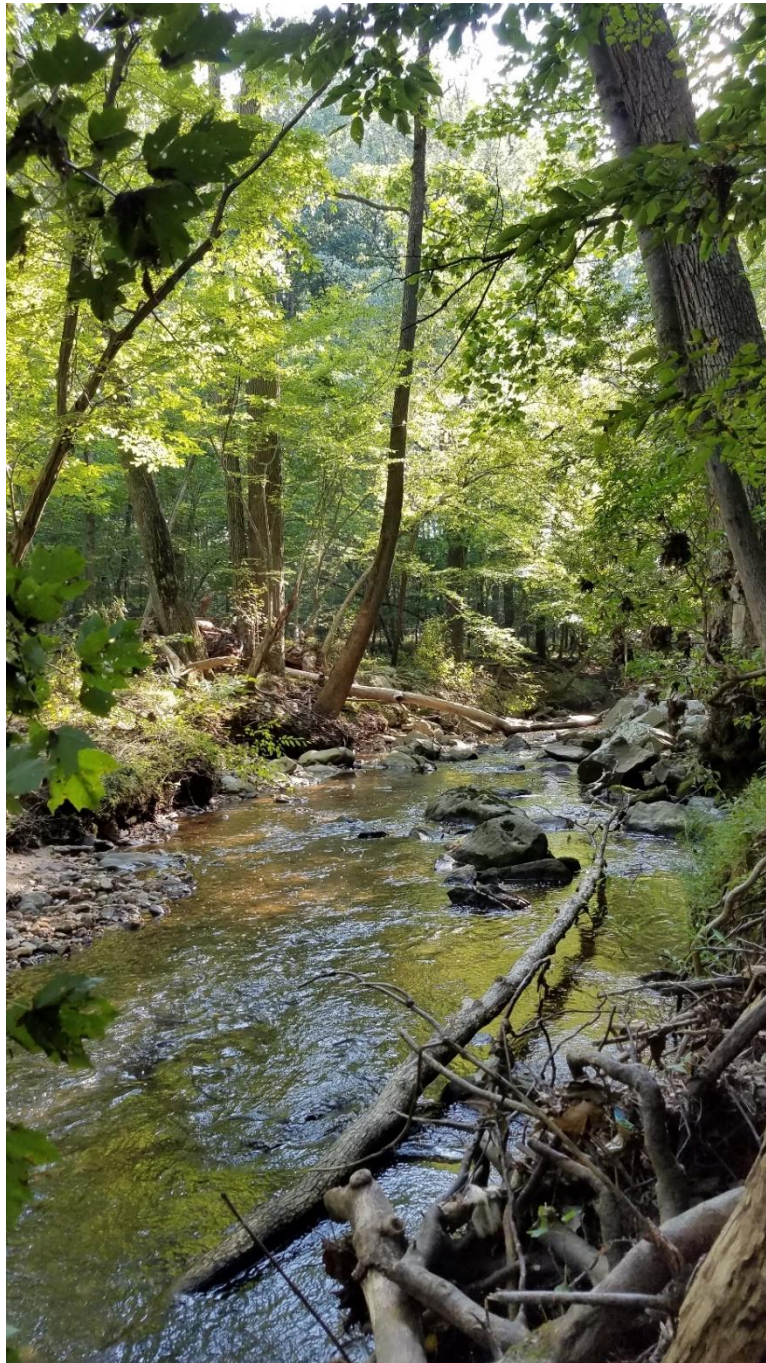




Hydrologic Evaluation of Wolf Trap National Park for the Performing Arts 2019

Sarah Paschal Gerenday – Geoscientist in the Parks





This report is available in digital format from the Urban Ecology Research Learning Alliance. To receive a copy of this report, please email ann_gallagher@nps.gov.

Please cite this publication as:

Gerenday, S. P., 2019. UERLA Report: Hydrologic Evaluation of Wolf Trap National Park for the Performing Arts.



Acknowledgements

This work would not have been possible without the help of Stephen Hay, Ann Gallagher, Matthew Schley, and Gary Smillie.

Contents

Introduction.....	4
Mapping and Geospatial Analysis	4
Hydrologic Modeling.....	11
Model Setup	11
Results	17
Interpretation.....	29
Problem Areas.....	32
Recommendations	39
References	44
Appendix: HEC-HMS Input Tables.....	46



Introduction

Wolf Trap National Park for the Performing Arts (WOTR) is a 0.47 km² national park located in Vienna, Virginia (Walsh et al. 2015). The park features outdoor performance venues, open space, and a forest with hiking trails. The park is situated within the Difficult Run watershed and contains two creeks: Wolf Trap Creek, which runs southeast to northwest through the park, and Old Courthouse Spring Branch (Courthouse Creek), which enters the park from the northeast and joins with Wolf Trap Creek. WOTR is surrounded by suburbs and bounded on the south side by the Dulles Toll Road. Runoff entering the park from the toll road and surrounding suburbs contributes to flow in the two creeks and erosion within the park. Given the continuing development of the watershed and the abundance of impervious surfaces in and around the park, attention has been paid to managing runoff. In 2012, the Dimple, a lawn and stormwater capture area, was converted to a native meadow with a high capacity for infiltration, while maintaining its bowl-like shape. In 2018, three bioretention basins and an oil water separator were installed around the maintenance yard to capture and treat runoff before it enters Wolf Trap Creek.

In the summer of 2019 a project was undertaken at WOTR to provide insight on runoff, flooding, and erosion in the park. To this end maps and hydrologic models of the park and surrounding area were created. Mapping and geospatial analysis were done using ArcGIS. Hydrologic modelling was done using the United States Army Corps of Engineers' Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS). Maps and models were based on 1/9 arc-second digital elevation models (DEM) from the United States Geological Survey (USGS), soil survey data from the National Resource Conservation Service (NRCS), the 2016 Virginia Land Cover Dataset from the Virginia Geographic Information Network (VGIN), the Fairfax County Stormwater Infrastructure interactive map, various surveys and construction plans on file at WOTR, and field observations.

Mapping and Geospatial Analysis

Fairfax County provides a detailed interactive map of stormwater infrastructure in the community surrounding WOTR, which is helpful for determining where water enters the park; however, the county map does not include WOTR's stormwater infrastructure. The park's stormwater infrastructure is documented in some of the park's existing maps and construction plans, but no shapefiles of the network existed prior to this point. The first objective of mapping was therefore to create these shapefiles (Figure 1). Storm drain inlets and outlets were recorded as points, while culverts connecting them were represented as lines. Another line shapefile was created for trench drains, and bioretention areas were represented by polygons. Having the shapefiles allows WOTR's stormwater network to be queried and easily added to any map.



Figure 1: Map of stormwater infrastructure and water monitoring points in WOTR.

Most of the geospatial analysis was done to support hydrologic modeling. Wolf Trap Creek and Courthouse Creek are the primary hydrologic features of the models with the surrounding land divided into subbasins which drain into them at certain points (or in some cases, along certain segments) (Figures 2-3). Subbasins were delineated based on a 1/9 arc-second DEM from the USGS. DEMs are raster datasets with an elevation value at each point in a grid covering the study area. The DEM was processed in ArcGIS using the Hydrology toolset from the Spatial Analyst toolbox. The subbasins were approached as miniature watersheds, so an outlet, referred to in ArcGIS as a pour point, had to be identified for each. Pour points were chosen at stream and tributary junctions, as is typical when defining watershed boundaries. Since WOTR's stormwater infrastructure was to be included in the model, storm drain inlets were also selected as pour points to determine the area in which runoff would be captured by each drain. Finally, since the DEMs show the elevations of the tops of bridges and culverts instead of the elevations of the flow paths underneath, these features appear to block channels in the DEMs.



Therefore, the upstream side of each major bridge or culvert on a stream of interest was designated as a pour point as well. This would allow for the creation of subbasins upstream and downstream of the feature, which could be added together to form a larger subbasin incorporating the bridge or culvert.

Before the DEM could be used to delineate subbasins, it had to be modified slightly. Noise barrier walls exist on both sides of the Dulles Toll Road along much of its length, preventing sheet flow from coming directly off of the road. The barrier walls are an important consideration for modelling runoff but are too thin to be consistently captured by the 1/9 arc-second DEM. Therefore, lines were drawn in ArcGIS over the DEM where walls were located, and the elevation values of pixels overlapped by the lines were increased by 10 meters. ArcGIS evaluates flow paths by determining each point's lowest neighbor, so raising the walls ensured that flow would not be directed through them except at designated outlets. Additionally, it is common for DEMs to contain points which are lower than all of their neighbors, known as sinks. Often, these sinks are single-pixel artifacts which interfere with evaluating flow direction and delineating watersheds, so the typical approach is to fill them using the Fill tool, which iteratively raises pixels until there is a continuous flow path. Many of the pour points appear as sinks, which should not be filled so that they can capture the intended flow. The Fill tool does allow the user to specify a that sinks below a certain depth should not be filled, but many of the pour points can only be distinguished from artifact sinks based on known location, not depth. Therefore, DEM cells coinciding with pour points were lowered by 10 meters so that they could be easily distinguished. The Fill tool was then used to fill sinks less than 1.656 meters, a depth chosen by trial and error to remove most artifact sinks and leave the intended ones. Afterwards, 10 meters was added to the pour points, returning them to their original elevations. With the majority of artifact sinks filled, the Flow Direction tool can be used to create a raster containing the direction that water would flow away from each cell in the DEM. Then the Watershed tool can be used with the flow direction raster and pour points as inputs to determine the catchment for each pour point.

The subbasins delimited with the semi-automated process must be edited and supplemented before incorporation into models. To start, subbasins up and downstream of a bridge or culvert were merged as explained previously. Additionally, storm drains can bring water into a subbasin from locations that would otherwise be outside its boundaries; therefore, the subbasins must be expanded to include the catchments of any stormwater infrastructure that directs water into them. There are many separate storm drains that only capture runoff from a small surface area but flow into the same drain line, thus contributing to a larger discharge that enters one of the streams at a single point. The catchments of some of these drains were combined to form a single subbasin for modeling purposes, represented in ArcGIS as a multipart polygon. Finally, any land in the park from which flow was not directed to any one pour point was divided into general subbasins feeding into a segment of stream.

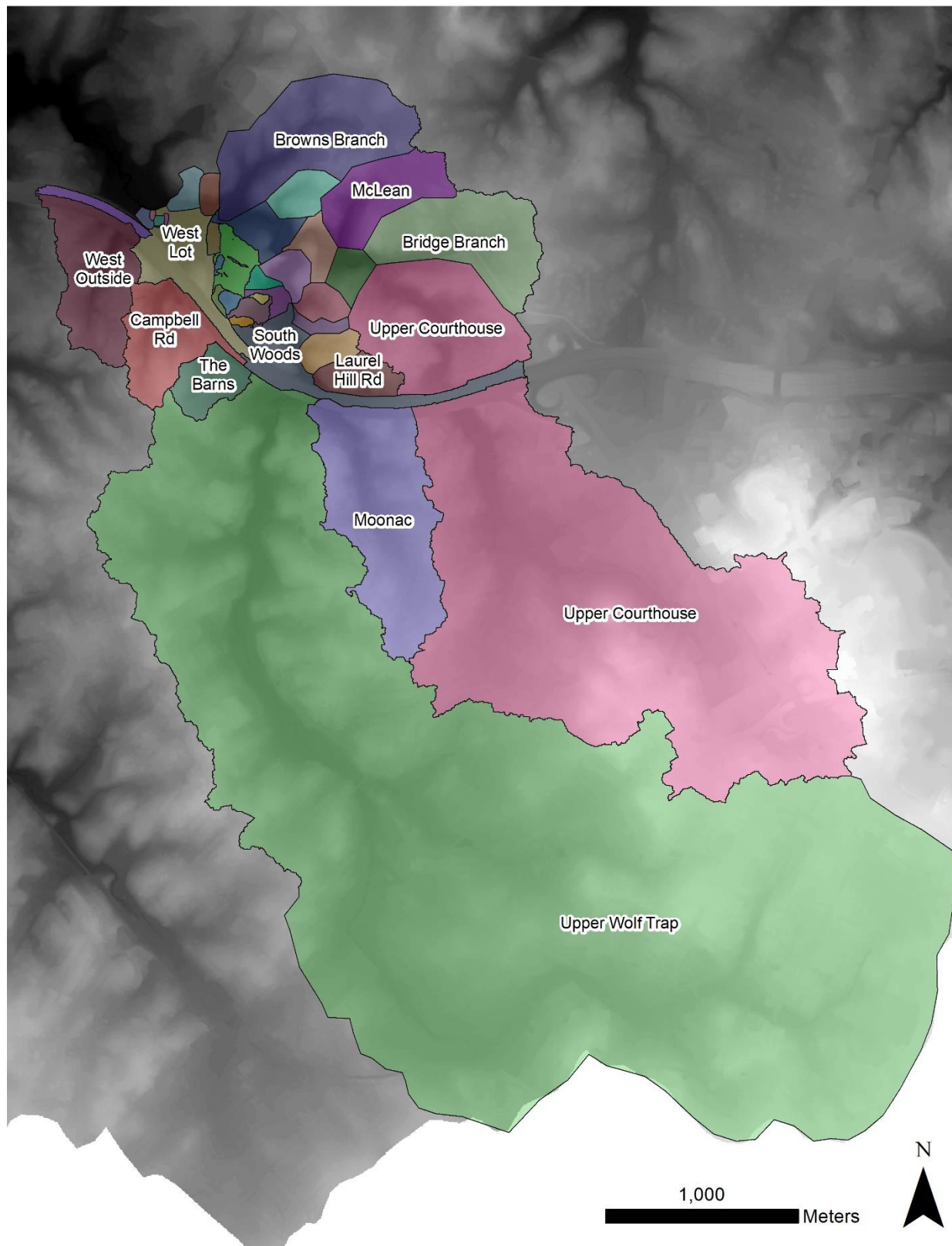




Figure 2: Subbasins used to model runoff and streamflow through WOTR.

