modeling parameters and BPA to the entire study watershed. As shown in Table 1~~2~~, parameters for the impervious land cover types changed little and were made equivalent for *n* and *DS*. As expected, parameters for the pervious land cover types needed more adjustment than those for the impervious. The initial value of K_{sat} was defined using the site–specific soil types (mainly silty loam clay), but the values for the individual pervious land cover types were varied by the model calibration effort. Whereas K_{sat} for forest area was adjusted only slightly (i.e., 1.6 initially to 1.52 for the final calibration), the values for lawn (or landscaped area) and agriculture required more~~a higher degree of~~ adjustment (from 1.6 initial to 1.02 for agriculture, and from 1.6 initial to 0.89 for lawns). The relatively large changes for K_{sat} are indicative of more~~a higher degree of~~ soil compaction for urban and agricultural soils compared to the expected native soil condition.

The measured rainfall intensities and stream flow rates, along with the calibrated model results are presented in Fig. 11~~2~~. The modeled hydrographs are well matched with the measured data at the watershed scale with a Nash–Sutcliffe coefficient = 0.852 and R^2 = 0.871.

Figure 11~~2~~. Watershed-scale SWMM modeling results from 1 July 2009 to 31 August 2009.

After making the model adjustments for the GI scenario, the relative percentages of the four classified subareas changed (Fig. 12~~3~~a). Using the hydrograph separation approach, the relative contribution of the primary hydrologic components with and without GI implementation were estimated for the period 1 July 2009 to 31 August 2009 (Fig. 12~~3~~b). A more detailed representation for the hydrograph separation is presented in Fig. 13~~4~~, which covers 72 hours from 22 to 24 July 2009. ~~During this period, there was a total of 164.6 mm rainfall.~~ It is interesting to note from Fig. 13~~4~~ that the peak flow for the event depicted in the figure is slightly higher in the GI scenario, but that the duration of flows slightly smaller than this peak is longer in the baseline scenario.

Figure 12~~3~~. Relative percentages of land cover and hydrologic components computed for the period 1 July 2009 to 31August 2009. In (b) "Others" represents surface runoff from areas other than DCIA, "Subsurface ~~Inter~~flow" is the subsurface contribution, and "Loss" is rainfall loss by evaporation or deep percolation.

Figure 13~~4~~. Hydrograph separation and volumetric percentages contributing to stream flow for the period 22 to 24 July 2009.

While the~~Validation of the modeling~~ results from applying the hydrograph separation cannot be validated without~~would require~~ extensive field measurements, ~~but~~ the exercise provides insight to the potential effectiveness and rationale for developing strategies for GI in the watershed. For instance, about 48 % of the volumetric stream flow was contributed through subsurface ~~inter~~flow over the simulation period, even though the study watershed is characterized with poorly infiltrating soils. After applying the GI scenario, although the subsurface ~~inter~~flow contributed a similar fraction to the stream flow, the fractional contributions of surface runoff from DCIA and the other areas are significantly changed (Fig. 12~~2~~b and 13~~3~~). This situation arises not from a change in land cover but the internal flow paths taken by the runoff. The result is reduced runoff from DCIA but increased runoff from the other areas (i.e., ICIA, BPA, and SPA).

From a water quality management perspective, it is necessary to consider hydrologic and contaminant discharge processes with respect to their sources and transport pathways. For example, if the watershed has water quality issues related to nutrients, the management effort might pay more attention to the stormwater discharge from pervious areas that include fertilizer applications. If GI were designed to intercept runoff from DCIA in the watershed, an unintended consequence could result from increased runoff volume traveling through a pervious area with elevated standing stocks of soluble or erodible nutrients. In this case, it would be important to consider turf management practices.

Another example of how the hydrograph separation approach (Fig. 13~~4~~) provides additional opportunities for interpreting hydrodynamics before and after applying the GI scenario is revealed by considering that disconnecting downspouts reduced the total runoff volume, but also resulted in a higher peak flow (note the 16:00 time point on 22 July 2009 in Fig. 13~~4~~). This result is like~~similar to~~ the single storm analysis using Option 5 (Fig. 5). Overall the flow volume is reduced from the GI scenario. However, when the peak occurred around 15:30 (shown in Fig. 13~~4~~) the capacity of the GI for controlling stormwater was already exceeded because of controlling runoff during the previous rainfall that occurred between 7:00 and 14:00. Under this saturated condition, even the direct rainfall to the GI area will be discharged with minimum abatement. If there is no GI (as in the baseline condition), the same area receives only direct rainfall, there is no additional run on from impervious area, and that rainfall is controlled by still available surface depression storage and not–saturated infiltration capacity. In the 22 July 2009 situation, the stormwater control capacity (mainly *DS* and infiltration) of the extended BPA is saturated by earlier rainfall. Once saturated the BPA discharges higher runoff. The modeled GI contributes much higher runoff volume from PA, which might be nutrient enriched. With the hydrograph separation analysis, we gain insight to the consideration of stormwater management objectives and extend the utility of SWMM.

4. Summary and ~~C~~conclusions

We demonstrate how high resolution spatial data can be applied to spatially discretize a watershed and develop a methodology that should decrease model output uncertainty with reduced calibration effort. The suitability of the spatial discretization approach for GI modelling was initially verified with a hypothetical urbanscape analysis using eight synthetic storms of various sizes. We evaluated our approach to SWMM subcatchment parameterization using the hypothetical analysis that allowed for the qualification of five different options relative to one that would be considered the most spatially explicit, and, therefore, result in the least amount of output uncertainty (see Fig 9). From the hypothetical analysis, the best option was selected to develop a watershed-scale SWMM model at the study area. The simulated hydrographs by the developed watershed-scale SWMM model were well matched with observed data over a two month continuous simulation (Nash–Sutcliffe coefficient = 0.852; R^2 = 0.871) after minimal calibration effort. A GI scenario that modeled downspout disconnection from all the main buildings that are DCIA was described. We demonstrate how simple model adjustments can be made to separate the total and surface runoff among primary pathways that runoff takes before discharging to the natural stream network. This hydrograph separation procedure can shed light on GI design requirements and water quality management.

