Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

Hydrology and Earth System Sciences
Discussions

Subcatchment characterization for evaluating green infrastructure using the Storm Water Management Model

Joong Gwang Lee[1], Christopher T. Nietch[2], Srinivas Panguluri[3]

[1]Center for Urban Green Infrastructure Engineering (CUGIE Inc). Milford, OH 45150, USA.
[2]Office of Research and Development, U.S. Environmental Protection Agency. Cincinnati, OH 45268, USA.
[3]CB&I Federal Services LLC. Cincinnati, OH 45212, USA.

Correspondence to: Joong Gwang Lee (jglee@ugiengineering.com)

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 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 validate the spatial discretization approach, six different representations were evaluated with eight 24 h synthetic storms. With minimal calibration effort, the suggested approach out–performed 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. We found that when all subcatchments are discretized with the same land cover types, instead of using an $j \times k$ array of calibration parameters, based on j subcatchments and k parameters per subcatchment, the values used for the parameter set for one subcatchment can be applied in all cases (i.e., just k parameters). This approach not only reduces the number of modeled parameters, but also is scale–independent and can be applied directly to a larger watershed without further amendment. 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 (WEF–ASCE, 2012; USEPA, 2014). GI includes structures like green roofs, rain barrels, bioretention areas, buffer strips, vegetated swales, permeable pavements, and infiltration trenches. 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 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, and in total, may provide a cost–effective alternative to more traditional larger centralized practices, like detention ponds. 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.

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, however, best modeling practices for simulating GI in SWMM have received comparatively little attention in the literature.

With this in mind, 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 pond, it would be modeled as a ‘storage unit’ that effectively intercepts runoff from one or more subcatchments before it is discharged to the drainage network of sewer pipes or open channels. Storage structures can also be positioned within the drainage network. In both cases, the consideration of how the upgradient area is spatially discretized into subcatchments and how those subcatchments are parameterized in SWMM is largely irrelevant to the simulation of the specific effectiveness of the management practice as long as the influent hydrographs are matched to observed data during model calibration. 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 cost–effective model set–up and output data management. For simulation of GI, however, the construction reality is that the GIs are built as part of building and landscape arrangements all upgradient of the drainage network (Dietz, 2007; Montalto et al., 2007;

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

USEPA, 2009; Zhou, 2014). Therefore, in order to accurately examine GI alternatives, a SWMM subcatchment should be defined as an area that drains runoff to an actual storm sewer inlet.

After the subcatchment delineation is performed in SWMM, each one 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. The subarea configuration of each subcatchment ultimately specifies the physical conditions used by SWMM's mathematical algorithms to simulate the dynamics of hydrologic and water quality 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, 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. Pending the type of GI, changes may need to be made to 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, the GI scenarios are not the same among subcatchments, or the internal properties among subcatchments are heterogeneous. A systematic approach to parameterizing subcatchments 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. A primary objective of this study is to examine SWMM subcatchment delineation and subarea parameterization with the goal of demonstrating an urban watershed spatial discretization approach that optimizes model performance in terms of tracking model input values and 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. In typical urban landscapes, directly connected impervious area (DCIA) discharges runoff to the existing storm sewer system without any control, while indirectly connected impervious area (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. We questioned how these spatial and hydrologic realities can be modeled using SWMM. 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 subcatchment, representing the parcel or lot–level, to a watershed level. In order 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 unit-area based analysis of spatial discretization alternatives to test our hypothesis related to the appropriateness of spatial and hydrologic response resolution. To quantify differences among the modeling approaches to urban watershed spatial discretization we used a detailed geographic information system (GIS) of a well-characterized 100 ha urban watershed in a headwater area east of Cincinnati, Ohio.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

Hydrology and Earth System Sciences
Open Access
Discussions

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 Division, 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.

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 are 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.

2.2.2 Detailed land cover and subarea categorization

In order to 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. 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, 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 4 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 subcatchment delineation procedure for SWMM modeling is completed (see below). All main buildings are DCIA because the rooftop downspouts 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.

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 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 on 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.

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

2.3 Watershed subcatchment delineation

Urban subcatchments for modeling 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 subcatchment in SWMM should be delineated as the area that drains runoff to an actual storm sewer inlet. In addition, the following two rules were applied for subcatchment delineation: 1) If two adjacent storm inlets were located side–by–side at one street location, and one of the two drainage areas was smaller than 2023.4 m^2 (0.5 acre), the two drainage areas are combined into one subcatchment, and 2) to help maintain hydrologic continuity the subcatchment boundaries were generally selected with an intent to keep all subcatchments a similar size. This second criterion breaks up large areas of homogeneous land cover that can result in mixed land use watersheds. The result of the subcatchment delineation for the entire SHC watershed is shown in Fig. 4.

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

2.4 SWMM parameterization

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,

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

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.

2.4.1 Subcatchment/subarea parameterization

A subcatchment is a basic component of a SWMM application, and is defined as an area that drains runoff to a storm sewer inlet, open channel, or another subcatchment. Each 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 the 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 slope, Manning's roughness coefficient (n), and surface depression storage (DS) for both IA and PA, and soil infiltration characteristics for 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). IA can be further divided into areas with or without DS. 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 land cover database 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 set to be 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 land cover data was spatially overlaid with the layer of subcatchment delineation using ArcGIS. With this overlay, the characteristics of each subcatchment could be defined using the detailed land cover status allocated to the subcatchment. Unique values for representing the corresponding area, percent imperviousness, width, slope, and infiltration parameters (K_{sat}, $Suct$, and IMD for the Green–Ampt) were defined per subcatchment. Two sets of n and DS were defined per 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). Although the status of each land cover type within each subcatchment is different, for testing the models ability to scale, the parameter values were assigned independent of the subcatchment in which it resided (Table 1). This parameter assignment methodology also reduces model complexity and allows for scaling across the watershed.

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

The area of each land cover type within a subcatchment was estimated using ArcGIS. Each land cover type in Table 1 is either all impervious or all pervious. “Length” represents the most typical length of overland flow for each land cover type. Using ArcGIS, the initial values for “Length” were decided by averaging multiple field measurements of perceived overland flow lengths for each land cover type. The SWMM parameter ‘characteristic width’ per subcatchment was estimated using an area–weighted flow length, as described in the SWMM Applications Manual (Gironás et al., 2009). 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 this width parameter to produce good fits to the measured runoff hydrographs. The following area–weighting calculation describes how the width of a subcatchment is estimated, where i represents all of the individual land cover types within the subcatchment:

$$Length = \sum(Length_i\, Area_i)\ /\ \sum(Area_i) \quad (1)$$

$$Width = \sum(Area_i)\ /\ Length \quad (2)$$

The initial values for slope, *n*, and *DS* in Table 1 were selected using reference data from SWMM manuals (Huber and Dickinson, 1988; Rossman, 2015). Initial infiltration parameters were also selected from the manuals based on the soil types of SHC, which are mainly silt loam and clay, but then K_{sat} for pervious land cover was downgraded to account for soil compaction typical of urban areas. (Horton et al., 1994; Gregory et al., 2006). The extent of each individual type of land cover is then used to area–weight the parameter values assigned for each subcatchment or subarea. This is 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). 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* and *n* based on an area–weighted average using the corresponding nominal values presented in Table 1, [$DS\_imp = \sum(DS_i\, \mathrm{IA}_i)\ /\ \sum(\mathrm{IA}_i)$], where *DS_imp* is *DS* for impervious area within a subcatchment, IA is the size of individual land cover type within a subcatchment, and *i* is an individual land cover types.

