August 2020

Ecosystem Services Project: Quantification of the Value of Green Infrastructure Hazard Mitigation Related to Flooding

Final Report

Prepared for

Chesapeake Bay Trust

Prepared by

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1. Introduction

Meeting the goals of the Chesapeake Bay Total Maximum Daily Load (TMDL) will require jurisdictions—including landowners, planners, resource managers, and districts—to continue to choose from and adopt a wide variety of best management practices (BMPs) approved by the Chesapeake Bay Program (CBP) (CBP, 2018). Many of these practices can be characterized as "green infrastructure" (GI) approaches. Although there is no universally agreed-upon definition for GI, one often-cited distinguishing feature of these approaches is that they mimic or take advantage of natural processes by capturing and infiltrating rainfall where it falls (Environmental Finance Center [EFC], 2017). Through this process, they not only filter contaminants from surface runoff, but they also can help to limit the magnitude of runoff flows during rainstorms.

One of the main tools available for evaluating and comparing the benefits and costs of different BMP implementation scenarios in the Chesapeake Bay watershed, particularly for the development of jurisdictions' watershed implementation plans (WIPs), is the Chesapeake Assessment Scenario Tool (CAST) (CBP, 2017). By design, the main focus of CAST is to provide users with a tool for estimating the nutrient and sediment load reductions provided by different BMP implementation approaches. In addition, it includes a module for estimating the costs and cost-effectiveness of these approaches.

Although nutrient and sediment control are necessarily the focus of WIP development and scenario analysis, there is also growing interest in understanding and accounting for a wide range of potential co-benefits offered by CBP-approved BMPs and GI approaches (USEPA, 2011; McGee et al., 2017). To support these efforts, the Chesapeake Bay Trust previously funded a study to develop simple scores (ranging from -5 to +5) for individual BMPs across a variety of ecosystem service co-benefit areas including fish habitat, climate adaptation, bacteria loads, and flood control/mitigation.

Building on these previous efforts, the purpose of this study is to develop and demonstrate a methodology for quantifying the flood mitigation co-benefits of selected GI BMPs. This approach is demonstrated through two case study applications – one in Frederick, MD and other in Chesterfield County, VA. A more specific objective is to show how flood reduction co-benefit estimates can be generated in a form most suitable for the CAST model. To parallel the main BMP benefit (pollutant load reduction) and unit cost estimates in CAST, this means generating co-benefit estimates that are expressed as average unit (per-acre) annual values. For the two case study areas, we estimate unit flood mitigation co-benefit estimates for different types of BMPs. We examine how these estimates vary depending on the characteristics of the case study area and the level (total acreage) of BMP implementation.

Based on these findings, in the final section of this report we present recommended next steps for applying and refining this approach and for extending it more broadly across the Chesapeake Bay watershed. We also discuss some of the lessons learned and implications for estimating other ecosystem co-benefits green infrastructure BMPs.

2. Background

Although flood mitigation is a frequently cited ecosystem service co-benefit provided by many types of GI, the number of empirical estimates of these benefits are somewhat limited, particularly on an average per acre basis.

In a study conducted for USEPA, Atkins (2015) evaluated the effects of GI on runoff retention and avoided flood losses in a sample of twenty hydrologic units (8-digit HUCs) throughout the contiguous United States. Three of the HUCS included in the study are within the greater Chesapeake Bay watershed and therefore provide study areas comparable to the ones analyzed in this study.[1] Detailed hydrologic models and building inventories were not developed for the watersheds analyzed. Rather than developing detailed, area-specific structure inventories (e.g. user-defined facility), the Atkins study employed the Federal Emergency Management Agency's (FEMA) General Building Stock (GBS). The GBS is developed from regional generalizations about building characteristics in a study area, rather than reflecting the area's true built environment (FEMA, 2019). The GBS is generalized at the Census block level and assets are assumed to be evenly distributed throughout the Census block (FEMA, 2009). Rather than developing detailed hydrologic models, the authors used stream flow records and simpler models to estimate the peak flows of their defined storm events. Atkins then estimated the runoff volume retained under various retention scenarios and storm events. Depending on the study area and scenario, GI was assumed to retain approximately one to two inches of storm volume. Although the Atkins study did not specify the types or acreage of GI implementation, their results can be used to estimate the acre-feet (AF) volume of water retained in each scenario and therefore also to estimate the average annual value of avoided losses per AF. For example, under a medium retention scenario (capturing stormwater volume associated with 85^{th} to 90^{th} percentile storms), the annual avoided losses across the three HUCs ranged from $8 to approximately $160 per AF retained. Assuming one inch per acre retention (as we have done in our "retention" BMP scenarios described later in this report), then these flood co-benefits estimates correspond with unit (per acre of GI implementation) values for annual avoided flood damages ranging from <$1 to approximately $13 per acre.

In a more recent study, Antolini et al. (2019) evaluated BMPs' potential for flood loss reduction as a co-benefit in four Iowa hydrologic units (12-digit HUCs). The authors employed a similar overall framework to our analysis, combining hydrologic modeling, flood frequency analyses, and economic loss estimates weighted by flood frequency (i.e., average annual flood loss with return periods ranging 2 to 500 years). The BMPs evaluated by Antolini et al. focused on alternative land use/land cover scenarios, including cover crop changes, conversion of cropland to forest or grass, and wetland construction.

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[1] The three 8-digit HUCS in the Chesapeake Bay watershed are the Lower Susquehanna (02050306), Upper James (02080201), and Middle James (02080205) river basins.

Despite similar underlying methodologies, direct comparisons between the Antolini analysis and our analysis are difficult given the differences in study areas. Antolini et al. evaluated study areas primarily classed as rural and/or agricultural, with only one significant area of inhabitation (La Porte City, population approximately 2,000). The authors also did not provide per-acre estimates of flood damages, rather, they provided total annual losses (AAL) and percent loss reduction estimates from baseline. Despite the sparsely populated study areas in the Antolini analysis, structural damage losses greatly exceeded agricultural losses; in populated watersheds, structural losses comprised approximately 60% to 80% of total losses. In areas with structural damage, losses were "highly irregular" due to the non-uniform distribution of structures within the flood extents, as compared to crops, which are approximately uniformly distributed within a geographic area. This finding highlights the variability and uncertainty associated with estimating structural flood losses. Furthermore, it emphasizes the difficulty in extrapolating structural loss estimates from a given study area due to temporospatial variability in structure distribution, density, and height, in addition to geographic and geomorphic variability.

Other studies evaluating GIs' retention capacity have demonstrated that flood co-benefits tend to be optimized under more frequent, smaller return period storms (Medina, Monfils & Baccala, 2011). This co-benefit pattern is typical with retention scenarios—GI typically retains stormwater volumes on the order of 0.5 to 2.0 inches; therefore, GI can retain a greater proportion of frequent, smaller return period storms, while its retention capacity is greatly exceeded under infrequent, larger return period storms.

3. Data and Methods

Using a case study approach, we developed a 9-step methodology for estimating flood mitigation co-benefits for selected types of BMPs. Each step is described separately in the following sections.

Step 1. Specification of Green Infrastructure Techniques

The current version of the CAST model contains almost 300 distinct approved BMPs for reducing nitrogen, phosphorus, and sediment loads; however, only a subset of those is expected to have meaningful flood mitigation effects. To focus our analysis on the most relevant BMPs we rely in part on the results of a previous analysis (CBT, 2017) which developed co-benefit scores for BMPs, including for flood mitigation. Unsurprisingly, most of the 30 highest scoring flood control/mitigation BMPs are classified as urban BMPs. Because our approach is focused on estimating avoided structural damages from flooding, we also focus our analysis on these top scoring urban BMPs.

The CAST model also categorizes BMPs according to how their load reductions are estimated in the model. For urban BMPs, the main distinction is between "load-source-change" and "efficiency value" BMPs. "Load sources" in CAST are fundamentally similar to land use categories. Therefore, load-source-change practices, as the name suggests, are treated as a change in the type of load source present on specific acres of land, each with its own assumed loading rate. In contrast, for efficiency value BMPs, a specified percentage (from 0 – 100%) of a baseline pollutant load is assumed to be removed from the existing load source's loading rate.

The urban load-source-change and efficiency value BMPs with the highest flood mitigation scores are listed in **Tables 3.1** and **3.2**, respectively.

To estimate the flood control-related reductions in surface runoff for BMPs, we apply this same distinction between load-source-change and efficiency value BMPs in our analysis. For load-source-change BMPs, rather than changing average annual pollutant loading rates per acre to correspond with different load source categories, we change the hourly surface runoff rates (in cubic feet per second [cfs] per acre). For efficiency value BMPs, we treat them as "retention" BMPs and assume they retain runoff from a 1-inch storm event (i.e., 1-inch of surface runoff per event per acre implemented (Center for Watershed Protection, 2013).

Table 3.1. Urban load-source-change BMPs in CAST with the highest flood reduction potential

BMP Name	Flood Benefit Score[a]	Original Load Source	New Load Source Type
Forest Buffer	3.5	MS4 Turf Grass	True Forest
	3.5	Non-Regulated Turf Grass	True Forest
Impervious Surface Reduction	3	MS4 Tree Canopy over Impervious	MS4 Tree Canopy over Turf Grass
	3	MS4 Roads	MS4 Turf Grass
	3	MS4 Buildings and Other	MS4 Turf Grass
	3	Non-Regulated Tree Canopy over Impervious	Non-Regulated Tree Canopy over Turf Grass
	3	Non-Regulated Roads	Non-Regulated Turf Grass
	3	Non-Regulated Buildings and Other	Non-Regulated Turf Grass
Tree Planting – Canopy	2	MS4 Roads	MS4 Tree Canopy over Impervious
	2	MS4 Buildings and Other	MS4 Tree Canopy over Impervious
	2	MS4 Turf Grass	MS4 Tree Canopy over Turf Grass
	2	Non-Regulated Roads	Non-Regulated Tree Canopy over Impervious
	2	Non-Regulated Buildings and Other	Non-Regulated Tree Canopy over Impervious
	2	Non-Regulated Turf Grass	Non-Regulated Tree Canopy over Turf Grass

[a] CBT (2017)

MS4 - municipal separate storm sewer system

Table 3.2. Urban efficiency (retention) BMPs in CAST with the highest flood reduction potential

BMP Name	Flood Benefit Score[f]
Bioretention/raingardens[a]	3.5
Bioswale	3.5
Wetlands[b]	3.5
Filter Strip Runoff Reduction	3
Filter Strip Stormwater Treatment	3
Infiltration Practices[c]	3
Permeable Pavement[d]	3
Vegetated Open Channels[e]	3
Wet Ponds[b]	3
Dry Detention Ponds and Hydrodynamic Structures	2.5
Dry Extended Detention Ponds	2.5

[a] CAST contains 3 BMPs in this category
[b] CAST currently combines wet ponds and wetlands in a single BMP category
[c] CAST contains 2 BMPs in this category
[d] CAST contains 6 BMPs in this category
[e] CAST contains 2 BMPs in this category
[f] CBT (2017)

Step 2. Case Study Selection

To be consistent with CAST and the CBP Partnerships Phase 6 Watershed Model ([Phase 6 model]; CBP, 2017), we initially considered conducting case study analyses at a "land-river segment" scale (i.e., the smallest geographic units used for Phase 6 model outputs). That is, we planned to use these segments to delineate the drainage area and BMP implementation area of interest, and then use the directly downstream river reach as the flood impact area for analysis. However, after reviewing several candidate sites, we concluded that flood impact analyses at a smaller geographic scale and on smaller river reach tributaries (i.e., subwatersheds that are subareas within CAST land-river segments) would be more appropriate, because these areas were more likely to contain significant numbers of structures within the floodplain. In addition, to take advantage of other analyses done at this scale, we focused on areas with existing FEMA flood insurance studies (FIS), geospatially defined structure points and high-resolution ground surface datasets.

Based on these considerations, we selected two case study applications – one in Frederick, MD (Potomac River Basin) and one in Chesterfield County, VA (James River Basin). Both sites have FEMA FIS studies available, have relatively high levels of urban/suburban development and are comprised of roughly 7,000 acres of drainage area. Maps and more detailed descriptions of these study areas are provided in Chapter 4.

Step 3. Baseline Load Source (Land Use) Characterization

The CBP's Phase 6 model uses a modified version of the Hydrologic Simulation Program Fortran (HSPF) model to represent and simulate river and stream hydrology in the Chesapeake Bay watershed. Model results are primarily generated at the land- and land-river segment scales. This HSPF land use simulation provides modeled unit area runoff (consisting of surface overflow, interflow, and active groundwater flow) per land use category in each land segment at an hourly time step over a 30-year historical period. To take advantage of these data and maintain consistency with the Phase 6 modeling system, we rely on these HSPF runoff estimates as the basis for selecting, characterizing, and analyzing peak flow events in the selected case study areas.

To assess BMP flooding benefits at a scale commensurate with where they are apparent, given the retention characteristics as described in Section 2, we chose to focus on specific headwater and corresponding downstream sections of each case study drainage area. We used the enhanced National Hydrography Dataset (NHDPlus) catchments to define these headwater water drainage areas (McKay et al., 2013). To apply the CBP modeling framework's HSPF runoff estimates, we need to know the area of each load source category within the selected catchments. One of the difficulties encountered for conducting this spatial allocation is that the CBP modeling framework does not currently provide land area (acreage) estimates for load source categories at the NHDPlus catchment level. However, the CBP Partnership has developed a high-resolution Phase 6 Land Used Database containing GIS coverage for 13 land use categories that are similar to load source categories.[2] The CBP data show estimated land uses by 10x10 meter cells across the case study areas. Therefore, for each case study area, we estimated the land area (in acres) for each load source category by developing a crosswalk from the Phase 6 land use categories to the load source categories (for details, see Appendix A). The 13 overlapping CBP land use raster datasets were aggregated into a single dataset, using ESRI's ArcPro desktop software, by keeping the highest cell value and corresponding land use value for each cell location. The acreage in each land use category was then assigned to its corresponding load source category from the crosswalk. These area estimates were then used to calculate runoff for peak flow events using the methods described in the next step. The computed runoff for the entire land segment, based on the crosswalk, was validated with the HSPF output for the selected events.

