# Evaluating the Performance of Low Impact Developments on Runoff Volume in Washington DC

Final Report

THE CATHOLIC UNIVERSITY OF AMERICA
Celebrating 125 Years

UNIVERSITY OF THE DISTRICT OF COLUMBIA
COLLEGE OF AGRICULTURE, URBAN SUSTAINABILITY AND ENVIRONMENTAL SCIENCES

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February 2012

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# Final Report: Evaluating the Performance of Low Impact Developments on Runoff Volume in Washington DC

## 1. ABSTRACT

The effectiveness of LID practices in reducing the stormwater runoff load in an area in the east side of the District of Columbia is evaluated. The EPA Stormwater Management Model (SWMM) is used for this evaluation. A few major simplifications have been made to make modeling of storm water possible over a large and highly heterogeneous area. These assumptions include: (i) The sewer network follow the land topography, (ii) Each sub-watershed is represented as composed of pervious and impervious areas discharging their waters directly into a main sewer pipe, (iii) The LIDs affect all of the runoff generated over the all of the pervious area. The third assumption means the runoff from houses and other impervious surfaces are equally impacted by the vegetated swales. The analysis is performed for four representative years including years 1969, 1984, 2003 and 2006 representing two wet years, one average year and one dry year. The simulations are performed for a baseline condition (assuming no LIDs) as well as three LID scenarios including the capture of runoff from respectively 10%, 20% and 50% of houses through vegetated swales represented by the infiltration trench feature of SWMM. It was found that vegetated swales can significantly reduce the total volume of runoff however they were less effective in reducing the peak runoff. This is due to the fact that the vegetated swales in urban areas have a limited capacity and overflow occurs as soon as the rain intensity exceeds a certain amount and therefore these practices are less effective for large storms. Moreover, most of small events can be fully captured by the vegetated swales in residential areas while they only can capture a fraction of the rain during large events. A more detailed study is needed for obtaining the optimal placements of the LID system to achieve the maximum reduction in runoff.

## 2. Introduction

Stormwater runoff from the urban areas is one of the major contributors to water quality impairment nationwide (EPA, 1998) and as a result remains one of the great challenges of modern water pollution control [*Pitt and Bozeman*, 1982]. This problem is particularly pronounced for most of the highly urbanized metropolitan areas including Washington DC. Recently an exclusive Chesapeake Bay TMDL has been established due to insufficient progress and continuous poor water quality in the Bay and its tidal tributaries despite extensive restoration efforts. The Chesapeake Bay TMDL constitute the nation's largest TMDL that will identify the necessary pollution reductions from major sources comprising of nitrogen, prosperous and sediment within the 64,000 sq. miles watershed across the District of Columbia and large sections of Delaware, Maryland, New York, Pennsylvania, Virginia and West Virginia, and sets pollution limits necessary to meet water quality standards in the Bay and its tidal rivers. (EPA 2010). The urban stormwater policy has changed over last few decades. After several decades of focusing on single purpose of controlling large floods and erosion control, which resulted in end-of-the-pipe control, has been changing to more comprehensive policy of hydrologic, environmental and ecological sustainability that include low impact development and mitigation-at-source [*Davis and McCuen*, 2010]. As the gradual shift from end-of-the-pipe control method to more sustainable mitigation-at-source methods strategies progresses in urban stormwater management, and the need for designing sustainable and cost-effective methods and technologies for stormwater runoff quantity and quality control such as Low Impact Development (LID) is becoming evident the need to quantitative assessment of the effectiveness of these approaches seems essential.

Stormwater pollution is a main source of concern in the waters around Washington, DC metropolitan area. High levels of nitrogen, phosphorus and sediment enter the water from a variety of sources, including urban and suburban runoff, wastewater facilities, onsite septic systems, air pollution, and other sources. The discharge of stormwater is more intense during intense rain events when the Blue-Plains wastewater treatment plant does not have the capacity needed to capture the combination of stormwater and raw sewage in the combined sewer system covering the central part of the city. Urban storm water runoff is responsible for about 16% of phosphorus, 11% of nitrogen, and 9% of sediment loads to the Chesapeake Bay. Furthermore, chemical contaminants (such as metals) from urban runoff can rival or exceed the amount reaching the Bay from industries, federal facilities and wastewater treatment plants (EPA). The city of Washington, DC and its metropolitan area is one of the major sources of urban stormwater into the bay.

The goal of this project is to develop an urban watershed model that will assess the impact of implementing various types of Low Impact Development (LID) strategies within the District of Columbia and their ability to control stormwater runoff volume.. For this purpose an urban watershed model has been developed using the EPA SWMM [*Rossman*, 2004] model for a region at the eastern part of the District. Simulations representing the baseline conditions as well as for the conditions after implementation of low impact development strategies including vegetated swales, and green roof were performed using the model and the effectiveness of LID approaches were evaluated in reducing the runoff volume for a number of representative years. The report is organized as follows: First, the selected study area is described, then the sources and preparation of all of the data used in the modeling including precipitation, topography, imperviousness of surfaces and sub-watershed boundaries are described. At the end the results under the baseline condition as well as under a number of hypothetical LID conditions are presented. The report ends with conclusions and recommendations.