2.4.2 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 as the most appropriate option to represent the actual BPA. The BPA area estimated from geoprocessing steps 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 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. The initial saturation was also equal across all subcatchments; set at 25 % (this value self–equilibrates after the model warm–up period, see Sect. 2.5). The percentage of subcatchment imperviousness contributing to the BPA (i.e., the ICIA) is obtained by dividing the ICIA by the total IA, subject to change with calibration.

2.4.3 The groundwater component

Because the natural stream draining the study area allows 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):

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

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}. 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. 5. 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.

Figure 5. Developed SWMM model for the Shayler Crossing watershed.

2.5 Model calibration

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. 5) 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. Changes were integrated one at a time into every subcatchment using the area–weighting approach in a spreadsheet. The calibrated modeling parameters for individual land cover types are given in Table 1 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 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. 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. 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:

$$Sensitivity = (\Delta MR/MR)/(\Delta p/p) \quad (4)$$

Where, MR = modeling result from SWMM run; ΔMR = change in SWMM modeling result based on change in parameter value; p = parameter value; and Δp = change in parameter value.

2.6 Model refinement and verification with a hypothetical urban area analysis

The most spatially refined approach to a SWMM set–up would be to discretize every piece of impervious and pervious surface as an independent subcatchment. This promises a decrease in output uncertainty (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, six plausible options for representing urban spatial constructs that are constrained by the SWMM subcatchment/subarea paradigm were examined (Fig. 6), with Option 6 being our recommended approach for GI modeling analyses, which simulates DCIA, ICIA, BPA, and SPA independently, yet uses only a single subcatchment.

The intention was to determine which among the plausible options strikes a balance between 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 representative of a typical urban drainage

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

area was defined and used to model eight synthetic single storm events for each of the 6 options (Fig. 6). The hypothetical area 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) BPA. 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 6. Conceptual representation of spatial discretization options modeled using SWMM. The arrows represent flow directions and the round circles represent storm sewer inlets.

In Option 1 five subcatchments are arranged for separately modeling transportation DCIA (Trpt) and building DCIA (Bldg) along with ICIA, BPA, and SPA. This is the lowest level of spatial aggregation. This option would increase the existing number of subcatchments (191) used to model SHC by a factor of 5. Option 2 combines the two DCIA subcatchments in Option 1. Option 3 aggregates to two subcatchments, and the routing and imperviousness per subcatchment need to be specified in SWMM with "Subarea Routing" option as "Pervious" or "Impervious" and the "Percent Routed" as 100 for both subcatchments. In Option 4 only two subareas are configured within each subcatchment, IA and PA, and the runoff from total pervious area (TPA) discharges through total impervious area (TIA). Option 5 is 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). This situation is modeled by adjusting the "Subarea Routing" option as "Pervious" and the "Percent Routed" as the ratio of ICIA/TIA. Finally, in Option 6, the one used for the original model set–up, LID modeling options are used for modeling BPA as a vegetated swale as described above.

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. The values selected are meant to represent typical residential areas in the Unites States. For example, the assumed values were derived using overland flow from the center to curb in a crowned 9.14 m (30 feet) wide neighborhood 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 *n* and 2.54 mm (0.1 inch) for *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.

Table 2. 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) selected from a regional rainfall frequency report developed 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 were estimated using the method presented in the same report (USEPA, 2009). Values in the "Cumulative" column of Table 2 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).

2.7 Modeling GI scenarios

GI implementation 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 one scenario we examined specifically was to decrease 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 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 of GI implementations – downspout disconnection and buffering area extension.

The characteristic width per subcatchment is a computed value that is usually treated as a calibration parameter in SWMM (see Sect. 2.4.1). Under conventional stormwater management modeling approaches, once the width value is set, it is not adjusted during management scenario analysis. This, however, is not the case for GI implementation. A GI by design changes the flow paths lengths and therefore the computed value of the "width" parameter as represented in SWMM. 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. However, the accuracy of this 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 Interflow. 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. 7a) 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. 7b).

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

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

$$Q_{total} = Q_{DCIA} + Q_{ICIA+BPA} + Q_{SPA} + Q_{interflow} \quad (5)$$

$$Q_{surface} = Q_{DCIA} + Q_{ICIA+BPA} + Q_{SPA} \quad (6)$$

$$Q_{interflow} = Q_{total} - Q_{surface} \quad (7)$$

$$Q_{SPA} = Q_{surface} - Q_{imperv} \quad (8)$$

$$Q_{ICIA+BPA} = Q_{imperv} - Q_{DCIA} \quad (9)$$

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 $Q_{interflow}$ = runoff through groundwater interflow (i.e., subsurface or lateral flow).

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

3. Results and discussion

The modeled parameter values pre– and post–calibration were presented previously in Table 1.

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. 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 area modeling analysis

The eight single storm–hypothetical area modeling analysis with the six discretization options resulted in 48 SWMM runs. 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). 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. The modeled flow rates and total runoff volumes are almost identical.

Figure 8. Hypothetical area 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. 8a through e).

In the smallest storm situation (Fig. 8a) 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. DCIA is modeled explicitly in the other five options. The inaccuracy in runoff estimates caused by modeling TIA as DCIA contribution diminished as larger storms are modeled, Fig. 8a to c. Option 4 is not suitable to modeling GI alternatives because it ignores the significance of characterizing DCIA and ICIA within a subcatchment. Option 5 shows the most significant variation among unit 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. 8d 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, the "ideal" green implementation scenario results in higher peak discharges than the other options.

From this 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. 8d 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 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.

Figure 9 depicts another way of comparing the results among the 6 options, showing the relative difference for peak flow, average flow, and total runoff volume for each of the 5 other Options compared to Option 1. Modeling results from Option 1, with 5 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. Comparison of the overall unit–area modeling results.

The relative differences 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. 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. This modeling outcome 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. Based on the results, Option 6 balances the combination of discretization criteria, especially in terms of the level of effort required in configuring parameter values and in tracking the relative accuracy of the modeling results.

3.3 Modeling results

The Option 6 spatial discretization approach was used to set up SWMM for SHC. The SHC model consists of 191 subcatchments and 269 junctions and conduits (Fig. 5). 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. (4) (Fig. 10). 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). 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 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.

Figure 10. 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, 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 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 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. The modeled hydrographs are very well matched with the measured data at the watershed scale with a Nash–Sutcliffe coefficient = 0.852 and R^2 = 0.871.

Figure 11. 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. 12a). 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. 12b). A more detailed representation for the hydrograph separation is presented in Fig. 13, which covers 72 hours from 22 to 24 July 2009. During this period, there was a total of 164.6 mm rainfall.

Figure 12. 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, "Interflow" is the subsurface contribution, and "Loss" is rainfall loss by evaporation or deep percolation.