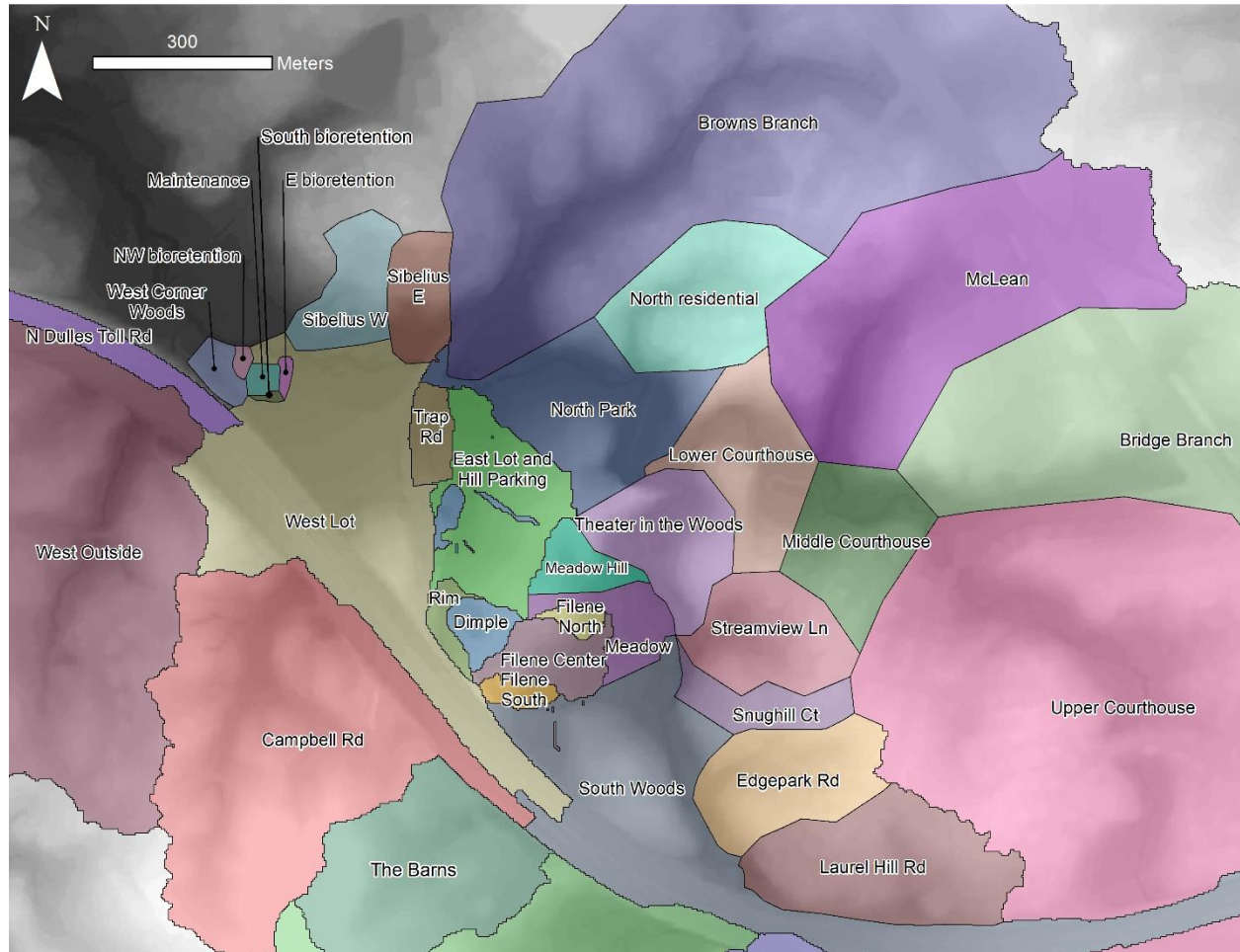


Figure 3: Close up of subbasins within and immediately surrounding WOTR.

The most significant factors influencing infiltration and runoff within each subbasin are landforms, soil, and landcover. A piece of land's capacity for infiltration can be described by its curve number, a unitless number between 0 and 100, where 0 represents total infiltration, and 100 represents total runoff. The curve number depends on the hydrologic group of the soil and on the landcover, both of which are documented at WOTR. A set of polygon shapefiles from NRCS with soil types covering all of the subbasin areas was classified based on soil hydrologic group. NRCS uses the letters A through D to denote hydrologic groups of natural soils, with A allowing the most infiltration and D the least. Soils in the model area were identified by NRCS as A, B, B/D, C, C/D, and "urban". A landcover raster from VGIN was classified as "impervious", "water", "grass", "trees", "forest", "rain garden", and "wetlands" then converted to another set of polygon shapefiles. A union of the two sets of polygons and the subbasins was calculated so that a soil group – landcover combination (e.g. group C, grass) could be identified



for each portion of each subbasin. Each combination was assigned a curve number based on United States Department of Agriculture (USDA) (Birckhead et al., 2017, Cronshey et al., 1986) and Water Environmental Research Foundation (2009) values. For areas with a dual soil designation, the average of their two curve numbers was used, and soil classified only as “urban” was assigned the highest curve number associated with the landcover at that location. The overall curve number for each subbasin was determined by area-weighted average. The total percentage of impervious area in each subbasin was calculated as well. An additional parameter, Manning’s number, describes a surface’s roughness and the friction it provides to flowing water. It is frequently presented as unitless but has dimensions of (time/ length^{1/3}). Each landcover class was assigned a Manning’s number based on the values provided by the USDA (Woodward et al., 2010), and an area-weighted average was computed for each subbasin.

Another important parameter calculated based on maps is the lag time. Lag time is the interval between the center of mass of a precipitation event (in terms of time, not space) and when peak runoff occurs. Lag time can be calculated as 60% of the time of concentration, which is the longest time needed for water falling within a subbasin to reach its outlet (Woodward et al., 2010). Since this relationship is typically used to describe natural watersheds, it is likely to be a better fit for the wooded parts of the park and surrounding area than for more developed subbasins.

$$T_{\text{lag}} = 0.6T_c$$

The NRCS velocity method calculates the time of concentration as the sum of the time water in a subbasin spends in sheet flow over the ground surface, shallow concentrated flow just below the soil surface, and channel flow.

$$T_c = T_{\text{sheet}} + T_{\text{shallow}} + T_{\text{channel}}$$

Sheet flow tends to be limited in extent and for the sake of modeling is assumed to end after 30.5 m unless there is a longer path over an impervious surface, in which case that path length is used. In the case of subbasins located at bioretention areas around the maintenance yard, sheet flow length is assumed to be half the length of the subbasin, as the basins have drains in the middle, which is less than 30.5 m from any edge. Sheet flow duration is calculated as

$$T_{\text{sheet}} = \frac{0.007(nl)^{0.8}}{P_2^{0.5} S^{0.4}}$$

where n is Manning’s number, l is sheet flow distance, P_2 is the maximum amount of precipitation falling in 24 hours which has a 50% chance of occurring in a given year, and S is surface slope as a decimal ratio. A P_2 of 4.4 cm was selected for all subbasins based on intensity-duration-frequency curves published by Fairfax County for Vienna and Tysons Corner. Average surface slope in the subbasins was calculated using the ArcGIS Slope and Zonal Statistics tools from the Spatial Analyst toolbox.



The distance of shallow concentrated flow in each subbasin is determined by using the Flow Accumulation tool in ArcGIS's Hydrology toolset to delineate likely flow paths based on topography. The length of the longest path before reaching a channel or exiting the subbasin minus the sheet flow distance is taken as the shallow concentrated flow length. The velocity is calculated using the equation

$$V = xS^{0.5}$$

from Birkhead et al. (2010) where S is decimal slope and $x = 6.962$ for flow in grassy areas, 20.328 for flow in paved areas, and 5.032 for flow in woods. T_{shallow} is then calculated by dividing distance by velocity.

Channel flow length is measured as the longest length along tributary or main channels in a subbasin and is 0 for some smaller subbasins. Channel flow velocity is calculated from Manning's equation:

$$V = \frac{1.49 R^{2/3} S^{1/2}}{n}$$

where n is Manning's number, S is decimal slope of the channel, and R is hydraulic radius, which is the ratio of channel cross sectional area to wetted perimeter (Figure 4). Wetted perimeter is the perimeter of the cross section excluding the air-water interface. Since channel flow is more concentrated in a single path than sheet flow, slope of the main identified channel in a subbasin was determined from the DEM with ArcGIS's Profile tool from the 3D Analyst toolbox instead of using the average slope of the whole subbasin. Main stream channels were modeled as trapezoids with a side slope of 1, depth of 3 cm, and a top width measured from aerial photographs. Smaller tributaries and ditches were modeled as triangles with the same depth and width assumptions. Channels and ditches were assigned Manning's numbers of 0.033 and 0.03, respectively, based on Chow (1959) tables.

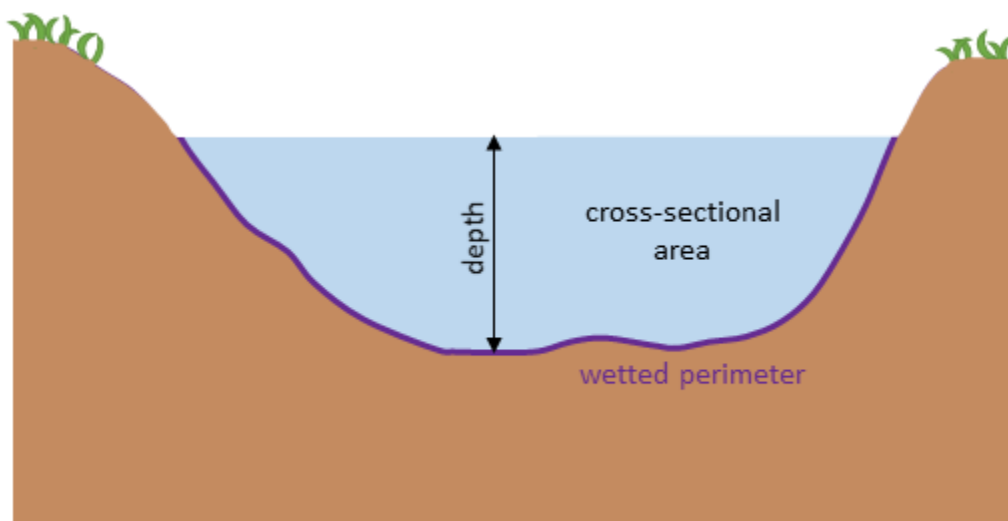


Figure 4: Illustration of channel cross-sectional dimensions. Wetted perimeter is the length of the boundary between the water and the bed or banks around the edge of the cross section.