## 3. Study Area

Figures 1-3 presents the locations of the study sites chosen for the research. The location is only composed of a portion of eastern Washington, District of Columbia that is serviced by separate stormwater and municipal wastewater networks (Figure 2). This area was selected in order to avoid the modeling complications associated with the mixing of municipal wastewater with the stormwater. Figure 1 shows the study area in the District of Columbia. The central part of the District is served by a combined sewer system and the stormwater runoff from generated from these areas is mostly treated at the Blue Plains wastewater treatment facility with the exception of overflows arising from large storms when the capacity of the plant is exceeded. The untreated overflows and runoff is discharged into the Potomac River, Anacostia River and the Rock Creek Stream. There are two areas, one in the east side and the other in the west side of the district that are covered by separate stormwater networks and the stormwater generated in those areas are mainly discharged into the surrounding water bodies. The eastern region is selected for this study.

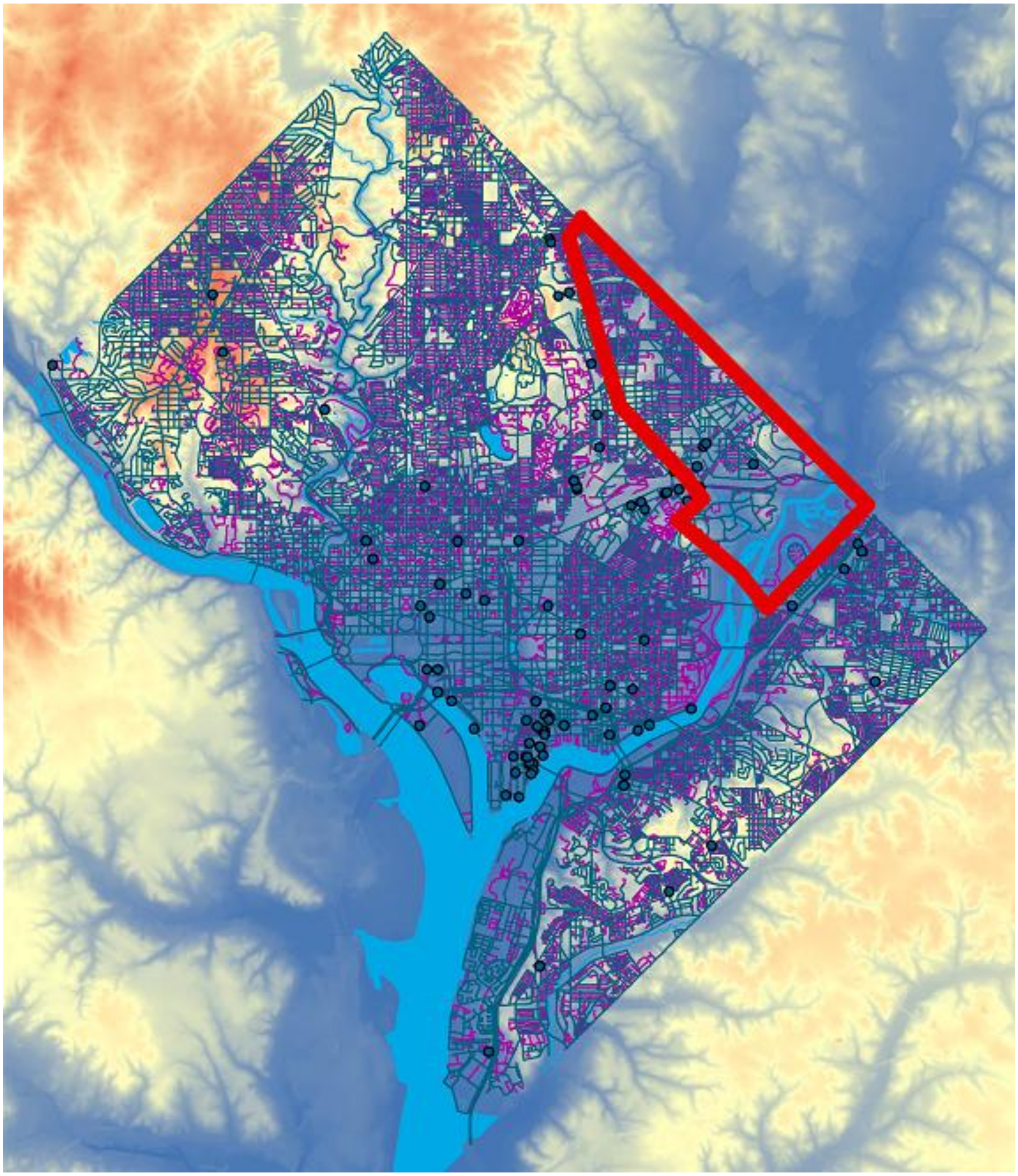

**Figure 1: The extents of the study area**

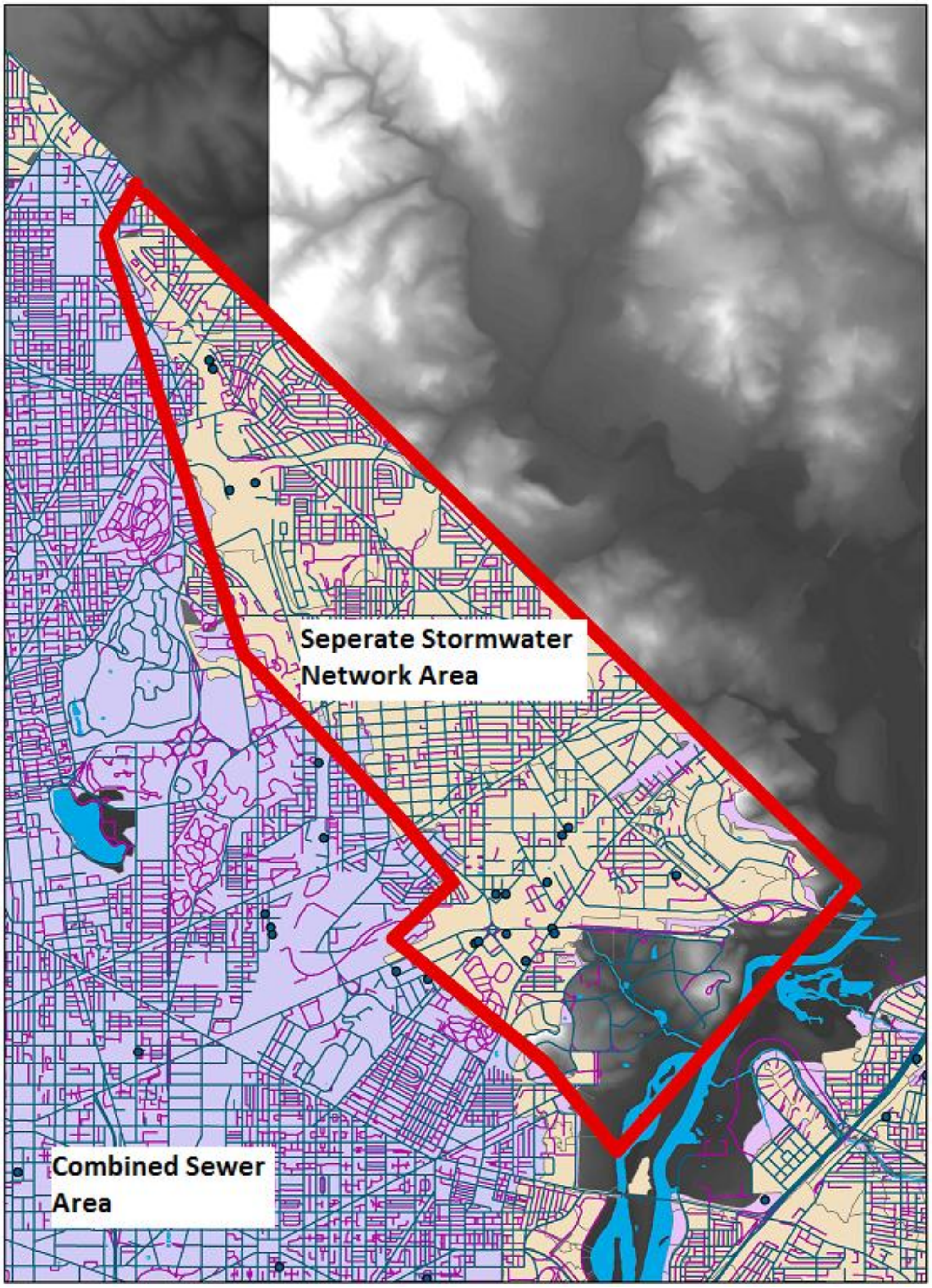


**Figure 2: The extent of the study area and the regions of the city of Washington Covered by Combined and separate sewer network**

## 4. Data-preparation

### 4.1 Topography:

The topography of the study area is needed in order to find sub-watershed boundaries, their areas, and average times of concentrations and slopes. The DEM data representing the topography of the area are downloaded from the USGS National Elevation Data (NED) database. The resolution of the DEM data are 1/3 arc-second which is approximately 10 meters. Figure 3 shows the topographic map of the study area which is prepared using the spatial analyst extension of the ArcGIS package.