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

Validation of the modeling results from applying the hydrograph separation will 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 interflow over the simulation period, even though the study watershed is characterized with clay type soils that are poorly infiltrating. After applying the GI scenario, although the interflow contributed a similar fraction to the stream flow, the fractional contributions of surface runoff from DCIA and the other areas are significantly changed (Fig. 12b and 13). 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 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) 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). This result is similar to the single storm analysis using Option 5 (Fig. 6). 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. Conclusions

We demonstrate how high resolution spatial data can be applied to spatially discretize a watershed and develop a methodology to increase model accuracy with reduced calibration effort. During the process of developing the spatial representation in SWMM, it is important to distinguish DCIA from ICIA, and BPA from SPA, and explicitly model these subareas. This approach is particularly useful when modeling the impact of small storms. Instead of using j × k calibration parameters, which are based on j subcatchments and k parameters per subcatchment, only k parameters need to be calibrated and applied to all subcatchments. The land cover based spatial discretization approach is scale–independent, can be applied directly to a larger watershed, and affords the opportunity to evaluate urban stormwater management strategies with improved accuracy and expanded applicability to GI planning, design, and implementation.

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

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

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

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

Hydrology and Earth System Sciences Discussions
Open Access

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)
$Q_{interflow}$	Runoff through groundwater interflow (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 CB&I; and Dr. Michael Tryby, Dr. Michael Elovitz, and Dr. William Shuster of USEPA. They provided critical data, suggestions, or critical reviews.

References

CHI: PCSWMM Professional. Computational Hydraulics Int. (CHI), Guelph, Ontario, Canada, 2015.

Debo, T. N., and Reese, A. J.: Municipal Stormwater Management. 2nd Edition. Lewis Publishers, CRC Press. ISBN–13: 978–1–4200–3226–0, 2003.

Dietz, M.E.: Low impact development practices: A review of current research and recommendations for future directions. Water, Air, and Soil Pollution, 186: 351–363. doi:10.1007/s11270–007–9484–z, 2007.

ESRI: ArcGIS Desktop: Release 10.2. Environmental Systems Research Institute (ESRI). Redlands, CA, USA, 2013.

Gironás, J., Roesner, L.A., and Davis, J.: Storm Water Management Model Applications Manual. EPA/600/R–09/077. National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency (USEPA). Cincinnati, OH, USA, 2009.

Gregory, J.H., Dukes, M.D., Jones, P.H., and Miller, G.L.: Effect of urban soil compaction on infiltration rate. J. Soil Water Conserv., 61(3): 117–124, 2006.

Guo, J.C. and Urbonas, B.: Maximized detention volume determined by runoff capture ratio. J. Water Res. Pl.-ASCE, 122(1): 33–39, 1996.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K.: Completion of the 2011 National Land Cover Database for the conterminous United States–Representing a decade of land cover change information. Photogramm. Eng. Rem. S., 81(5): 345–354, 2015.

Horton, R., Ankeny, M.D., and Allmaras, R.R.: Effects of compaction on soil hydraulic properties. pp. 479–500. In: Soil Compaction in Crop Production. Elsevier Science B.V., Amsterdam, Netherlands, 1994.

Huber, W.C. and Dickinson, R.: Storm Water Management Model User's Manual, Version 4. EPA/600/3–88/001a (NTIS PB88–236641/AS). Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency (USEPA). Athens, GA, USA, 1988.

Huff, F.A. and Angel, J.R.: Rainfall Frequency Atlas of the Midwest. National Weather Service, National Oceanic and Atmospheric Administration and Illinois State Water Survey, A Division of the Illinois Department of Energy and Natural Resources. Bulletin 71 (MCC Research Report 92–03) http://www.sws.uiuc.edu/pubdoc/B/ISWSB-71.pdf (accessed on 14 February 2015), 1992.

Montalto, F., Behr, C., Alfredo, K., Wolf, M., Arye, M., and Walsh, M.: Rapid assessment of the cost–effectiveness of low impact development for CSO control. Landscape Urban Plan., 82(3): 117–131. doi:10.1016/j.landurbplan.2007.02.004, 2007.

Niazi, M., Nietch, C., Maghrebi, M., Jackson, N. Bennett, B.R., Tryby, M. and Massoudieh, A.: Storm Water Management Model (SWMM)–Performance review and gap analysis. Journal of Sustainable Water in the Built Environment, doi: 10.1061/JSWBAY.0000817, 2017.

NOAA: Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States. NOAA Technical Report NWS 34. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. Washington, D.C. December 1982. http://www.nws.noaa.gov/oh/hdsc/PMP_related_studies/TR34.pdf (accessed on 15 February 2015), 1982.

NRC: Urban Stormwater Management in the United States. Committee on Reducing Stormwater Discharge Contributions to Water Pollution. National Research Council (NRC). National Academies Press. Washington, DC. ISBN 978–0–309–12539–0, 2009.

Pitt, R.: Small storm hydrology and why it is important for the design of stormwater control practices. Adv. Mod. Manag. Stormw., 7: 61–91, 1999.

Rossman, L.A.: Storm Water Management Model User's Manual, Version 5.1. EPA/600/R–14/413b, Revised September 2015. U.S. Environmental Protection Agency, Office of Research and Development, Water Supply and Water Resources Division, Cincinnati, OH, USA, 2015.

Rossman, L.A. and Huber, W.C.: Storm Water Management Model Reference Manual, Volume I – Hydrology (Revised). EPA/600/R–15/162A, Revised January 2016. U.S. Environmental Protection Agency, Office of Research and Development, Water Supply and Water Resources Division, Cincinnati, OH, USA, 2016.

Sun, N., Hall, M., Hong, B., and Zhang, L.: Impact of SWMM catchment discretization: case study in Syracuse, New York. J. Hydrol. Eng., 19(1): 223–234. doi: 10.1061/(ASCE)HE.1943–5584.0000777, 2014.

USDA: Urban Hydrology for Small Watersheds. Technical Release 55 (TR–55). Natural Resources Conservation Service, Conservation Engineering Division, U.S. Department of Agriculture (USDA), 1986.

USEPA: Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act. United States Environmental Protection Agency, Office of Water (4503T), Washington, DC 20460, EPA 841–B–09–001. December 2009. http://www.epa.gov/oaintrnt/documents/epa_swm_guidance.pdf (accessed on 8 June 2015), 2009.

USEPA: What is Green Infrastructure? (Last updated on 13 June 2014) Office of Water, U.S. Environmental Protection Agency. Washington, DC 20460. http://water.epa.gov/infrastructure/greeninfrastructure/gi_what.cfm (accessed on 8 May 2015), 2014.

WEF–ASCE: Design of Urban Stormwater Controls. WEF Manual of Practice (MOP) No. 23. ASCE Manuals and Reports on Engineering Practice No. 87. Water Environment Federation (WEF). Environmental & Water Resources Institute, American Society of Civil Engineers (ASCE). ISBN–13: 978–0071704441, ISBN–10: 0071704442, 2012.

Zhou, Q.: A review of sustainable urban drainage systems considering the climate change and urbanization impacts. Water, 6: 976–992. doi:10.3390/w6040976, 2014.

