Measuring the Performance of Stormwater Best Management Practices at the Goddard Space Flight Center Using the EPA's SWMM

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Abstract

Urban development has severe negative impacts on streams, including ecosystem degradation (Klein 1979), flooding (Booth 1991), and increased erosion (Neller 1988). Stormwater management seeks to prevent these negative impacts with treatment structures and development strategies known collectively as stormwater best management practices (BMPs). However, it is difficult to predict the effectiveness of a system of BMPs prior to construction without modeling, which can be time-consuming. This study seeks to model relevant BMPs to inform the decision-making of water quality managers at the NASA Goddard Space Flight Center (GSFC) in Maryland, USA. The standard of ideal performance in stormwater management is completely replicating pre-development hydrological conditions, and so these conditions were also modeled as a standard for success. During various modeled storm events, both peak discharge and total runoff volume were reduced by the BMPs relative to current conditions but remained substantially higher than predicted pre-development conditions. BMPs that significantly exceed the Maryland sizing criteria were then modeled, and these replicated pre-development hydrological conditions. These results indicate that, in this case, effective stormwater management requires implementation of management strategies beyond those required by government regulations, supported by site-specific information and performance evaluations.

1 Background

Urban areas in the United States have been expanding for decades (USDA 2013), and urban populations are expected to continue to increase (UN 2014). Urbanization covers undeveloped land with impervious surfaces, which prevents rainfall infiltration and increases flooding (Booth 1991), increases erosion (Neller 1988), and degrades downstream aquatic ecosystems (Klein 1979). Stormwater management regulations have sought to address these problems for over 50 years. During the first decades of stormwater management, regulations focused on controlling the peak flows of large storms with detention basins, but this approach does not attenuate flow for most smaller events and continues to cause stream erosion and habitat degradation (Roesner et al. 2001). Mimicking the natural hydrologic environment for storm events of all sizes is a necessary step towards maintaining healthy stream ecosystems (Roy et al. 2008), and is becoming the standard for stormwater management.

Critical to replicating the predevelopment runoff environment are both an understanding of the nature of this environment and the tools and strategies necessary to reproduce it. The former is often accomplished with numerical watershed models with surface characteristics corresponding to the natural land cover. These models are forced with rainfall input, which should be as representative of the local climate as possible.

The tools and strategies used to modify built environments towards predevelopment conditions are a variety of best management practices (BMPs), consisting of both decentralized structures and non-structural practices, such as redirecting runoff to pervious areas. Low impact development (LID) designs are best management practices (BMPs) that detain runoff onsite and allow it to partially infiltrate and recharge groundwater. These include grass swales, bio-retention basins, infiltration trenches, and many more. The success of these strategies is measured by the degree to which they adequately replicate natural runoff conditions, and this is evaluated with the same numerical models mentioned above.

This case study uses a parameterized and calibrated stormwater runoff model to test LID options of different sizes for a small catchment in the NASA Goddard Space Flight Center (GSFC), Maryland, USA (Figure 1). The U.S. Environmental Protection Agency's Stormwater Runoff Model (SWMM; Rossman 2010) was selected because it is widely used and provides an array of built-in LID objects. The forcing for the model was a selection of storm events close to the 90^{th} percentile storm for the region, taken from a historical dataset collected on the center. This size was chosen because it corresponds to the water quality volume (WQ_v), an important sizing criteria in the Maryland stormwater regulations which is designed to be addressed with LIDs (MDE 2009). Storms up to this size supposedly constitute 90% of annual rainfall, and while they are not responsible for the greatest flooding damage they contribute the majority of pollutants to the water supply (MDE 2009).

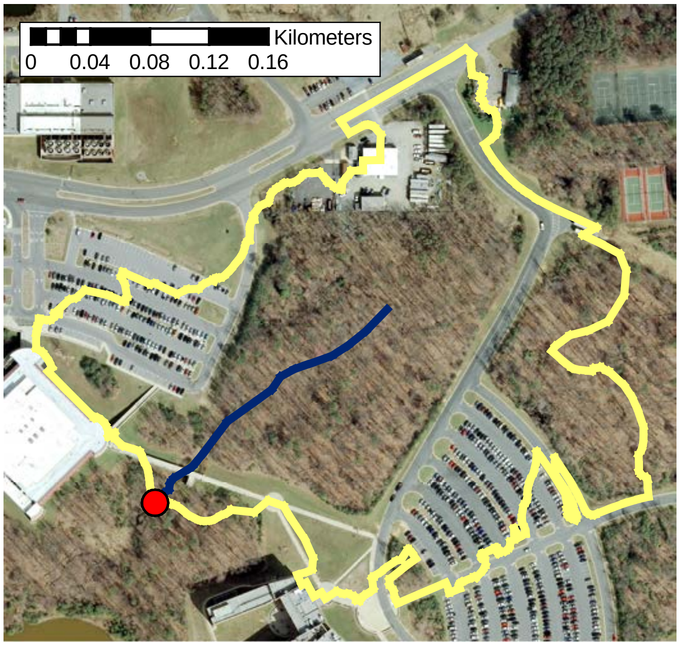

Figure 1: Satellite image of the study area, which is bounded by the thick yellow line. The blue line through the center represents the stream, and the red dot is the catchment outflow. The building along the bottom edge of the image is Building 33, which houses the three rain gauges used in this study.

2 Data

Two rainfall datasets were used in this study. Data from the National Climatic Data Center (NCDC) Cooperative Observer Network (COOP) station in Beltsville, MD, provided a long-term historical record with limited sensitivity. This data was used to find a local measurement of the 90th percentile storm size. High sensitivity rain gauges located at GSFC provided a local, high temporal resolution dataset used for identifying discrete storm events to be used as model input. In addition to rainfall, a digital elevation model and stream flow data were needed for configuring and calibrating SWMM, respectively. Each of these datasets is described below.

2.1 NCDC COOP Rainfall

The NCDC COOP dataset is collected by a network of volunteer weather observers throughout the United States. This study uses dataset 3260, which consists of observations collected at 15 minute intervals with a tipping bucket gauge (NCDC 2005). The gauge at the Beltsville, MD, station has a sensitivity of 2.54 mm, and data has been collected from 1971 through the end of 2013. This station is located 8.8 km from the study area. This dataset includes accumulated rainfall values associated with certain time intervals, which are periods when the total accumulated rainfall is known, but the time of each bucket tip is not. The dataset for this station also contains a substantial quantity of missing data. Specifically, on average 34.8 days have some missing data each year. These days with missing data were excluded from the frequency analysis, which effectively leaves 38.9 years of data. Since the missing dates occur randomly and several decades of data remain for analysis, the results should not be biased.