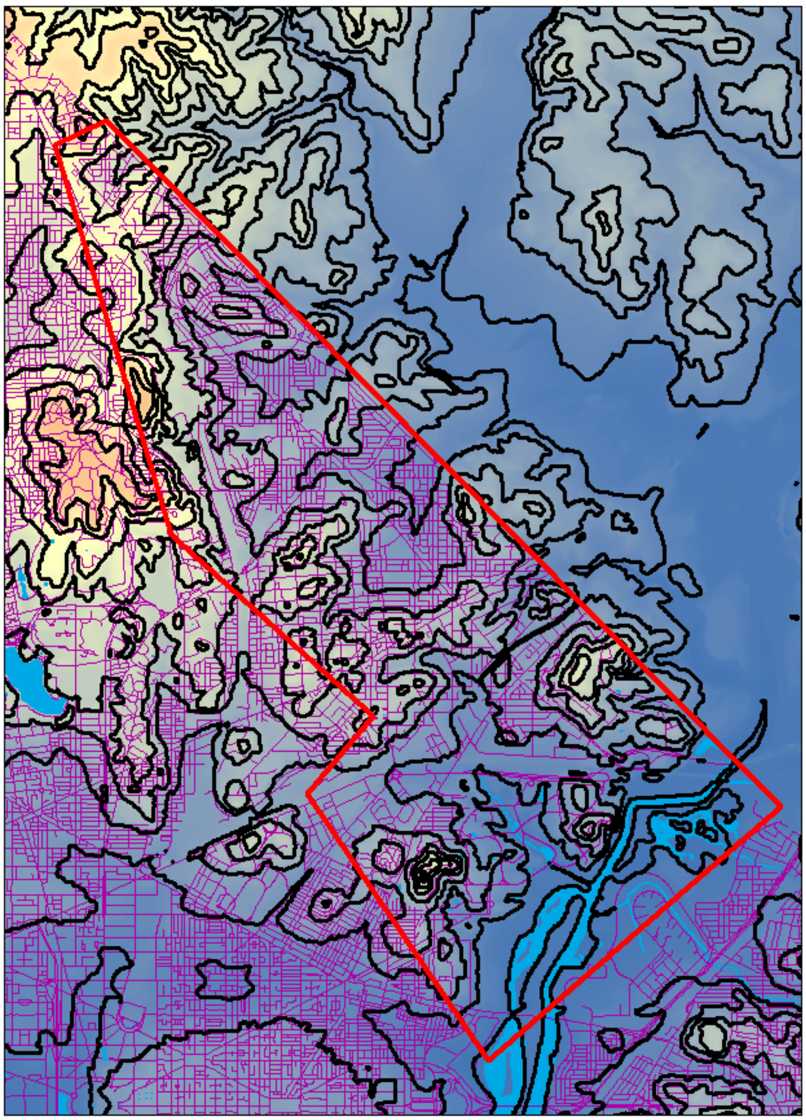

**Figure 3: Topographic contour lines of the study site.**

## 4.2 Climatic Data

Climatic Data consists of Precipitation, temperature, wind speed, snow, and evaporation which were collected by the climate file downloaded from the National Climatic Data Center at the Ronald Reagan Airport Station.

Precipitation has the unit is mm per hour and its rain year in this project started recording on the first of September and finished recording on the first of September of the following year. The objective here is to evaluate the impact of LID development on the runoff volume for three representative years including a dry year, an average year and a wet year. Based on the analysis of the historical precipitation records, 4 representative years were selected for the analysis: Including two years 1969 and 2006 representing the wettest years in the record, year 2003 representing the average year and 1984 represented the driest rain year. The rain data for these four years were prepared as timeseries with the format needed for SWMM program.

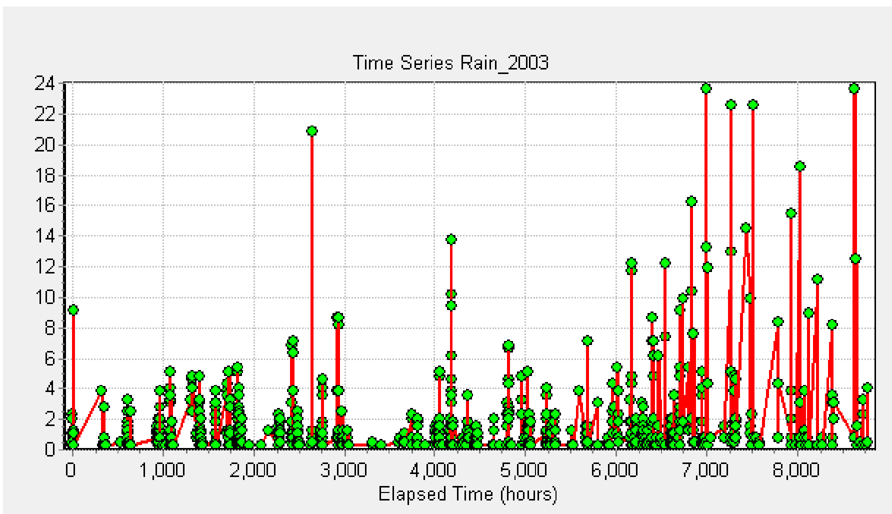


**Figure 4: Year 2003 precipitation**

In order to estimate the evaporation and the form of precipitation (rain/storm) temperature and wind data is also needed. Daily temperature data was available and its mean daily values were applied into SWMM model as the 4 rain years. Evaporation data extracting from the climate file, was used as monthly averages. The values used for monthly evaporation are listed in Table 1. Table 2 shows the average monthly rain speeds and Table 3 list the parameters needed to estimate the snow accumulation on the surfaces and the rate of snowmelt.