Table 1. 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

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

Hydrology and Earth System Sciences
Open Access
Discussions

Table 2. 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 %

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

Hydrology and Earth System Sciences
Open Access
Discussions

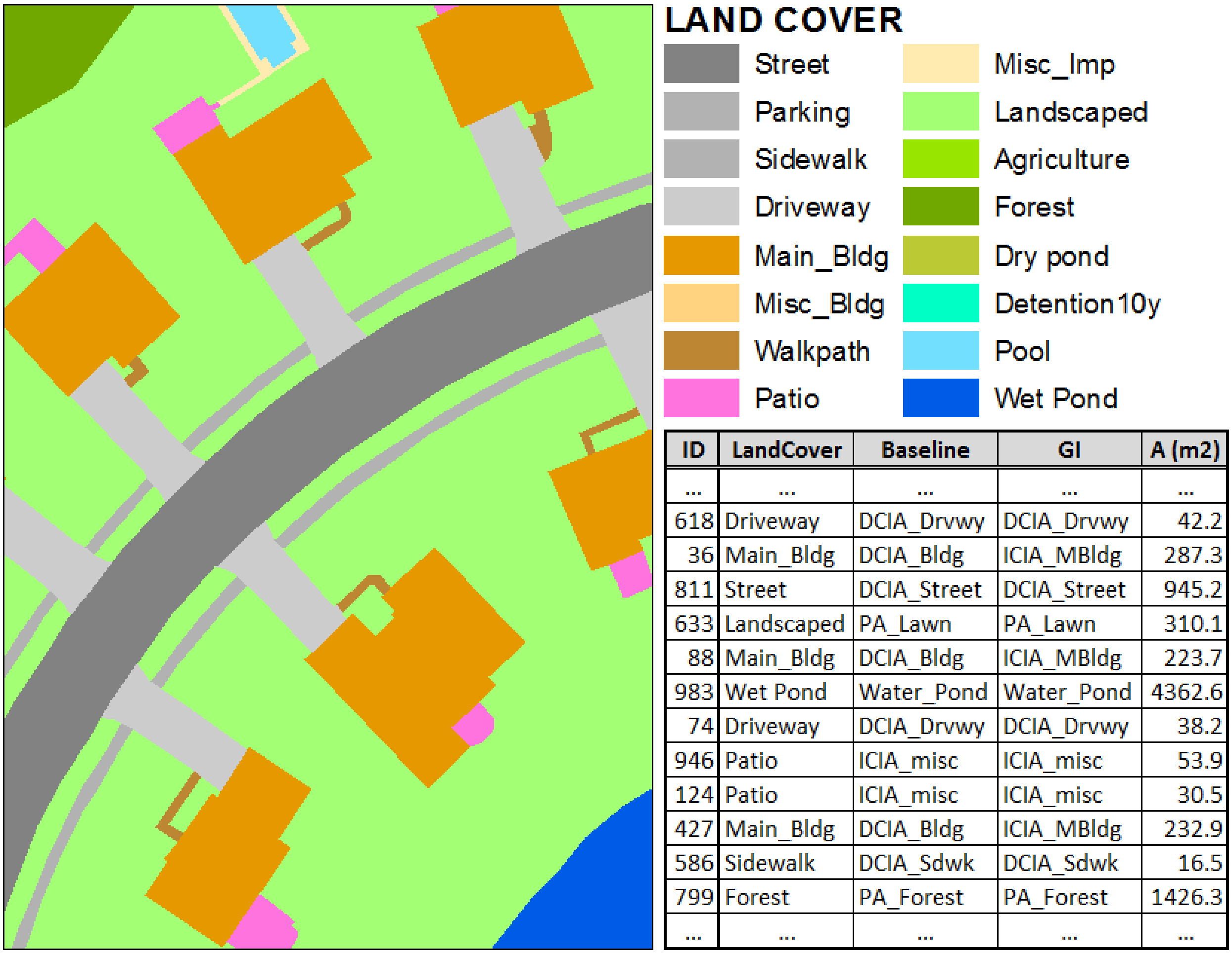
Table 3. Land cover status of Shayler Crossing watershed.

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.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

Hydrology and Earth System Sciences
Open Access
Discussions



ID	LandCover	Baseline	GI	A (m2)
...	...	...	...	...
618	Driveway	DCIA_Drvwy	DCIA_Drvwy	42.2
36	Main_Bldg	DCIA_Bldg	ICIA_MBldg	287.3
811	Street	DCIA_Street	DCIA_Street	945.2
633	Landscaped	PA_Lawn	PA_Lawn	310.1
88	Main_Bldg	DCIA_Bldg	ICIA_MBldg	223.7
983	Wet Pond	Water_Pond	Water_Pond	4362.6
74	Driveway	DCIA_Drvwy	DCIA_Drvwy	38.2
946	Patio	ICIA_misc	ICIA_misc	53.9
124	Patio	ICIA_misc	ICIA_misc	30.5
427	Main_Bldg	DCIA_Bldg	ICIA_MBldg	232.9
586	Sidewalk	DCIA_Sdwk	DCIA_Sdwk	16.5
799	Forest	PA_Forest	PA_Forest	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.