2.2 GSFC Rainfall

Rainfall data was obtained from three co-located Met One Inc. tipping bucket rain gauges installed on the roof of Building 33 at the GSFC (Tokay et al. 2014a) (Figure 1). The time of tip, which corresponds to 0.254 mm, was recorded to a Madge Tech data logger. The gauge observations were aggregated to 5 minutes, which is considered the minimum reliable observation for rain intensity (Tokay et al. 2014b). These gauges have been operating from June 2010 to present. The NCDC data provide a long term record of rainfall for the region with limited sensitivity. The GSFC data provide a short term record with greater sensitivity, located very close to the study area, and are used to identify discrete storm events for model input.

Tipping bucket gauges such as those used at this site and the NCDC COOP site (above) are susceptible to certain errors. Windy conditions can cause measurement errors when raindrops fall at an angle from vertical and strike the side of the bucket (Duchon and Essenberg 2001), and when wind tips the bucket by itself. Under-estimation can also occur during the elapsed time required as the bucket changes its position after a tip; this is of concern during heavy rain (Duchon et al. 2014). Also, in the presence of light rain, the time of tip may not reflect the timing of rainfall. For example, if it rains at 0.1 mm h^{-1} over a period of time, it takes 152.4 minutes to tip. Evaporation may also play a role in light rain. With the exception of evaporation, these errors are mostly mitigated through co-located gauge measurements in the case of the GSFC dataset.

2.3 Elevation

The elevation data used for delineation of model subcatchments was gathered by the Land, Vegetation, and Ice Sensor (LVIS) instrument, designed and operated by the Goddard Space Flight Center’s Laser Remote Sensing Laboratory. LVIS is an aircraft-mounted instrument that emits a laser signal towards the surface and, by measuring the time that elapses before the laser signal returns, determines the distance to the target. Analysis of the difference between the outgoing and returning waveforms allows estimation of both the elevation of the surface and the elevation of structures above the surface, typically trees.

This study used the 8 m spatial resolution LVIS ground elevation dataset, which is "the mean elevation of the lowest detected mode within the waveform," and can be assumed to represent the elevation of the surface, except in areas of very dense tree cover (Blair et al. 2006). Anomalous elevation data were replaced by interpolation from nearby data points. Figure 1 shows the study area, a portion of the GSFC including a variety of surfaces such as a forest patch, grassy stretches, parking lots and two buildings.

2.4 Stream Gauging

Accurate calibration and validation of the model requires discharge measurements at the catchment outflow that span several rainfall events. These measurements were gathered at a reference pole installed at the outflow. The stream gauging site was chosen to minimize bends, rapid changes in slope, large obstructions, and other features that might confound discharge estimates. The flow meter used was a Flowatch® from JDC Electronics SA, which has a precision of ±2% and a resolution of 3 cm/s. The stream was divided into three width sections based on a cross-section, and during each storm event velocity was gathered for each section once every 5 minutes.

3 Methods

3.1 Rainfall Input

In order to determine the rainfall associated with a 90th percentile storm, the 43 years of NCDC COOP rainfall data were aggregated into daily totals and the 90th percentile value of days with rainfall was computed, based on the entire dataset. Accumulated data was included if the entire period of accumulation fell within one day. Any days containing missing data were excluded. As the state of Maryland defines storm events as 24-hour periods with rainfall (MDE 2009), this 90th percentile value is analogous to the quantity of rainfall that serves as the basis for the WQ_v. The 90th percentile storm calculated from the NCDC COOP data was found to be 27.94 mm, which is relatively close to the value that the state of Maryland found for the eastern part of state, 25.4 mm (MDE 2009).

Only 5 years of data are available in the GSFC rainfall dataset, which is insufficient for a long-term frequency analysis. Instead, the high sensitivity of this data allows for identification of discrete storm events and accurate measurement of the intensity of rainfall. To establish a basis for comparison with the NCDC COOP dataset, the GSFC data was aggregated into daily totals and compared with the NCDC data for the period of overlap (Figure 2). The level of agreement varies with the size of the storm event, but in general the two datasets show similar results.