**Table 1: Monthly evaporation for DC area in year 2003. The values are in (mm)**

| Jan | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 130.3 | 145.29 | 166.88 |
| Jul | Aug | Sep | Oct | Nov | Dec |
| 185.67 | 157.23 | 120.65 | 84.84 | 61.98 | 0 |

**Table 2: Average monthly wind speed in DC area for year 2003. The values are in km/hr.**

| Jan | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|
| 14.17 | 12.77 | 12.37 | 14.22 | 10.68 | 10.95 |
| Jul | Aug | Sep | Oct | Nov | Dec |
| 11.4 | 10.41 | 12.18 | 11.52 | 12.24 | 12.58 |

**Table 3: Parameters used to calculate the rates of snowmelt.**

| Dividing Temperature Between Snow and Rain | ATI Weight (fraction) | Negative Melt Ratio (fraction) | Elevation above MSL | Latitude (degrees) | Longitude Correction (+/- minutes) |
|---|---|---|---|---|---|
| 2 | 0.5 | 0.6 | 30 | 39 | 0 |

### 4.4. Geographic characteristic of sub-watershed

Since we were not able to obtain the accurate map of sewer network in the study area an assumption was made that the sewer pipes follow the topography. In order to determine the hydrographs as a result of the precipitation scenarios the study region was divided into 21 sub-watersheds. For this purpose 21 discharge points were identified on the boundaries of the study area. The determination of the discharge points were conducted through analyzing the flow paths based on the topography. The sub-watersheds corresponding to each of the discharge point was determined using ArcGIS spatial analyst. The steps to determine the flow paths and the sub-watersheds include 1) determining the flow path for each "pixel" representing a digital elevation map grid cell; 2) finding the flow accumulation (i.e. the number of cells discharging into every cell) and 3) determining the areas are discharging into the selected discharge points. The geometrical parameters of the 21 sub-watersheds are presented in Table 4.

**Figure 5: Steps for obtaining the geometries of the 21 sub-watersheds representing the study area.**

**Table 4: The geometrical properties of the sub-watersheds.**

| Sub-watershed ID | Area ($m^2$) | Length (m) | Width (m) | Slope | Impervious fraction |
|---|---|---|---|---|---|
| 1 | 96764.89217 | 481.231 | 201.07784 | 3.53% | 5.65% |
| 2 | 424834.2307 | 716.557 | 592.88267 | 2.23% | 53.31% |
| 3 | 243534.5338 | 721.651 | 337.46857 | 3.46% | 41.15% |
| 4 | 453085.5607 | 1265.321 | 358.07954 | 2.85% | 44.57% |
| 5 | 506905.6654 | 509.826 | 994.2719 | 1.77% | 39.98% |
| 6 | 637597.4275 | 846.722 | 753.01861 | 1.30% | 36.31% |
| 7 | 251433.4084 | 680.511 | 369.47736 | 1.62% | 36.01% |
| 8 | 850061.0234 | 722.827 | 1176.0228 | 1.94% | 41.86% |
| 9 | 857514.3008 | 1065.461 | 804.82937 | 3.28% | 33.04% |
| 10 | 587065.0846 | 914.181 | 642.17599 | 0.98% | 33.73% |
| 11 | 634743.3421 | 823.691 | 770.60857 | 0.97% | 43.31% |
| 12 | 712294.3005 | 955.972 | 745.09954 | 1.46% | 51.67% |
| 13 | 632469.2448 | 1047.033 | 604.05856 | 2.96% | 36.26% |
| 14 | 767764.4351 | 1133.695 | 677.22309 | 1.50% | 44.55% |
| 15 | 482304.2927 | 1144.876 | 421.27208 | 1.92% | 37.79% |
| 16 | 544313.0452 | 955.917 | 569.41455 | 1.78% | 39.59% |
| 17 | 481965.4357 | 760.874 | 633.43659 | 2.37% | 42.51% |
| 18 | 259799.6732 | 919.772 | 282.46095 | 3.26% | 16.46% |
| 19 | 541605.9864 | 763.716 | 709.17198 | 1.05% | 58.60% |
| 20 | 1070989.877 | 1257.96 | 851.37038 | 1.35% | 58.42% |
| 21 | 386659.9271 | 667.459 | 579.30139 | 2.40% | 41.15% |

### 4.4 Soil Retention Characteristics

The hydraulic conductivity and other soil retention properties were obtained from the national soil database of the Natural Resources Conservation Service (NRCS). The soil type maps were imported into ArcGIS and the fractions of each soil type covering each sub-watershed was calculated. The values of soil percolation parameters including porosity, field capacity, wilting point were obtained by looking up for the typical values for the soil types.