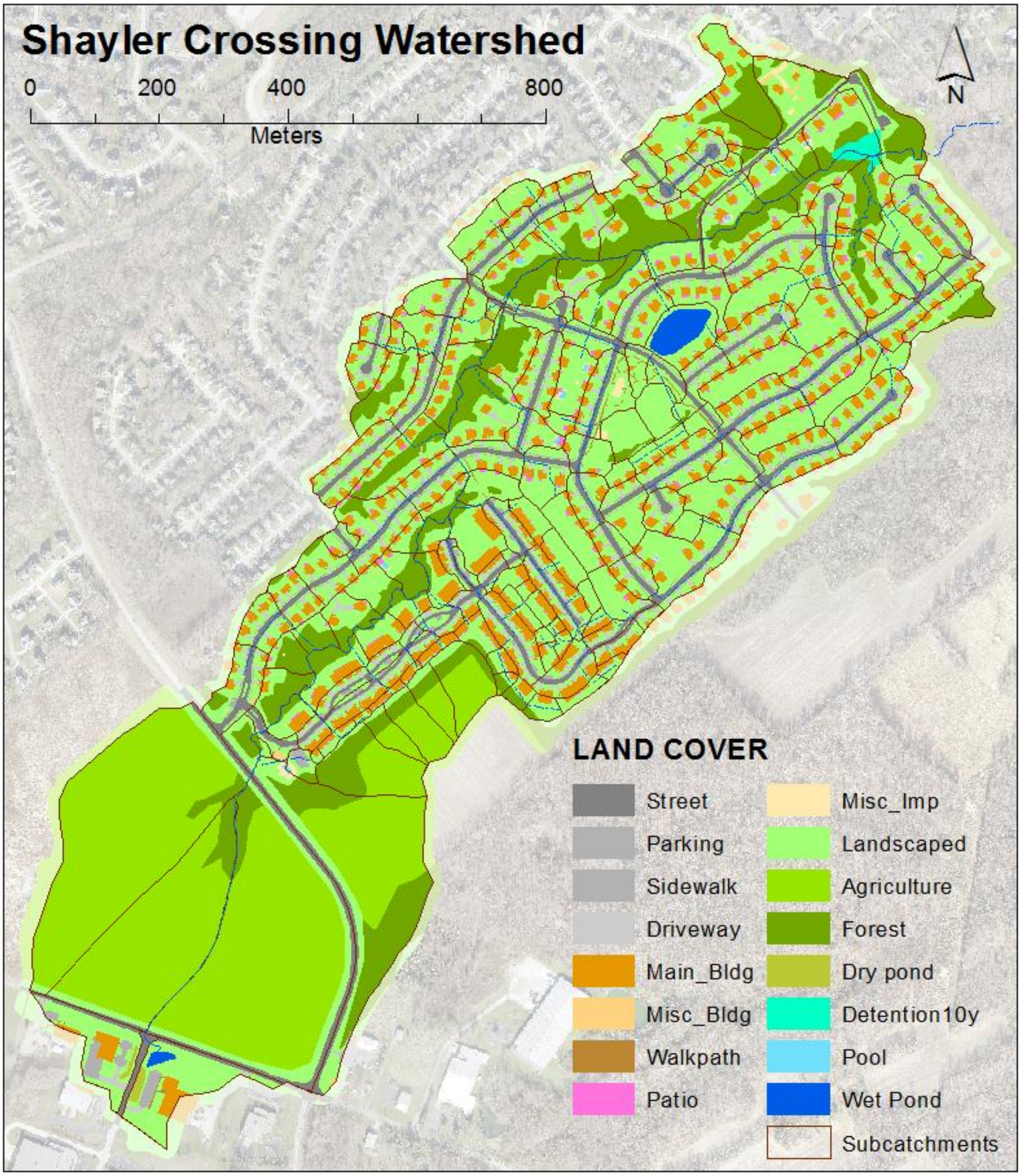


Figure 4. Detailed spatial representation of the Shayler Crossing watershed.

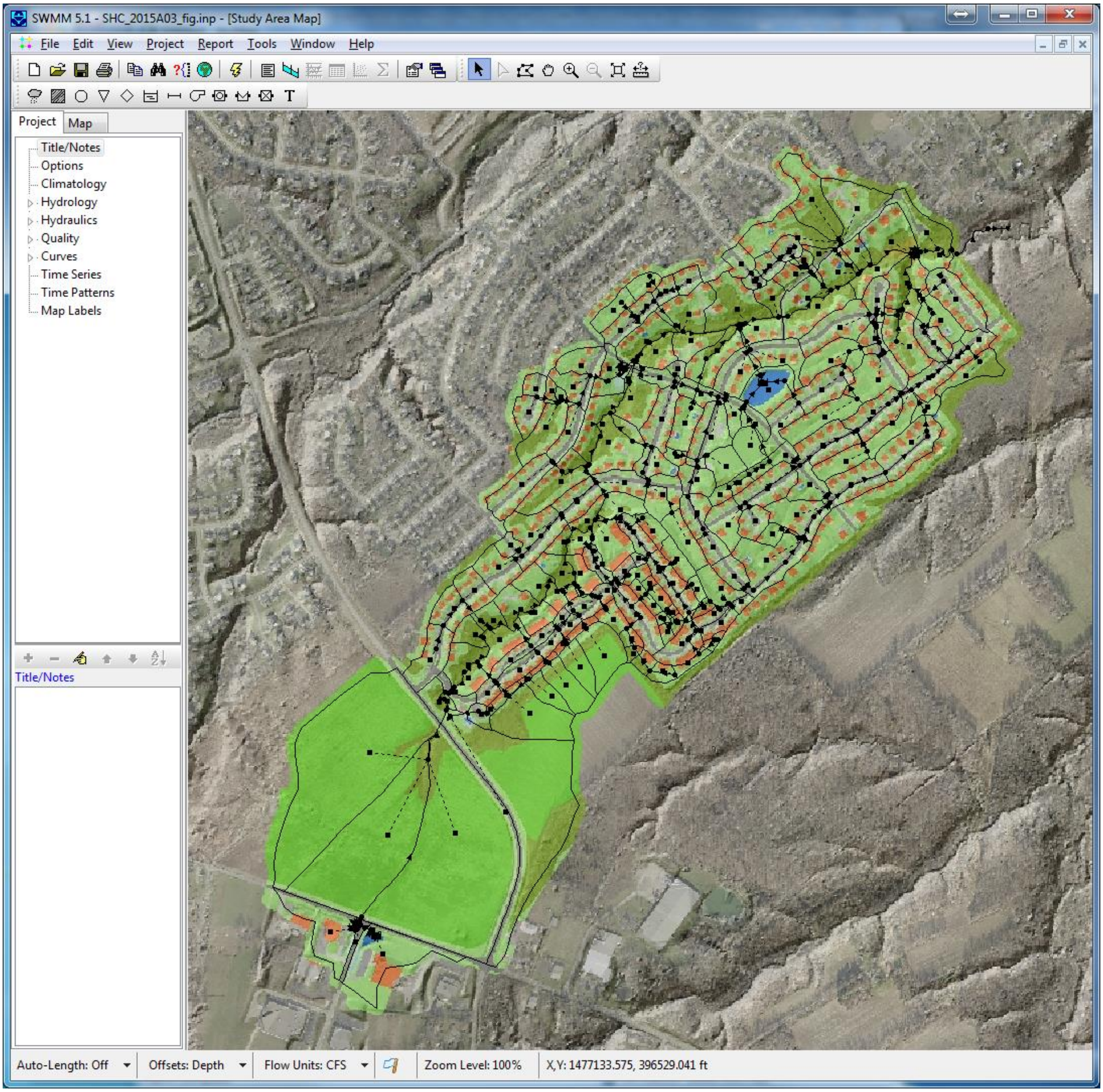


Figure 5. Developed SWMM model for the Shayler Crossing watershed.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