~~During the process of simulating the spatial representation of reality in SWMM, it is important to~~ The optimal spatial discretization scheme distinguishes DCIA from ICIA, and BPA from SPA, and explicitly models these as subareas within each subcatchment parameterization in SWMM. This approach is particularly useful when modeling the impact of small storms, i.e., when BPA can control all or most of ICIA runoff. The land cover based spatial discretization approach is scale–independent, can be applied directly to a larger watershed as long as any heterogeneity in landscape properties is accounted for in the GIS set–up (e.g.~~i.e.~~, by dividing land cover components into multiple sub–groups such as flat and slanted rooftops, high and low sloped urban hillslopes, or B and C type hydrologic soil types~~, for example~~), and affords the opportunity to evaluate urban stormwater management strategies with presumably decreased output uncertainty~~improved accuracy~~ for small storms and expanded applicability to GI planning, design, and implementation. Parameters are adjusted per SWMM subcatchment in a typical calibration approach, which is scale–dependent and requires more effort in larger watersheds. In our approach, a SWMM model is calibrated by adjusting parameters per land cover component, which are categorized by urban development codes or general construction specifications for land uses. Overall this study demonstrates the relative effectiveness of different approaches in drainage area characterization using highly resolved spatial data to the set–up and analysis of a SWMM model that should improve its utility for simulation of GI.

~~The suitability of the spatial discretization approach was verified with eight synthetic storms of various sizes. In the SHC watershed, the modeled hydrographs matched observed data over a two month continuous simulation (Nash Sutcliffe coefficient = 0.852; R^2 = 0.871). A GI scenario that modeled downspout disconnection from all the main buildings that are DCIA was described. We demonstrate how simple model adjustments can be made to separate the total and surface runoff volume among primary pathways that runoff takes before discharging to the natural stream network. This hydrograph separation procedure can shed light on GI design requirements and water quality management.~~

List of Abbreviations

A_1, A_2, and A_3	Empirically derived coefficients
ASCE	American Society of Civil Engineers

B_1 and B_2	Empirically derived coefficients
Bldg	Building
BPA	Buffering pervious area that receives and controls runoff from impervious area
CHI	Computational Hydraulics Int.
DCIA	Directly connected impervious area
DS	Depression storage
DS_imp	Depression storage for impervious area
EFW	East Fork (of the Little Miami River) watershed
ESRI	Environmental Systems Research Institute
GI	Green infrastructure
GIS	Geographic Information System
H^*	Threshold groundwater height
H_{gw}	Height of saturated zone above the bottom of aquifer
H_{sw}	Height of surface water above the bottom of the aquifer
IA	Impervious area
ICIA	Indirectly connected impervious area
IMD	Initial (soil) moisture deficit
K_{sat}	Saturated hydraulic conductivity
LID	Low impact development
LiDAR	Light Detection and Ranging
MR	Modeling result
ΔMR	Change in modeling result based on change in parameter value
n	Manning's roughness coefficient
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NSE	Nash–Sutcliffe coefficient
p	Parameter value
Δp	Change in parameter value
PA	Pervious area
Q_{DCIA}	Runoff from DCIA only
Q_{gw}	Groundwater Flow Rate
$Q_{ICIA+BPA}$	Runoff from ICIA and BPA
Q_{imperv}	Runoff from impervious area (DCIA and ICIA through BPA)

$Q_{interflow\,subsurface}$	Runoff through groundwater ~~inter~~flow (i.e., subsurface or lateral flow)
Q_{SPA}	Runoff from SPA only
$Q_{surface}$	Surface runoff without groundwater flow
Q_{total}	Total runoff with groundwater flow in SWMM
R^2	Coefficient of determination
SHC	Shayler Crossing Watershed
Suct	Capillary Suction Head
SPA	Standalone pervious area that does not receive or control any impervious area runoff
SWMM	Storm Water Management Model
TPA	Total pervious area
TIA	Total impervious area
Trpt	Transport
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
WEF	Water Environment Federation

Disclaimer

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded, managed, and collaborated in the research described herein. It has been subjected to the Agency's administrative review and has been approved for external publication. Any opinions expressed in this paper are those of the author(s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Acknowledgments

The authors would like to thank Mr. Bill Mellman of Clermont County; Mr. Paul Weaver of APTIM; and Dr. Michael Tryby, Dr. Michael Elovitz, and Dr. William Shuster of USEPA. They provided critical data, suggestions, or critical reviews.

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Appendix. Miscellaneous procedures for SWMM modeling for GI analysis

For a full description of the steps used to set-up a SWMM model for GI analysis using the methods outlined here see Lee et al 2017 that is available for free download from the USEPA at: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100TJ39.PDF?Dockey=P100TJ39.PDF. The procedure for developing the baseline model is schematically diagrammed in Fig. A-1. To reduce model complexity, the original 16 land cover types (mentioned in Sect. 2.2.2) were reduced to 10 by merging the paved walking paths, patios and miscellaneous impervious areas with other impervious areas, the dry ponds were merged with lawn areas, the detention area was merged with forest, and the surface areas for wet ponds and pools were modeled as IA without *DS*. The structures of the dry ponds, detention areas, and wet ponds were modeled as SWMM storage units. The final 10 land cover classifications include: main buildings, miscellaneous buildings, streets, driveways, parking, sidewalks, other impervious areas, lawn, forest, and agriculture.

Commented [JGL5]: Details on the methods are re-located under this Appendix. The contents of Appendix are not completely presented in the EPA report (Lee et al., 2017).

A.1 Determining values for SWMM subcatchment parameters: Area-weighting approach

Unique values for representing the corresponding area, width, slope, imperviousness, *n*, *DS*, and infiltration parameters (K_{sat}, *Suct*, and *IMD* for the Green–Ampt) were defined per SWMM subcatchment using GIS and a spreadsheet.

Figure A-1. Procedures for SWMM modeling for GI analysis. LC stands for land cover. Conceptual workflow for each of the colored boxes is given in the middle of the diagram. Symbols (⬢ ⊙ ◆ □ ◇) are used to label workflow connections within the colored boxes. Top panel depicts the general steps used for baseline model set–up, while the bottom panel adds GI considerations. "Acceptable?" means whether the statistical significance between the modeled and the observed hydrographs (e.g., Nash–Sutcliffe coefficient or R^2) is 'acceptable'. "Satisfied?" means whether the modeling results are 'satisfied' with the GI requirements.