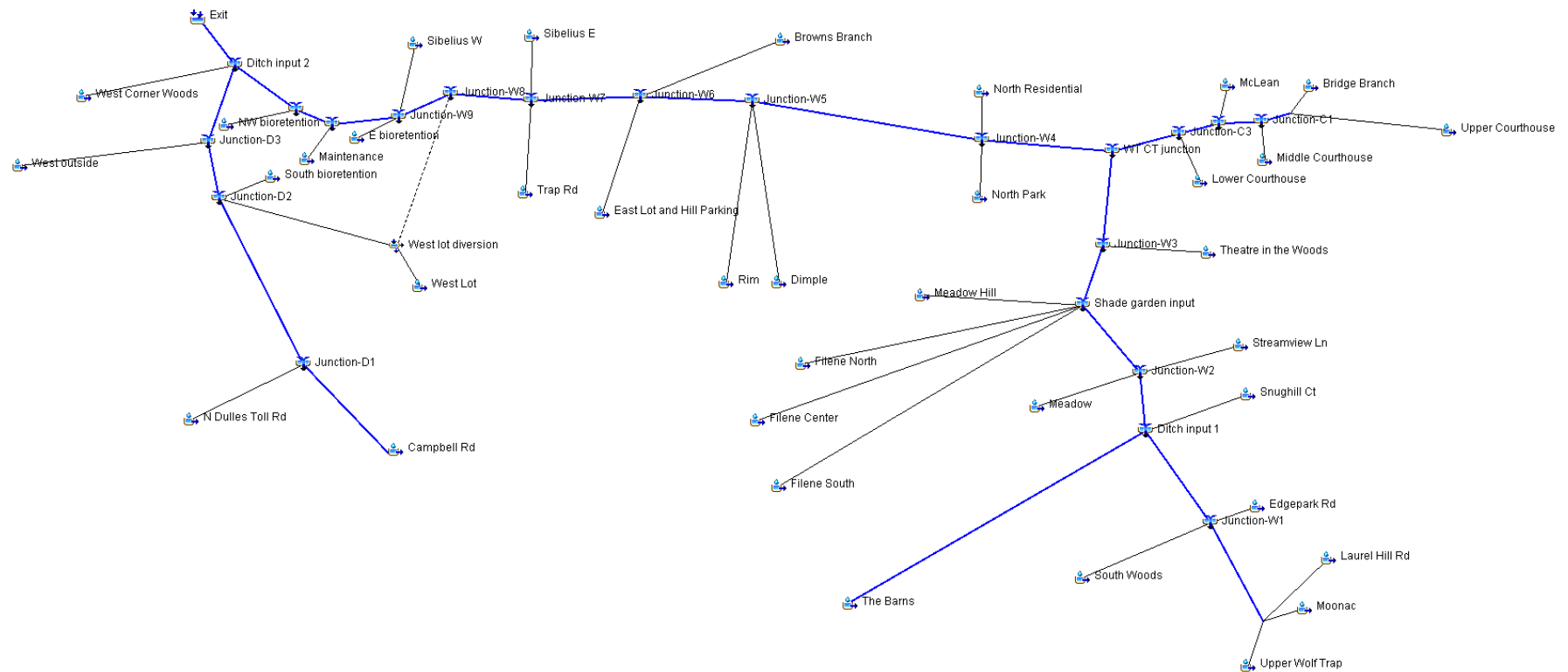
Hydrologic Modeling

Model Setup

A preliminary stormwater runoff and stream discharge model of WOTR was developed to determine where runoff is most intense and identify the main factors that contribute to it. This is expected to be of help in targeting best management practices (BMPs) for maximum effectiveness. The model was created in HEC-HMS, a software, developed by the US Army Corp of Engineers, which considers the model area to be a hydrologic basin containing subbasins in which precipitation falls before being routed through the rest of the drainage network. The program is commonly used on a larger scale to model rivers and their watersheds, but is used here to show how water moves through WOTR and the surrounding community during storms at 1-minute intervals. The model was based on a hydrologic network of 37 subbasins in which precipitation falls and runoff is generated, with parameters calculated as previously discussed. These basins were connected with 16 reaches representing segments of Wolf Trap Creek, 4 reaches representing segments of Courthouse Creek, and 5 reaches representing large ditches. The runoff from each subbasin is routed directly into one of the channels except for the West Lot subbasin, where water is split 60/40 between the adjacent ditch and Wolf Trap Creek based on the approximate areas of the parking lot in which runoff is observed to flow towards one channel or the other. The Dimple and three bioretention basins were represented as areas with a high infiltration capacity and an outlet at the center (Figure 5). Water entering a storm drain is assumed to be immediately carried to its outlet. Data used for modeling was largely compiled during the mapping and geospatial analysis phase. Inputs used in model are included in the



appendix. Additional information was provided by the National Oceanic and Atmospheric Administration (NOAA) as well as the National Park Service (NPS) Inventory and Monitoring (I&M) program. I&M maintained continuous depth loggers in Courthouse Creek and Wolf Trap Creek from 2012 to 2015 and have collected discrete depth, width, velocity, and discharge data for Wolf trap Creek since 2005 and Courthouse Creek since 2006.



13



The model does not use any canopy or surface methods but does specify loss, transform, and baseflow methods. The loss method controls how the model accounts for the infiltration of rainwater. Loss in the model is defined as the amount of water that infiltrates (calculated as depth), which is subtracted from what falls as precipitation. The remaining amount, referred to as excess precipitation becomes runoff. In this model, the Soil Conservation Service (SCS) Curve Number method was selected. This method calculates infiltration in each subbasin based on its curve number and the percentage of its area that is impervious.

The transform method determines how to simulate the conversion of excess precipitation from a subbasin to runoff at its outlet. The basis for this is a unit hydrograph, a discharge vs time curve representing the discharge of water from a subbasin that results from one unit of direct runoff distributed evenly across the subbasin during a specified time interval. A storm hydrograph for a particular event can then be created by adding up unit hydrographs multiplied by depth of precipitation in each time interval, creating a larger discharge vs time curve for the subbasin for the duration of the storm (Feldman, 2000). The transform method chosen is the SCS Unit Hydrograph method. This method creates a standard, dimensionless, single-peak unit hydrograph for each subbasin based on its lag time, which was calculated as described above. No transform method was used for NW bioretention subbasin because of its short lag time. In order for the transform calculations to proceed properly, the computation interval must be less than 29% of the lag time, which in the case of NW bioretention would have required an interval of less than one minute. Instead of using a unit hydrograph, runoff in this subbasin is assumed equal to excess precipitation.

Baseflow is continuous, fair weather streamflow from earlier precipitation which has not yet exited the watershed. Subbasins upstream of I&M depth loggers were assigned baseflow using the Recession method so that creek discharge would not be calculated as zero when precipitation was not falling. The Recession method computes baseflow from a subbasin at a given time (t) as

$$Q_t = Q_0 k^t$$

Where Q_0 is the initial baseflow in the subbasin at the start of the simulation, and k is the recession constant, defined as the ratio of baseflow at time t to the baseflow one day earlier. Q_0 was input as discharge per unit area of the subbasin and was estimated based on shallow flows recorded by the I&M depth logger divided by upstream catchment area. Since the Wolf Trap Creek depth logger was located downstream of the junction with Courthouse Creek, it was necessary to determine what percentage of discharge came from Courthouse Creek and what percentage came from subbasins that feed into Wolf Trap Creek. By comparing discrete



discharge measurements taken from 2005 to 2018 in both creeks by I&M on the same day, it was determined that on average 64% of the discharge measured at the Wolf Trap Creek monitoring point was likely from subbasins feeding into Wolf Trap Creek as opposed to Courthouse Creek. The five subbasins feeding into Courthouse Creek upstream of the logger were assigned a Q_0 of $0.016 \text{ m}^3/\text{s} / \text{km}^2$, and the twenty-two feeding into Wolf Trap Creek upstream of its logger were assigned a Q_0 of $0.012 \text{ m}^3/\text{s} / \text{km}^2$. A recession constant of 0.96 was determined for all subbasins with baseflow.

No gain or loss of water from the channels was modeled, as doing so would require comparing discharges at multiple points along the creeks with no surface inflow between them, and such data was not available. Since the creeks at WOTR are fed primarily by surface water, not groundwater, and the underlying bedrock is not prone to karst that could serve as a drain, it is reasonable to assume that channel inflow is equal to outflow within a single reach (Pieper et al. 2012, Thornberry- Ehrlich, 2008). For longer channel reaches, the model included routing calculations to convert inflow hydrographs to outflow. Routing in these reaches is modeled with the Normal Depth routing method, which is based on Manning's equation. Inputs for the equation were determined in the same way as when calculating channel flow velocity for the lag time. The routing method requires one additional input which is the index flow or maximum discharge in the channel. This was calculated from Manning's equation using a maximum expected depth of 60 cm. The majority of reaches were too short for routing, so inflow was instantaneously converted to identical outflow.

The model was first run with 3.3 cm of precipitation falling at a uniform rate over 40 minutes across the model area, which has an approximately 50% chance of occurring in a given year. This allowed for an evaluation of all of the subbasins and channel reaches under identical, ordinary circumstances. A second run was done to model the storm which occurred on July 8, 2019 that flooded parts of the park and community. Precipitation for this event came from the NOAA's Next Generation Weather Radar (NEXRAD) system level III data. NEXRAD produces gridded precipitation datasets at approximately 5-minute intervals. Sets of precipitation grids covering the durations of the storm were imported into NOAA's Weather and Climate toolkit. Three virtual rain gage locations were selected, and the Point Subset tool was used to extract a time-series of precipitation at each location (Figure 6). Precipitation in each subbasin was assigned by Thiessen gage weights, meaning that each basin received an average of the precipitation measured at the gages weighted by the percentage of subbasin area that is closer to each gage than any other.

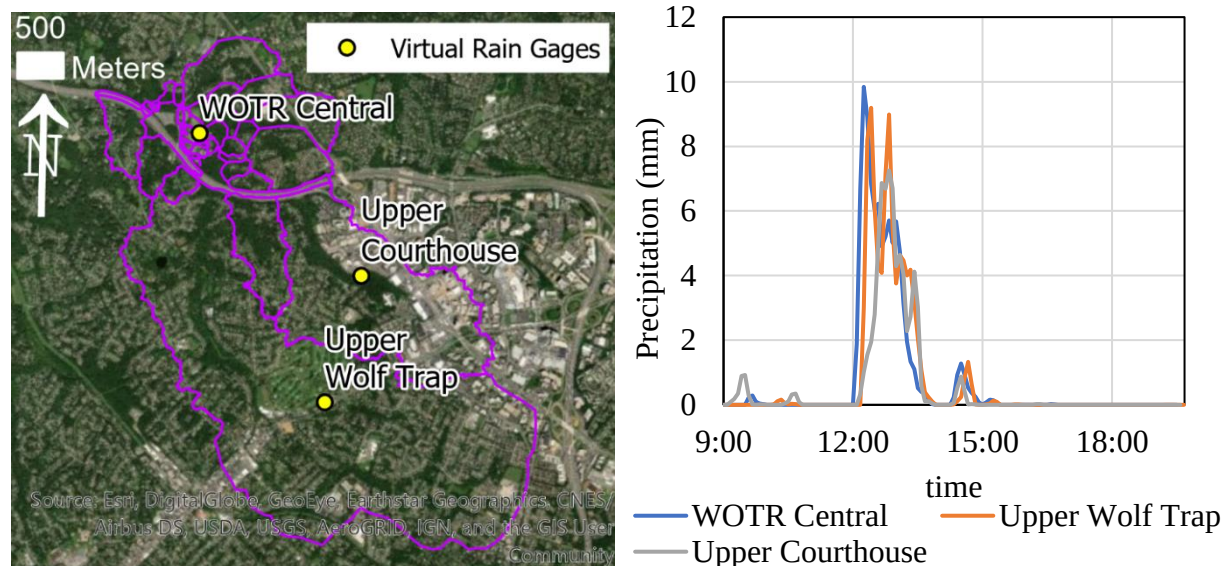


Figure 6: (Left) Virtual rain gages marking the locations from which NEXRAD precipitation data was used. (Right) Precipitation during July 8th flood event.

Given time and data constraints on the project, not everything required to create an ideal model could be accomplished. A few items remain to improve the model's usefulness. A deeper assumed channel flow depth for calculating lag time may improve routing accuracy. Additionally, the model is based on a limited set of existing data and has not been calibrated. Sufficient discharge data does not exist for the past four years. This is part of why the model is desirable, as it can be used to predict discharge where measurements do not exist, but it makes evaluating its accuracy difficult. Assuming minimal change in channel form, discharge for 2013 through 2015 can be estimated from the I&M continuous depth data and used in conjunction with precipitation records from NCEI to calibrate the model for this time period. This would likely improve the accuracy of the model for areas in the park, which have not changed much since that time, but may underestimate discharge from areas outside the park which continue to develop. Additionally, subbasins and reaches west of Trap Road could not be calibrated using the I&M data because they are downstream of the logger.

If achievable levels of accuracy are deemed sufficient, several additional aspects of the park can be included in modeling. HEC-HMS can be used to model sediment transport and erosion, which would be of interest for protecting park landscapes and water quality. Initial data for this could be obtained from the NRCS soils database, but additional data about soil transport would need to be gathered in the park. Measuring the volume of gullies formed in areas such as Gill's Hill or the gravel road to Theatre in the woods between gradings could be a good place to start. Additionally, for a more in depth look at the effectiveness of WOTR's stormwater infrastructure, more detailed models of the smaller subbasins could be created in the U.S.



Environmental Protection Agency's Stormwater Management Model (SWMM) software. These could be based on much of the same subbasin data in addition to the information on the stormwater infrastructure contained in the GIS files. This would allow users to predict when and where drains are likely to back up and evaluate the effect of the new bioretention basins on reducing peak discharges.

Results

Though the HEC-HMS model is preliminary, it can provide general information about runoff that can be useful for planning purposes. Running the model with uniform precipitation demonstrates that, as is typically the case, there is a strong, positive correlation between the percentage of a subbasin's area that is impervious and the amount of water per unit area that it discharges. This trend is also present but slightly weaker for curve number and total area-normalized water volume (Figure 7). Additionally, there is an inverse correlation between Manning's number and a subbasin's area-normalized volume and possibly between a subbasin's average slope and normalized discharge as well (Figures 8-9). At junctions between channels or inputs from subbasins, peak discharge is proportional to upstream drainage area. There may be a similar correlation for subbasins, though it is much weaker (Figure 10).