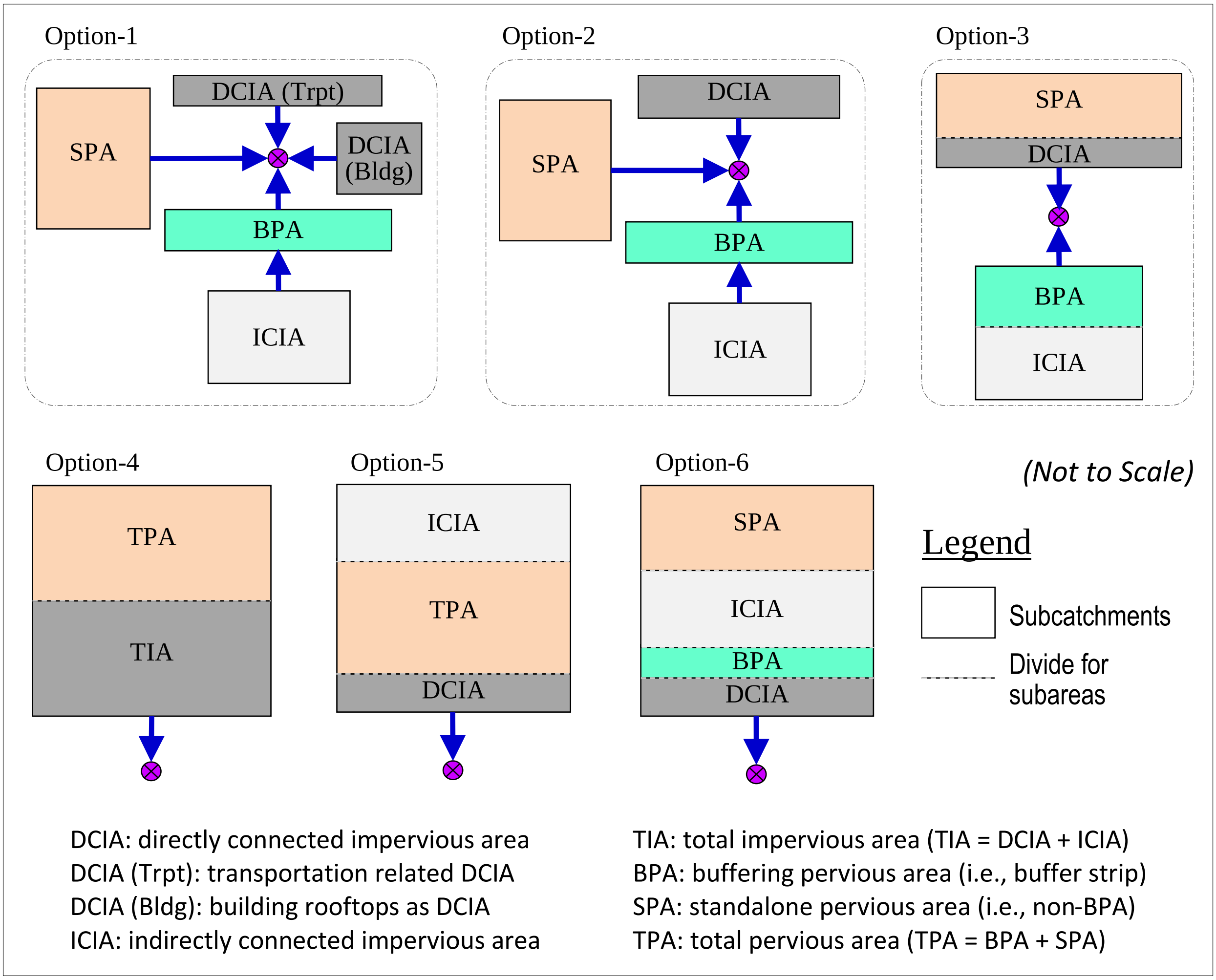
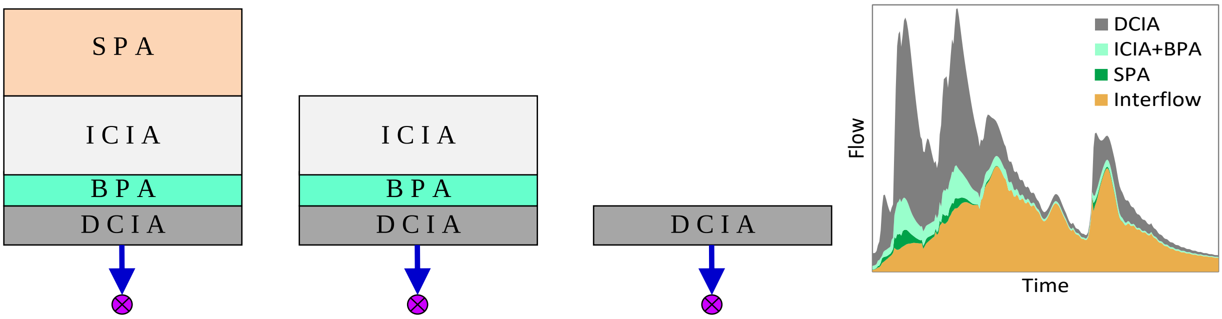


Figure 6. Conceptual representation of spatial discretization options modeled using SWMM. The arrows represent flow directions and the round circles represent storm sewer inlets.



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

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

Hydrology and Earth System Sciences
Discussions
Open Access

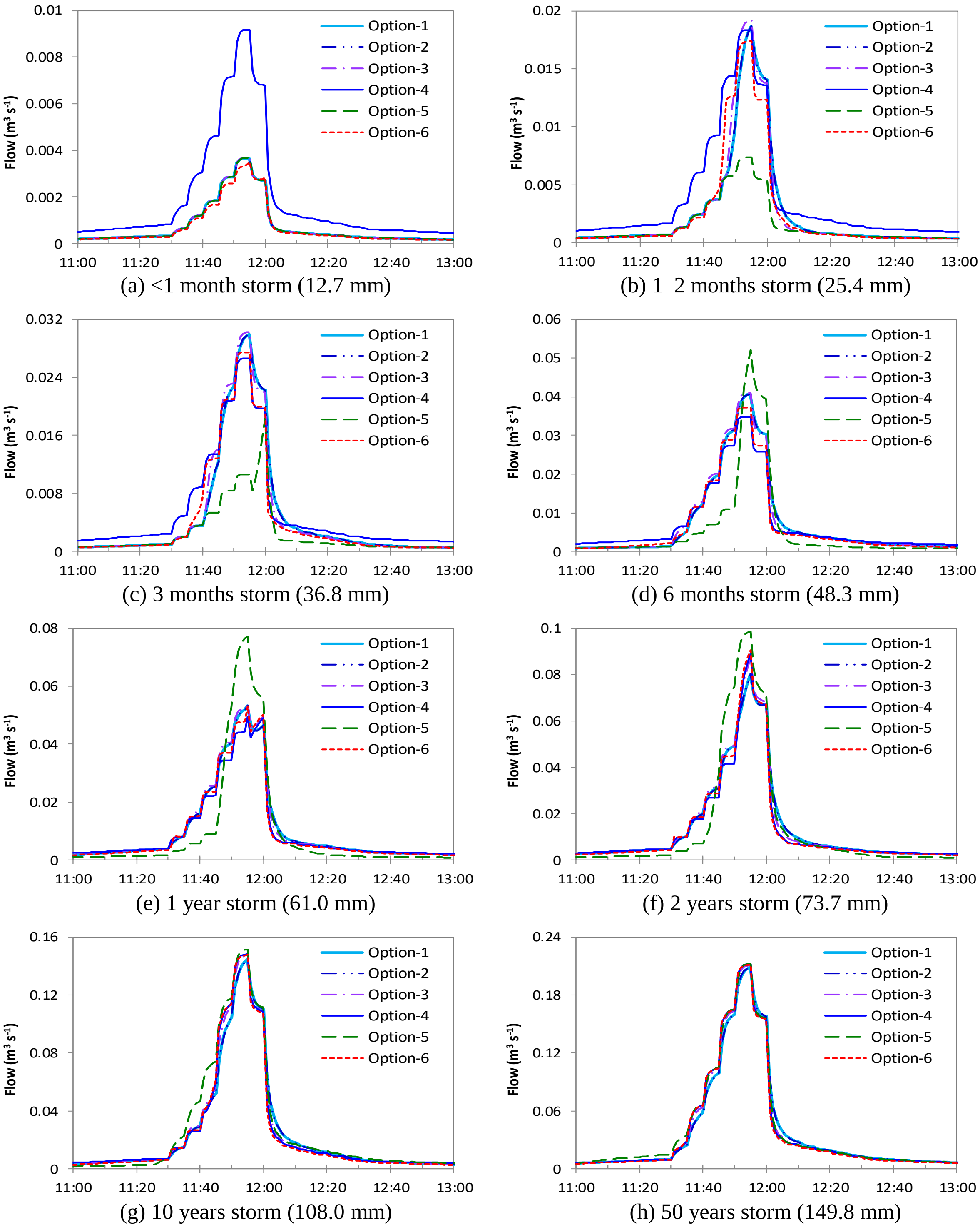
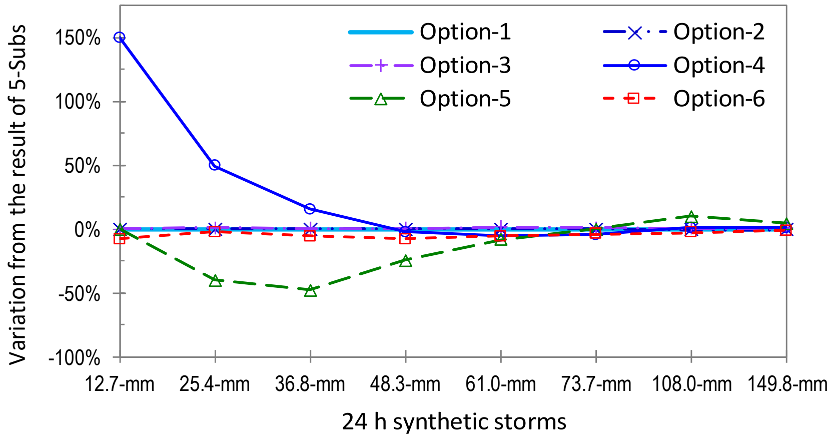
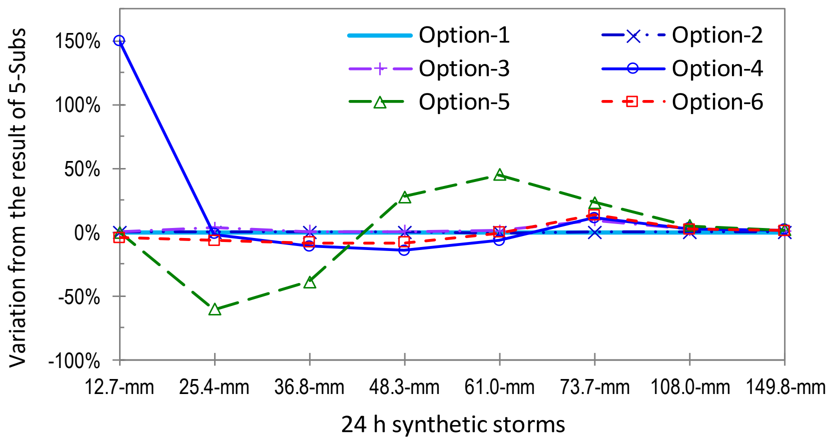