The area of each land cover type within a subcatchment was estimated using ArcGIS. The SWMM parameter 'characteristic width' was estimated using an area–weighted flow length, as recommended in the SWMM Applications Manual (Gironás et al., 2009). This manual suggests "If the overland flow length varies greatly within the subcatchment, then an area–weighted average should be used." Comparatively, in conventional SWMM modeling, the 'characteristic width' is computed by dividing the subcatchment area by the average maximum overland flow length. Then adjustments are made to the characteristic width during model calibration to produce the best fit to the measured runoff hydrographs. The following area–weighting calculation describes how the characteristic width for a SWMM subcatchment was estimated in this study, where *i* represents all the individual land cover types within the subcatchment:

$$Length = \sum(Length_i \, Area_i) \,/\, \sum(Area_i) \qquad \text{(A-1)}$$

$$Width = \sum(Area_i) \,/\, Length \qquad \text{(A-2)}$$

Other parameters were also defined as area–weighted averages per subcatchment (e.g., slope and infiltration parameters) or subarea (e.g., *n* and *DS*). This area–weighting step is used following the typical approach recommended to account for the spatial lumping that effectively averages patchy land cover types within SWMM subcatchments (Gironás et al., 2009; Rossman and Huber, 2016). Hence, the extent of each individual type of land cover in a subcatchment is used to area–weight the assigned parameter values. For example, if IA within a subcatchment consists of two building rooftops, two driveways, and one section of street, the associated IA in SWMM is assigned values for *DS* based on an area–weighted average using the corresponding nominal values presented in Table 1~~2~~, $[DS\_imp = \sum(DS_i\, A_i) \,/\, \sum(A_i)]$, where *DS_imp* is the assigned *DS* for the impervious subarea within the subcatchment, *A* is the size of an individual impervious land cover type within the subcatchment, and *i* is an individual land cover type. Calculations for area–weighting were all done in a Microsoft Excel ~~(MS Excel)~~ spreadsheet that was configured for direct copy and pasting as the SWMM input file using the EPA–SWMM Excel Editor function (See Lee et al., 2017 for specifics and Fig. A-1). Two sets of *n* and *DS* were defined per SWMM subcatchment – one set for the impervious subarea and the other for the pervious subarea. Where available, relevant values were obtained from experience in the watershed or using GIS (e.g., overland flow length), or as suggested by the SWMM manual (Huber and Dickinson, 1988; Rossman, 2015). The SHC watershed has silty loamy clay soils throughout. Based on this soil type, *Suct* was set to be 165 mm using the SWMM User's Manual (Rossman, 2015). *IMD* was modeled using the default value (0.22) in the EPA–SWMM. The actual *IMD* is dynamically updated at every modeling time step. The developed SWMM model runs for a six–month period where the first four months of this period are used to stabilize the continuous simulation (i.e., the warm–up period). Hence, the *IMD* value when modeling results are first reported may not reflect the initial value assigned during model setup. The values for K_{sat} were amended during the model calibration to comprise surface compaction in lawn, agricultural, and forest areas (Horton et al., 1994; Gregory et al., 2006). However, we did not try to change the values of *Suct* and *IMD* during the calibration. Although the status and spatial extent of each land cover type within each HRE are different, the parameter values were assigned independent of the HRE in which it resided (Table 1~~2~~). This parameter assignment methodology at the level of land cover components reduces model complexity by minimizing the amount of subcatchment specific parameterizations that may need to be considered during calibration.

A.2 Setting up the BPA

The baseline BPA (that controls runoff from ICIA) was modeled by parameterizing the subcatchment LID controls of SWMM. The LID process 'vegetated swale' was selected among the LID control options in SWMM as the most appropriate option to represent the actual BPA. The BPA area estimated from the geoprocessing steps described above was added as well as values for the width, initial saturation, and % of subcatchment imperviousness draining to the BPA. The width was set to 18.3 m (60 feet), was equal across all subcatchments, and was based on the average linear footage of BPA around the existing ICIA from distance measurements made using the GIS on a number of common ICIA features in the watershed, e.g., driveways, sidewalks, and miscellaneous outbuildings. Individual BPAs within a subcatchment are assumed to be parallelly aggregated in setting-up the vegetated swale. The initial saturation was also equal across all subcatchments; set at 25 % (this value self–equilibrates after the model warm–up period, see Sect. 2.6). The berm height of the vegetated swale was set at 2.54 mm (0.1 inch) to minimize any storage effect within the berm, which is the case for real BPA, and vegetation volume fraction was set to be 0. The percentage of subcatchment imperviousness contributing to the BPA (i.e., the ICIA) is obtained by dividing the ICIA by the total IA. Since the total pervious area (TPA) remains identical for each HRE, the sizes of SPA for individual HREs can be determined as SPA = TPA – BPA for the three different sizes of BPA, which were derived by applying three different distances for the proximity analysis in GIS. When we calibrated the model, we checked which one, among the three cases of BPA sizes established above would calibrate the best for various storm sizes.

A.3 The groundwater component

In SWMM groundwater flow is estimated by the following equation (Rossman, 2015):

$$Q_{gw} = A_1(H_{gw} - H^*)^{B_1} - A_2(H_{sw} - H^*)^{B_2} + A_3 H_{gw} H_{sw} \quad \text{(A-3)}$$

Where, Q_{gw} = groundwater flow rate [L^3T^{-1}]; H_{gw} = height of saturated zone above the bottom of aquifer [L]; H_{sw} = height of surface water above the bottom of the aquifer [L]; H^* = threshold groundwater height [L]; and A_1, A_2, A_3, B_1, and B_2 = empirically derived coefficients.

The top of the saturated zone is placed somewhere between the soil surface and the bottom of the aquifer. The H^* is identical to the height of the streambed above the bottom of the aquifer (Rossman, 2015). No measurement data were available for relative elevations of the saturated zone or the bottom of the aquifer for the study area, but even with these values the groundwater parameterization in SWMM cannot be explicitly configured given the five coefficients that need specification (Eq. 1). Therefore, as is typical, we based the groundwater simulation on the elevation difference between individual subcatchment surface and its nearest stream bottom, which affects H_{gw}. Groundwater modeling parameters were defined using the SWMM Reference Manual (Rossman and Huber, 2016) and SWMM users' group knowledge base (e.g., https://www.openswmm.org/Topic/1465/groundwater-parameters; https://www.openswmm.org/Topic/4840/groundwater-values). As part of simulating soil moisture content, evaporation is modeled by localized average daily rates for individual months obtained from an existing report (NOAA, 1982). The rates were taken directly based on the location of the study site without adjustment.

Table 12. Initial and calibrated modeling parameters for the Shayler Crossing watershed.