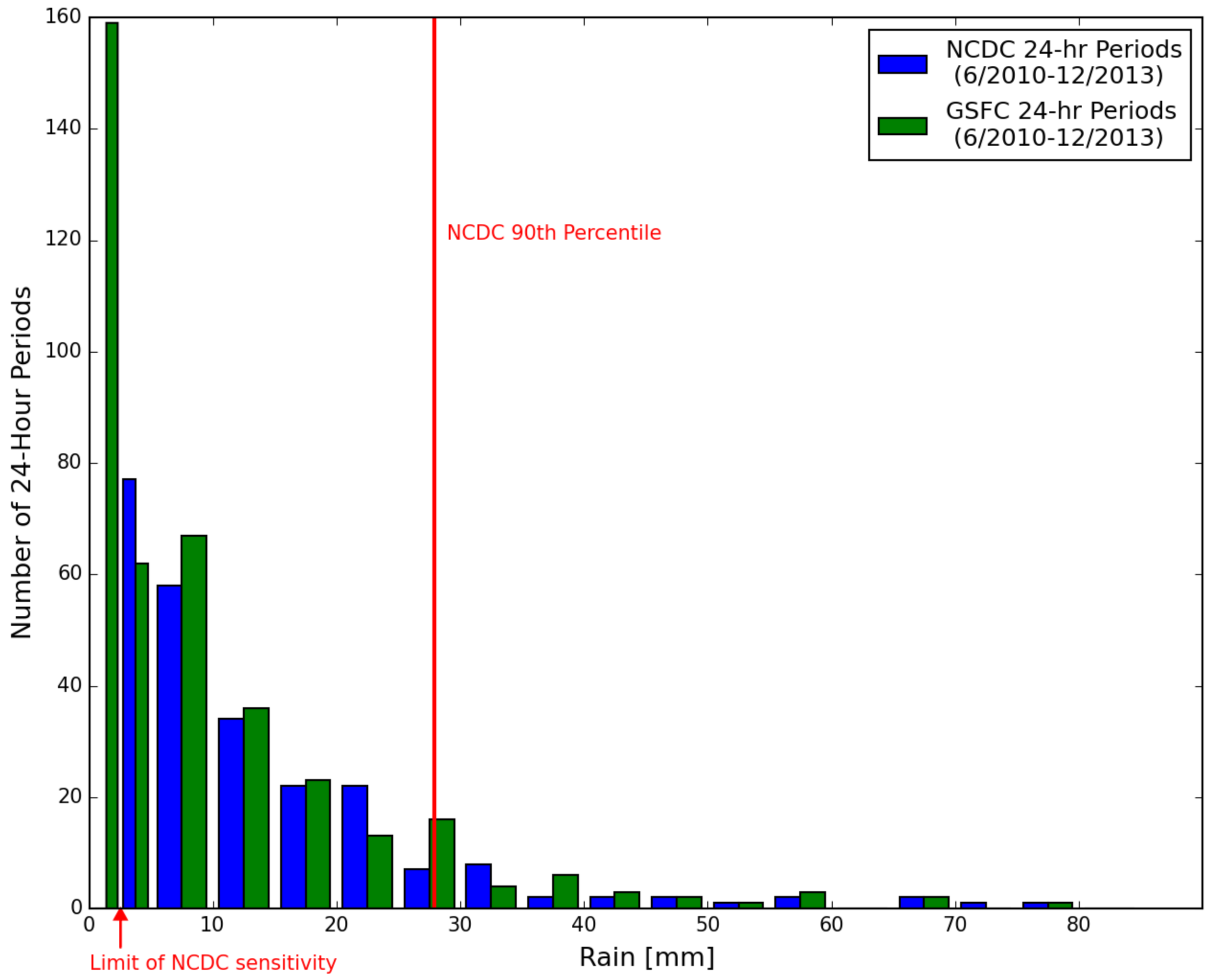

Figure 2: Histogram of 24-hour periods with rainfall during the overlap between the NCDC COOP and GSFC datasets (June 2010 through December 2013). The 90th percentile of the NCDC COOP dataset is marked with a red line. Also, note that the smallest bin does not contain any data for the NCDC COOP dataset because this is below the sensitivity of the gauge.

Discrete storm events were then found in the GSFC dataset, and duration, intensity, and total rainfall were calculated for each. A moving frame technique was used to identify the beginning and end of storm events in the GSFC data. Specifically, the beginning of a storm event was defined as greater than or equal to 1.524 mm of rain in 30 minutes, and the end was defined as less than or equal to 0.508 mm of rain in 30 minutes. The storm events identified in the record are summarized in Figure 3. The storm events selected for simulation are summarized in Table 1, and were selected to be similar in size to the 90th percentile storm, but of variable intensity.

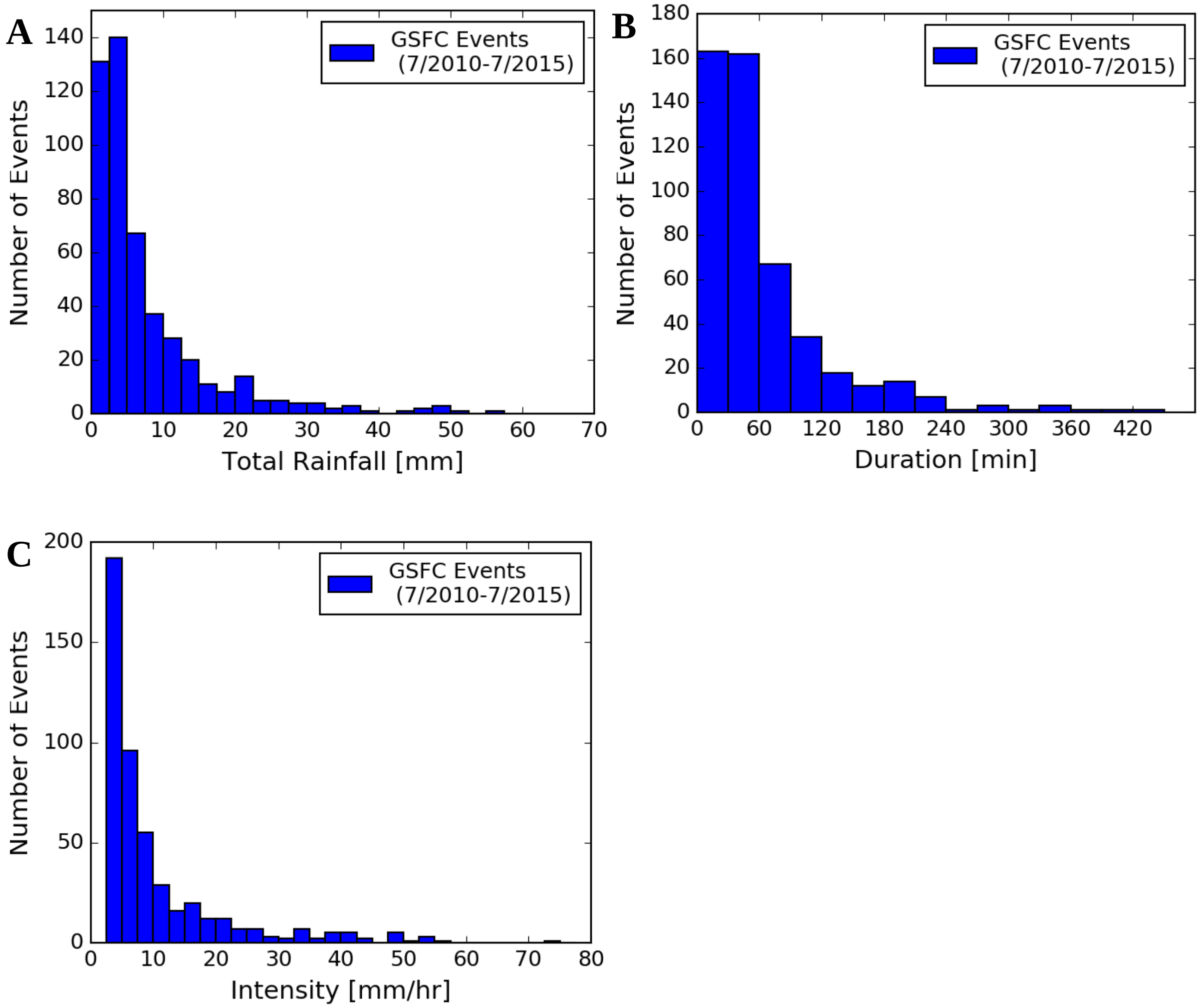

Figure 3: Histograms of total rainfall **(A)**, duration **(B)**, and intensity **(C)** for all GSFC rain events. Parts **A** and **B** were cropped to exclude a single extreme outlier. In part **C**, the smallest bin is not included as this is below the minimum required for event detection. The data in these figures was collected over a period of five years.