Step 4. Selection and Runoff Estimation for Peak Flow Events

A key objective of the analysis is to estimate the *annual* flood reduction benefits of specific GI practices; however, flood events vary significantly in size and frequency, with the most damaging events occurring infrequently and less damaging events occurring more frequently. For this reason, we apply a probabilistic event-based approach. That is, we estimate damages for multiple discrete flood events of different magnitudes and return probabilities, and we pro-rate these damages based on their probability of occurring in any given year.

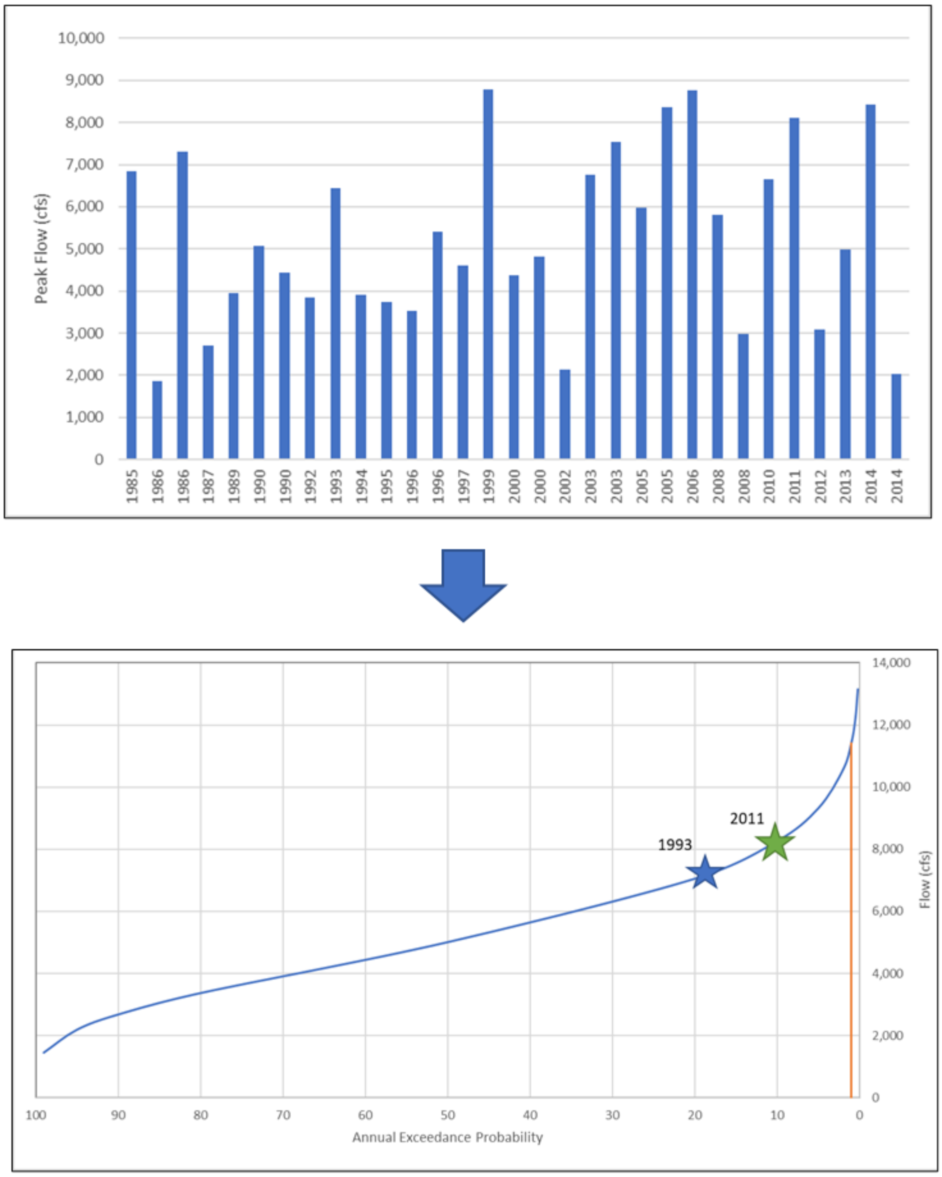
To select and define flood events that covered a range of frequencies for our analysis, we used 30 years of HSPF hourly flow estimates for the land-river segments containing our case study areas. For each year, we selected the highest hourly (peak) flow value (in cubic feet per second [cfs]). Based on these selected peak flow data, we developed a flow-frequency relationship for each area by conducting a Bulletin 17B Flood Flow Frequency analyses (USGS, 1981) using the US Army Corps of Engineers (USACE) Statistical Software Package (HEC-SSP). As shown in **Figure 3.1**, this method allows us to extrapolate from (1) the 30 selected yearly peak flow values to (2) a continuous flow-frequency relationship. For any given flow value (in cfs), the flow-frequency relationship answers the following question: *what is the probability, in any given year, that the peak flow value would be higher than this selected cfs value?* The figure shows that higher peak flow values are associated with lower probability values and, therefore, less frequent events.

Using this estimated flow-frequency relationship, we can also estimate the expected frequency (i.e., exceedance probability) of the 30 selected yearly peak flow values. As examples, Figure 3-1 shows that the HSPF peak flow value observed in 1993 has an

[2] The Chesapeake Bay Phase 6 Land Use dataset is described in and can be viewed at https://chesapeake.usgs.gov/phase6/map/#map=5/-7703853.89/5423776.5/0.0/0,4

estimated exceedance probability of just under 20% and the 2011 peak value has a 10% exceedance probability.

Figure 3.1. HSPF yearly peak flow and resulting flow vs. frequency relationship

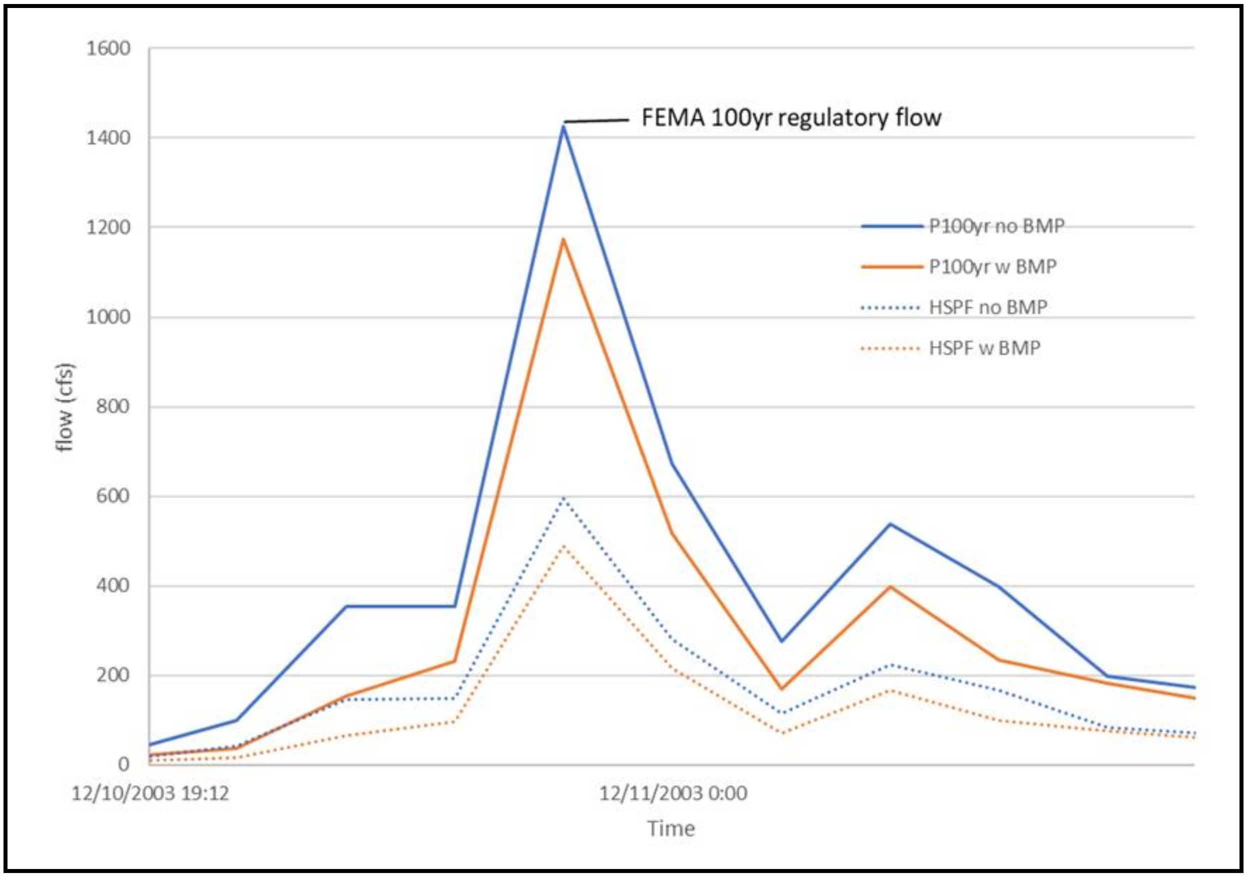


Using the estimated flow-frequency relationships for each study area, we then selected events from the period of record whose flow values correspond with four specific exceedance probabilities –10%,2%, 1%, and 0.2%. In terms of "return frequency" events, these probabilities correspond with 10-year, 50-year, 100-year and 500-year return period floods, respectively. Higher frequency flood events were not modeled as part of the analysis, based on the assumption that relatively few structures of value are getting flooded more than once every ten years.

We then used HSPF model estimates to calculate average hourly flows for the four selected return-frequency events in each catchment in our study areas. Specifically, we took the HSPF unit runoff (in cfs/acre) estimates for each event and load source category in the land segment,[3] and we multiplied them by the number of acres in the corresponding load source category in each catchment.

For validation, we then compared our HSPF-derived flow estimates with comparable return period flows published in the FEMA FIS. In general, we found that there was a poor match. A comparison between the HSPF results and USGS gage flows for discrete flood events revealed that the peak flows from the HSPF results varied greatly from actual stream flow. Additionally, a range of low frequency return period floods (including 500-year events) were not present in the HSPF 30-year period of record. To address these limitations and accurately model frequency-based flood events, the published FIS flows (10-, 50-, 100- and 500-yr) and their return frequencies were adopted for this analysis. The range of flows published in the FIS is adequate for an annualized damage analysis. To translate the HSPF hourly flow estimates to the FIS published flows, the selected events were scaled using a multiplier so that the peak flows from each event matched the return flow published in the FIS. An example, using a 100-year event is shown in **Figure 3.2**. Baseline HSPF peak flow estimates in this case were scaled up from 600 to over 1400 cfs to correspond with the FEMA 100-year flow data. We then applied the same multiplier to the HSPF output for the BMP scenarios. Because the HSPF results did not contain an event equivalent to the 500-year return frequency, the 100-year HSPF event was scaled to produce the 500-year storm for the analysis. The resulting peak flows were applied to the hydraulic model as described in Step 5.

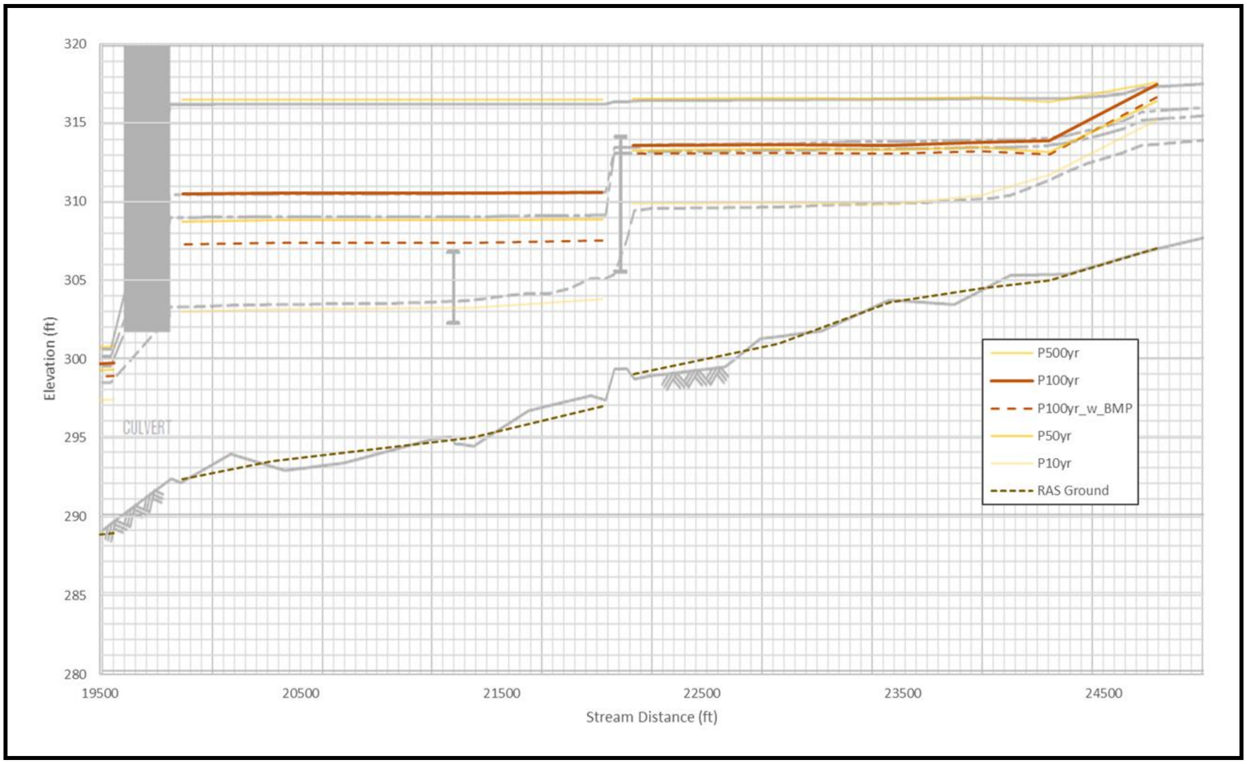
Figure 3.2. Example of information used to scale HSPF flow estimates



Step 5. Flood Depth and Extent Modeling

A one-dimensional steady state USACE River Analysis System (HEC-RAS) hydraulic model was developed for each study area to produce estimates of water depth at points along the selected river reaches for specific flood events. The peak flows from the flood event hydrographs (such as the one shown in Figure 3.2 and discussed in Step 4) were applied to the hydraulic models, which were developed for each study area using detailed ground surface information. **Figure 3.3** provides an example cross-section representation of HEC-RAS modeled flood event profiles for a 5,000 foot length of river. The length of the river is shown along the horizontal axis (with flow from right to left), and the elevation (depth) at the deepest point is shown on the vertical axis. Pertinent features affecting depth, such as bridges and culverts (represented here as vertical bars) were included in these models, and calibration was performed so the resulting modeled flood profiles without BMPs (shown as solid red and yellow lines) for the 10-year (P10yr), 50-year (P50yr), 100-year (P100yr), and 500-year (P500yr) events generally agreed with the corresponding FIS profiles (shown in grey) for each study area. Flood depth raster datasets showing the extent of the inundated area for each event were then produced using the HEC-RAS Mapper tool within the hydraulic model. The elevation and flood depth profiles were developed for multiple flood events under baseline conditions and then rerun in each case using the flow inputs from the BMP implementation scenarios. The resulting decrease in water level for the 100-year event is represented in **Figure 3.3** by the dashed red line**.**

Figure 3.3. Example of HEC-RAS modeled flood event profiles (yellow and red) compared to FIS profile (gray)



Step 6. Property Damage Estimation for Selected Flood Events

In this step, we estimate the total value of flood damages to building structures and building content in each study area due to the peak flows and flood extents estimated for each of the four main types of selected flood events – i.e., 10-year, 50-year, 100-year, and 500-year return period floods.