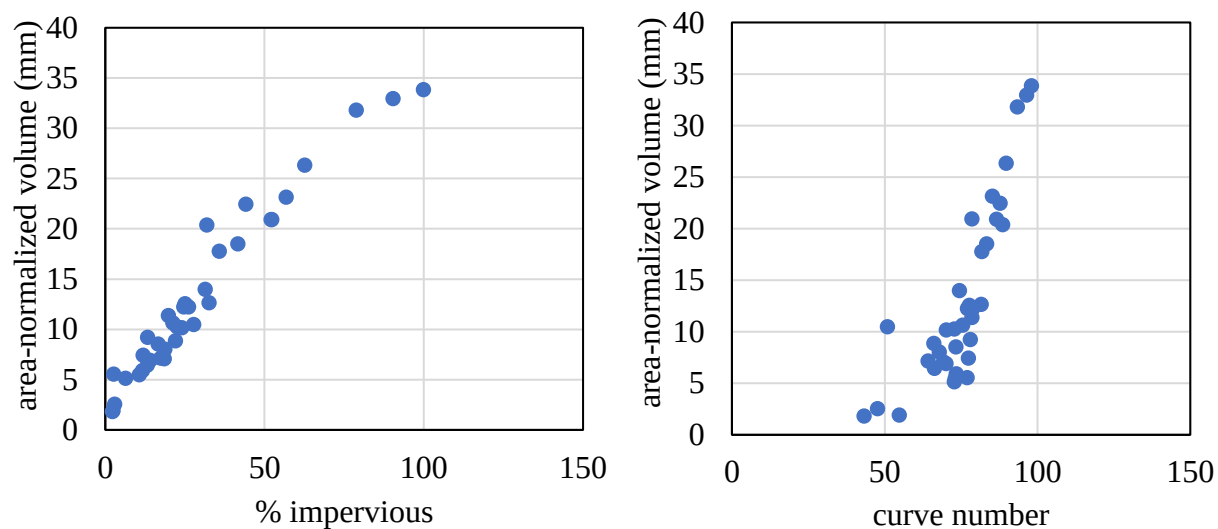


Figure 7: Area normalized discharge vs percent impervious area (Left) and curve number (Right).

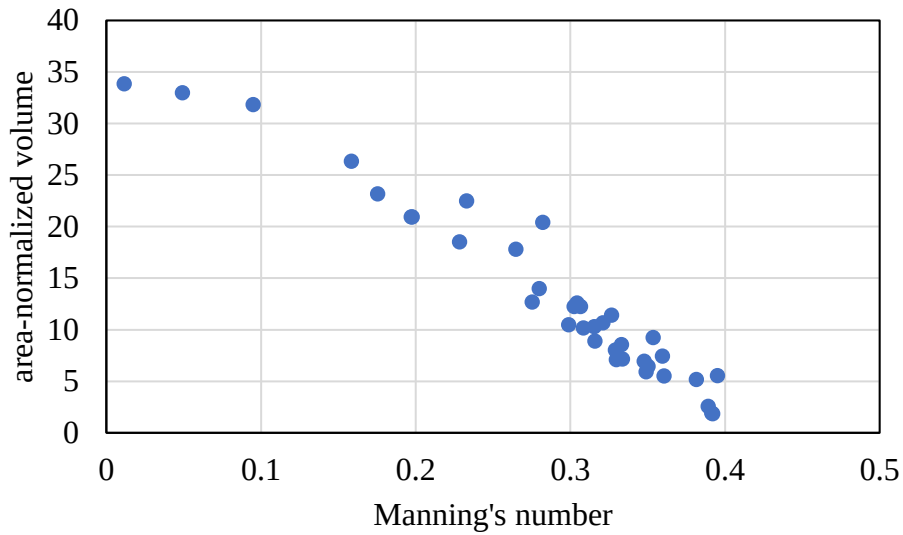


Figure 8: Subbasin area-normalized volume versus surface Manning's number.

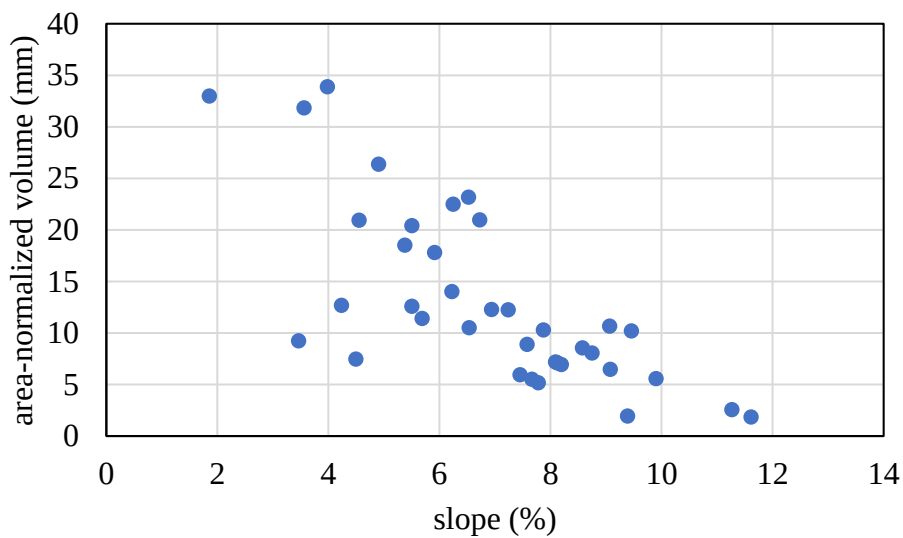


Figure 9: Subbasin area-normalized volume versus average surface slope.

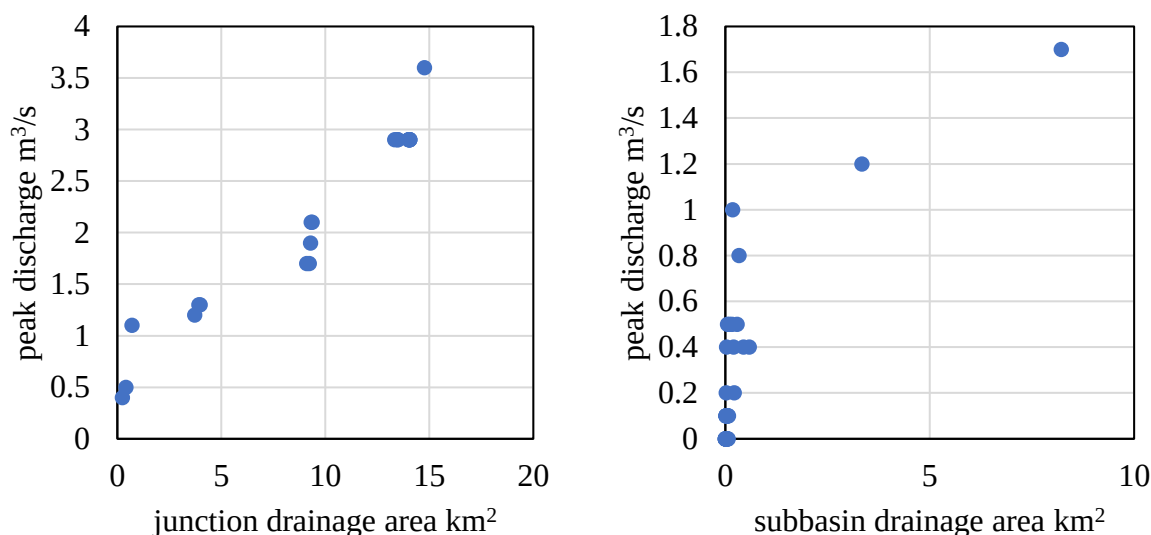


Figure 10: Peak discharge versus upstream drainage areas at junctions (Left) versus subbasin outlets (Right).

The Upper Wolf Trap and Upper Courthouse subbasins, which are by far the largest in the model, have much wider and later peaks with greater total discharge than most of the other subbasins, which results in bimodal (double-peaked) channel hydrographs from the beginnings of their respective channels to the exit (Figures 11-12). On the other hand, The N Dulles Toll Rd and Trap Rd subbasins, both of which contain mostly impervious roadway, exhibit sharp hydrographs that respond almost immediately to precipitation. In the case of N Dulles Toll Rd, the response is pronounced enough to create a bimodal hydrograph in the west ditch, which receives the rest of its water from subbasins with smaller, later peaks. Though the N Dulles Toll Rd and Trap Rd hydrographs are similarly shaped, the N Dulles Toll Rd subbasin produces 6% more runoff per unit area than the Trap Rd subbasin and has a peak discharge which is four times greater.

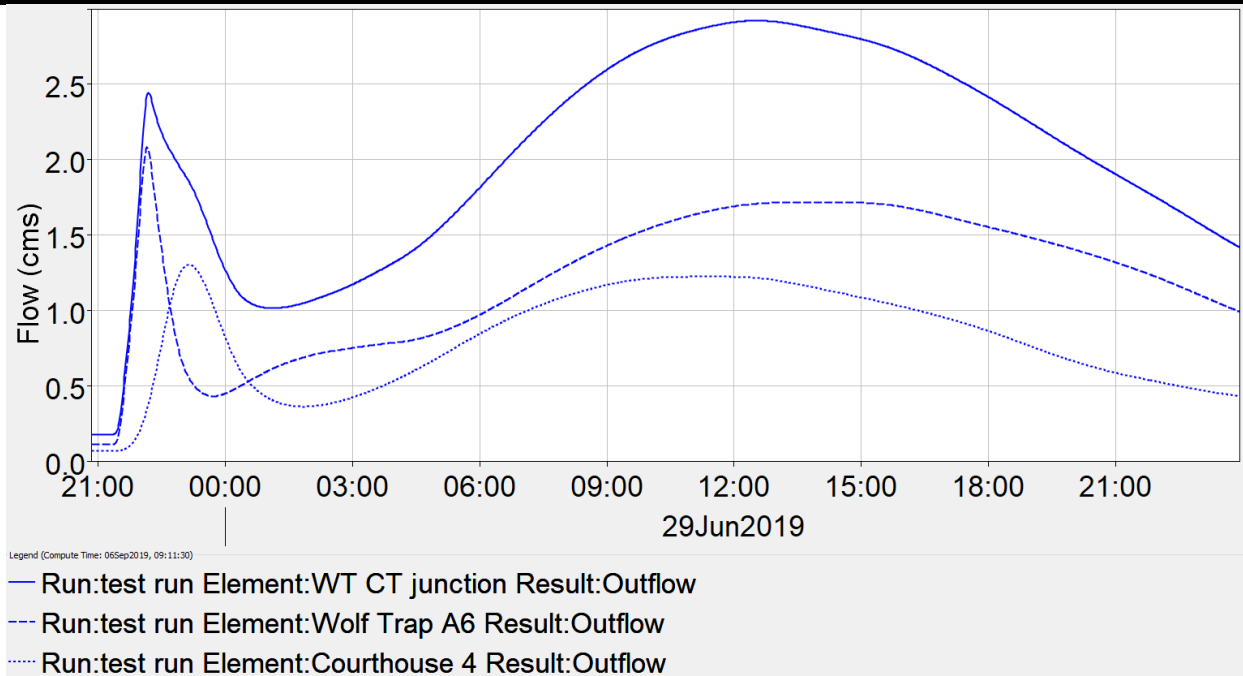


Figure 11: Discharge from Wolf Trap Creek and Courthouse Creek combined at their junction for a total hydrograph. The date assigned to the hydrograph is arbitrary, as the precipitation event used in the model is hypothetical.

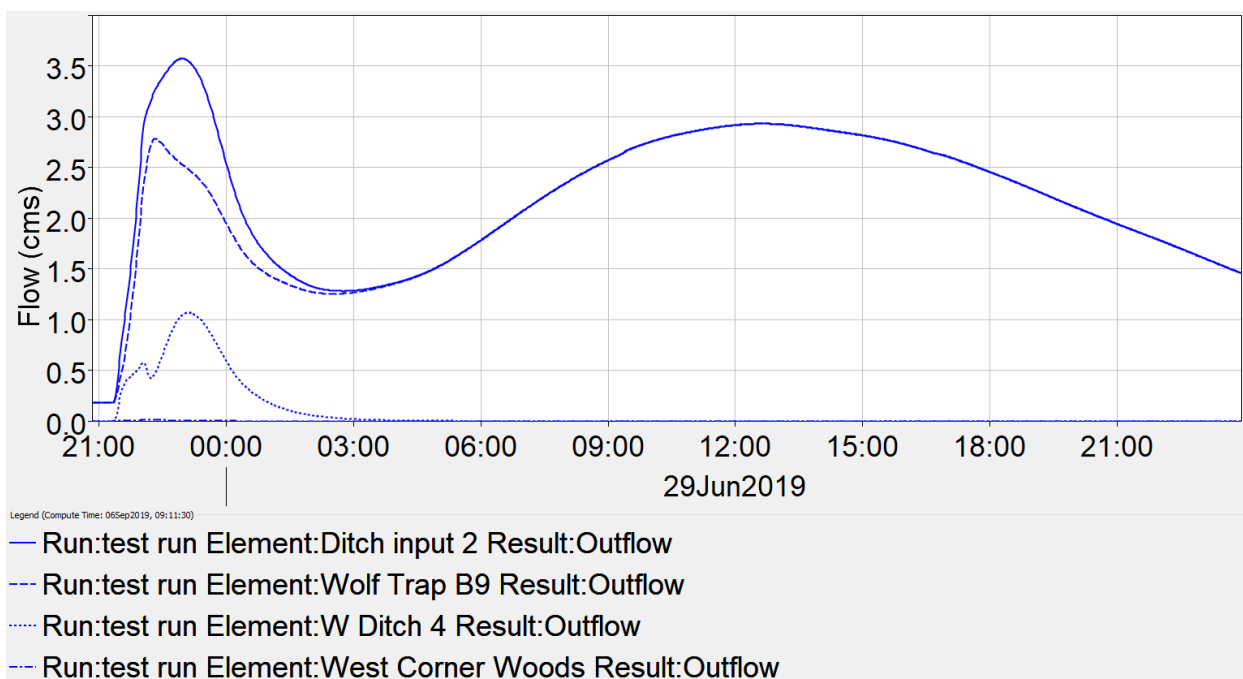




Figure 12: Total and component hydrographs at the final junction in the model.