Table 1: Historical Storm Events Selected for Modeling

	A	B	C
Date	6/10/2013	6/3/2014	1/23/2015
Start Time	20:15	13:55	20:55
Total Rainfall (mm)	21.6	28.7	23.6
Total Rainfall (in)	0.850	1.13	0.929
Duration (min)	95	45	370
Intensity (mm/hr)	13.6	38.3	3.83

3.2 SWMM Model

SWMM represents the modeled watershed as a collection of sub-catchments: small, homogenous, user-defined subareas with an outlet node that is either a storm sewer or another subcatchment. Slope, impervious area, Manning's coefficient for surface runoff, and pervious and impervious depression storage can all be specified separately for each subcatchment, allowing representation of a broad spectrum of surface types. SWMM represents the drainage system with a network of nodes (sewer entrances, pipe junctions, outfalls, etc.) and links (pipes and natural channels) (Rossman 2010).

A topographical map of the study area generated from the LVIS data was used to identify ridgelines and delineate subcatchments for use in SWMM. A separate subcatchment was delineated for every storm drain linked to the model area. In addition, several areas, including the large wooded area in the center of the model domain, were further divided to better reflect the conceptualization of a subcatchment used by SWMM, which is a rectangular plane with a uniform slope draining into a stream along one edge (Rossman 2010). An effort was also made to separate pervious and impervious area into different subcatchments, with a special focus on directly-connected impervious area, which has been shown to have a significantly greater impact on runoff than other impervious area (Lee and Heaney 2003). The GSFC Facilities Management Division provided GIS representations of the storm drain system. Whenever necessary, ridgeline and drainage system feature locations were validated with a commercial grade GPS handset. The resulting division consists of 46 subcatchments (Figure 3). All simulations were begun after a period of at least seven days without rainfall, and initial soil saturation was assumed to be at a minimum.

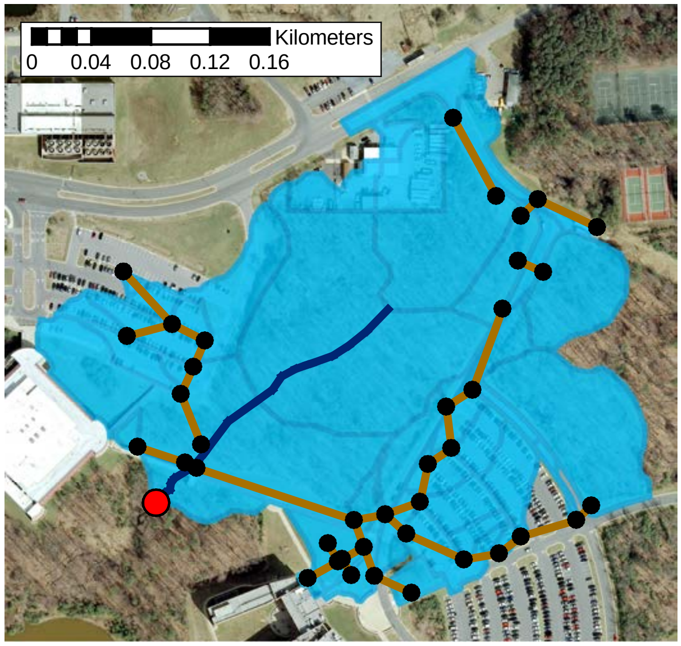

Figure 4: Map of the study area overlain with the objects of the current conditions model. The large red dot is the drainage basin outflow, the blue line is the stream, the black dots are drainage system junctions, and the orange lines are storm sewers.

3.2.1 Calibration

Model calibration with stream gauging data is necessary for generation of reliable results. Many calibration methodologies exist, and in this study traditional procedures similar to those described by James and Burghes (1982) were used. Four storm events from those with available stream gauging data were selected for calibration (Table 2), chosen to provide a variety of rainfall quantities and intensities. To quantify the differences in both peak discharge and total flow volume, relative error was calculated:

$$Relative\ error = \frac{(S - R)}{R} \times 100$$

S is the simulated value and R is the recorded value. Pearson's coefficient of correlation (*r*) was computed between the simulated and recorded series as a third calibration metric. In addition, time series plots of observed and modeled discharge and scatterplots of observed versus modeled discharge were visually inspected.

Table 2: Calibration Storm Events

	C1	C2	C3	C4
Date	10/15/2014	12/16/2014	6/23/2015	7/30/2015
Total Rainfall (mm)	20.1	8.13	20.1	6.60
Duration (min)	500	110	40	55

To improve the calibration, several different parameters were adjusted within the model. Liong et al. (1991) divides SWMM calibration parameters into two categories: traditional parameters which are difficult or impractical to measure reliably, such as roughness coefficients, surface depression storage, and the parameters of the Green-Ampt infiltration equation; and non-traditional parameters which can be measured or derived from measured values, such as slope, width, and impervious area. The traditional parameters may be adjusted within an accepted range, and while the non-traditional parameters can theoretically be measured, they may also be used as calibration parameters within the error of their measured values. Width, equivalent to the quotient of subcatchment area and the length of the average overland flow path, is particularly difficult to measure accurately, and so may be manipulated considerably during calibration (Gironas et al. 2009).

These parameters were altered in an iterative, informal fashion until it was judged that an acceptable fit had been achieved. Table 3 presents the range in which each parameter was adjusted and the final value. The final hydrograph corresponding to the storm event with the most available stream gauging data is displayed in Figure 4, and the calibration metrics for all four events are summarized in Table 4. The quality of this calibration would be improved with more diversity in the stream gauging data for this watershed. Specifically, more data points are needed at high flow events to confirm the upper end of the rating curve for the drainage basin.