For this analysis, we applied the FEMA HAZUS tool (FEMA, 2018), which was developed to provide a consistent methodology for estimating losses associated with natural disasters. A key component of HAZUS's flood module are damage curves, which relate flood depths to replacement values for structures and contents. To implement this methodology, we applied FEMA's supplemental tool, the Flood Assessment Structure Tool (FAST), which is underlain by HAZUS methods and assumptions and runs on open-source Python script. FAST provides a rapid, user-friendly, and easily-inspectable method for analyzing structure-level flood risks and damages (i.e. user-defined facility analyses).

The inputs required for FAST analyses are: 1) structure-level data (i.e. a "building inventory"),[4] and 2) flood depths and extents (i.e. "depth grids"). We developed the building inventories using tax parcel data from each study area, further discussed herein. The depth grids for various flood scenarios were obtained from the hydraulic modeling step (See Step 5). The output of the FAST analysis is a file containing economic losses—structural damage losses and content losses—for each structure in the study area's building inventory, calculated as a function of inundation depth expected at the structure's location. FAST was run under riverine flooding conditions for each study area's various BMP implementation scenarios.

To develop detailed building inventories, GIS parcel files with attribute data and structure footprints were obtained from the State of Maryland's GIS Data Catalog (data.imap.maryland.gov) and Chesterfield County's GeoSpace webpage (geospace.chesterfield.gov), for the Carroll Creek and Chesterfield study areas, respectively. Structure footprint and parcel data were merged in ArcGIS Pro (e.g. spatial joins, attribute joins). These merged spatial datasets provided information related to structures' locations and structures' physical and economic attributes.

Municipal codebooks were also obtained for each study area and were used to create FEMA-coded building inventories to run in FAST. This primarily involved matching the study areas' municipal land use codes with FEMA occupancy classes. The building inventory file for each study area ultimately contained the occupancy class, the building value (assuming assessed value is equal to the replacement value), the building area, number of stories, foundation type, first floor height, the value of the building's content, and the approximate latitude/longitude for each structure. Building contents were estimated as 50% of the value of the structure. First floor height was assumed to be two feet above grade. The remaining attributes were developed or estimated directly from parcel or structure data. In some cases, parcel records had insufficient data to make FEMA classification assignments; in such cases, visual inspection of aerial photographs and reviews of records available online were used to develop best-estimates for FEMA classifications.

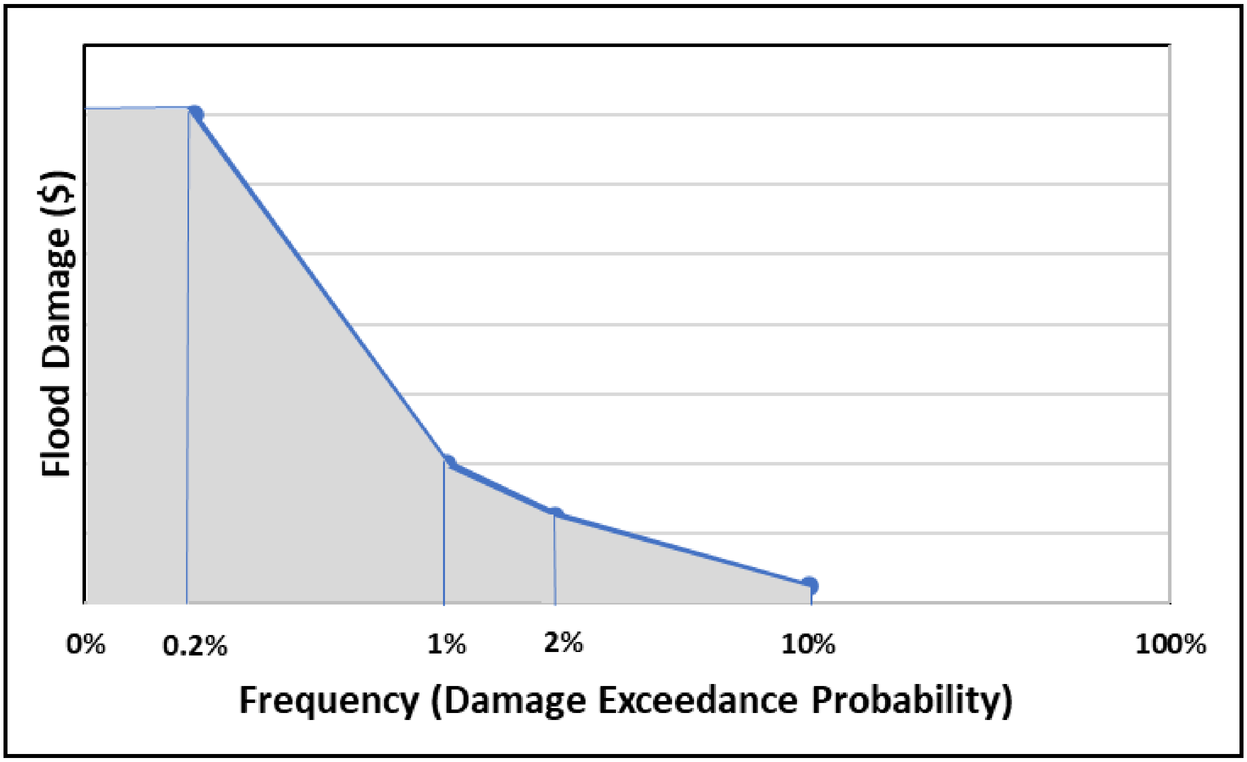
Combining the flood damage estimates from FAST across the four flood events allows us to generate a damage-frequency curve, such as the example shown in **Figure 3.4**. This curve shows how the size of flood damages is inversely related to the probability of each event.

Next, given this flood damage-frequency relationship, we estimate the total expected (i.e., probability weighted) flood damages in any given year. To fully estimate this expected

[4] As discussed in Section 5, this analysis does not include flood damages to other structures such as roads, bridges, and sewer infrastructure.

value, we would need to (1) estimate a continuous damage-frequency curve, specifying a damage values across the entire 0-100% probability range and (2) estimate the area under this continuous curve. As an approximation, we estimate the area under the piece-wise linear curve connecting the damage estimates for the four selected events (represented as the grey areas under the curve in Figure 3.4).

Figure 3.4. Example of a generalized flood damage-frequency curve



Step 7. Specification of Green Infrastructure (BMP) Scenarios

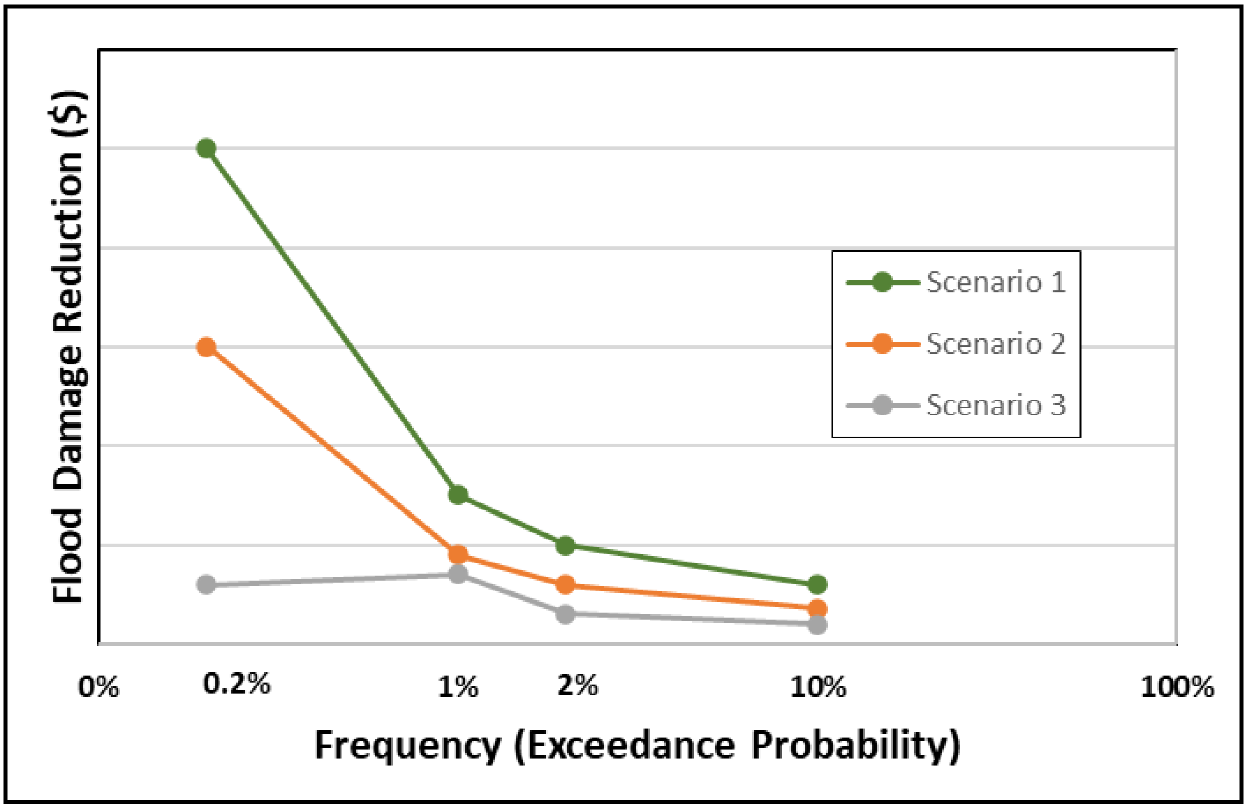
We then developed BMP implementation to scenarios to simulate the flood control effects and estimate the avoided damages resulting from different types of BMPs. For load-source-change BMPs, we focused initially on the three main BMPs identified in Table 3.1 – forest buffers, impervious surface reduction, and tree planting. For each BMP, we began by specifying the total number of acres in each of the "*from* Load source" categories corresponding to that BMP (as shown in the Table 3.1). We then specified four scenarios, in which a percentage – ranging from 5 percent to 100 percent— of the available acres were converted to the "*to* load source" category. In the model simulation runs, we replaced the HSPF hourly unit runoff (cfs/acre) estimates for these acres with the lower values corresponding to the "to load source" categories. We selected these relatively large and wide-ranging land use conversions, not because they represent an expected or realistic scale of BMP implementation in these areas, but rather to capture a wide range of potential flood damage reductions and to examine the sensitivity of average (per-acre) benefits across this range.

For the retention BMPs, we developed similar scenarios; however, rather than simulating the effects of reducing runoff through land use change, we assumed that a fixed amount of flow volume would be removed from the baseline load source category. Because the retention amount is fixed per acre, the results do not depend on where (i.e., which load source) the BMPs are applied, as they only depend on the total number of acres of BMPs implementation.

Step 8. Simulation of Flood Events and Damages for Selected BMP Scenarios

In this step, we rerun the flood extent and flood damage estimation steps for each BMP scenario, replacing the baseline runoff estimates for each flood event with the scenario-specific runoff estimates (as described in Step 7). This step produces a new damage-frequency curve for each BMP scenario, which can be represented as a downward shift from the baseline curve. This change can also be represented as a frequency-based damage *reduction* curve for each scenario (relative to baseline) as shown in **Figure 3.5**.

Figure 3.5. Examples of scenario-specific damage reduction-frequency curves



Step 9. Estimation of Green Infrastructure Flood Mitigation Benefits

Finally, for each BMP scenario, we first estimate the **total** expected flood mitigation benefits per year (in terms of avoided damages to structures), incorporating the range of 10-year to 500-year events. Then, dividing by the number of BMP acres in each scenario, we estimate the corresponding **unit** – i.e., average per BMP acre – benefits.

The total annual benefits are calculated as the reduction in annual expected flood damages relative to baseline scenario. In other words, total benefits can be approximated by the *change* (reduction) in area under the damage-frequency curves, going from baseline to each scenario. Alternatively, it can be estimated as the area under each scenario's frequency-based damage reduction curve.