Land Cover	Length (m)		Slope (%)		*n*		*DS* (mm)		K_{sat} (mm/hr)	
	Initial	Calibrated	Initial	Calibrated	Initial	Calibrated	Initial	Calibrated	Initial	Calibrated
Main Building	9.1	7.6	10	15	0.014	0.01	2.0	1.3	n/a	n/a
Misc. Building	4.6	4.6	10	15	0.014	0.01	2.0	1.3	n/a	n/a
Street	3.0	3.0	2	2.5	0.011	0.01	2.5	1.3	n/a	n/a
Driveway	4.6	3.7	2	1.5	0.012	0.01	2.5	1.3	n/a	n/a
Parking	3.0	3.0	1	1.5	0.012	0.01	3.0	1.3	n/a	n/a
Sidewalk	0.9	0.9	1	1.5	0.012	0.01	3.0	1.3	n/a	n/a
Other Impervious	3.0	2.4	1	1.5	0.012	0.01	3.0	1.3	n/a	n/a
Lawn	24.4	24.4	2	2	0.2	0.3	5.1	5.1	1.6	0.89
Forest	24.4	24.4	3	2	0.6	0.6	10.2	7.6	1.6	1.52
Agriculture	30.5	30.5	2	2	0.3	0.3	7.6	5.1	1.6	1.02

Table 21. Profile of the selected eight 24 h single storm statistics.

Rain (mm)	Frequency	Percentile	Cumulative
12.7	< 1 month	64.8 %	32.7 %
25.4	1–2 months	87.4 %	63.1 %
36.8	3 months	95.0 %	80.7 %
48.3	6 months	97.7 %	89.2 %
61	1 year	99.2 %	95.3 %
73.7	2 years	99.6 %	97.3 %
108	10 years	100 %	99.8 %
149.8	50 years	100 %	100 %

Note: The Percentile and Cumulative, percentage-based statistics qualify the exceedance probability of each event and the relative contribution of events of similar size or lower to the annual rainfall, respectively.

Table 3. Land cover status of Shayler Crossing watershed.

Surface Components		DCIA (m^2)	ICIA (m^2)	Sum (m^2)	Fraction
Impervious areas	Building	91770.0	3756.2	95526.2	9.6 %
	Street	57610.5	14897.2	72507.7	7.3 %
	Driveway	33554.7	2083.7	35638.4	3.6 %
	Parking	2362.7	3154.1	5516.8	0.6 %
	Sidewalk	1646.9	9990.3	11637.2	1.2 %
	Miscellaneous	–	17766.8	17766.8	1.8 %
	Sum of IA	186944.7	51648.4	238593.1	24.0 %
Pervious areas	Lawn			400667.4	40.3 %
	Agriculture			219430.4	22.1 %
	Forest			128558.1	12.9 %
	Sum of PA			748655.9	75.4 %
Water	Wet pond			5014.2	0.5 %
	Swimming pool			998.9	0.1 %
	Sum of Water			6013.0	0.6 %
Sum				993262.0	100 %

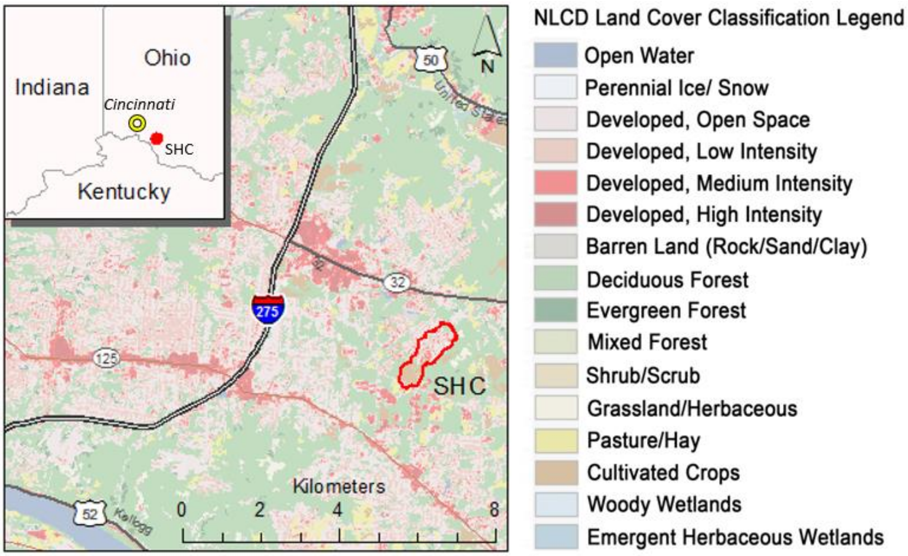
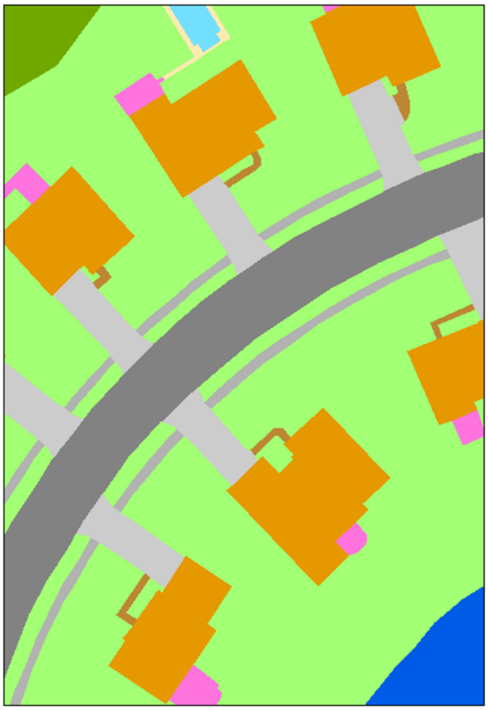


Figure 1. Location of the Shayler Crossing watershed. **I-275 is an interstate highway around the Cincinnati metropolitan area.**



ID	LandCover	Baseline	GI	A (m2)
...	...	...	...	...
618	Driveway	DCIA	DCIA	42.2
36	Main_Bldg	DCIA	ICIA	287.3
811	Street	DCIA	DCIA	945.2
633	Landscaped	PA	PA	310.1
88	Main_Bldg	DCIA	ICIA	223.7
983	Wet Pond	Water	Water	4362.6
74	Driveway	DCIA	DCIA	38.2
946	Patio	ICIA	ICIA	53.9
427	Main_Bldg	DCIA	ICIA	232.9
586	Sidewalk	DCIA	DCIA	16.5
799	Forest	PA	PA	1426.3
...	...	...	...	...

(Note: The data table in this figure does not show the entire records of the database.)

Figure 2. Sample GIS classified representation of the land cover and hydrologic characteristics.

Figure 3. Depiction of the different distances applied for the estimation of BPA in the baseline condition using ArcGIS.