In addition, there are several other potential sources of error in the stream gauging measurements. The drainage basin is very small and the stream responds to rainfall very quickly, which means that discharge measurements are highly sensitive to the time of collection. Also, the measurements were collected with a handheld sensor deployed throughout a cross-section of the stream in real time, introducing error from imperfect sensor placement by the experimenter. Measurements collected at fixed stations with installed flow meters, V-notch weirs, and automated stage readers would produce more consistent results but were not possible at this site. Finally, the cross-section of the stream was measured in July 2014, and it is possible that the cross-section changed due to accrual of sediment and debris during the period of collection, which concluded in August 2015. The calibration results are not ideal, but they are adequate for the purposes of this study, which focuses on the relative differences in the hydrological regime caused by installation of BMPs.

Table 3: Calibration Parameter Ranges and Selected Values

Parameter [units]	Range	Value
Percent impervious area [%]	±15% of baseline[a]	-15%
Slope [%]	±30% of baseline[a]	-30%
Width [ft]	±50% of baseline[a]	-50%
Impervious depression storage [in]	0.05 – 0.10	0.05
Pervious depression storage [in]		
Grass	0.10 – 0.20	0.20
Grass/forest mix	0.20 – 0.30	0.30
Forest	0.30	0.30
Impervious Manning's *n*	0.011 – 0.012	0.011
Pervious Manning's *n*		
Grass	0.15	0.15
Grass/forest mix	0.15 – 0.40	0.40
Forest	0.40 – 0.80	0.40
Link Manning's *n*		
Pipe	0.011 – 0.015	0.015
Regular natural channel	0.030 – 0.070	0.060
Irregular natural channel	0.040 – 0.100	0.090
Saturated hydraulic conductivity [in/hr]		
Undisturbed soil	0.15 – 0.30	0.26
Disturbed soil	0.00 – 0.05	0.05
Suction head [in]		
Undisturbed soil	3.50 – 6.69	6.69
Disturbed soil	8.27 – 12.60	8.27
Initial moisture deficit		
Undisturbed soil	0.217 – 0.231	0.217
Disturbed soil	0.097 – 0.154	0.154

[a] Baseline value was determined individually for each subcatchment based on satellite imagery and DEM data, and this value was adjusted by relative quantities during calibration.

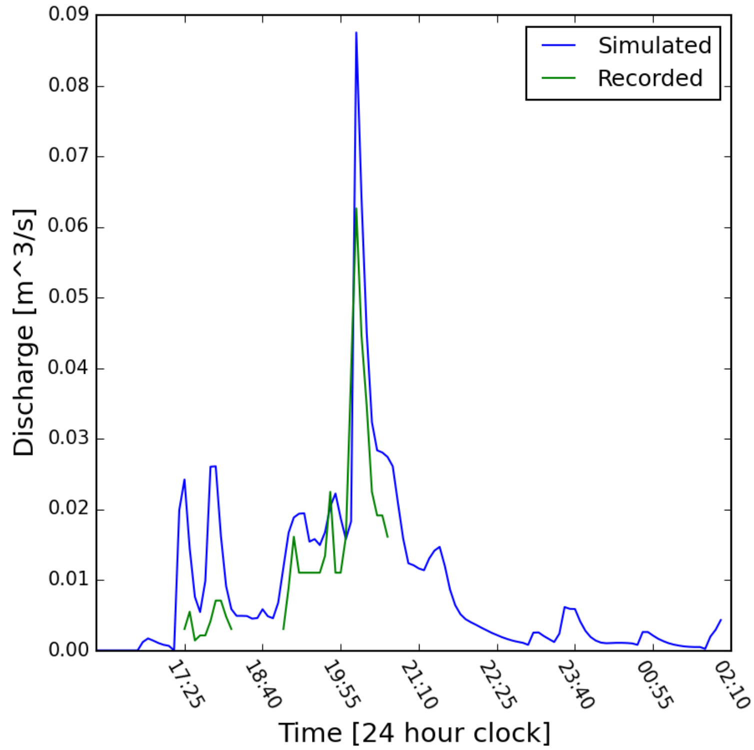

Figure 5: The final calibration for the model of a storm event that occurred on 10/15/14. Gaps in the line of stream observations are time periods for which data was not gathered. This is storm event C1 in Table 2.

Table 4: Calibration Results

	Storm Event			
Metric	**C1**	**C2**	**C3**	**C4**
Peak discharge relative error [%]	39.78	--[a]	--[a]	57.49
Total volume relative error [%]	50.70	-45.45	-1.99	53.91
Pearson's *r*	0.864	0.900	0.839	0.923

[a] The peak discharge was not captured in the stream gauging dataset for this storm.

3.2.2 Validation

Validation was conducted using the exact same methodology as calibration. Five separate storm events were selected (Table 5), once again representing a diversity of sizes and intensities. The results are presented in Table 6. The errors and correlation coefficients are broadly similar to those of the calibration storm events, although the validation results show more variability. This further shows that conclusions may only be drawn from the relative changes in model results between different simulations.

Table 5: Validation Storm Events

	V1	V2	V3	V4	V5
Date	10/22/2014	11/17/2014	11/26/2014	12/2/2014	6/1/2015
Total Rainfall (mm)	17.8	11.2	11.7	6.86	27.2
Duration (min)	450	170	235	140	285

Table 6: Validation Results

	Storm Event				
Metric	**V1**	**V2**	**V3**	**V4**	**V5**
Peak discharge relative error [%]	--[a]	-25.33	-52.80	-29.29	--[b]
Total volume relative error [%]	-13.61	-33.58	-60.91	-64.33	17.24
Pearson's *r*	0.400	0.874	0.786	0.948	0.943

[a] The peak discharge was not captured in the stream gauging dataset for this storm.

3.2.3 BMP Implementation

In addition to the current conditions model, three other possibilities were simulated: a pre-development model, to provide a baseline for quantifying the effects of development; and two organic filter models. The first organic filter model was sized according to the Maryland design guidelines, and the second was modeled to be larger, able to contain the entire volume of water resulting from 25.4 mm of rainfall, which the state of Maryland defines as the upper limit of the storms that should be included in the water quality volume (WQ_v) regulation (MDE 2009). Henceforth, these models will be referred to as the "Maryland" and "full" organic filters, respectively.

In the pre-development model, all parking lots and other impervious areas were converted to pervious forest area, and the area was simulated as several large subcatchments lacking all artificial features of the current drainage system. To allow for an equitable comparison with other conditions, the total area of the drainage basin was not altered, despite the fact that the installation of storm sewers and alteration of the topography during development may have changed the drainage basin area.