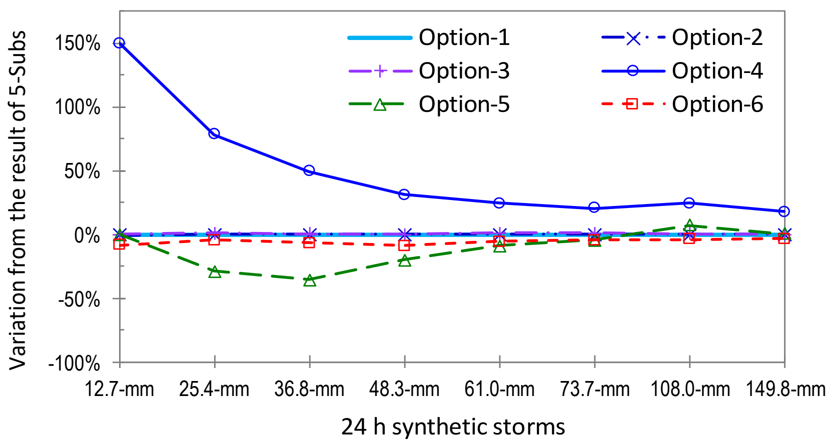
Figure 8. Hypothetical area SWMM modeling results.



(a) Average flow rate



(b) Peak flow rate



(c) Total runoff volume

Figure 9. Comparison of the overall unit–area modeling results.

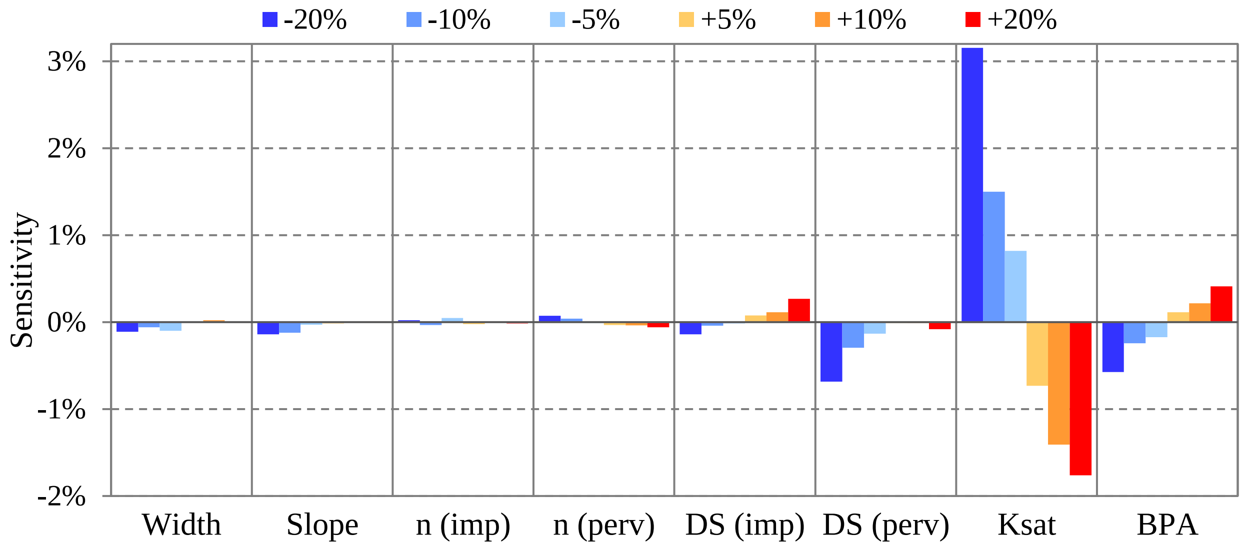


Figure 10. Sensitivity analysis of the SWMM parameters at SHC.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-166, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 19 May 2017