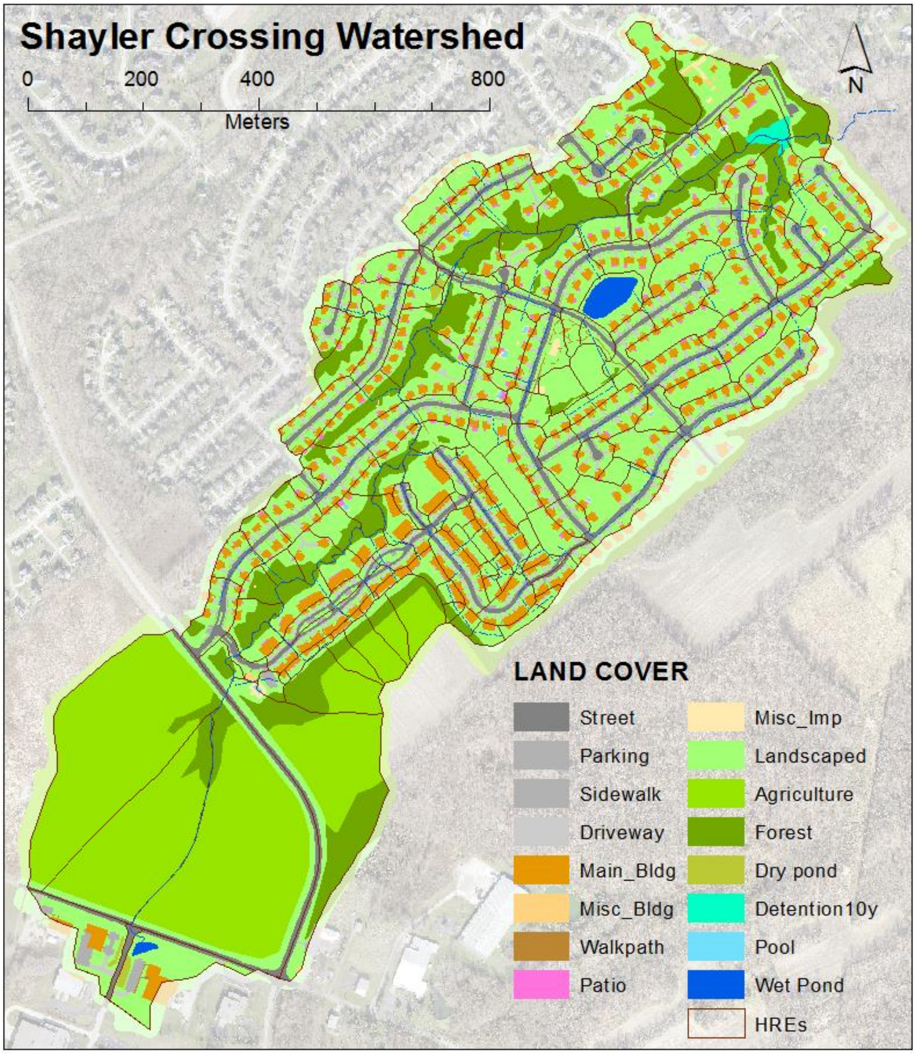


Figure 4. Detailed spatial representation of the Shayler Crossing watershed.

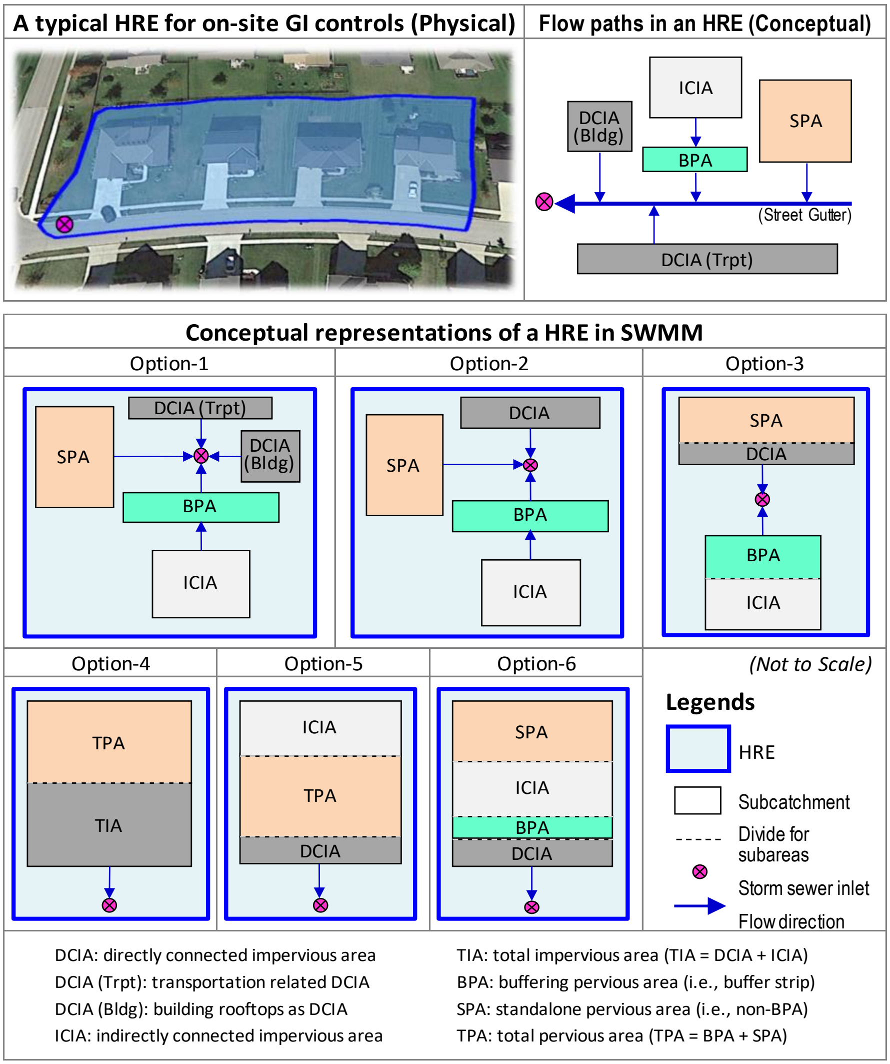


Figure 5. A conceptual representation of the hypothetical HRE (20% DCIA, 30% ICIA, 10% BPA and 40% SPA) and the 6 options considered for representing this area in the set–up of a SWMM model.