For the two organic filter models, filters were modeled receiving and treating runoff from both parking lot 32, to the west of the central forested area, and parking lot 33, to the east of the central forested area (Figure 5). The Maryland Stormwater Design Manual describes an organic filter as a practice that captures and temporarily stores the WQ_v and passes it through a filter bed of organic matter (MDE 2009). The WQ_v is given by:

$$WQ_v = \frac{(P)(R_v)(A)}{12}$$

P is the rainfall depth to treated, in inches, which is 1 in. in the Eastern rainfall zone. A is drainage basin area (acres) and R_v is the volumetric runoff coefficient, given by:

$$R_v = 0.05 + 0.009(I)$$

I is the percent impervious cover of the drainage basin. By these formulae, the WQ_v was found to be 93.7 m^3 for the parking lot 32 organic filter and 260 m^3 for the parking lot 33 organic filter. These values were used for the organic filters modeled to Maryland criteria, but for the “full” organic filters, it was assumed that all of the rainfall incident on the drainage basin would produce runoff, and a value of $R_v = 1.0$ was used. This was done to establish an arbitrary but larger organic filter size for comparison with the standard size. This yielded WQ_v values of 103 m^3 for parking lot 32 and 602 m^3 for parking lot 33.

Organic filter locations

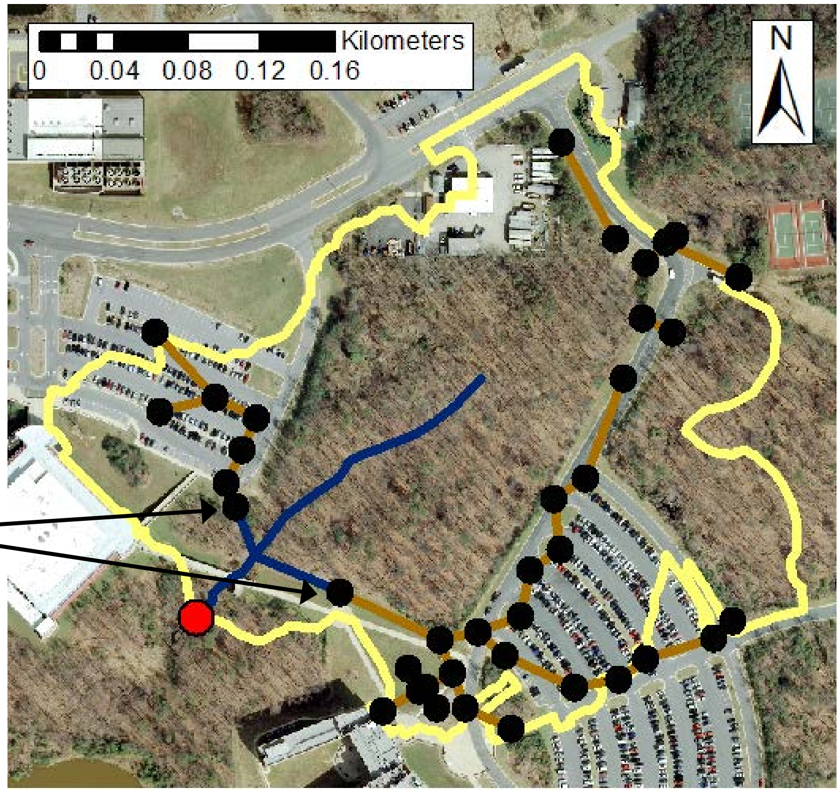

Figure 6: Map of the organic filter model. The organic filter basin locations are labeled with arrows. The large red dot is the drainage basin outflow, the blue lines are streams, the black dots are drainage system junctions or BMPs, and the orange lines are storm sewers.

The modeled organic filter bed consists of several layers: from the surface, a 3” (76.2 mm) layer of topsoil, an 18” (457.2 mm) layer of 50/50 peat/sand mixture, and a 6” (152.4 mm) layer of sand. In addition, a 6” (152.4 mm) diameter underdrain should be installed beneath all of these layers. Bio-retention cells, one of the low impact development (LID) objects available in SWMM, with these properties were used to represent these BMPs. The LID objects were placed in the modeled environment to receive the runoff from the existing parking lot drainage systems. The pipes leading from the parking lots to the stream were modeled to terminate halfway down the slopes to the streambed, at outflows leading into the LID objects.

Filtration practices are highly susceptible to clogging with sediment and debris (Gulliver et al. 2010), and the MDE requires pretreatment with a sedimentation basin. In SWMM, these sedimentation basins were modeled as small rain gardens, a second SWMM LID object, with a surface area equal to roughly half of that of the bio-retention cell. The sedimentation basins and organic filters were connected by a conduit specified to represent a short open channel. At the downstream end, the organic filter was configured to spill into another open channel modeled to resemble the existing streambed. According to the Maryland specifications, the combined surface storage of the organic filter and the sedimentation basin must be 75% of the WQ_v (MDE 2009), and the surface area and berm height of these objects was adjusted to meet this criteria for the Maryland organic filters. For the full organic filters, the surface area and berm height were adjusted to contain 100% of the alternate, “full” WQ_v, calculated as described above. This means the full organic filters were larger in two ways: a larger WQ_v was calculated using a runoff coefficient of 1.0, and the filter systems were modeled to contain the entirety of this larger WQ_v, rather than 75%.

4 Results

The changes in peak discharge and total flow volume between the pre-development model and current conditions are given in Table 7. According to both metrics, the model predicts that this drainage basin had almost no surface runoff before development for storms similar in size to the 90^{th} percentile storm.

Table 7: Pre-Development and Organic Filter Simulation Results[a]

Storm Event	A	B	C
Total Runoff			
Pre-Development [%]	-100.0	-99.14	-100.0
Maryland Organic Filter [%]	-54.20	-37.49	-59.77
Full Organic Filter [%]	-77.19	-68.71	-83.19
Peak Discharge			
Pre-Development [%]	-100.0	-99.49	-100.0
Maryland Organic Filter [%]	-33.56	-20.47	-24.09
Full Organic Filter [%]	-79.33	-68.21	-82.57

[a] Results are expressed in terms of percent change from current conditions. Letters denote the storm event simulated, which are shown in Table 1. A: 6/10/13; B: 6/3/14; C: 1/23/15

Table 7 also presents the peak discharge and total flow volume results for the organic filter simulations. The hydrographs are displayed in Figure 9 for the Maryland organic filter simulations and Figure 10 for the full organic filter simulations. These model results suggest that the regulation size organic filters produce substantial reductions in total flow volume, varying between 37% and 60%. However, the full organic filters perform much better, decreasing total flow volume by between 69% and 83% compared to current, developed conditions. An even greater difference is observed with peak discharge, where the normal Maryland organic filters produced reductions between 20% and 34% and the full organic filters produced reductions between 68% and 83%. The greatest reductions were generally observed during storm C, followed by storm event A. The hydrographs show that all of the organic filters tend to delay the time of peak discharge considerably, and the full organic filters significantly flatten the hydrological response into a state that is relatively close to pre-development conditions.