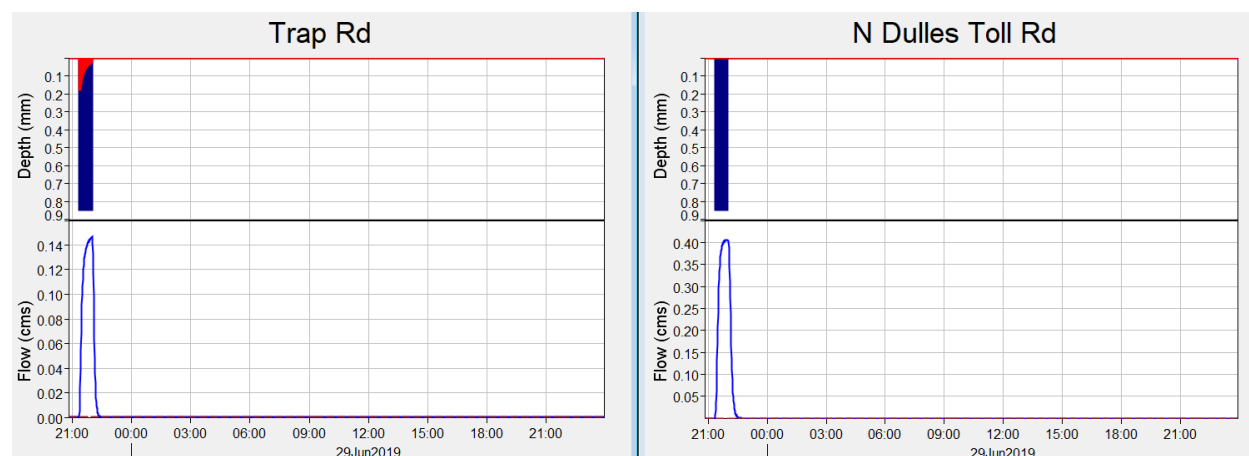


Figure 13: Precipitation and runoff graphs for Trap Rd and N Dulles Toll Rd subbasins. Precipitation depth in millimeters is shown on the top in blue, with infiltrated precipitation shown in red. Discharge or flow from runoff in cubic meters per second is shown on the bottom.

Table 1: Results summary from uniform precipitation model run.

Hydrologic Element	Drainage Area (km ²)	Peak Discharge (m ³ /s)	Time of Peak (hr)	Total Area-Normalized Volume (mm)
Bridge Branch	0.33637	0.01	2.3	17.80
Browns Branch	0.44814	0.01	3.4	12.26
Campbell Rd	0.21784	0.01	2.3	7.09
Courthouse 1	3.67690	0.10	14.7	20.65
Courthouse 2	3.72430	0.11	14.7	20.47
Courthouse 3	3.92330	0.11	2.2	20.14
Courthouse 4	3.97380	0.11	2.3	19.90
Dimple	0.01352	0.00	1.2	10.49
Ditch input 1	9.22110	0.26	16.9	12.72
Ditch input 2	14.76800	0.42	2.1	14.56
E bioretention	0.00128	0.00004	1.2	18.52
East Lot and Hill Parking	0.05264	0.001	1.3	20.41
Edgepark Rd	0.04946	0.00	1.3	7.17
Exit	14.76800	0.42	2.1	14.56
Filene Center	0.01951	0.001	1.4	22.48



Filene North	0.00380	0.0001	1.2	5.56
Filene S ditch	0.09778	0.003	1.3	11.40
Filene South	0.00543	0.0002	1.2	10.66
Junction-C1	3.72430	0.11	14.7	20.47
Junction-C2	3.92330	0.11	2.2	20.14
Junction-C3	3.97380	0.11	2.2	19.92

Table 1 continued

Hydrologic Element	Drainage Area (km ²)	Peak Discharge (m ³ /s)	Time of Peak (hr)	Total Area-Normalized Volume (mm)
Junction-D1	0.24661	0.01	1.2	10.22
Junction-D2	0.41330	0.01	2.3	11.69
Junction-D3	0.70429	0.02	2.3	11.92
Junction-W1	9.10300	0.26	17.0	12.75
Junction-W10	14.05500	0.40	15.8	14.69
Junction-W11	14.05700	0.40	15.8	14.70
Junction-W2	9.28180	0.26	1.3	12.69
Junction-W3	9.36720	0.27	1.3	12.65
Junction-W4	13.47200	0.38	15.8	14.69
Junction-W5	13.49200	0.38	15.8	14.65
Junction-W6	13.99200	0.40	15.8	14.59
Junction-W7	14.02400	0.40	15.8	14.60
Junction-W8	14.02400	0.40	15.8	14.71
Junction-W9	14.05300	0.40	15.8	14.69
Laurel Hill Rd	0.07521	0.002	2.0	10.28
Lower Courthouse	0.05054	0.001	2.4	2.56
Maintenance	0.00268	0.0001	1.2	32.98
McLean	0.19902	0.01	2.1	14.00
Meadow	0.01765	0.0005	1.3	9.24
Meadow Hill	0.01355	0.0004	1.3	5.16
Middle Courthouse	0.04738	0.001	2.3	6.46
Moonac	0.58674	0.02	4.9	12.58
N Dulles Toll Rd	0.02877	0.001	1.2	33.86
North Park	0.06922	0.002	3.3	1.92
North Residential	0.06201	0.002	1.6	10.18
NW bioretention	0.00143	0.00004	1.2	26.35



Rim	0.00579	0.0002	1.2	6.93
Shade garden input	9.32400	0.26	1.3	12.70
Sibelius E	0.02125	0.001	1.3	8.55
Sibelius W	0.02682	0.001	1.4	5.92
Snughill Ct	0.02028	0.001	1.2	8.89
South bioretention	0.00065	0.00002	1.4	7.45
South Woods	0.17462	0.005	1.5	20.95
Streamview Ln	0.04302	0.001	1.3	8.04
The Barns	0.09778	0.003	1.3	11.40
Theatre in the Woods	0.04318	0.001	2.6	1.85

Table 1 continued

Hydrologic Element	Drainage Area (km ²)	Peak Discharge (m ³ /s)	Time of Peak (hr)	Total Area-Normalized Volume (mm)
Trap Rd	0.01080	0.0003	1.2	31.83
Upper Courthouse	3.34050	0.09	14.7	20.94
Upper Wolf Trap	8.21700	0.23	17.4	12.67
W Ditch 1	0.21784	0.01	2.3	7.09
W Ditch 2	0.24661	0.01	1.2	10.22
W Ditch 3	0.41330	0.01	2.3	11.69
W Ditch 4	0.70429	0.02	2.3	11.92
West Corner Woods	0.00667	0.0002	1.4	5.51
West Lot	0.16604	0.005	2.3	23.17
West lot diversion	0.16604	0.005	2.3	13.90
West outside	0.29099	0.01	2.2	12.24
Wolf Trap A1	8.87900	0.25	17.0	12.61
Wolf Trap A2	9.10300	0.26	17.0	12.75
Wolf Trap A3	9.22110	0.26	16.9	12.72
Wolf Trap A4	9.28180	0.26	1.3	12.69
Wolf Trap A5	9.32400	0.26	1.3	12.70
Wolf Trap A6	9.36720	0.27	1.3	12.65
Wolf Trap B1	13.34100	0.38	15.8	14.78
Wolf Trap B10	14.76800	0.42	2.1	14.56
Wolf Trap B2	13.47200	0.38	15.8	14.66
Wolf Trap B3	13.49200	0.38	15.8	14.65
Wolf Trap B4	13.99200	0.40	15.8	14.59



Wolf Trap B5	14.02400	0.40	15.8	14.60
Wolf Trap B6	14.02400	0.40	15.8	14.71
Wolf Trap B7	14.05300	0.40	15.8	14.69
Wolf Trap B8	14.05500	0.40	15.8	14.69
Wolf Trap B9	14.05700	0.40	15.8	14.70
WT CT junction	13.34100	0.38	15.7	14.81

The July 8th storm dropped significantly more precipitation than the model 50% probability storm used in most of the analysis (approximately 9.1 cm, as opposed to 3.3 cm). Rains lasted longer, were more intense, and were not uniform in space or time. Peak rainfall was slightly lower and later at the Upper Wolf Trap virtual gage than at WOTR Central, and at Upper Courthouse versus Upper Wolf Trap, and Upper Wolf Trap experienced two distinct spikes. In small to mid-sized subbasins, the varying precipitation intensity resulted in smaller bumps in addition to the main peak in outflow hydrographs. This can be observed at the end of the first peak in the Wolf Trap Creek discharge at the Wolf Trap – Courthouse junction, but the biggest subbasins, Upper Wolf Trap and Upper Courthouse, still experienced one large, late peak due to the smoothing effect their larger drainage area has on outflow. In subbasins cases, high levels of infiltration smoothed the multiple precipitation peaks, as was the case for the North Park subbasin, which in which most of the precipitation infiltrated. This subbasin exhibited a more even, nearly symmetrical hydrograph as opposed to the nearby and similarly sized North Residential subbasin, which has more impermeable area (Figure 16).

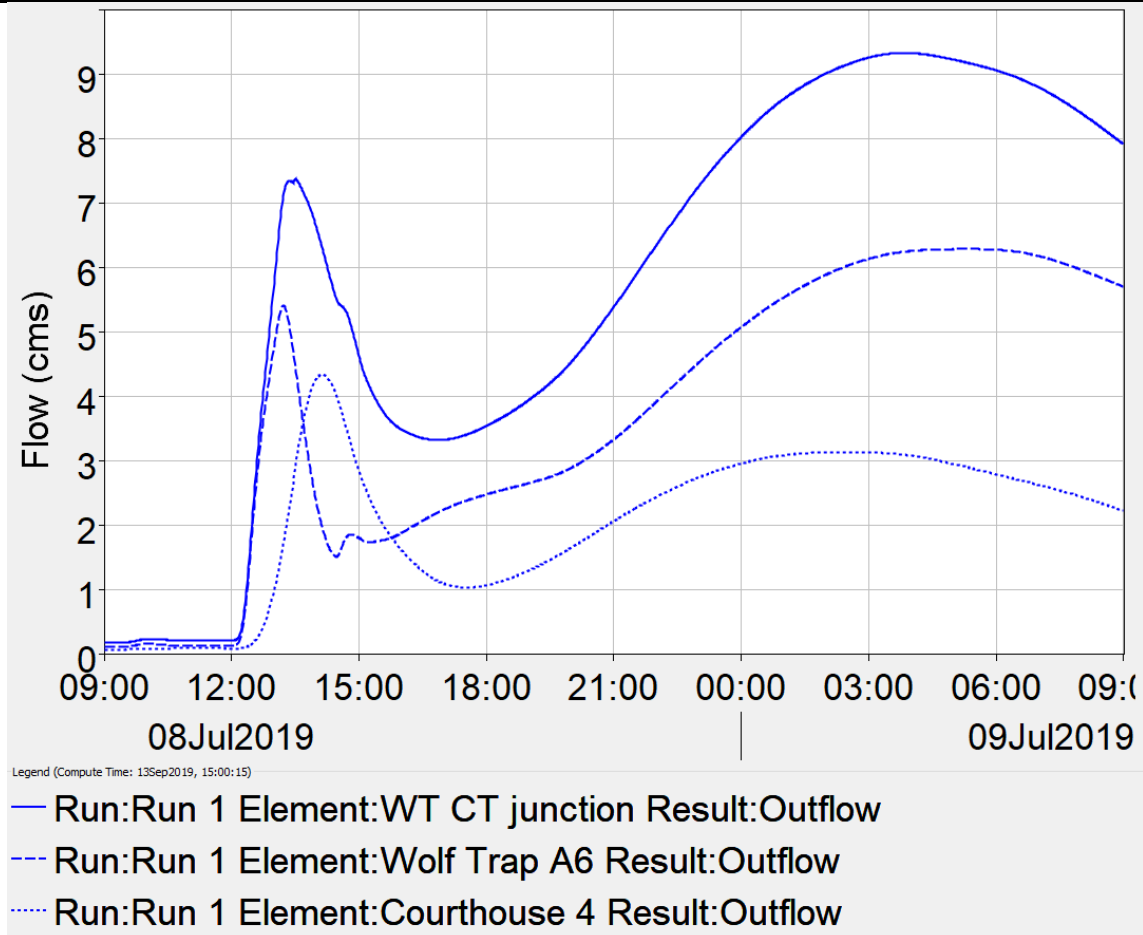


Figure 14: Discharge at the junction of Wolf Trap Creek and Courthouse Creek in the July 8th storm scenario. Note small bump following the first peak coming from Wolf Trap Creek (Wolf Trap A6), which is subsequently overshadowed by the discharge from Courthouse Creek.