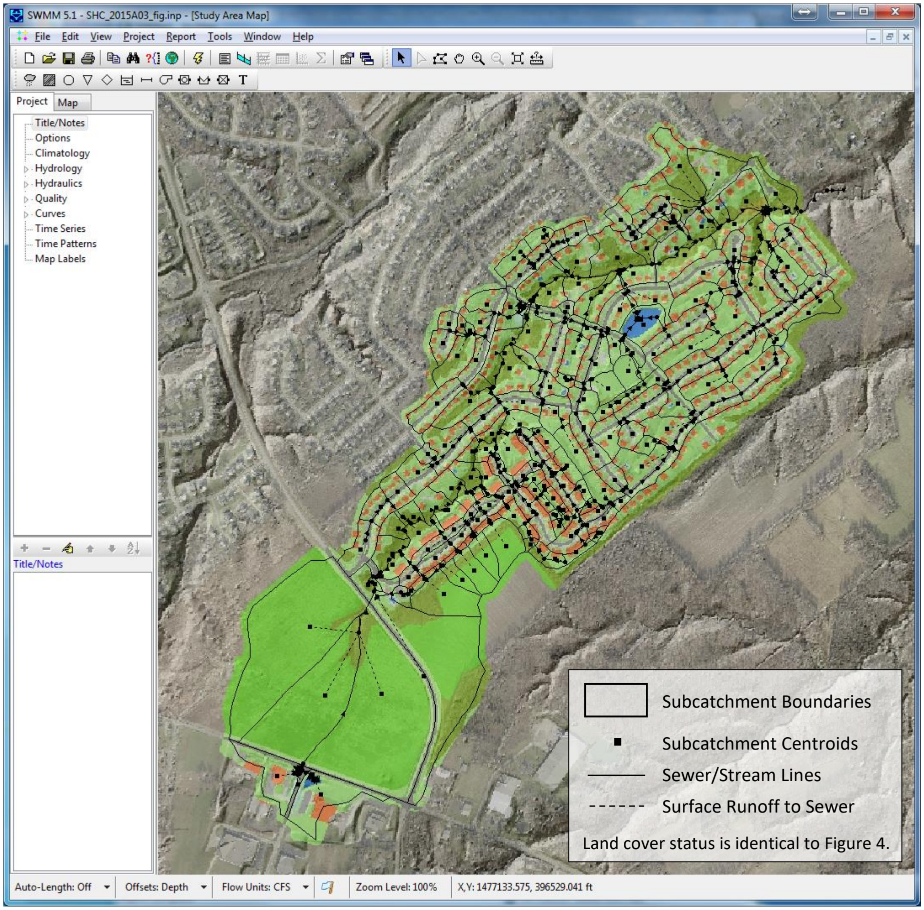
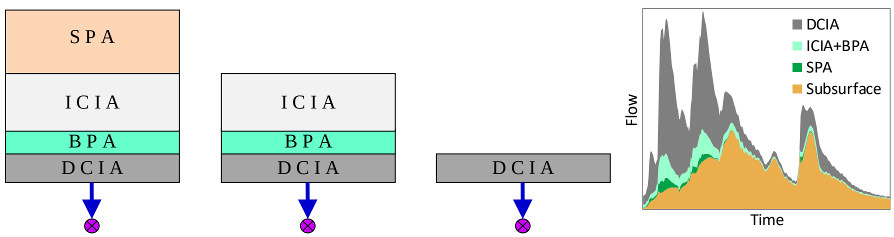
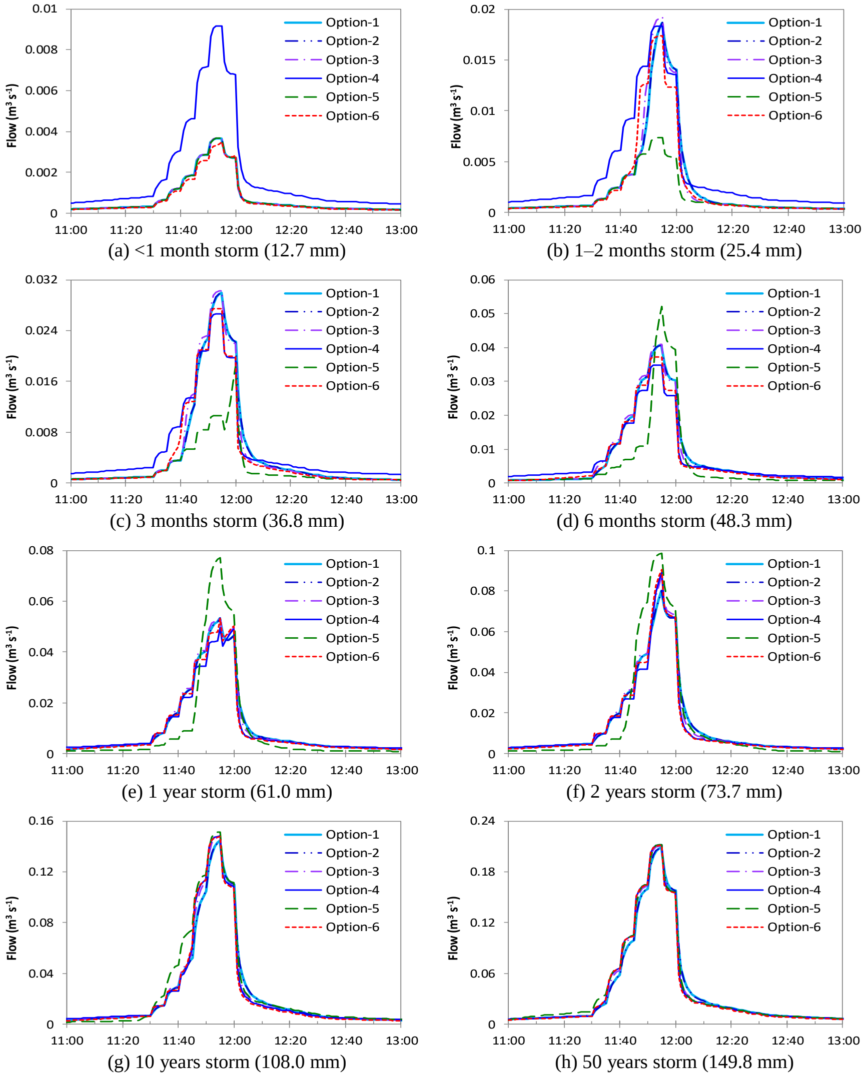


Figure 67. Diagram of the developed SWMM model for the Shayler Crossing watershed.



(a) Complete (b) Impervious (c) DCIA only (d) Example hydrograph

Figure 78. Conceptual representations of discrete SWMM models for hydrograph separation.