The unit (average per acre) flood mitigation benefits (in dollars per acre per year) for each BMP are estimated by dividing the total annual benefits for each scenario by the corresponding total number of BMP implementation acres.

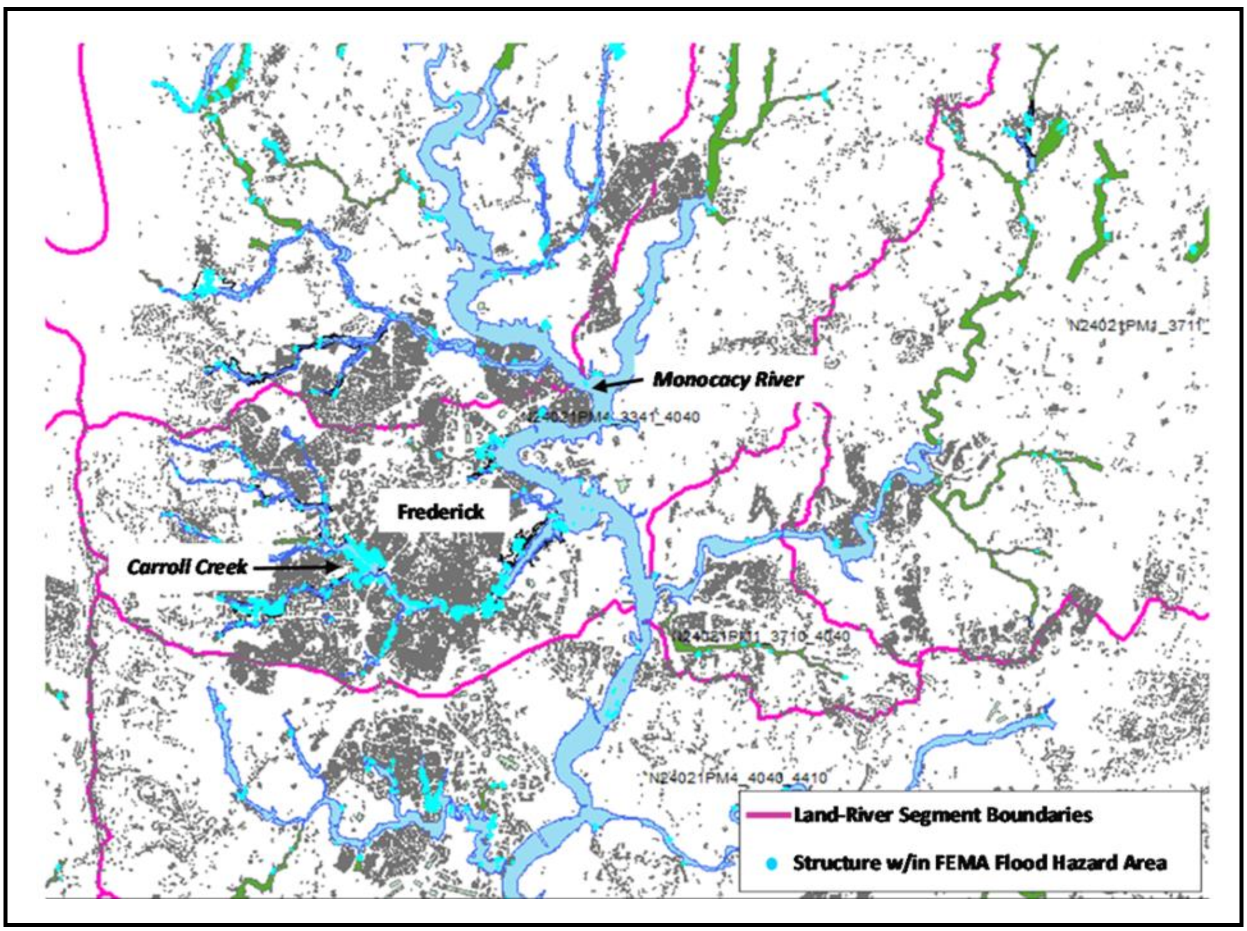
4. Results

The analytical steps described in the previous section for estimating the flood mitigation co-benefits of GI BMPs were applied in two case study areas. The results from these two applications are discussed separately in the following two subsections of the report

4.1 Frederick, MD (Carroll Creek) Case Study

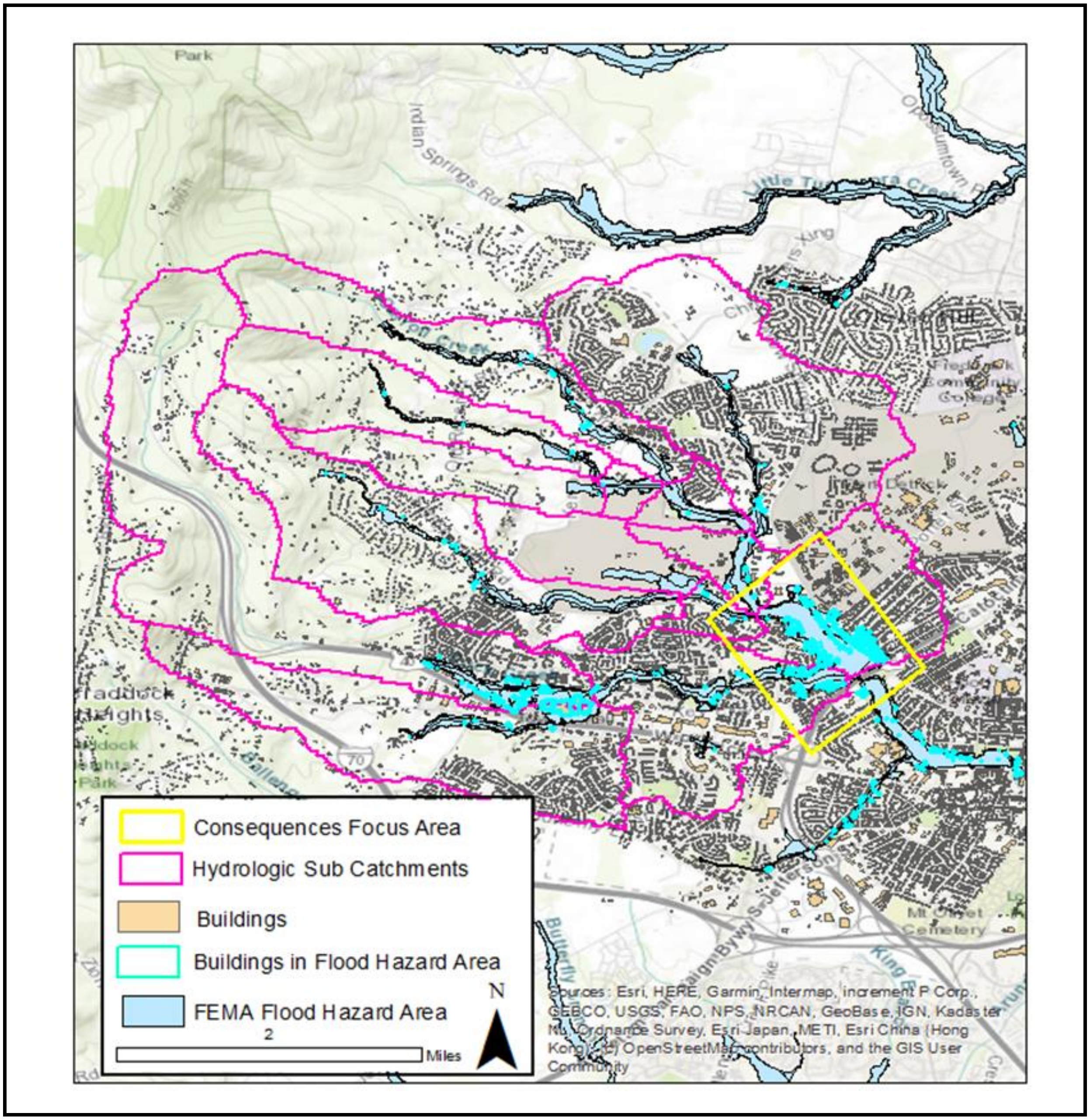
As a first case study application, we focus on a portion of the land-river segment shown in **Figure 4-1** (N24021PM4_3341_4040, where N24021 provides the land segment identifier for which HSPF results were obtained). Located within the Potomac River Basin, this segment includes most of the city of Frederick, MD, and its main river reach is a section of the Monocacy River. The two main tributaries that make up this land-river segment are Israel Creek, which drains from the east, and Carroll Creek, which drains from the west and runs through the center of the city. The river and stream boundaries shown in Figure 4.1 are expanded to include the FEMA flood hazard areas and to also display the location of structures within these areas.

Figure 4.1. Land-River Segment Containing the Carroll Creek Case Study area



A GIS analysis of this land-river segment showed that most of the potentially vulnerable structures (i.e., those within the 500-year floodplain) were likely to be found along Carroll Creek. For this reason, we focused our analysis on a middle section of Carroll Creek shown in **Figure 4.2** and on the 12 NHDPlus catchments that drain to this section. This selected drainage area covers just over 7,200 acres.

Figure 4.2. Case study drainage area (NHDPlus catchments) and impacted portion of Carol Creek[a]



[a]The hydrologic sub catchments listed in the figure legend are NHDPlus V2 catchments

Using the crosswalk approach described in Section 2 (Step 3) and Appendix A, we then converted data from the CBP's Phase 6 Land Use database to estimate the number of acres in different load source categories. These estimates are summarized in **Table 4.1**. The category with largest area, covering 46 percent of the combined NHDPlus catchments is MS4 Turf Grass, followed by True Forest with 21 percent. The four other MS4 categories together cover another 20 percent of the drainage area.

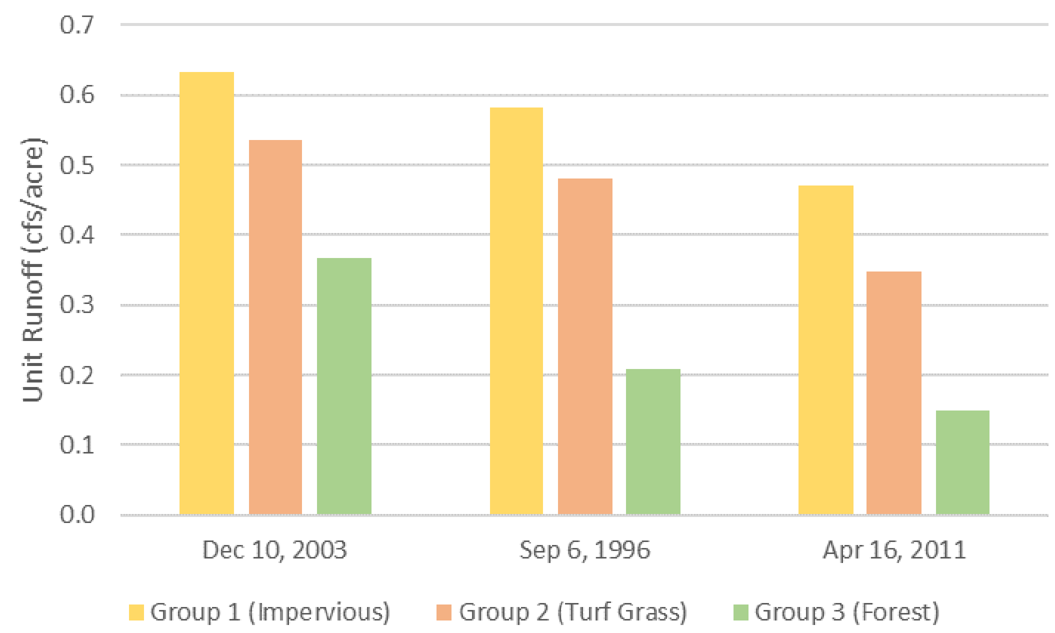
Table 4.1. Breakdown of the case study drainage area by load source category

Load Source Category	Load Source Code	Total Area	
		Acres	%
MS4 Tree Canopy over Impervious	Mci	88	1%
MS4 Roads	Mir	166	2%
MS4 Buildings and Other	Mnr	299	4%
MS4 Turf Grass	Mtg	3,322	46%
True Forest	For	1,533	21%
MS4 Tree Canopy over Turf Grass	Mch	901	13%
Mixed Open	Osp	65	1%
Pasture	Pas	537	7%
Full Season Soybeans	Soy	79	1%
Water	Wat	202	3%
Non-tidal Floodplain Wetland	Wfp	8	0%
Headwater or Isolated Wetland	Wto	2	0%
Group 1 (Impervious) Total		552	8%
Group 2 (Turf Grass) Total		3,322	46%
Group 3 (Forest) Total		1,533	21%
Other Total		1,794	25%
All Load Sources		7,201	100%

To estimate the flood control benefits of load-source-change BMPs, we also specified three distinct groups of load source categories – Impervious, Turf grass, and Forest — which are color-coded in **Table 4.1**. As previously shown in Table 3.1, changes from the Impervious group (Group 1) to Turf Grass (Group 2) correspond with the impervious surface reduction BMP, and changes from the Turf Grass (Group 2) to Forest (Group 3) correspond with the forest buffer BMP. Importantly for the analysis, CBP Phase 6 HSPF model provides distinct unit runoff estimates (cfs/acre) at an hourly time-step for each of these groups.[5] The use of these groups for specifying BMP scenarios is described in more detail later in this section.

Figure 4.3 shows how the Phase 6 HSPF model's peak flow unit runoff estimates vary across load source groups, using peak flow events for three different years (1996, 2003, and 2011) in the land segment as examples. Across the three events, the peak flow unit runoff estimates are roughly 20 percent lower for Turf Grass than for Impervious, and on average almost 50 percent lower for Forest than for Turf Grass.