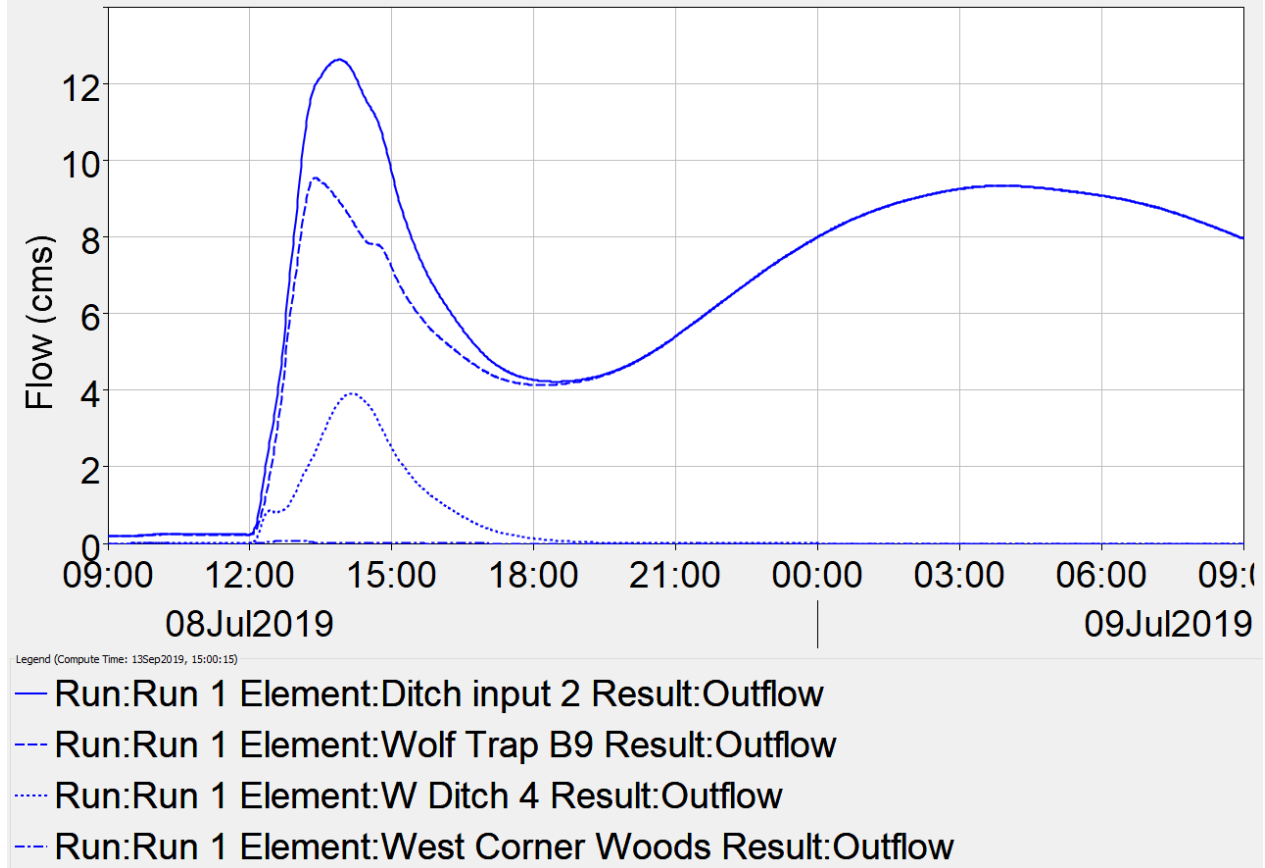


Figure 15: Discharge at exit in July 8th storm scenario equal to outflow at the “Ditch 2 input” junction. Note small peak early peak in W Ditch 4 outflow from N Dulles Toll Rd, where runoff was sharp and instantaneous.

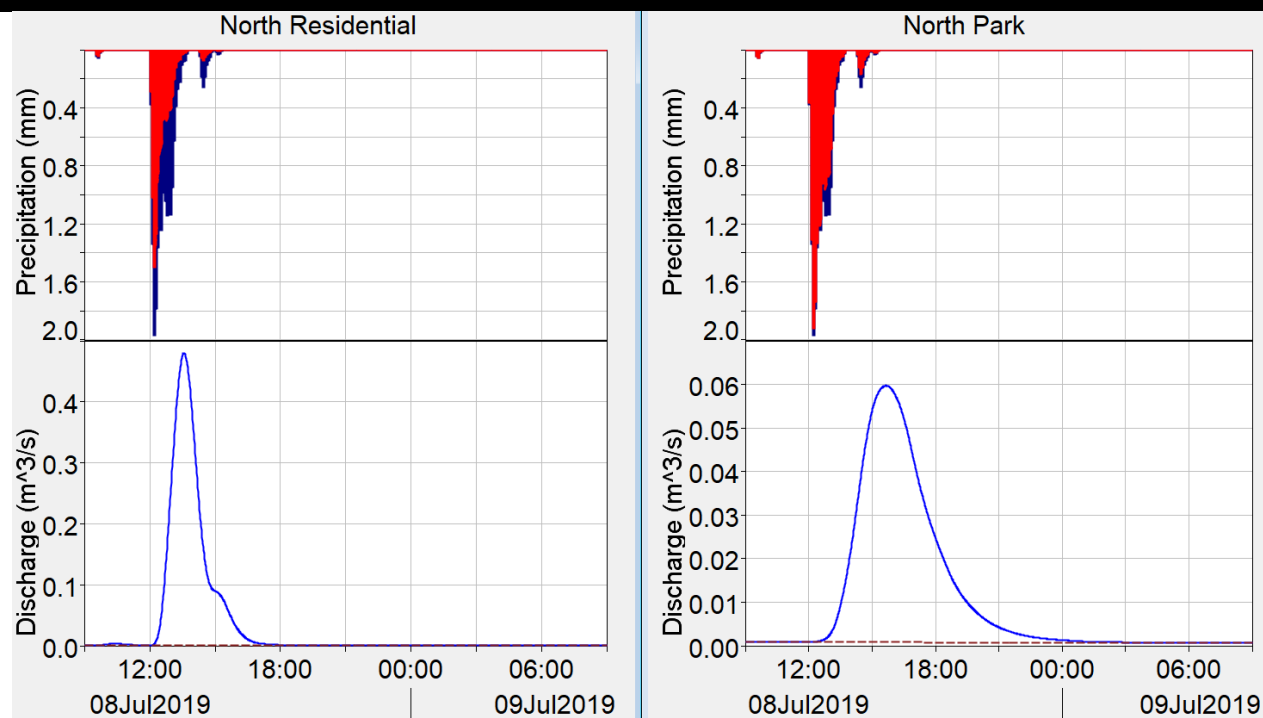


Figure 16: Comparison of runoff discharge from the North Residential and North Park subbasins. North Park experienced more infiltration and as a result exhibited a smoother and smaller hydrograph.

Table 2: Results summary from July 8th storm model run.

Hydrologic Element	Drainage Area (km ²)	Peak Discharge (m ³ /s)	Time of Peak (hr)	24-hour Area-Normalized Runoff Volume (mm)
Bridge Branch	0.33637	2.6	5.17	65.02
Browns Branch	0.44814	1.7	6.35	53.18
Campbell Rd	0.21784	1	5.23	38.76
Courthouse 1	3.67690	3.1	17.52	45.17
Courthouse 2	3.72430	3.1	17.52	45.02
Courthouse 3	3.92330	4.3	5.08	45.48
Courthouse 4	3.97380	4.3	5.13	44.87
Dimple	0.01352	0.1	3.43	31.28
Ditch input 1	9.22110	6.3	20.32	34.42



Ditch input 2	14.7680	12.6	4.90	38.79
E bioretention	0.00128	0.02	3.45	68.17
East Lot and Hill Parking	0.05264	0.9	3.72	72.82
Edgepark Rd	0.04946	0.4	4.32	33.53

Table 2 continued

Hydrologic Element	Drainage Area (km ²)	Peak Discharge (m ³ /s)	Time of Peak (hr)	24-hour Area-Normalized Runoff Volume (mm)
Exit	14.7680	12.6	4.88	38.79
Filene Center	0.01951	0.3	4.15	75.36
Filene North	0.00380	0.04	4.12	41.19
Filene S ditch	0.09778	1.3	4.15	52.70
Filene South	0.00543	0.1	4.10	49.18
Junction-C1	3.72430	3.1	17.52	45.02
Junction-C2	3.92330	4.3	5.08	45.48
Junction-C3	3.97380	4.3	5.10	45.01
Junction-D1	0.24661	1.0	5.53	45.02
Junction-D2	0.41330	1.9	5.20	45.28
Junction-D3	0.70429	3.9	5.15	49.39
Junction-W1	9.10300	6.3	20.32	34.22
Junction-W10	14.0550	9.5	4.38	38.26
Junction-W11	14.0570	9.5	4.38	38.26
Junction-W2	9.28180	6.3	20.32	34.47
Junction-W3	9.36720	6.3	20.32	34.43
Junction-W4	13.4720	9.3	18.87	37.32
Junction-W5	13.4920	9.3	18.90	37.18
Junction-W6	13.9920	9.3	18.90	37.83
Junction-W7	14.0240	9.3	18.90	37.88
Junction-W8	14.0240	9.3	18.90	38.24
Junction-W9	14.0530	9.5	4.38	38.25
Laurel Hill Rd	0.07521	0.5	4.88	46.50
Lower Courthouse	0.05054	0.03	5.58	8.21
Maintenance	0.00268	0.1	3.25	91.35
McLean	0.19902	1.4	4.93	54.16



Meadow	0.01765	0.2	4.15	48.52
Meadow Hill	0.01355	0.1	4.13	36.83
Middle Courthouse	0.04738	0.2	5.25	33.25
Moonac	0.58674	1.2	8.00	43.10
N Dulles Toll Rd	0.02877	0.8	3.40	92.35
North Park	0.06922	0.1	6.65	12.73
North Residential	0.06201	0.5	4.57	44.41
NW bioretention	0.00143	0.04	3.25	82.05

Table 2 continued

Hydrologic Element	Drainage Area (km ²)	Peak Discharge (m ³ /s)	Time of Peak (hr)	24-hour Area-Normalized Runoff Volume (mm)
Rim	0.00579	0.1	4.12	37.92
Shade garden input	9.32400	6.3	20.32	34.57
Sibelius E	0.02125	0.2	4.18	43.64
Sibelius W	0.02682	0.3	4.25	39.87
Snughill Ct	0.02028	0.2	4.15	38.69
South bioretention	0.00065	0.01	4.28	45.87
South Woods	0.17462	2.2	4.38	66.17
Streamview Ln	0.04302	0.4	4.25	38.37
The Barns	0.09778	1.3	4.12	52.70
Theatre in the Woods	0.04318	0.01	5.70	4.81
Trap Rd	0.01080	0.3	3.37	89.57
Upper Courthouse	3.34050	3.1	17.52	43.17
Upper Wolf Trap	8.21700	6.3	20.42	32.96
W Ditch 1	0.21784	1.0	5.23	38.76
W Ditch 2	0.24661	1.0	5.53	45.02
W Ditch 3	0.41330	1.9	5.20	45.28
W Ditch 4	0.70429	3.9	5.15	49.39
West Corner Woods	0.00667	0.1	4.03	38.85
West Lot	0.16604	1.5	5.17	76.12
West lot diversion	0.16604	0.9	5.17	45.67
West outside	0.29099	2.0	5.10	55.22



Wolf Trap A1	8.87900	6.3	20.32	33.59
Wolf Trap A2	9.10300	6.3	20.32	34.22
Wolf Trap A3	9.22110	6.3	20.32	34.42
Wolf Trap A4	9.28180	6.3	20.32	34.47
Wolf Trap A5	9.32400	6.3	20.32	34.57
Wolf Trap A6	9.36720	6.3	20.32	34.43
Wolf Trap B1	13.3410	9.3	18.87	37.42
Wolf Trap B10	14.7680	12.6	4.90	38.79
Wolf Trap B2	13.4720	9.3	18.90	37.19
Wolf Trap B3	13.4920	9.3	18.90	37.18
Wolf Trap B4	13.9920	9.3	18.90	37.83
Wolf Trap B5	14.0240	9.3	18.90	37.88
Wolf Trap B6	14.0240	9.3	18.90	38.24

Table 2 continued

Hydrologic Element	Drainage Area (km ²)	Peak Discharge (m ³ /s)	Time of Peak (hr)	24-hour Area-Normalized Runoff Volume (mm)
Wolf Trap B7	14.0530	9.5	4.38	38.25
Wolf Trap B8	14.0550	9.5	4.38	38.26
Wolf Trap B9	14.0570	9.5	4.38	38.26
WT CT junction	13.3410	9.3	18.83	37.54

Interpretation

Given that HEC-HMS is a mathematical model, not a physical experiment done in a real watershed, any analysis of model results will, of necessity, be in part an analysis of how the model itself works. Impervious area plays a significant role in determining a subbasin's curve number, so it makes sense for the same general correlation to exist between impervious area and discharge as between curve number and discharge. On the other hand, pervious surfaces tend to be more heterogeneous than impervious ones, and both soil type and landcover must be taken into consideration when determining their curve number. This can result in areas with the same curve number and different degrees of surface roughness, which may explain the poorer fit. The inverse correlation between a subbasin's Manning's number and its total, area-normalized volume is likely due to infiltrative losses. A rougher surface, described by a higher Manning's



number, results in slower flow through the subbasin and more time for infiltration. This can be observed in the case of totally forested subbasins, which produced very little runoff. In contrast, it is unclear why there would be an inverse correlation between slope and discharge, as a greater slope in a subbasin should mean faster progress towards the outlet and less time for infiltration. The large late hydrographs for the Upper Wolf Trap and Upper Courthouse subbasins are likely due to their large drainage areas. A larger subbasin accumulates more water, resulting in a higher peak discharge. There is also more distance for the water to travel on average, making the peak later, but some water still falls near the outlet. The wideness of the hydrographs can be attributed to the difference in travel times between water falling near the outlet and water falling far from it.