(a) <1 month storm (12.7 mm)

(b) 1–2 months storm (25.4 mm)

(c) 3 months storm (36.8 mm)

(d) 6 months storm (48.3 mm)

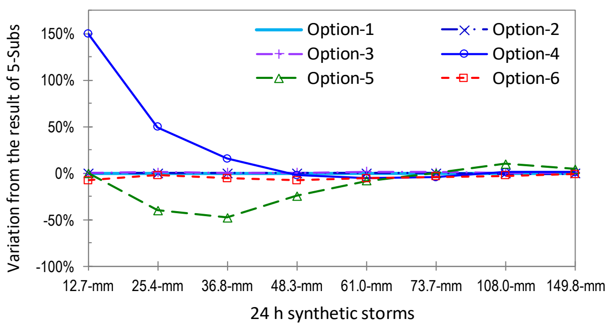
(e) 1 year storm (61.0 mm)

(f) 2 years storm (73.7 mm)

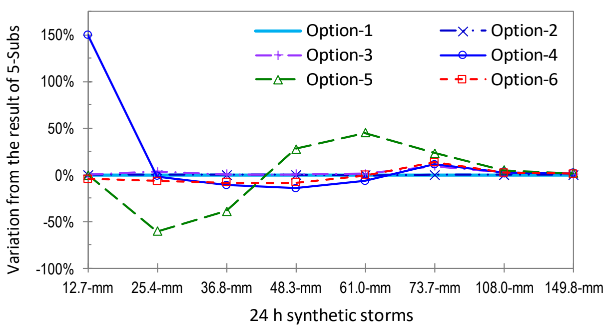
(g) 10 years storm (108.0 mm)

(h) 50 years storm (149.8 mm)

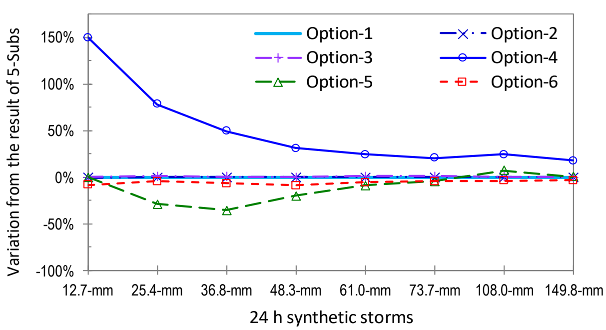
Figure 89. Hypothetical HRE SWMM modeling results.



(a) Average flow rate



(b) Peak flow rate



(c) Total runoff volume

Figure 9~~10~~. Comparison of the hypothetical HRE modeling results.

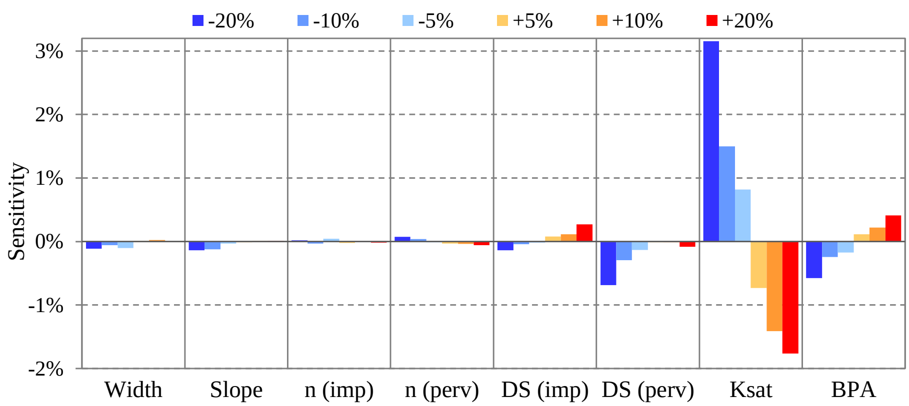


Figure 101. Sensitivity analysis of the SWMM parameters at SHC.

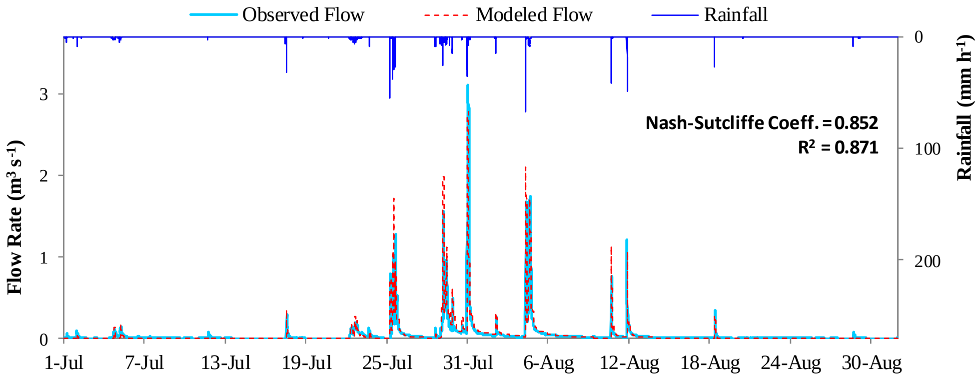
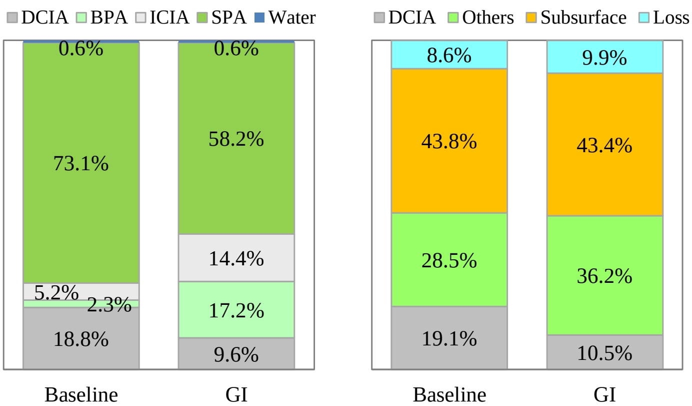
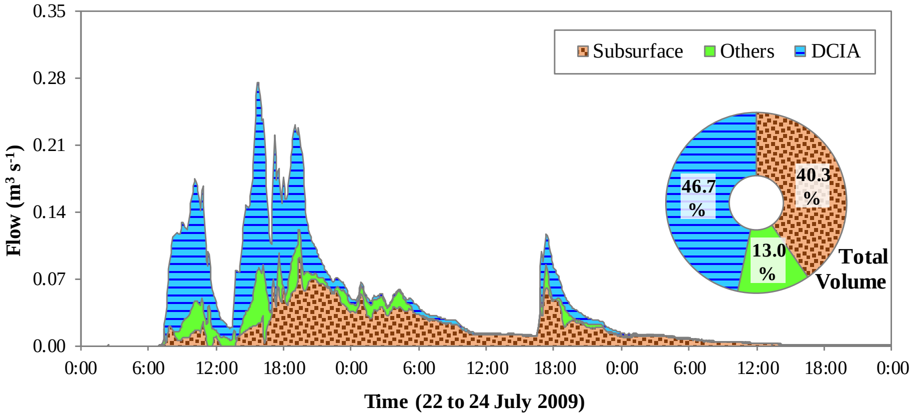


Figure 112. Watershed-scale SWMM modeling results from 1 July 2009 to 31 August 2009.