Figure 4.3. Comparison of peak flow unit runoff estimates across load source groups for three high flow events in the land segment



To estimate the flood mitigation benefits of GI, we defined separate BMP implementation scenarios for load-source-change BMPs and retention BMPs. We begin here by describing the scenarios and results for the load source change BMPs. As previously discussed, the largest reductions from load source changes are expected to come from conversions of Turf Grass (Group 2) cover to Forest (Group 3) cover (i.e., corresponding to the forest buffer BMP). To examine the sensitivity of estimated flood mitigation benefits to the extent of BMP implementation, we varied these conversions from 100 percent of Group 2 acres (3,322

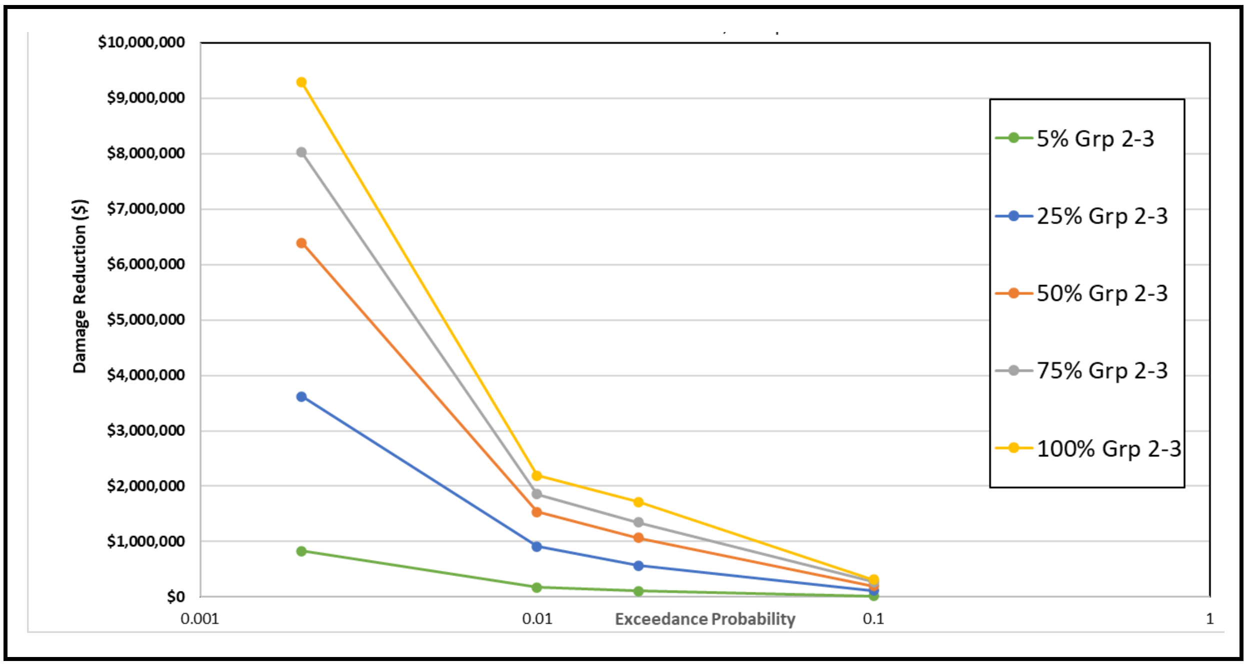
[5] There was generally no difference in the unit runoff estimates between the "from" and "to" load sources corresponding to the urban tree planting BMP. In the model, adding tree cover to either impervious surface or turf grass does not result lower runoff. For this reason, the tree planting BMP could not be included in the analysis using this methodology.

acres) to 5 percent (166 acres). The upper parts of this range are not intended to represent actual or realistic BMP implementation scenarios, but rather to examine how the average benefits per acre vary across a broad level of implementation.

The other type of load-source-change we evaluate is the conversion of Impervious areas (Group 1) to Turf Grass (Group 2), which corresponds with the impervious surface reduction BMP. For this type of BMP, we only evaluated scenarios with 100 percent and 25 percent conversion, which in this case includes 552 acres and 136 acres of impervious area, respectively.

Applying our event-based flood damage assessment approach to each BMP scenario, we estimated the reduction in flood damages for each of four selected return-frequency flood types – i.e., 10-year (10 percent probability), 50-year (20 percent probability), 100-year (1 percent probability), and 500-year (0.2 percent probability). The results of this analysis are shown in **Figure 4.4** for the scenarios involving conversion from Group 2 to Group 3 and in **Figure 4.5** for the Group 1 to Group 2 conversion scenario.

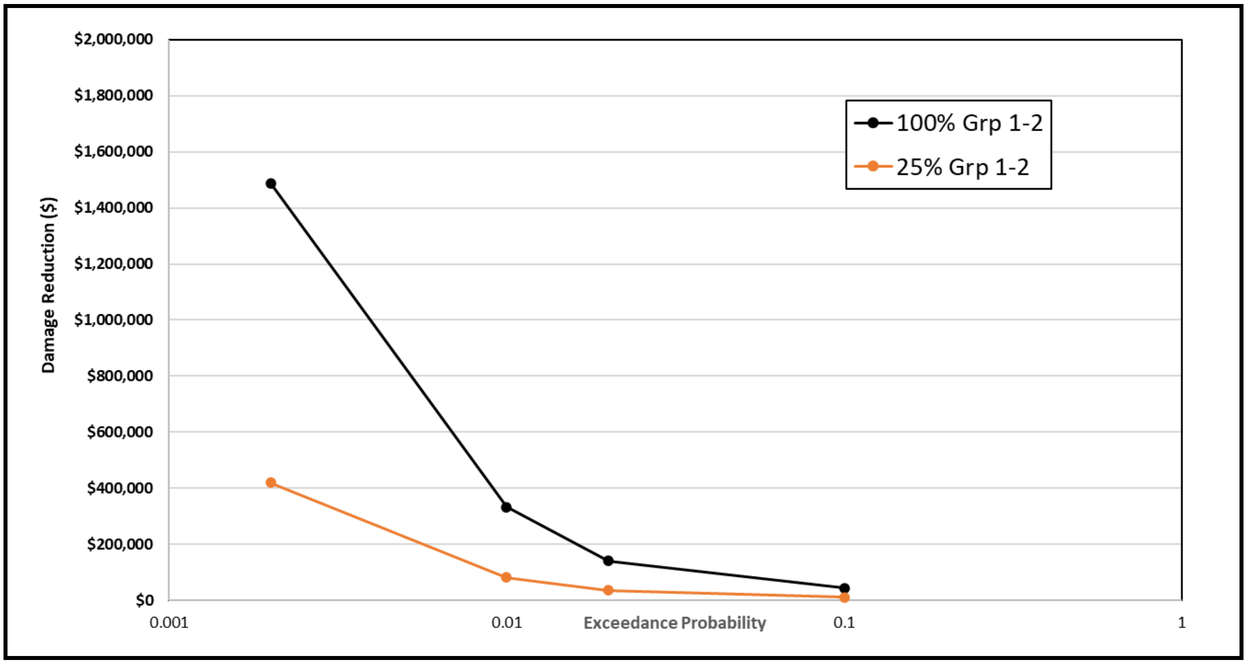
Figure 4.4. Damage Reduction-Frequency Curves for Load-source-change BMP Scenarios: Conversion of Turf Grass (Group 2) to Forest (Group 3)



As expected, the 100 percent conversion scenario results in the largest estimated damage reductions for each of the four return-period/probability events, and the damage reductions decrease as the extent of BMP implementation decreases. In the 100 percent conversion scenario shown in Figure 4-4, converting all 3,322 acres from Turf Grass to Forest results in damage reduction that is estimated to exceed $9 million for the 500-year (0.2 percent probability) flood event and almost $2 million for the 50-year (2 percent probability) event. In contrast, the 5 percent conversion scenario is estimated to reduce damages by less than $1 million for the 500-year event and by roughly $100,000 for the 50-year event.

Figure 4.5 shows a similar pattern of damage reductions for the 100 percent and 25 percent conversion scenarios from Impervious (Group 1) to Turf Grass (Group 2). The values are lower than the corresponding scenarios in Figure 4-4, in part because the involve fewer acres of conversion but also because the per-acre runoff reductions are lower.

Figure 4.5. Damage Reduction-Frequency Curves for Load-source-change BMP Scenarios: Conversion of Impervious (Group 1) to Turf Grass (Group 2)



Applying the final steps of our methodology, we then estimated (1) the total expected annual flood reduction benefits for each BMP scenario and (2) the average (per acre) annual benefits, as shown in **Table 4.2**. As expected, the total value of expected flood damages avoided increases as the number of acres converted increases, with an upper bound of over $165,000 per year when all 3,322 acres of Turf Grass (Group 2) are converted to Forest (Group 3). However, the *average* per-acre values are higher for the lower levels of BMP implementation. The average values decrease from almost $50/acre/year for the 100 percent scenarios to between $70-75/acre/year for the lowest levels of implementation (5 and 25 percent) – which are also the more likely and realistic scenarios.

For the scenarios involving conversion from Impervious (Group 1) to Turf Grass (Group 2), the average per-acre values are lower than for the corresponding Group 2 to Group 3 load-source-change scenarios. These values are lower primarily because they involve less of a reduction in unit runoff according to the HSPF model. Like the Group 2 to Group 3 conversion, the *average* per-acre values are higher for the lower levels of BMP implementation, but the difference is not as great. The average values increase from roughly $36/acre/year for the 100 percent scenarios to $38/acre/year for the 25 percent scenario.

Table 4.2. Total and average (per acre) annual flood reduction benefits by load-source-change BMP scenarios

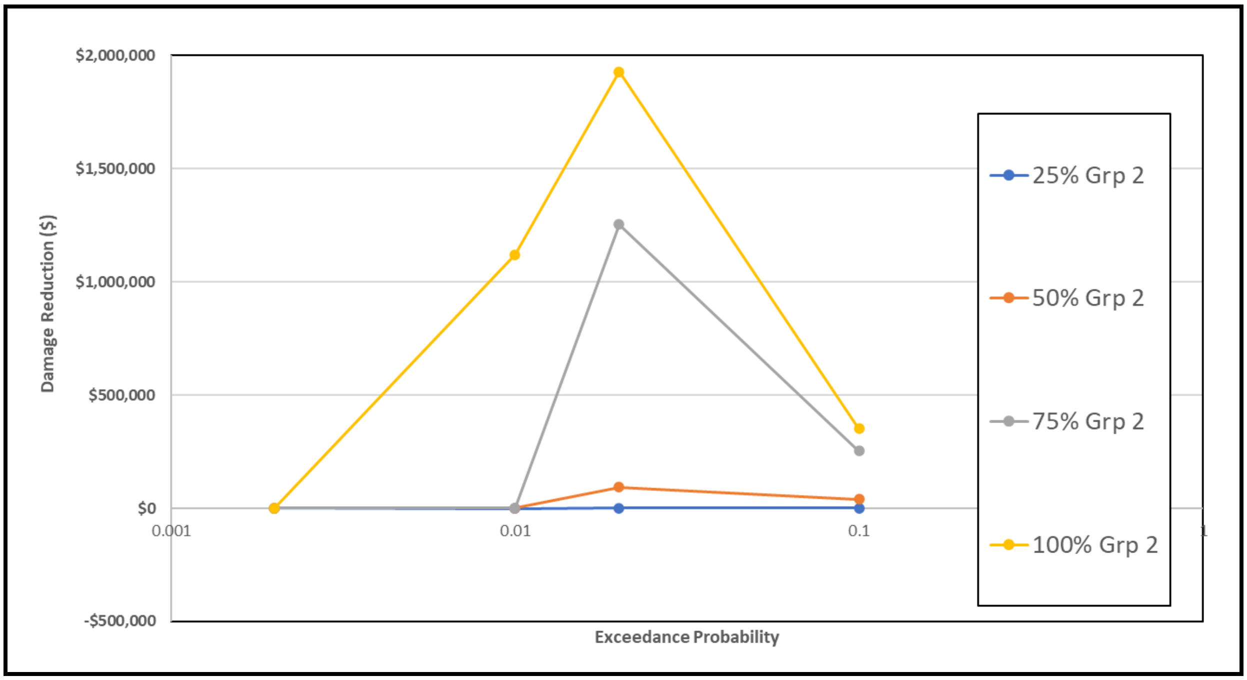
BMP Scenario	Acres Converted	Annual Damage Reduction, $	
		Total Expected	**Average Per-Acre**
5% Group 2-3 Conversion	166	12,314	74.13
25% Group 2-3 Conversion	830	59,913	72.14
50% Group 2-3 Conversion	1,661	108,160	65.12
75% Group 2-3 Conversion	2,491	136,466	54.77
100% Group 2-3 Conversion	3,322	165,227	49.74
25% Group 1-2 Conversion	138	5,274	38.19
100% Group 1-2 Conversion	552	19,964	36.14

We now turn to the scenarios and results for retention BMPs, such as the ones listed in Table 3.2. As previously discussed, we do not distinguish between different types of retention BMPs in this analysis. Rather, we assume they all retain runoff from a 1-inch storm event. Importantly, the flood mitigation effects and benefits of retention BMPs do not depend on the type of load source where they are applied. Nevertheless, to generate flood reduction benefit estimates that can be directly compared to the load-source-change scenarios, we assumed they would be applied to the Group 2 (Turf Grass) acreage. In addition, to provide a direct comparison with the Group 2-3 Conversion scenarios, we applied the retention BMPs to a number of acres equivalent to 25%, 50%, 75%, and 100% of the acres in Group 2. In other words, we varied the acres implemented from 830 acres to 3,322 acres.

Figure 4.6 compares the estimated flood damage reduction by return frequency/probability across four retention scenarios. As in the load-source-change scenarios, the damage reductions increase with the level (acreage) of BMP implementation; however, the pattern of damage reductions across return-frequency events is different. In this case, none of the retention scenarios produce damage reductions for the 500-year storm event, and only the 100 percent implementation scenario produces positive reductions for the 100-year event. Overall, the largest damage reductions are predicted to occur for the 50-year event.