Hydrology and Earth System Sciences
Discussions
Open Access

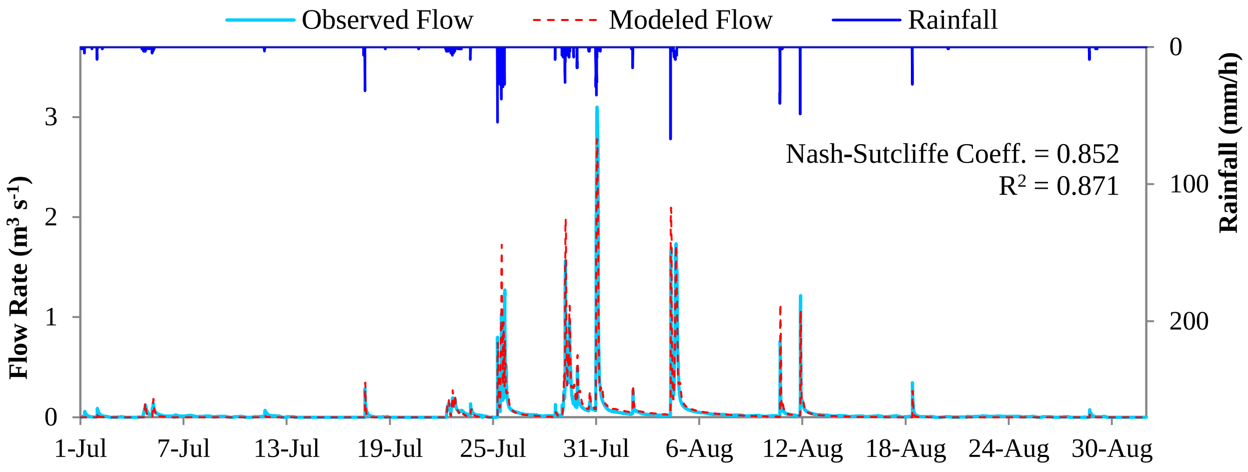
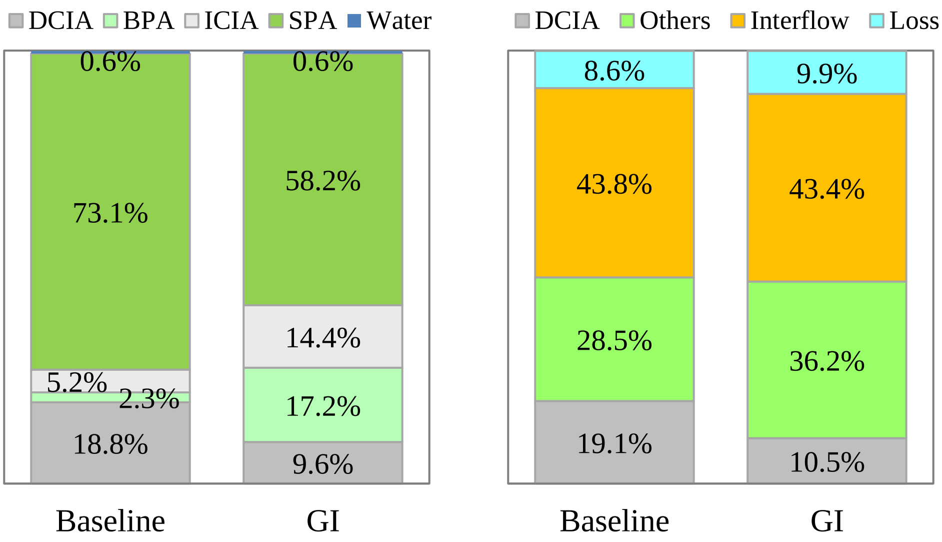
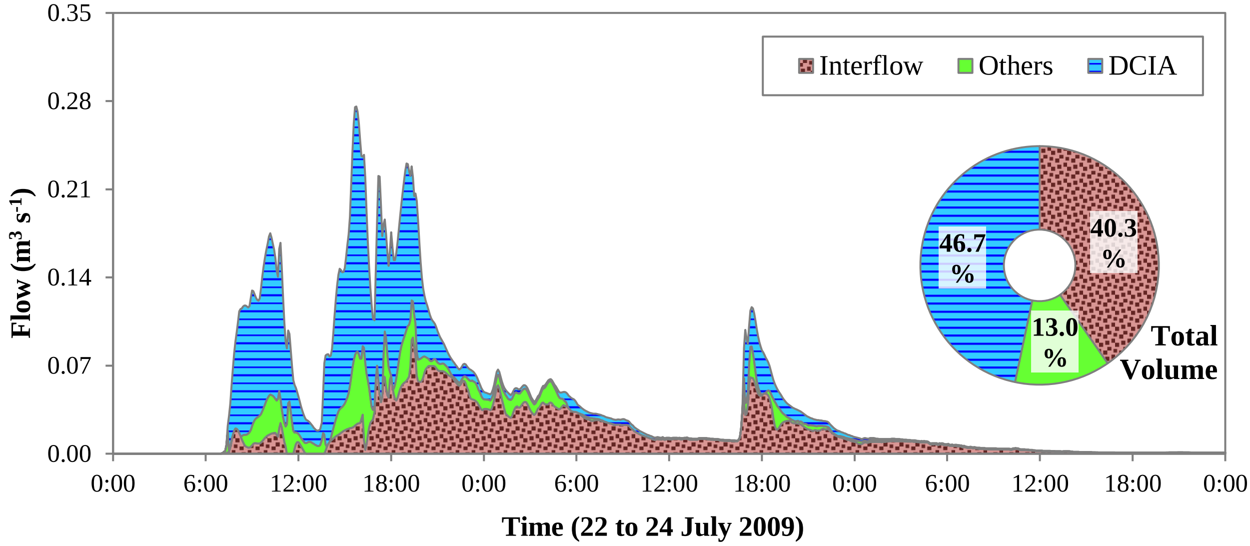


Figure 11. SWMM modeling results from 1 July 2009 to 31 August 2009.

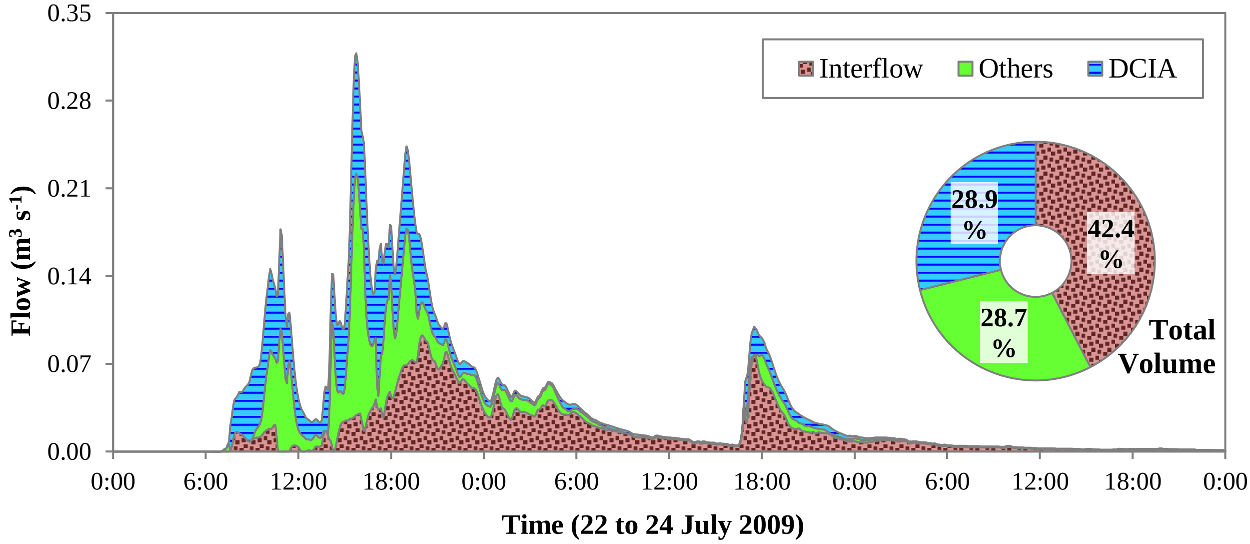


(a) Land cover components b) Hydrologic components

Figure 12. 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, "Interflow" is the subsurface contribution, and "Loss" is rainfall loss by evaporation or deep percolation.



(a) Baseline condition



(b) GI implementation scenario

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