In terms of the two roadway subbasins, the grass median in the middle of Trap Road is likely the cause of the less intense discharge originating in the Trap Rd subbasin versus N Dulles Toll Rd. The smaller drainage area of the Trap Rd subbasin could be partly related to its lower peak discharge, but the other subbasins do not show a strong trend in this regard, and the size difference is not especially large, so it is probably not the main factor. The model does not consider how runoff leaves the subbasin in which it originates, but it is worth noting from a management perspective that runoff from Trap Road flows off the sides in a dispersed manner, while runoff from the toll road is concentrated in culverts. This can be expected to cause more erosion where the water discharges. Since there is approximately 10 times as much area on the Dulles Toll Road that drains into the park than there is on Trap Road, the total quantity of runoff from the toll road can be expected to be greater as well.



Problem Areas

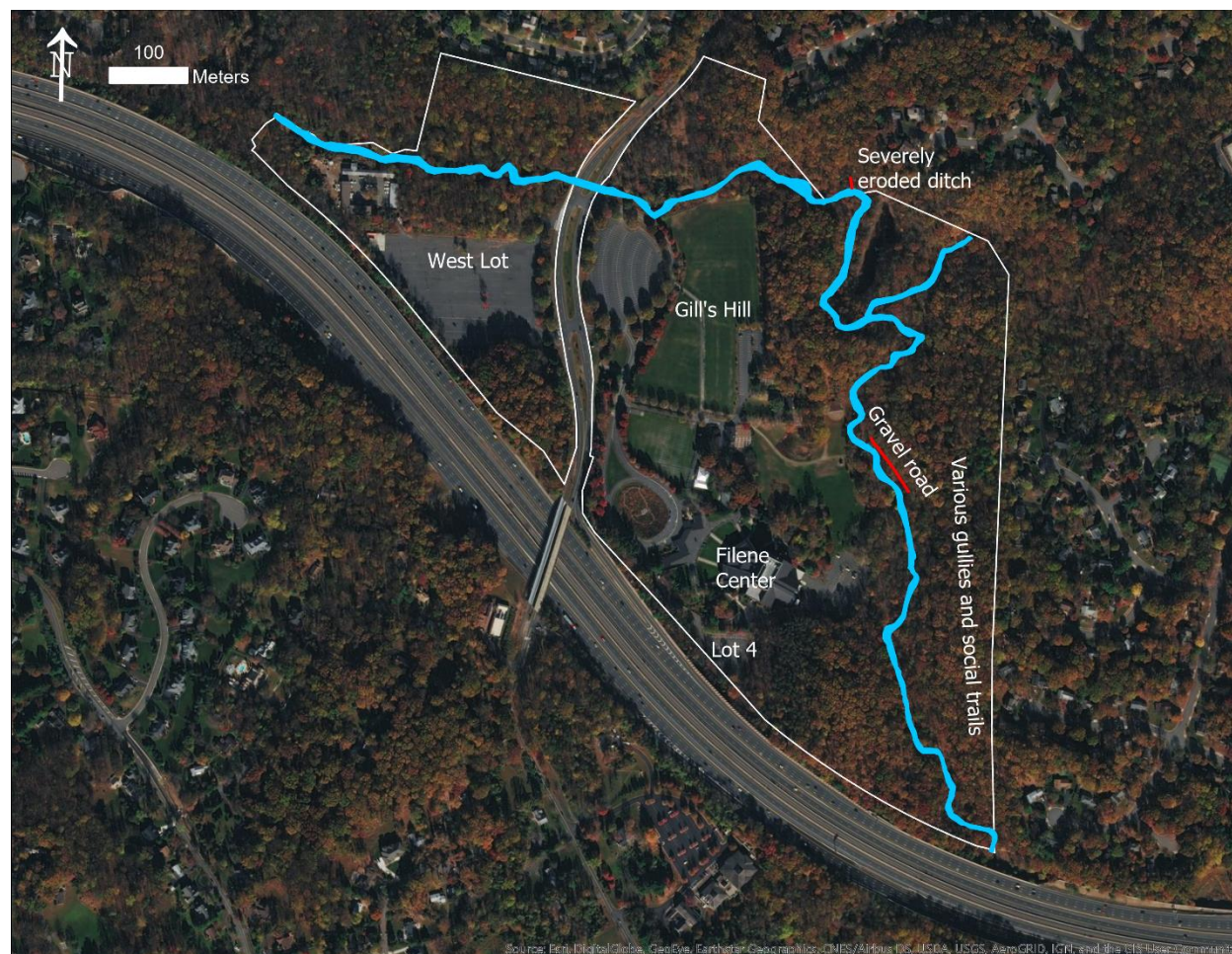


Figure 17: Map of areas of concern in WOTR.

Field observations and discussions with NPS employees revealed several areas of concern in the park with regard to runoff and erosion (Figure 17). The Dulles Toll Road is a large expanse of impermeable area which drains largely into the park (Figure 18). Most of the drainage is directed towards West Lot and Lot 4, which can cause excessive sheet flow in the parking lots. Gill's Hill, a sloped grass parking area, does not receive road runoff but has a history of erosion problems due to its slope and regular vehicular traffic (Figure 19). Gullying necessitates regrading every year, and during the July 8th flood event, a plume of sediment could be seen flowing from Gill's Hill into East Lot. The influx of sediment from Gill's Hill has contributed to clogging of East Lot storm drains (Figure 20).



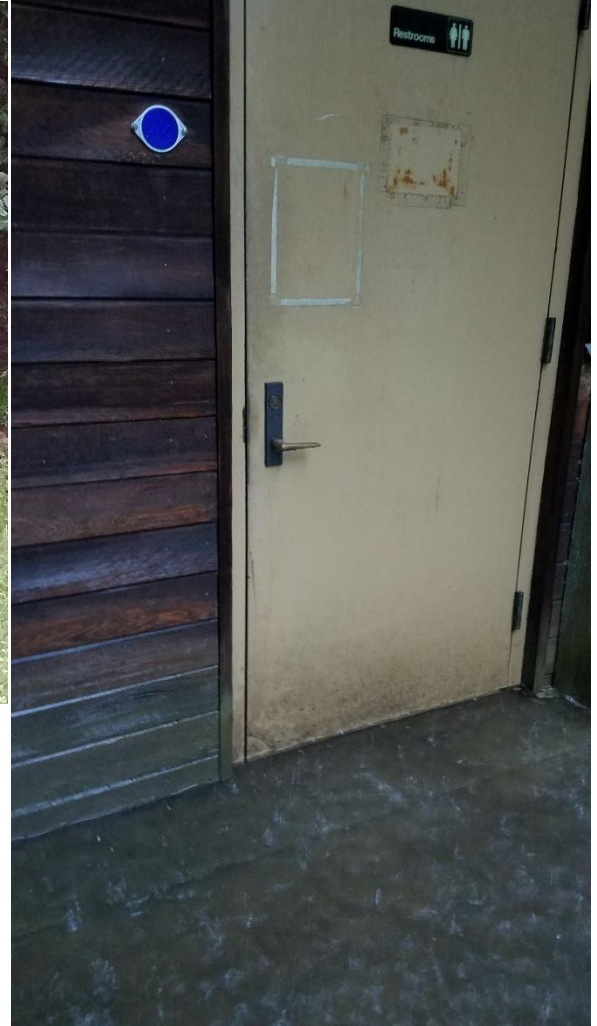
Figure 18: (Left) Area adjacent to Lot 4 previously clear cut to access noise barrier wall for repair and location of one of two culverts draining into the park. Heavy runoff makes reestablishment of vegetation difficult. (Right) Ditch which carries runoff from Dulles Toll Road towards West Lot during storm events.



Figure 19: Sediment erosion on Gill's Hill.



Figure 20: Sediment accumulating in East Lot.



Drainage is a problem around the Filene Center. The storm drains in the plaza are insufficient to accommodate the water that pools above them during storms. Also, the slope of the lawn towards the building and the walls that extend from the sides tend to funnel runoff into corners against the building. This can lead to water flowing into doors and caused a storm drain on the northwest side to be completely buried by a thick layer of sediment, exacerbating the problem (Figures 21-22). Additionally, runoff from the raised walkways and heavy foot traffic during performances is detrimental to the grass and soil on the lawn facing the Filene Center.

Figure 21: Stormwater accumulating at doors of Filene Center during July 8, 2019 flood event.



Figure 22: Worker excavates a storm drain adjacent to the Filene Center which had been buried by sediment eroding from uphill.

Another area of concern is the gravel road along Wolf Trap Creek leading to Theatre in the Woods. Its relatively soft construction, low elevation, and proximity to the creek cause the road to be washed out frequently (Figures 23-24). Various areas of the woods are also experiencing gullying, related in large part to inflows of runoff from outside the park (Figure 25). This is of greatest concern where a drainage ditch starting between Wolftrap Run Road and Cricklewood Court enters Wolf Trap Creek (Figures 26-27). The mouth of the ditch is extremely eroded, and the erosion is approaching a buried sanitary sewer line. If the sewer line is exposed and undercut, it is more likely to settle and leak, which would cause problems for the utility and present a risk of water contamination in the park.



Figure 23: Standing water in depression in the gravel road to Theatre in the Woods.



Figure 24: Gravel road to Theatre in the Woods following July 8th flood.



Figure 25: Gully in eastern woods associated with runoff from neighboring communities.





Figure 26: Severe erosion at mouth of drainage ditch entering Wolf Trap Creek from the north, likely to continue propagating uphill. (Looking uphill)



Figure 27: Outlet of eroded ditch in figure 26 into Wolf Trap Creek.

Recommendations

Various possibilities exist for addressing the sheet flow in West Lot. Permeable pavement would allow for improved drainage while maintaining the lot's current parking capacity; however, water sometimes rises from cracks in the existing pavement, suggesting that the drainage of the underlying soil would need to be improved as well for the lot to remain dry. Alternatively, a large bioretention basin could be added to the middle of the parking lot, which for maximum effectiveness, would require the lot to be regraded to drain into it. This option would reduce runoff and improve water quality, while providing visual interest and possibly pollinator habitat. On the other hand, adding a bioretention basin in the middle of the lot would reduce available parking space. This would not be an issue during the day and in evenings without performances, as the middle of West lot is rarely used during those times; however, it would present a logistical problem for sold out shows, as WOTR's parking is already insufficient for some large events. Both possibilities would be expensive and take a long time to implement, since they would require repaving the lot. In the meantime, conditions can be improved by keeping the adjacent drainage ditch clear and free of debris and not allowing soil or vegetative material to pile up on the edge of the lot, as this prevents water from flowing off of the



pavement. Lot 4 is much smaller than West Lot, so installing similar design elements would be less worthwhile. Stormwater management in this location would be better focused on reducing the velocity of runoff from the toll road and stopping erosion nearby. Planting shrubs in the area that was previously clear cut to access the wall or adding other roughness elements such as straw wattle could help with this.

Attempts have been previously made to address erosion on Gill's Hill by installing geotextile along the edges of the road; however, these measures have not succeeded at preventing erosion. Given the frequent use and steep slope of the hill, no measures short of completely paving it are likely to eliminate erosion, and that approach would be highly problematic in terms of runoff. Open grass pavers or geogrid similar what is installed on Encore Hill could improve soil stability, provided the substrate allows for sufficient infiltration. Another action which may be desirable is to increase the width of the vegetative buffer and the capacity of the ditch at the bottom of the hill to capture eroded sediment and the water that carries it before it reaches East Lot.

At the Filene Center, increasing the size of the pipes draining the plaza could reduce ponding, but replacing them is probably too involved to be worthwhile unless other intensive repairs are being done at the same time. Regrading so that water flows off to the sides could be helpful but would also make the lawn muddier. Nearer to the Auditorium itself, a berm could be added to direct water away from doors. If the design of the elevated walkways allows, suspending narrow planters from their edges could slow the water sheeting off of their surfaces; however, these would likely be difficult to maintain and would add weight to the structure. Alternatively, large gutters could carry rainwater off of the walkways but would concentrate it at the outlets. If routed onto the ground, this could result in a small area of intense erosion, though this might be mitigated by discharging onto gravel. Delivering water from gutters directly to a storm drain would avoid erosion problems but would result in flashier discharge. As an ongoing maintenance item, regardless of other stormwater management options chosen, the existing storm drains must be kept clear.

There are two main options for addressing the persistent washing out of the gravel road to Theatre in the Woods. The first option is to pave the road. This will keep it intact longer but will result in increased runoff. A paved road adjacent to the creek also has a greater potential for undercutting, which could go unnoticed as the problem progresses. Repairs to a paved road beyond small cold patches would also be more difficult than regrading the existing gravel road. Alternatively, it has been proposed that of the two bridges crossing Wolf Trap Creek to the road, the one closer to Theatre in the Woods could be replaced with a larger one to accommodate all foot and vehicular traffic, and the one farther from the Theater could be removed. With a single bridge close to the Theatre, there would no longer be a need for the section of road between the



two current bridge locations. The road section could be abandoned, allowing the stream to migrate and flood naturally with less concern for infrastructure damage.