The difference in the estimated pattern of flood damage reductions between the load-source-change BMPs and retention BMPs is due mainly to their modeled impact on peak flows. The load-source-change BMPs reduce runoff in each hourly time step of the HSPF model, including the peak flow period. In contrast, the retention BMPs retain a fixed volume of water per acre per storm event. Therefore, if total retention capacity is reached before the peak flow period occurs – which is more likely to occur in larger flood events – then there will be no estimated reduction in peak flow levels, which are the key determinants of damages. In other words, largest precipitation events will generally overwhelm in-place BMPs, whereas runoff from mid-size events (in this case the 50-year floods) can be more effectively reduced because a greater percentage of the runoff is captured by the BMP.

Figure 4.6. Damage Reduction-Frequency Curves for Retention BMP Scenarios



The estimated flood reduction benefits for these retention BMP scenarios, on both a total acreage and per-acre basis, are reported in **Table 4.3**. As expected, the total estimated flood avoidance benefits tend to increase with the level (acreage) of retention BMP implementation. However, in contrast to the load-source-change BMP scenarios, there are no estimated benefits for the lowest (25 percent) implementation scenario. In addition, due to the previously described differences in how the different BMPs affect peak flows, the *average* (per-acre) damage reduction benefits for the retention BMP scenarios *increase* with the level of implementation. The per-acre benefits increase from $0 and $3 in the 25 and 50 percent implementation scenarios respectively, to over $33 for the 100 percent scenario.

It is important to note that the benefit estimates described for the retention BMPs in Table 4.3 are based on a one inch per acre retention assumption. These estimates can be relatively easily rescaled for different assumptions. For example, doubling the retention assumption from one inch to two inches per acre, will change the total benefit estimates by the same amount as doubling the acreage with 1-inch retention. So, for example, 50 percent implementation (1,661 acres) with 2-inch retention BMPs should have the same total benefit as the 100 percent implementation with 1-inch retention ($100,973), and therefore an average benefit of $66.81 (=110,973/1,661) per acre per year.

Table 4.3. Total and average (per acre) annual flood reduction benefits by retention BMP scenarios

		Annual Damage Reduction, $	
BMP Scenario	**Acres Treated**	**Total Expected**	**Average Per-Acre**
25% Implementation	830	0	0.00
50% Implementation	1,661	5,747	3.46
75% Implementation	2,491	66,607	26.73
100% Implementation	3,322	110,973	33.41

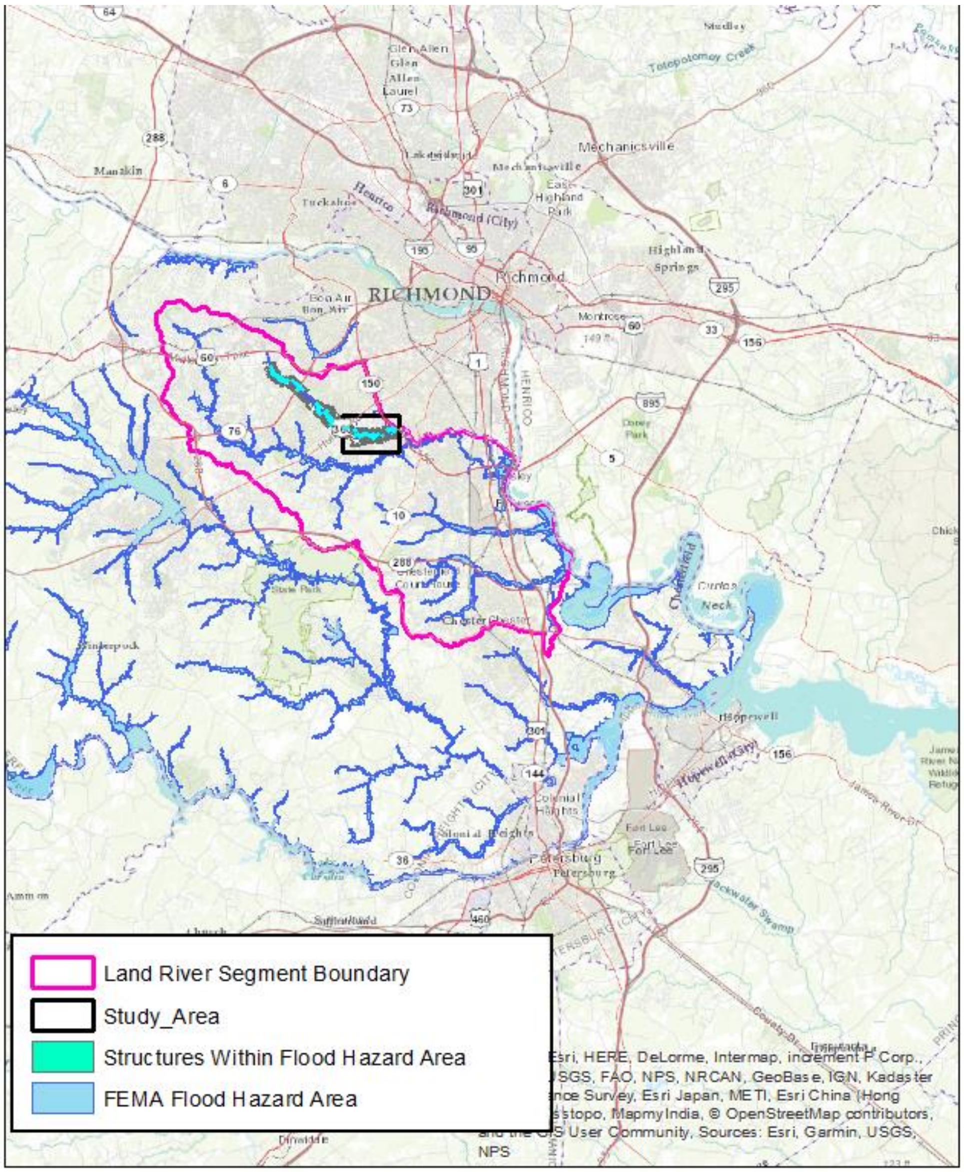
4.2 Chesterfield County, VA (Pocoshock Creek) Case Study

The second case study application focuses on a portion of one land-river segment (N51041JB0_7071_0000, where N24021 provides the land segment identifier for which HSPF results were obtained) in the James River Basin, located in Chesterfield County, VA, south of the city of Richmond. The specific area of analysis is a middle section of Pocoshock Creek shown in **Figure 4.7**. Comprised of 13 NHDPlus catchments, this study area is similar in size to the other case study area, with a total drainage area of roughly 7,000 acres.

In addition to being similar in size to the Frederick, MD case study area, the load source breakdown of the drainage area for this application is also fairly similar (**Table 4.4**). In this case, the Impervious (Group 1) load source accounts for 11 percent of total acreage, Turf Grass (Group 2) is 60 percent, and Forest (Group 3) is 12 percent.

We apply the same general configuration of load-source-change and retention BMP scenarios to estimate flood reduction benefits for the Chesterfield County case study area. In particular, we analyze the same percentage changes (5-100%) in BMP implementation for the different load source groups as in the Frederick, MD case study. However, due to differences in the baseline number of acres in each category, the number of acres converted under each scenario is different from the other case study.

Figure 4.7. Chesterfield Study Area Overview Map



(continued)

Figure 4.7. Chesterfield Study Area Detail Map (continued)

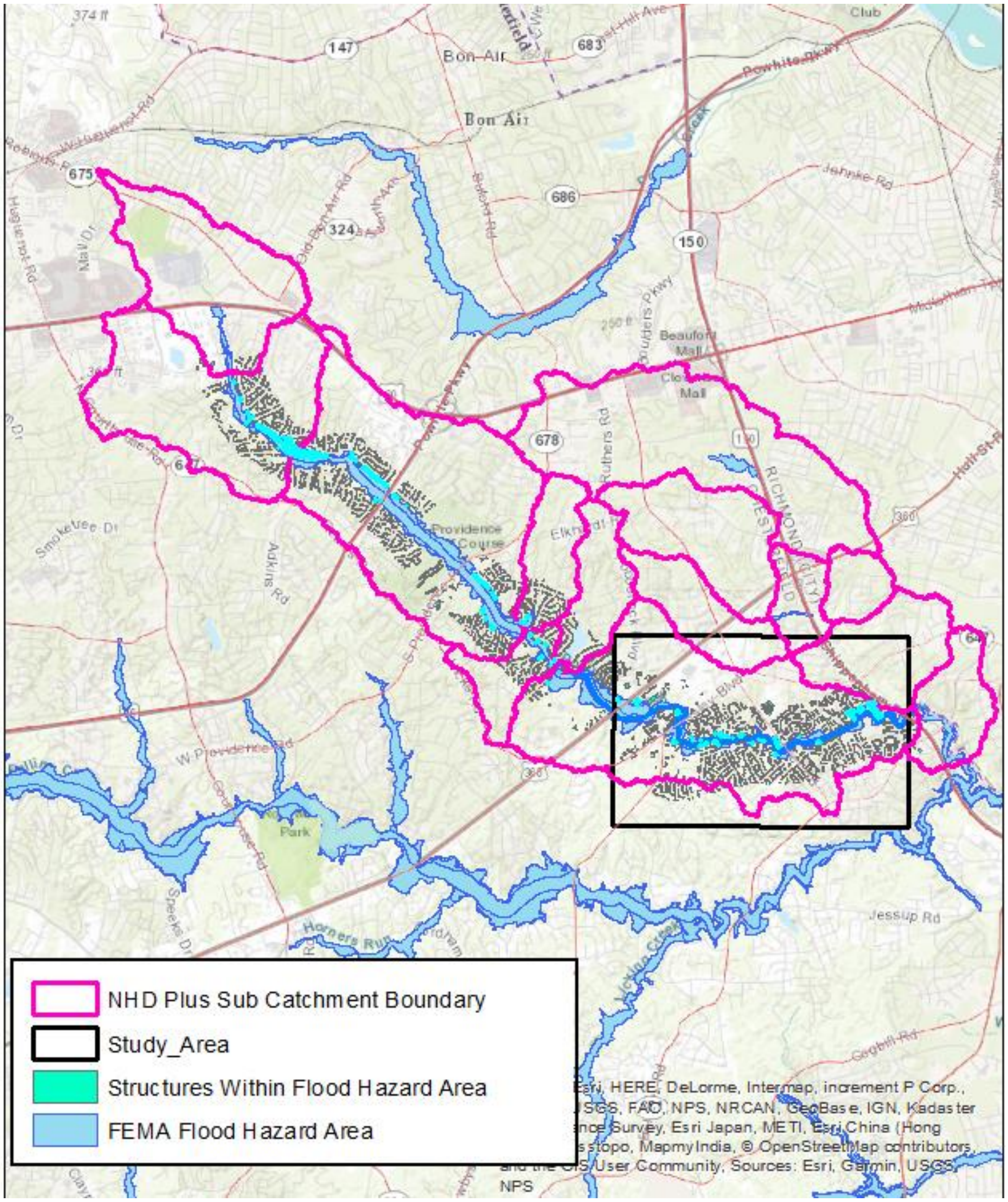


Figure 4.8 summarizes the flood damage reduction estimates (for the four return-frequency events) for the Group 2 to Group 3 load-source-change BMP scenarios. Although the number of acres converted is larger than for the comparable scenarios in the Frederick case study, the flood reduction benefits are noticeably lower in this area. The largest damage reductions are for the 100 percent scenario, with a maximum estimate of slightly more than $800,000 for the 500-year flood event. The main reason for these lower overall benefits is that the number and total value of structures in the affected floodplain is lower

for this case study area. This difference between the two study areas underscores the importance of built environment characteristics and geographic/geomorphic variability as critical determinants of expected co-benefits.

Table 4.4. Breakdown of the case study drainage area by load source category

Load Source Category	Load Source Code	Total Area	
		Acres	%
MS4 Tree Canopy over Impervious	mci	4	0%
MS4 Roads	mir	255	4%
MS4 Buildings and Other	mnr	516	7%
MS4 Turf Grass	mtg	4,209	60%
True Forest	for	827	12%
MS4 Tree Canopy over Turf Grass	mch	716	10%
Mixed Open	osp	83	1%
Pasture	pas	6	0%
Full Season Soybeans	soy	-	0%
Water	wat	133	2%
Non-tidal Floodplain Wetland	wfp	256	4%
Headwater or Isolated Wetland	wto	53	1%
Group 1 (Impervious) Total		775	11%
Group 2 (Turf Grass) Total		4,209	60%
Group 3 (Forest) Total		827	12%
Other Total		1,246	17%
All Load Sources		7,057	100%

The damage reduction estimates for the Group 1 to Group 2 load-source-change scenario are show in **Figure 4.9**. In this case study, this scenario only includes a 100% conversion, which converts 775 acres of Impervious to Turf Grass, these damage reduction estimates are similar in magnitude to those of the 5-percent Group 2 to Group 3 conversion scenario, which only converts 225 acres. This scenario requires more land conversion to achieve the same benefit because it involves a smaller reduction in unit (cfs/acre) runoff.