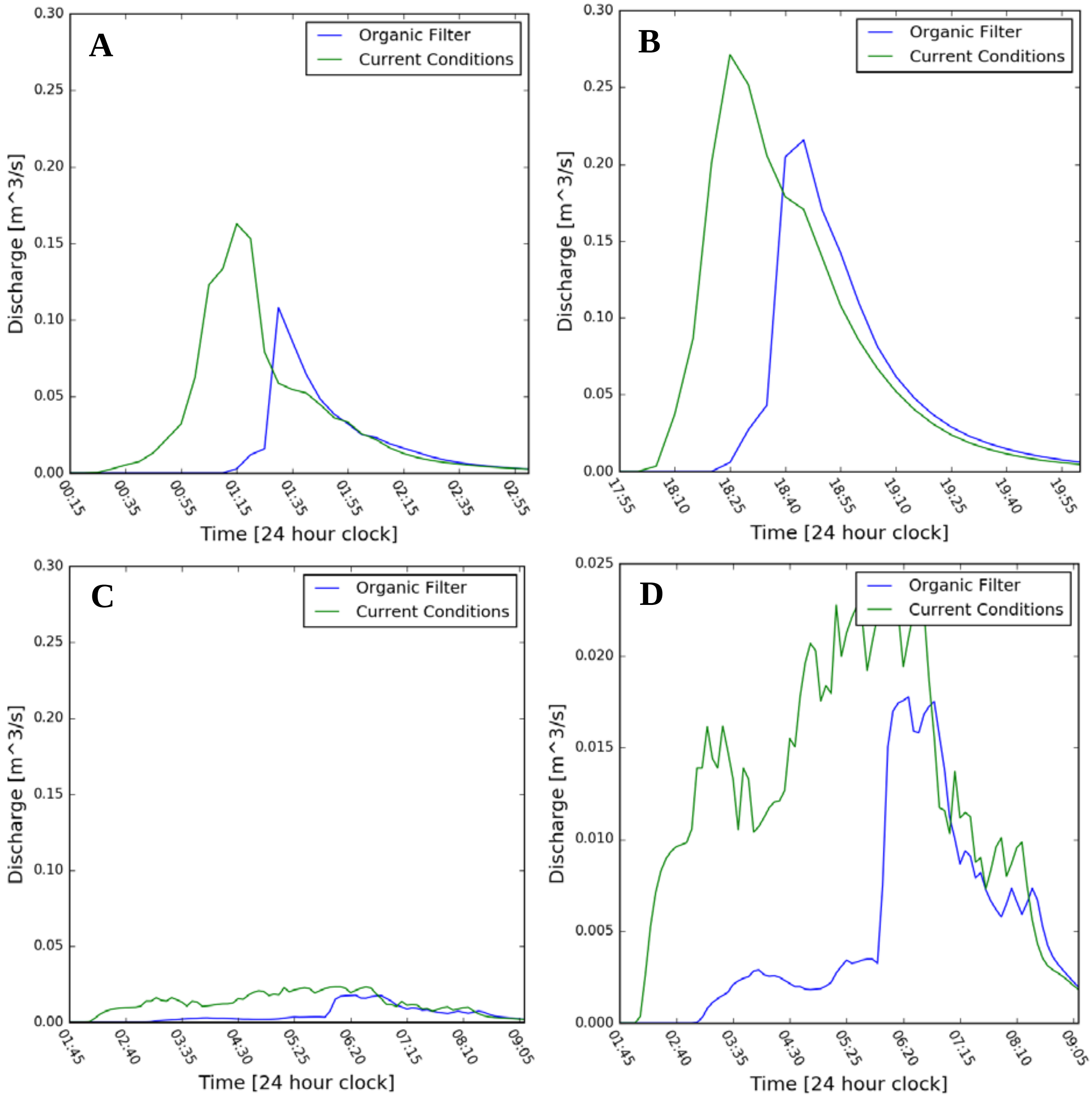

Figure 7: Hydrographs of current conditions and Maryland organic filter model results for all three storm events described in Table 1 are shown in **A** through **C**, with the letters corresponding to those in Table 1. **D** shows storm event C with a reduced y-axis scale to allow better discernment of the differences between the organic filter and current conditions results.