Since much of the gullying in the woods is related to runoff from outside the park, addressing it may require working with the surrounding communities to find ways to reduce runoff. Elements such as permeable walkways and driveways and small rain gardens could be beneficial in this regard. A more organized entry of visitors could also be helpful. Social trails from neighborhoods into the back of the park can contribute to erosion. A single official entry to the park on the east side with fences or shrubs in other locations to discourage entry could cut down on the number of social trails and reduce erosion in the woods. Planting additional vegetation in highly eroded areas could help stabilize the soil, though the severely eroded ditch at the park's northern boundary will require an engineered solution such as steps or check dams.



Table 3: Summary of recommendations

Location	Problem	Recommendation	Benefits	Drawbacks
West Lot	Runoff from toll road and excessive sheet flow	Permeable pavement	Reduced runoff	Seepage from under lot. Cost.
		Regrading and addition of bioretention basin	Runoff captured. Improved water quality.	Reduced parking area. Cost.
		Keep existing drainage clear	Reduced standing water in lot	Continued runoff
Lot 4	Runoff from toll road and excessive sheet flow	Planting shrubs or adding other roughness elements between noise wall and lot	Reduced runoff and erosion	Young plants may require extra care to become established.
Gill's Hill	Soil erosion. Sediment accumulating in downhill East Lot.	Grass pavers/ geogrid	Reduced erosion	Cost
		Increase vegetative buffer width and drainage ditch capacity.	Captures eroded sediment	Gullying will continue on Hill.
Filene Center	Insufficient drainage on Plaza	Increase drain capacity	Reduced ponding	Cost
		Regrade pavement to drain grass	Reduced ponding	Lawn likely to become muddier.
	Water flowing into building	Install berms	Protects doorways	May require changes to sidewalks.
		Continuous storm drain maintenance	Reduced ponding	Labor
	Runoff from elevated walkways	Install gutters and downspouts	Protects lawn	Concentrated runoff elsewhere
		Suspend planters on sides of walkways	Reduced runoff intensity. Aesthetics.	Increased maintenance. Structure may not be suitable.
Gravel road to Theatre in the Woods	Frequently washed out.	Paving	Less frequent maintenance required. Smoother surface.	Increased runoff. Potential for undercutting. More difficult repairs.



Table 3 continued

Location	Problem	Recommendation	Benefits	Drawbacks
Gravel road to Theatre in the Woods	Frequently washed out.	Replace north bridge and abandon road	Allows natural channel migration.	Fewer options for creek crossing location.
Woods (various locations)	Gullying	Improved stormwater management in surrounding communities	Reduces runoff. Opportunity for public education.	May be difficult to obtain community buy-in. Existing development may inhibit addition of stormwater infrastructure.
		Official back entry	Fewer social trails/ less off-trail foot traffic	Requires access agreement with community members.
		Planting additional vegetation along sides of ditches	Reduced bank erosion	Plants may not take root.
		Engineered solution (e.g. steps, check dam, etc.) for severely eroded ditches and gullies	Stabilizes headcuts and prevents erosion from continuing uphill.	Likely to fail if design is not highly suitable for location.



References

- Birckhead, H., Bonta, J., Frevert, D., Hoeft, C., Hawkins, R., La Plante, R., Meadows, M., Miller, J., McCutcheon, S., Moglen, G., Moody, H., Powers, D., Ramirez-Avila, Tollner, William, Van Mullem, J., Ward, T., Woodward, D. 2017. Part 630 Hydrology National Engineering Handbook, Chapter 9: Hydrologic Soil-Cover Complexes. United States Department of Agriculture – Natural Resources Conservation Service. Proposed update.
- Chow. 1959. Reference tables for Manning's n values for Channels, Closed Conduits Flowing Partially Full, and Corrugated Metal Pipes. Accessed via fsl.orst.edu. August 2019.
- Cronshey, R., McCuen, R., Miller, N., Rawls, W., Robbins, S. 1986. Technical Release 55. United States Department of Agriculture. Second edition. (210-VI-TR-55, Second Ed., June 1986)
- Fairfax County. 2011. Fairfax County Public Facilities Manual – Intensity Duration Frequency Curves.
- Fairfax County. Fairfax County Stormwater Infrastructure interactive map. Accessed August 2019.
- Feldman, Arlen. 2000. Hydrologic Modeling System HEC-HMS Technical Reference Manual. United States Army Corps of Engineers – Hydrologic Engineering Center.
- National Oceanic and Atmospheric Administration – National Centers for Environmental Information. 2019. NEXRAD III precipitation data from NEXRAD:KLWX Sterling, VA US station for July 8, 2019. Accessed August 25, 2019.
- National Park Service – Inventory and Monitoring. 2015. Stream monitoring data for Wolf Trap and Courthouse Branch creeks. Unpublished.
- Pieper J. M., M. E. Norris, and T. Watts. 2012. National Capital Region Network FY 2010 water resources monitoring data report: water chemistry, nutrient dynamics, and surface water dynamics vital signs. Natural Resource Data Series NPS/NCRN/NRDS—2012/381. National Park Service, Fort Collins, Colorado.
- Thornberry-Ehrlich, T. 2008. Wolf Trap National Park for the Performing Arts Geologic Resource Evaluation Report. Natural Resource Report NPS/NRPC/GRD/NRR—2008/041. National Park Service, Denver, Colorado.
- United States Department of Agriculture – Natural Resources Conservation Service. 2018. Custom soil resource report for Fairfax County, Virginia. Accessed via Web Soil Survey.



United States Geological Survey. 2013. USGS NED
ned19_n39x00_w077x25_va_wvmd_fema_r3lot5_2012 1/9 arc-second 2013 15 x 15
minute IMG. Raster digital elevation model.

United States Geological Survey. 2013. USGS NED
ned19_n39x00_w077x50_va_wvmd_fema_r3lot5_2012 1/9 arc-second 2013 15 x 15
minute IMG. Raster digital elevation model.

Virginia Geographic Information Network. 2017. 2016 Land Cover Raster Tiles Bay Area 2.
Raster dataset.

Walsh, B. M., S. D. Costanzo, W. C. Dennison, J. P. Campbell, M. Lehman, M. Nortrup, B.
Chittenden, P. Goetkin, and C. Schuster. 2015. Natural resource condition assessment for
Wolf Trap National Park for the Performing Arts. Natural Resource Report
NPS/WOTR/NRR-2015/1030. National Park Service, Fort Collins, Colorado.

Water Environmental Research Foundation. 2009. Stormwater BMP Interactive Model.
<https://www.werf.org/liveablecommunities/toolbox/model.htm>. Accessed August 2019.

Woodward, D., Hoeft, C., Kent, K., Humpal, A., Cerrelli, G., Jacobsen, S., Merkel, W., Moody,
H., Quan, Q., Owens, L., Pierce, W., Self, S. 2010. Part 630 Hydrology National
Engineering Handbook. United States Department of Agriculture – Natural Resources
Conservation Service. (210–VI–NEH, May 2010).

Zeedyk, B. and Jansens, J. 2006. An Introduction to Erosion Control. A joint publication from
Earth Works Institute, the Quivira Coalition, and Zeedyk Ecological Consulting. Second
edition.



Appendix: HEC-HMS Input Tables

Table A1: Subbasin Area

Subbasin	Area (km ²)
Bridge Branch	0.336370
Browns Branch	0.448140
Campbell Rd	0.217840
Dimple	0.013518
E bioretention	0.001282
East Lot and Hill Parking	0.052637
Edgepark Rd	0.049461
Filene Center	0.019505
Filene North	0.003798
Filene South	0.005426
Laurel Hill Rd	0.075212
Lower Courthouse	0.050542
Maintenance	0.002684
McLean	0.199020
Meadow	0.017655
Meadow Hill	0.013550
Middle Courthouse	0.047382
Moonac	0.586740
N Dulles Toll Rd	0.028771
North Park	0.069217
North Residential	0.062007
NW bioretention	0.001427
Rim	0.005794
Sibelius E	0.021253
Sibelius W	0.026818
Snughill Ct	0.020281
South bioretention	0.000646
South Woods	0.174620
Streamview Ln	0.043018
The Barns	0.097778
Theatre in the Woods	0.043179
Trap Rd	0.010797



Upper Courthouse	3.340500
Upper Wolf Trap	8.217000
West Corner Woods	0.006672
West Lot	0.166040
West outside	0.290990

Table A2: Curve Number Loss

Subbasin	Curve Number	% Impervious
Bridge Branch	81.74	35.8
Browns Branch	77.10	24.6
Campbell Rd	69.19	18.5
Dimple	50.91	27.7
E bioretention	83.40	41.6
East Lot and Hill Parking	88.63	31.9
Edgepark Rd	64.21	17.4
Filene Center	87.74	44.1
Filene North	76.94	2.6
Filene South	75.47	21.2
Laurel Hill Rd	72.75	22.5
Lower Courthouse	47.69	2.9
Maintenance	96.43	90.3
McLean	74.45	31.4
Meadow	77.99	13.3
Meadow Hill	72.79	6.4
Middle Courthouse	66.32	13.2
Moonac	77.66	25.0
N Dulles Toll Rd	97.96	99.9
North Park	54.77	2.4
North Residential	70.14	24.0
NW bioretention	89.73	62.6
Rim	70.05	14.1
Sibelius E	73.29	16.6
Sibelius W	73.38	11.7
Snughill Ct	66.05	22.0
South bioretention	77.38	11.9
South Woods	78.54	52.3



Streamview Ln	67.87	18.7
The Barns	78.56	19.8
Theatre in the Woods	43.24	2.2
Trap Rd	93.43	78.8
Upper Courthouse	86.64	52.1
Upper Wolf Trap	81.59	32.6
West Corner Woods	73.08	10.7
West Lot	85.25	56.8
West outside	78.79	26.1

Table A3: SCS Transform

Subbasin	Graph Type	Lag Time (min)
Bridge Branch	Standard	85.36
Browns Branch	Standard	153.82
Campbell Rd	Standard	85.42
Dimple	Standard	9.42
E bioretention	Standard	7.18
East Lot and Hill Parking	Standard	14.28
Edgepark Rd	Standard	24.88
Filene Center	Standard	22.77
Filene North	Standard	9.40
Filene South	Standard	8.41
Laurel Hill Rd	Standard	65.66
Lower Courthouse	Standard	96.17
McLean	Standard	70.67
Meadow	Standard	13.95
Meadow Hill	Standard	10.44
Middle Courthouse	Standard	85.44
Moonac	Standard	240.24
N Dulles Toll Rd	Standard	7.53
North Park	Standard	149.90
North Residential	Standard	45.09
NW bioretention	Standard	3.57
Rim	Standard	10.04
Sibeliuss E	Standard	15.92
Sibeliuss W	Standard	20.71



Snughill Ct	Standard	12.59
South bioretention	Standard	24.52
South Woods	Standard	35.82
Streamview Ln	Standard	20.63
The Barns	Standard	11.38
Theatre in the Woods	Standard	103.54
Trap Rd	Standard	5.40
Upper Courthouse	Standard	813.59
Upper Wolf Trap	Standard	974.19
West Corner Woods	Standard	3.98
West Lot	Standard	88.45
West outside	Standard	80.10

Table A4: Recession Baseflow

Subbasin	Initial type	Initial Discharge (m ³ /s /km ²)	Recession Constant	Threshold Type	Ratio to Peak
Bridge Branch	Discharge Per Area	0.0164916	0.96243	Ratio to Peak	0.0005
Browns Branch	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Dimple	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
East Lot and Hill Parking	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Edgepark Rd	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Filene Center	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Filene North	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Filene South	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Laurel Hill Rd	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Lower Courthouse	Discharge Per Area	0.0164916	0.96243	Ratio to Peak	0.0005
McLean	Discharge Per Area	0.0164916	0.96243	Ratio to Peak	0.0005



Meadow	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Meadow Hill	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Middle Courthouse	Discharge Per Area	0.0164916	0.96243	Ratio to Peak	0.0005
Moonac	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
North Park	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
North Residential	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Rim	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Sibelius E	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Snughill Ct	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005

Table A4 Cont.

Subbasin	Initial type	Initial Discharge (m ³ /s /km ²)	Recession Constant	Threshold Type	Ratio to Peak
South Woods	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Streamview Ln	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
The Barns	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Theatre in the Woods	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Trap Rd	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005
Upper Courthouse	Discharge Per Area	0.0164916	0.96243	Ratio to Peak	0.0005
Upper Wolf Trap	Discharge Per Area	0.0115815	0.96243	Ratio to Peak	0.0005

Table A5: Normal Depth Routing



Reach	Initial Type	Length (m)	Slope (m/m)	Manning's n	Index Flow (m ³ /s)	Shape	Width (m)	Side Slope (xH: 1V)
Courthouse 4	Discharge = Inflow	318	0.014	0.033	85.86	Trapezoid	9.8	1
Filene S ditch	Discharge = Inflow	377	0.041	0.033	0.38	Triangle		1
Wolf Trap A1	Discharge = Inflow	388	0.022	0.033	85.86	Trapezoid	15.8	1
Wolf Trap B1	Discharge = Inflow	242	0.007	0.033	85.86	Trapezoid	23.3	1
Wolf Trap B2	Discharge = Inflow	291	0.01	0.033	85.86	Trapezoid	23.3	1