Figure 4.8. Damage Reduction-Frequency Curves for Load-source-change BMP Scenarios: Conversion of Turf Grass (Group 2) to Forest (Group 3)

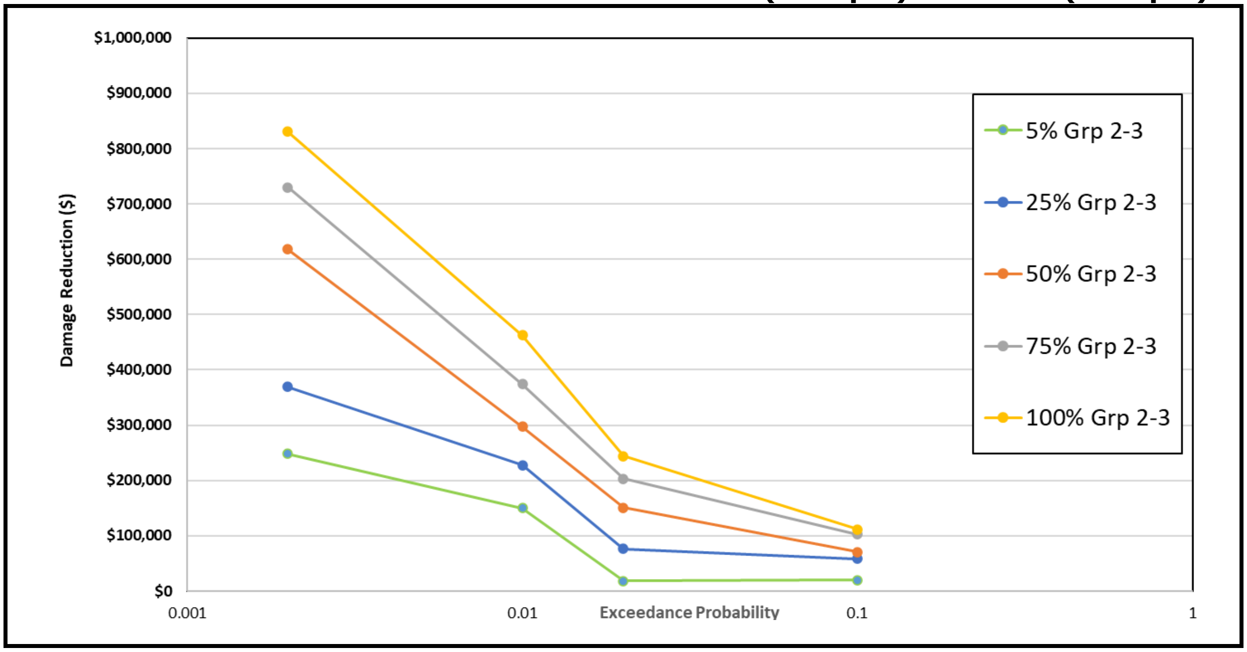
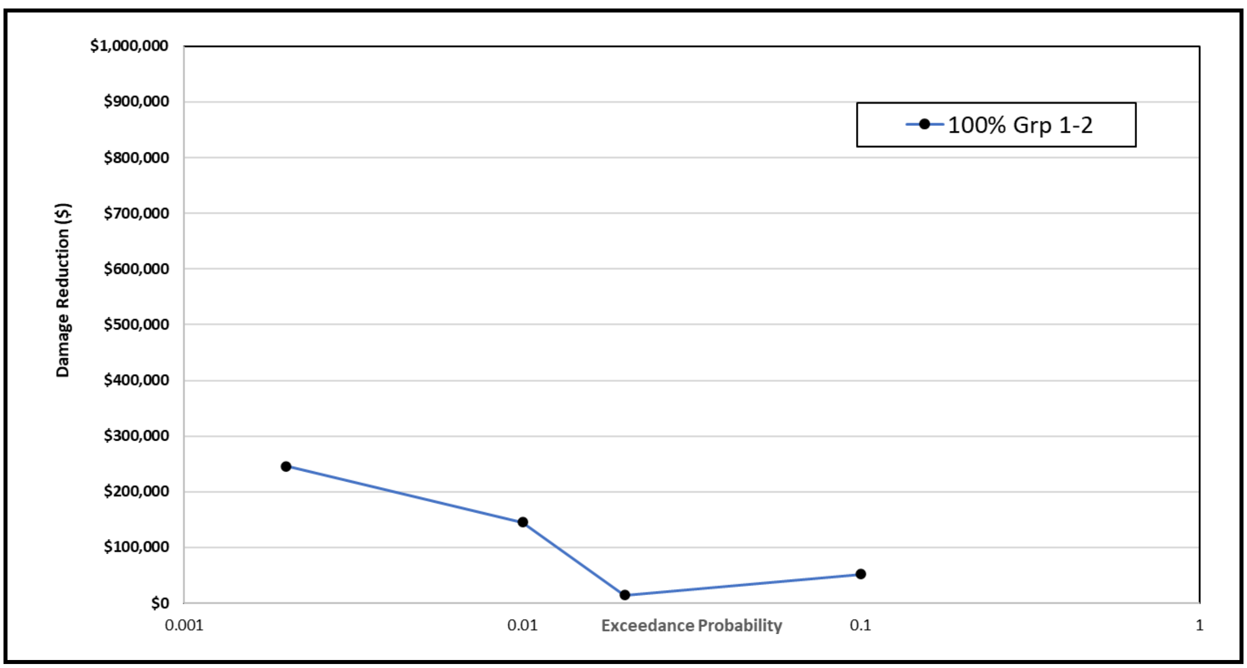


Figure 4.9. Damage Reduction-Frequency Curves for Load-source-change BMP Scenarios: Conversion of Impervious (Group 1) to Turf Grass (Group 2)



Applying the final steps of our methodology, we then estimated (1) the total expected annual flood reduction benefits for each BMP scenario and (2) the average (per acre) annual benefits, as shown in **Table 4.5**. The total damage reduction benefits increase with the number of acres converted, but as in the Frederick MD case study, the average (per-acre) benefits decrease with respect to the number of acres converted from Turf Grass to Forest. The scenario with the lowest amount of conversion (210 acres) has the highest average benefit, equal to over $21/acre/year. The average benefit from converting 775 acres from Impervious to Turf Grass is estimated to be roughly $7/acre/year.

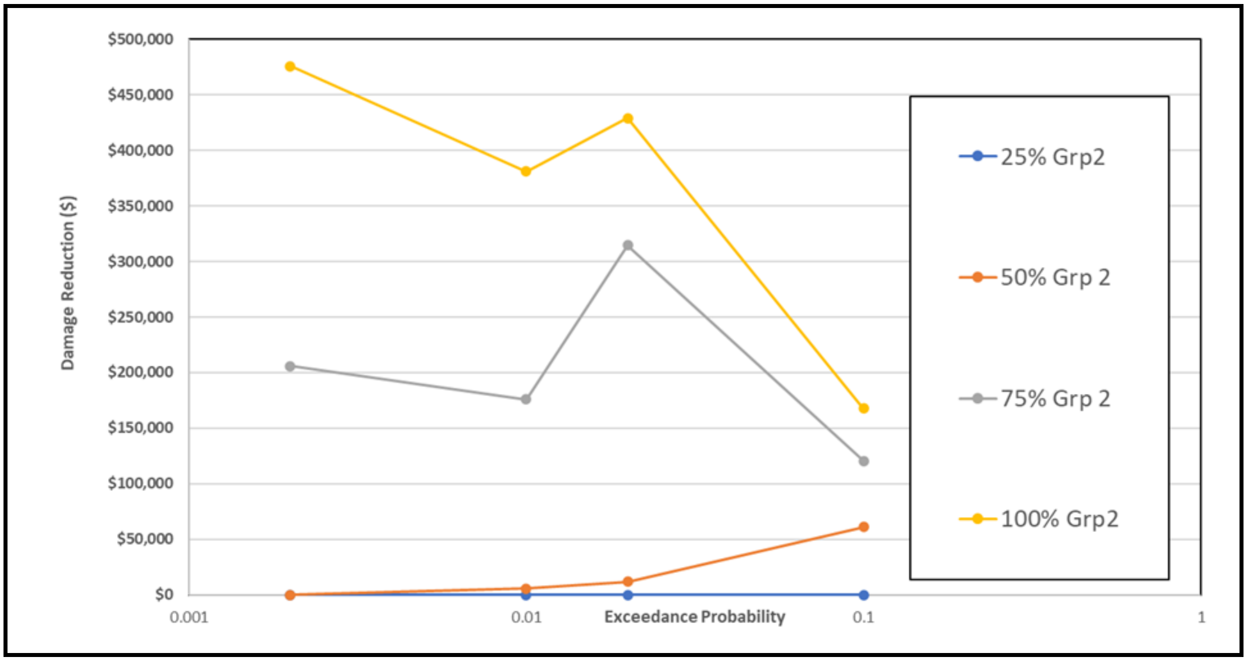
To evaluate the flood reduction benefits of retention BMPs in this case study area, we again selected scenarios using BMP acreage that is comparable to the load-source-change scenarios – i.e., we varied the acres implemented from 1,052 acres to 4,209 acres, which corresponds with 25 percent to 100 percent of the Group 2 (Turf Grass) area.

Table 4.5. Total and average (per acre) annual flood reduction benefits by load-source-change BMP scenarios

BMP Scenario	Acres Converted	Annual Damage Reduction, $	
		Total Expected	Average Per-Acre
5% Grp2-3 Conversion	210	4,473	21.25
25% Grp2-3 Conversion	1,052	10,040	9.54
50% Grp2-3 Conversion	2,105	15,989	7.60
75% Grp2-3 Conversion	3,157	20,984	6.65
100% Grp2-3 Conversion	4,209	24,595	5.84
Grp 1-2 Conversion	775	5,529	7.14

Figure 4.10 compares the estimated flood damage reduction by return frequency/ probability across four retention scenarios.

Figure 4.10. Damage Reduction-Frequency Curves for Retention BMP Scenarios



The estimated flood reduction benefits for these retention BMP scenarios, on both a total acreage and per-acre basis, are reported in **Table 4.6**. As in the Frederick case study, we find no flood reduction benefits for the lowest level scenario (25 percent) but increasing total benefits from the 50 to 100 percent scenarios. We also find a similar pattern of increasing average per-acre benefits as the level of BMP implementation increases. However, in this case study location, the average benefits are of lower magnitude, ranging from roughly $1 to $8/acre/year from the 50 to 100 percent scenarios.

Table 4.6. Total and average (per acre) annual flood reduction benefits by retention BMP scenarios

		Annual Damage Reduction, $	
BMP Scenario	**Acres Treated**	**Total Expected**	**Average Per-Acre**
25% Implementation	1,052	0	0.00
50% Implementation	2,105	3,033	1.44
75% Implementation	3,157	21,805	6.91
100% Implementation	4,209	32,311	7.68

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5. Discussion and Conclusions

As states, counties, and municipalities within the Chesapeake Bay watershed continue to make progress towards meeting the TMDL goals for the Bay, increasing attention is being paid to the full range of potential ecosystem service co-benefits offered by CBP-approved BMPs and related GI approaches. The purpose of this study is to focus on one of the well-recognized but relatively unquantified benefits offered by a subset these BMPs – flood hazard mitigation benefits. We develop and demonstrate a methodology for quantifying these benefits through two case study applications – one in Frederick, MD and other in Chesterfield County, VA. A specific objective is to examine how these flood reduction co-benefits can be estimated and expressed in a form that is most useable in the CAST model – i.e., as average unit (per-acre) annual values.

5.1 Summary of Findings

Our analysis examines two general categories of urban BMPs included in CAST – load-source-change and efficiency BMPs. It leverages data, methods, and results provided by the CBP Phase 6 modeling system, in combination with other data collection and modeling tools, to estimate how these BMPs are expected reduce flood levels and damages in the selected areas. We find that the benefits per acre of BMP implementation vary considerably across case study areas, type and category of BMP, and level (i.e., acreage) of BMP implementation.

For our case study applications, we selected areas that are similar in terms of surrounding levels of urban/suburban development and the presence of structures within the FEMA floodplain. Therefore, they both represent areas with non-negligible flood risks and where urban BMPs could be used both for nutrient/sediment control and for flood control. However, the two areas differ with respect to the number of flood-vulnerable structures, and they were selected with the expectation that, with similar levels of BMP implementation, they would produce a range of avoided flood damages.

As expected, due mainly to differences in the number of at-risk structures, the average flood damage mitigation benefits of BMPs are higher in the Frederick case study area than in the Chesterfield case. For the load-source-change scenarios representing urban forest buffer BMP (conversion from Turf Grass to Forest), the highest estimate of average annual benefit is $74/acre/year in Frederick compared to $21/acre/year in Chesterfield. In both cases, these high-end per-acre estimates come from the scenario with the fewest number of acres converted (166 and 210, respectively), which is also likely to be the most realistic scale of change. For the scenarios representing the impervious surface reduction BMP (conversion from Impervious to Turf Grass), the per-acre benefits are roughly half as high as for the forest buffer BMP in both areas. The per-acre flood mitigation benefits for the retention BMP scenarios are also considerably higher in the Frederick study area than in Chesterfield. The highest estimate in Frederick, which required over 3,000 acres of retention BMPs, is $33/acre/year, compared to $7/acre/year in the Chesterfield area for a similar number of acres.

One of the main differences between the per-acre benefit estimates for the load-source-change BMPs and retention BMPs is how they vary with respect to the number of acres implemented. In both case study applications, the per-acre benefits of the load-source-change BMPs are higher for the scenarios with lower levels (acres) of BMP implementation, whereas the opposite is true for the retention BMPs. In fact, the per-acre benefits are zero in both locations for the retention scenarios involving less than 1,000 acres (and assuming 1 inch per acre of retention). This difference is due in part to differences in the modeling approach and assumptions used for the two types of BMPs. For the load-source-change BMPs, we rely on the hourly unit-area runoff estimates from the HSPF model. This approach implies that, with BMP implementation, the rate of runoff is lower over the entire course of each storm event, including the peak flow, which is the primary determinant of flood damages. In contrast, retention BMPs are assumed to hold a fixed amount of runoff per acre for each event. In this case, larger precipitation events can overwhelm in-place BMPs, such that flow reductions occur before but not during peak flow. Runoff from smaller events is more effectively reduced because a greater percentage of the runoff is captured by the BMP. Similarly, larger areas of BMP implementation are able to capture a greater percentage of runoff and are more likely to reduce peak flow levels.

These results demonstrate that while there are potentially significant flood-mitigation co-benefits from the CBP-approved urban green infrastructure BMPs, the per-acre benefit values are highly variable. They depend on several factors, including the geographic and development characteristics of the area, the types of storm events experienced, the type of runoff control provided by the BMP, and the total area of BMP implementation.

5.2 Limitations and Uncertainties

It is important to also point out and acknowledge several caveats and uncertainties underlying these benefit estimates. First, to develop and demonstrate the methodology, we deliberately selected case study locations with relatively high potential for structural flood damages. They were not randomly selected or intended to be broadly representative of developed areas in the watershed. Consequently, the results should be interpreted as providing high-end benefit estimates compared to most other areas in the watershed.