**Table 5: The dominant soil type in the 21 sub-watersheds considered for modeling**

| Watershed ID | Type of Soil | Name | Porosity | Field Capacity | Wilting Point | Conductivity | Suction Head | Initial Deficit |
|---|---|---|---|---|---|---|---|---|
| 1 | SgC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 2 | SgC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 3 | SgC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 4 | SgC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 5 | SgC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 6 | SgC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 7 | SgB | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 8 | SgC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 9 | UkC | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 10 | SgB | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 11 | SgB | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 12 | SgB | Sandy Loam | 0.453 | 0.19 | 0.085 | 10.922 | 109.982 | 0.0526 |
| 13 | CfB | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |
| 14 | CfB | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |
| 15 | CfC | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |
| 16 | CfC | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |
| 17 | CfC | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |
| 18 | MvC | Loamy Sand | 0.437 | 0.105 | 0.047 | 29.972 | 60.96 | 0.0664 |
| 19 | CfC | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |
| 20 | CfC | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |
| 21 | CfC | Silty Loam | 0.501 | 0.284 | 0.135 | 6.604 | 169.926 | 0.04342 |

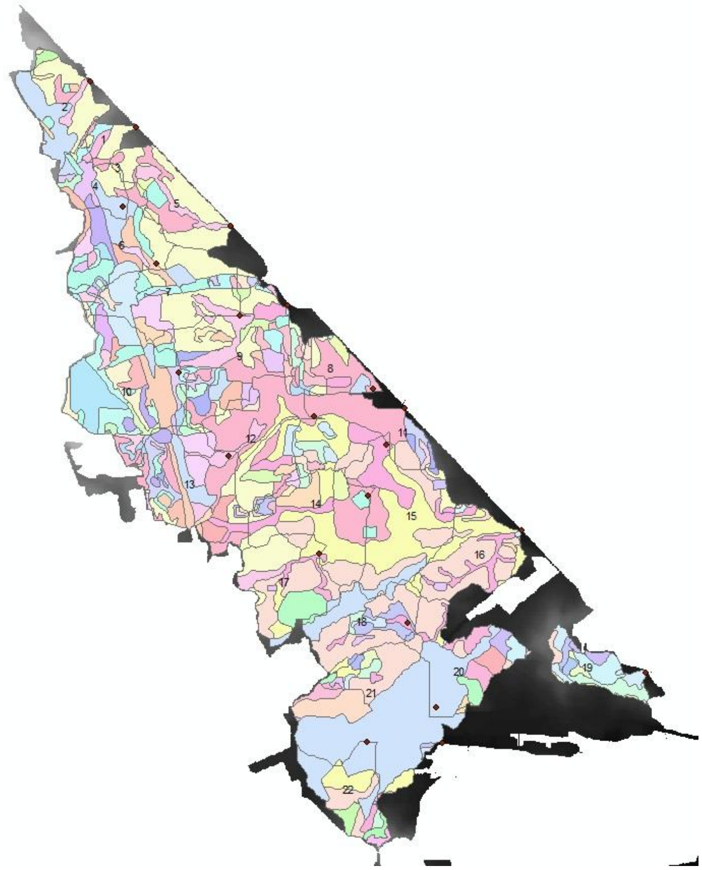

**Figure 6: Study area soil type map**

### 4.5. Impervious Fractions of sub-watersheds

The map of impervious areas in the Study area was obtained from the DC government Office of the Chief Technology Officer website (Figure 7). The fraction of impervious areas in each sub-watershed was calculated by overlapping the impervious area map and the map of sub-watersheds.

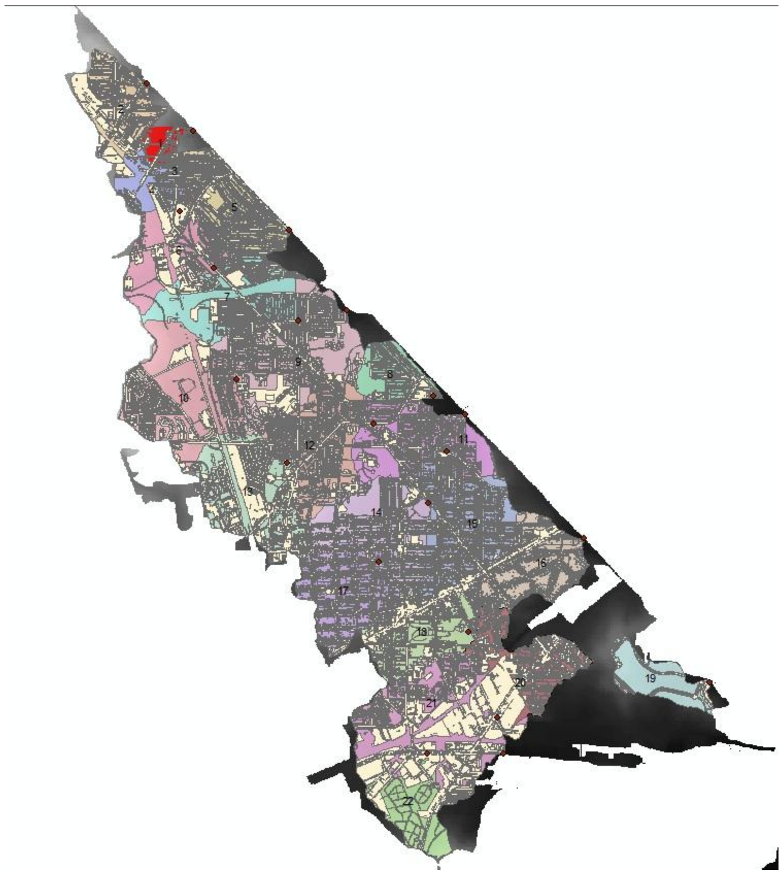

**Figure 7: The map of impervious areas in the 21 sub-watersheds considered for modeling**

## 5. Results

In this study the impact of three LID scenarios were evaluated in addition to the baseline scenario including:

- The runoff from 10% of the houses were assumed to be diverted into vegetated swales (represented by infiltration trench in SWMM). For this case the year 2003 precipitation data (wet year) was applied.
- The runoff from 20% of the houses were assumed to be diverted into vegetated swale. For this case all the four representative years precipitation data 1969, 1984, 2003 and 2006 were applied.
- The runoff from 50% of the houses were assumed to be diverted into infiltration trenches. For this case the year 2003 precipitation data (wet year) was applied.

Vegetated swales were assumed to have a surface depth of 10cm and a storage depth of 95cm with a void ration of 0.75. The medium of the vegetated swales were assumed to have a hydraulic conductivity of 10mm/hr being drained into the natural sub-soil. The width of the vegetated swales was assumed to be 3m (Figure 8).

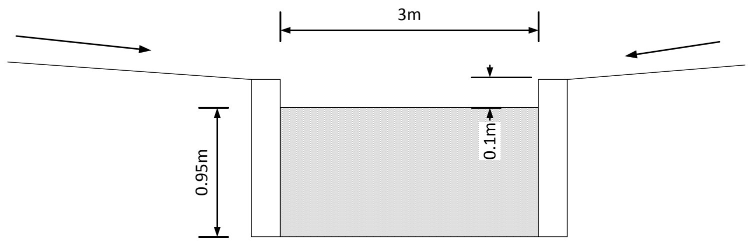


**Figure 8: The cross-section of the schematic of the generic vegetated swale LID**

SWMM was used to produce the hydrographs at each of the discharge points for all of the scenarios and then the total runoff volumes generated over the study area as well as the peak runoff was calculated.

**Table 6: Total yearly flow ($m^3$) under the baseline scenario and the three infiltration trench installation scenarios for the four representative years**

| | 1969 | 1984 | 2003 | 2006 |
|---|---|---|---|---|
| Baseline | 1537.52 | 1452.41 | 1824.92 | 1673.1 |
| 10% Covered by IT | - | - | 1492.78 | - |
| 20% Covered by IT | 1230.32 | 1063.12 | 1356.37 | 1398.34 |
| 50% Covered by IT | - | - | 987.01 | - |