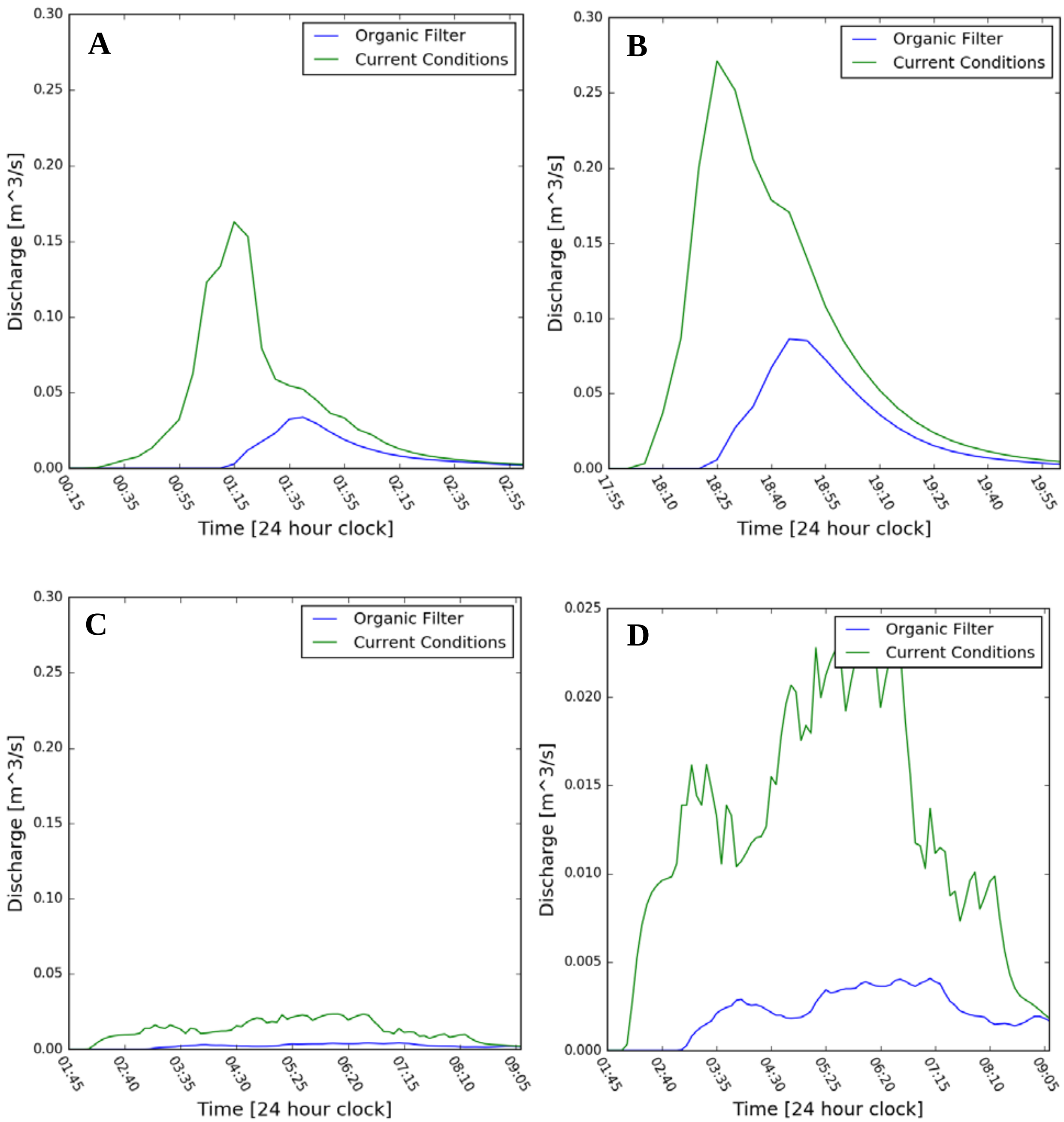

Figure 8: Hydrographs of current conditions and full organic filter model results for all three storm events described in Table 1 are shown in **A** through **C**, with the letters corresponding to those in Table 1. **D** shows storm event C with a reduced y-axis scale to allow better discernment of the differences between the organic filter and current conditions results.

In fact, the organic filter models cannot be expected to completely reduce runoff to pre-development levels, as a portion of impervious area at the northern end of the drainage basin does not route into the organic filters, but rather into the central forested catchment to form the first stretch of the stream. The contribution of this area to post-development runoff was found to be roughly equal to the remaining difference between the full organic filter model and pre-development conditions. In other words, the full organic filters are completely removing runoff from their treated areas.

5 Discussion

All of the organic filter models were predicted to have a substantial impact on runoff metrics, but the full organic filter performed dramatically better than the filters modeled according to standard Maryland specifications. The reduction in total flow volume was 20-25% better, and the reduction in peak discharge was 45-55% better, as a percentage of current conditions. When one accounts for the untreated impervious area in the northern part of the drainage basin, it becomes clear that the full organic filters are essentially mimicking pre-development runoff conditions, which is a highly desirable goal of stormwater management (Konrad and Booth 2005).

In both organic filter models, the filters were typically more effective in lower intensity storm events. This was true with respect to both runoff metrics, although the differences were somewhat greater for total flow volume. This result is not surprising, as longer storm events allow more time for water to infiltrate, but it shows that intensity may be an important consideration in the design and selection of BMPs. However, the differences related to intensity only seem to be dramatic for storm event B, which has an uncommonly high intensity of 38.3 mm/hr (Figure 8). The organic filters performed in a more similar manner during storm events A and C, which both have reasonably common intensities.

One possible caveat to these conclusions is that groundwater and subsurface discharge were not included in any of the models in this study, which means that the pre-development basin may have had some base flow due to subsurface discharge. This might marginally close the gap between the results of the organic filter and pre-development models, but it is unlikely the difference would prove significant. The drainage basin is quite small (7.2 ha), and the percent impervious cover after development is approximately 20%. Any possible change in groundwater discharge is unlikely to be similar in magnitude to the modeled differences in streamflow caused by development.

In this modeling investigation, organic filters constructed according to the Maryland WQ_v regulation were effective but not sufficient to mimic the pre-development environment, which is important for the protection of aquatic stream ecosystems. Responsible management therefore may require going beyond the regulations to implement practices that bring the post-development runoff environment as close to the pre-development baseline conditions as possible. Complete replication of the pre-development environment is not practical in some cases, but this should be evaluated on a site-by-site basis. It should also be noted that the rainfall analysis indicated that an annual average of 4.4 rain events exceed the 90th percentile storm. The hydrological impacts of these high volume or high intensity storms are not addressed by this study but may be worth considering for truly effective stormwater management.

Conclusion and Future Work

This study sought to investigate the effectiveness of BMP development options specified by the state of Maryland. The results show that while the BMPs, organic filters, have a substantial impact on runoff when constructed according to Maryland specifications, they only fully replicate the pre-development runoff environment when constructed according to a considerably larger specification. Effective watershed management would therefore require exceeding the official specifications for BMPs and constructing structures predicted to be effective under the particular conditions of this site. It is likely the same conclusion holds at many other sites, and this highlights the importance of performing site-specific investigations prior to construction, rather than adhering to the minimum standard of the regulations. In the future, it would be beneficial to model other BMPs that may be considered for this and other sites on the GSFC, as well as collect additional and more accurate stream gauging data to improve the model calibration.

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Regional Earth Science Applications Center (RESAC) at the University of Maryland. This dataset is obtainable from http://lvis.gsfc.nasa.gov/Data_Download.html.

The imagery in Figures 1, 3, and 5 is a high-resolution aerial photography product from the Maryland State Imagery Acquisition Partnership. The dataset is named 201103_south_central_maryland_state_md_6in_sp_cnir and the specific image may be retrieved from the High Resolution Orthoimagery dataset in the Aerial Imagery section of earthexplorer.usgs.gov with the entity ID 2645106_34478902.

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