Second, for the areas we selected, our approach does not capture all the potential flood-related losses and damages that could be mitigated with BMP implementation. In this regard, our benefit estimates should be interpreted as lower-bound estimates for the areas analyzed. Specifically, our analysis only includes damages to building structures. Damages to other structures, such as roads, bridges, or power infrastructure are not included, nor are damages to sensitive ecosystems, habitats, or other natural resources, to cropland, or to human health and safety. In addition, it only includes damages within one NHDPlus catchment downstream from our BMP implementation areas. Damages upstream and further downstream from this catchment are expected to be lower, but additional analysis is needed to determine their relative magnitude.

Third, all the retention BMP scenarios in our analysis assume retention of one inch per acre per storm event. Higher levels of retention are certainly possible, which would then of course entail higher benefits. As discussed in Chapter 4, our estimates for retention BMPs can be relatively easily rescaled for different assumptions. In addition, although our analysis examines how the scale (i.e., number of acres) of retention BMP implementation affects per-acre benefits, it does not examine how the benefits of retention BMPs are affected by combining them with load-source-change BMPs (or vice-versa) on the same acres. This type of analysis is recommended for future extensions of this work.

Fourth, our simplified approach for representing the flood-damage frequency curve does fully capture damages in the extremes of the distribution – i.e., higher consequence but less than 0.2 percent probability events and lowest consequence but more than 10 percent probability events. However, the missing benefits from this simplified approach are expected to be relatively small. For example, higher frequency flood events were not modeled as part of the analysis, because relatively few structures of value are expected to be flooded more than once every ten years.

Finally, our approach does not account for future changes in baseline flood risks and damages due to climate change and increasing development within the current 500-year floodplain. Both factors are likely to contribute to higher flood damages under a no-BMP scenario and to higher benefits (i.e., avoided flood damages) from BMP implementation. Recommendations for addressing this limitation are discussed in the next section.

5.3 Recommendations for Next Steps

This study provides and demonstrates a 9-step approach for estimating the per-acre flood mitigation benefits of selected urban BMPs in selected urban/suburban locations. Although the benefit estimates described in Chapter 4 and summarized above could be used as approximations and potentially transferred to other similar areas in the watershed, developing robust estimates for the watershed as a whole will require additional analysis. We believe that the approach outlined in this report can provide a template for assessing flood mitigation co-benefits more broadly across the watershed.

One approach for extending and eventually extrapolating these benefit estimates for the watershed as whole would be to apply a meta-regression approach similar to the one used by Atkins (2015) at a national scale. This approach requires conducting a large number and variety of case studies using the same methodology across the study area and then using the results as data in a regression analysis. The minimum number of case studies needed to support this type of meta-analysis would depend on the observed variation in conditions and results across studies; however, as an example, the Atkins study used 20 HUC-8 sites across the U.S. in their analysis. The objectives of this type of meta-regression analysis are to (1) explore and test which observable characteristics of the study areas are the most statistically significant explanatory factors/determinants of co-benefits and (2) apply the resulting regression relationship to extrapolate beyond the study sites, by predicting co-benefits for the non-study sites based on the observed characteristics of those areas.

One way to refine the analytical approach described in this report would be to eventually incorporate projected future changes in storm intensity-frequency relationships due to climate change (e.g., see Mino et al., 2020). Projected changes in the frequency of specific size rainfall events can be used to shift the baseline (i.e., no-BMP) damage-frequency curves (such as in Figure 3.4) for future year and to re-estimate the damage reduction benefits of BMP scenarios from that new reference point. Similarly, projections of land use change (i.e., development growth) within floodplain can be used to estimate increases in the number and total value of properties at-risk for flood damage. These estimates can also be used to shift the damage-frequency surveys and re-estimate future benefits.

Although the approach described in this report deals specifically with riverine flooding, the steps can be adapted and, in some cases, directly transferred for estimating coastal flood mitigation co-benefits. The main types of CBP-approved BMPs that are expected to provide protection against coastal flooding are either forest/grass buffers or a category referred to as "shoreline management (urban and non-urban)" practices. The latter includes "a range of practices that can limit tidal shoreline erosion and protect property [such as] living shorelines, revetments and/or breakwater systems, bulkheads and seawalls." [6]

In the case of coastal flooding, the process through which BMPs can reduce flooding is different than for riverine flooding. Therefore, a modified modeling approach is needed. Rather than by retaining and infiltrating water, they reduce flood damages by increasing surface roughness or by changing topographic features in a way that reduces the distance that waves travel inland during storm surge events such as the 10-year, 50-year, 100-year storms.

Rather than developing flow-frequency curves to characterize flood events, in coastal areas the relevant relationship is a sea level-frequency curve (i.e., annual exceedance probability curves relative to mean high water or low water reference points). For example, the National Oceanic and Atmospheric Administration (NOAA) publishes these curves for eleven stations across the Chesapeake Bay (https://tidesandcurrents.noaa.gov/est/). The BMP-

[6] It also includes tidal wetlands, as CBP-approved BMPs designated as wetland are specifically defined for non-tidal areas.

associated change in inland flood depths associated with specific sea level and storm surge events can be estimated using coastal flood models such as the FEMA Coastal Hazard Analysis Modeling Program (CHAMP) (FEMA, 2007).

With estimates of coastal flood depths under different BMP scenarios, the same procedures for estimating damage reductions for riverine flooding (as described in Chapter 4, steps 6, 8 and 9) can be applied. In particular, the HAZUS/FAST modeling approach can be used to determine damages for estimated event-specific flood extents and levels, and from there the annual total and average damage reduction calculations are the same.

The findings from this BMP co-benefits analysis also highlight some the key issues and challenges with developing unit value (i.e., average dollar per acre) estimates for BMP co-benefits in general, including for other ecosystem services benefits such as habitat protection, drinking water protection, and carbon sequestration. There are several factors that complicate the estimation of unit value co-benefits for an area as large as the Chesapeake Bay watershed. Depending on the type of co-benefit being analyzed, some of the factors may be even more challenging to overcome than for flood avoidance benefits, whereas others may be simpler.

A first factor is the scientific uncertainty regarding the main processes and magnitudes of different impacts. For flood impacts, the scientific understanding of surface water hydrology, runoff retention, and flood damages is likely to be fairly advanced compared to other processes such as those related BMP impacts on groundwater systems and natural habitats. Therefore, accounting for and communicating these uncertainties for other unit co-benefit estimates may often be even more of a challenge for than for flood avoidance benefits.

Second, spatial and temporal variation in the physical characteristics affecting benefits can make it more difficult to develop and rely on simple unit values. As described in this report, differences in landscape and stream geomorphology across study areas can greatly impact the flood benefits of BMPs. In contrast, for other co-benefits such as the filtration of air pollutants by trees, landscape variation is likely to be much less of a factor.[7] As also described in this report, temporal variations in precipitation and streamflows are fundamental complicating factors for assessing flood benefits, and they are addressed using probabilistic approaches. For other co-benefits such as habitat provision, this type of short-term variability is likely to be much less of a factor. However, long term changes in physical conditions due to factor such as climate change and land use change are likely to affect all BMP co-benefits, albeit in different ways.

Third, interactive effects with other BMP acres can lead to significant variation in the benefits provided by individual BMP acres. In other words, the benefits of adding or treating one additional acre with a specific BMP may depend (either positively or negatively) on the

[7] Variations in air quality, however, would be much more of a factor for this type of a co-benefit.

number (or spatial distribution) of other acres that already have the BMP in place. This "nonlinear" effect of BMPs is shown for flood control in Tables 4.2 and 4.3 (Frederick case study) and in Tables 4.5 and 4.5 (Chesterfield case study). As previously mentioned, there may also be interactive effects between different types of BMPs, such as between load-source-change and retention BMPs. The presence and significance of these types of interactive effects will vary depending on the type of co-benefit being analyzed. For example, carbon sequestration benefits can generally be thought of as linear (i.e., each additional ton of carbon sequestered provides the same magnitude of climate change mitigation benefits) regardless of how much is being sequestered in the rest of the landscape, whereas habitat provision benefits can depend heavily on the existing level and spatial pattern (e.g., connectivity) of existing green infrastructure.

Fourth, spatial (and temporal) variation in size and characteristics of affected human populations can also be a strong determinant of BMP co-benefits. For estimating flood control benefits, knowing the number, value, and location of residential and commercial structures directly downstream of the BMP implementation area is critical. Accounting for how these numbers, values, and locations are expected to vary in the future can also be critical. For other co-benefits, the role and importance of these beneficiary characteristics can vary substantially. For example, recreation-related co-benefits often depend importantly on the travel times between improved or protected natural areas and potential users' residential locations. In contrast, carbon sequestration benefits are fundamentally insensitive to local short-term population characteristics and depend much more on global and long-term demographic patterns.

Finally, the certainty and overall importance attached to the *monetary* value of co-benefits can vary depending on how direct and observable the benefits are. For some co-benefits, such as flood avoidance, there are direct pecuniary ("out-of-pocket") impacts – e.g., avoided property/asset damage, avoided income losses, or reductions in out-of-pocket costs. These types of monetary values can generally be easily understood and can be estimated with relatively high confidence. For other types of co-benefits – such as habitat provision and recreation – the benefits may be large and very real, because they enhance individuals' well-being, but they do not have a direct pecuniary impact. Estimating these types of benefits requires "non-market" valuation approaches (see, for example, USEPA [2010]), which are generally subject to greater uncertainty.

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Appendix A:
Crosswalk for Converting Land Use to Load Source Categories

Applying the unit (csf/acre) runoff estimates from the CBP Phase 6 HSPF model to estimate total runoff (in cfs) from a sub-catchment requires estimates of land area (acreage) in the sub-catchment by load source category. The CBP watershed model contains 41 load source categories as shown in **Table A-1**. However, at the NHD sub-catchment level, the closest approximation we have for these areas is from the CBP land use dataset, which includes 13 land use categories. To connect the two classification schemes, we first assigned a single land use category to each load source category based on our own assessment of the best match. These assignments are shown in Table A-1, grouped by the 13 land use categories. Next, the 41 load source categories can be grouped into 12 distinct unit-runoff groups, based on the HSPF model estimates of runoff levels. This grouping is also shown in the table. Finally, we selected one load source category to represent runoff levels for each land use category. These selections are shown in red font in the table.

Table A.1.

Load Source			Land Use		Unit Runoff Group
Regulation Category	Type	Code	Code	Name	
Agriculture	**Commodity Crops Full Season Soybeans**	**soy**	**CRP**	**Crop**	**8**
Agriculture	Grain without Manure	gom	CRP	Crop	8
Agriculture	Grain with Manure	gwm	CRP	Crop	8
Agriculture	Silage with Manure	swm	CRP	Crop	8
Agriculture	Silage without Manure	som	CRP	Crop	8
Agriculture	Small Grains and Grains	sgg	CRP	Crop	8
Agriculture	Small Grains and Soybeans	sgs	CRP	Crop	8
Agriculture	Other Agronomic Crops	oac	CRP	Crop	8
Agriculture	Specialty Crops Specialty Crop High	sch	CRP	Crop	8
Agriculture	Specialty Crop Low	scl	CRP	Crop	8
Agriculture	Other Ag Open Space	aop	CRP	Crop	3
Agriculture	Non-Permitted Feeding Space	fnp	CRP	Crop	11
Agriculture	Permitted Feeding Space	fsp	CRP	Crop	11
Combined Sewer System	True Forest	cfr	FOR	Forest	1
Natural	**True Forest**	**for**	**FOR**	**Forest**	**2**
Natural	Harvested Forest	hfr	FOR	Forest	7
Combined Sewer System	Construction	ccn	INR	Impervious non-roads	10
Combined Sewer System	Buildings and Other	cnr	INR	Impervious non-roads	11
Municipal Separate Storm Sewer Systems	Construction	mcn	INR	Impervious non-roads	10
Municipal Separate Storm Sewer Systems	**Buildings and Other**	**mnr**	**INR**	**Impervious non-roads**	**11**
Non-regulated Developed Areas	Buildings and Other	nnr	INR	Impervious non-roads	11
Combined Sewer System	Roads	cir	IR	Impervious roads	11
Municipal Separate Storm Sewer Systems	**Roads**	**mir**	**IR**	**Impervious roads**	**11**
Non-regulated Developed Areas	Roads	nir	IR	Impervious roads	11
Combined Sewer System	Mixed Open	cmo	MO	Mixed Open	5
Natural	**Mixed Open**	**osp**	**MO**	**Mixed Open**	**6**
Agriculture	**Hay and forage Pasture**	**pas**	**PAS**	**Pasture**	**4**
Agriculture	Legume Hay	lhy	PAS	Pasture	4
Agriculture	Other Hay	ohy	PAS	Pasture	4

Load Source			Land Use		Unit Runoff Group
Regulation Category	Type	Code	Code	Name	
Combined Sewer System	Tree Canopy over Impervious	cci	TCI	Tree cover over impervious	11
Municipal Separate Storm Sewer Systems	**Tree Canopy over Impervious**	**mci**	**TCI**	**Tree cover over impervious**	**11**
Non-regulated Developed Areas	Tree Canopy over Impervious	nci	TCI	Tree cover over impervious	11
Combined Sewer System	Tree Canopy over Turf grass	cch	TCT	Tree cover over turf grass	9
Municipal Separate Storm Sewer Systems	**Tree Canopy over Turf grass**	**mch**	**TCT**	**Tree cover over turf grass**	**9**
Non-regulated Developed Areas	Tree Canopy over Turf grass	nch	TCT	Tree cover over turf grass	9
Combined Sewer System	Turf Grass	ctg	TG	Turf grass	9
Municipal Separate Storm Sewer Systems	**Turf Grass**	**mtg**	**TG**	**Turf grass**	**9**
Non-regulated Developed Areas	Turf Grass	ntg	TG	Turf grass	9
Natural	**Water**	**wat**	**WAT**	**Water**	**0**
Natural	**Non-tidal Floodplain Wetland**	**wfp**	**WLF**	**Wetland Floodplain**	**2**
Natural	**Headwater/isolated Wetland**	**wto**	**WLO**	**Wetland Other**	**2**