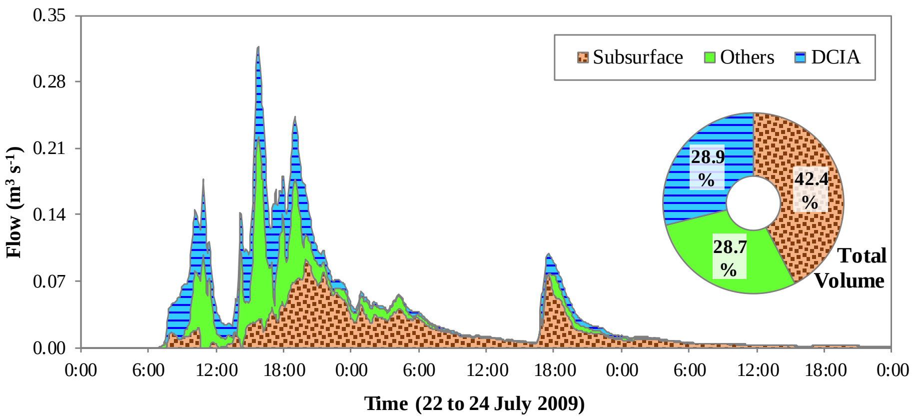


(a) Land cover components (b) Hydrologic components

Figure 123. Relative percentages of land cover and hydrologic components computed for the period 1 July 2009 to 31August 2009. In (b) "Others" represents surface runoff from areas other than DCIA, "Subsruface Interflow" is the subsurface contribution, and "Loss" is rainfall loss by evaporation or deep percolation.



(a) Baseline condition



(b) GI implementation scenario

Figure 134. Hydrograph separation and volumetric percentages contributing to stream flow for the period 22 to 24 July 2009.

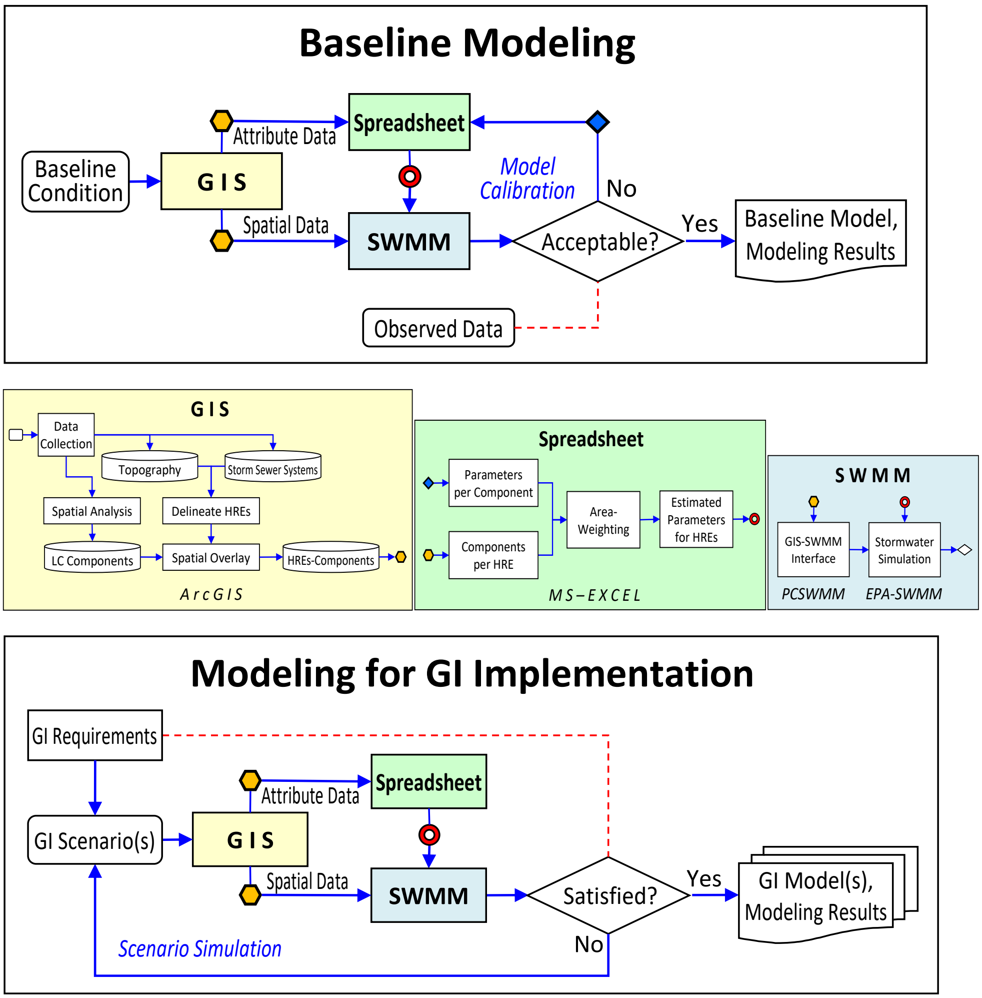


Figure A-16. Procedures for SWMM modeling for GI analysis. LC stands for land cover. Conceptual workflow for each of the colored boxes is given in the middle of the diagram. Symbols (⬢ ⭘ ◆ ▭ ◇) are used to label workflow connections within the colored boxes. Top panel depicts the general steps used for baseline model set–up, while the bottom panel adds GI considerations. "Acceptable?" means whether the statistical significance between the modeled and the observed hydrographs (e.g., Nash–Sutcliffe coefficient or R^2) is 'acceptable'. "Satisfied?" means whether the modeling results are 'satisfied' with the GI requirements.