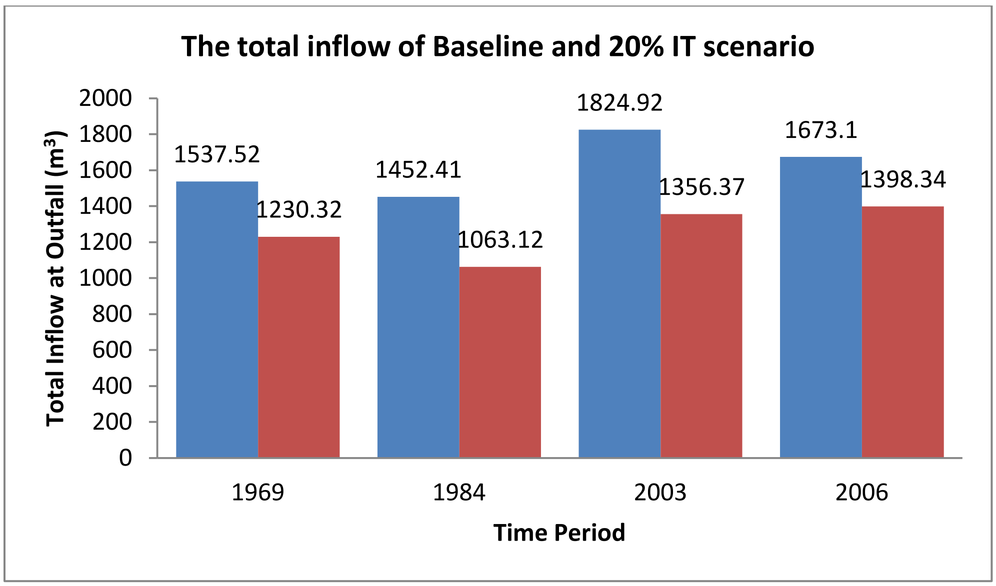


**Figure 9: The impact of diverting the runoff from 20% of houses into infiltration trenches**

Figure 9 presents the runoff volume under the baseline condition compared to under the 20% infiltration trench scenario. On average collecting the runoff from 20% of houses reduce the total yearly runoff by between 17% to 26%. The reduction in during the wetter seasons seems to be higher probably due to the fact that during these years the contribution of impervious surfaces in the runoff is higher. It should be noted that already a large portion of roof water in the district are first being discharge into exposed soil strips around the building in the district that behave like vegetated swales and this is not taken into account in our baseline analysis. On the other hand the slopes of the vegetated areas around the houses are quite steep and there is doubt about their effectiveness in trapping the water. The result of the study suggests that increasing and maintaining these vegetated swales or strips around the buildings, improving their design in terms of their capability in allowing the water to infiltrate, and directing the gutter ends into them can drastically decrease the total runoff from the roof area. Also it worth noting that in our study the runoff generated over the streets was not treated separately than the roof runoff as the two surfaces were lumped together as impervious surfaces. So the assumption here is that the vegetated swales can trap the same fraction of the street runoff which is not a realistic. Table 7 shows the total reduction in the volume of runoff under different scenarios of placement of vegetated swales. As it can be seen a 10% increase in the effectiveness of the vegetated swales can reduce the total runoff by 18%. This is assuming that the street runoff can be also as effectively collected by the vegetated swales. Further (more detailed) study is needed to treat the street runoff separately.

**Table 7: The percentage reductions in total runoff as a result of different**

| | 1969 | 1984 | 2003 | 2006 |
|---|---|---|---|---|
| 10% Covered by IT | - | - | 18.20% | - |
| 20% Covered by IT | 19.98% | 26.80% | 25.68% | 16.42% |
| 50% Covered by IT | - | - | 45.91% | - |

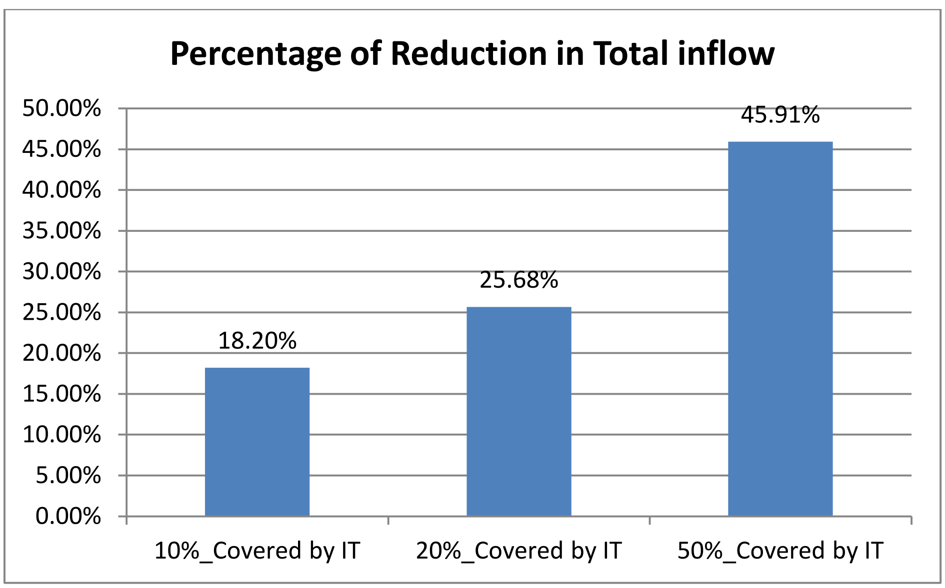


**Figure 10: Percent reduction in the total runoff volume as a result of different LID scenarios.**

An analysis on the impact of the LID practices on the reduction of peak discharge was also conducted. The outcome shows that all scenarios of LID had a much more effective role in reducing the total volume of runoff compared to their effect on the peak runoff. This is due to the fact that during large precipitation events, a) pervious areas can be a major contributor to the runoff b) a smaller fraction of the runoff can be captured by vegetated swales and other LID techniques. So other methods that target the accumulated runoff such as retention and detention ponds can be more effective in reducing the peak runoff.

## 6. Conclusion and Future Work

In this research the effectiveness of LID practices similar to vegetated swale in urban environment on the reduction of the volume of runoff is evaluated using stormwater modeling. EPA SWMM 5.0 was used for this purpose. A region in the east side of the city of Washington DC is selected as the study site. A few major simplifications have been made to make modeling of storm water possible over a large and highly heterogeneous area. These assumptions include: (i) The sewer network follow the land topography, (ii) Each sub-watershed is represented as composed of pervious and impervious areas discharging their waters directly into a main sewer pipe, (iii) The LIDs affect all of the runoff generated over the all of the pervious area. The third assumption means the runoff from houses and other impervious surfaces are equally impacted by the vegetated swales. It was found that if properly designed the vegetated swales can significantly reduce the total volume of runoff. However they are significantly less effective in reducing the peak runoff. In fact most of small events can be fully captured by the vegetated swales in residential areas while they only can capture a fraction of the rain during large events. A more detailed modeling can provide us with the optimal placement of vegetated swales. This research require considering the exact sewer network configuration as well as various areas contributing into the stormwater including roofs, grassed areas, streets and sidewalks. It should be noted that although smaller events contribute a small fraction of the total yearly runoff, due to the first flush effect they can contain a significant portion of the contaminants. Also smaller events can lead to higher concentration of pollutants in the receiving waters due to lower dilution. A detailed modeling can reveal the effectiveness of LID practices in reducing the pollutant loads in the receiving waters.

**Acknowledgement:** Funding for this project was provided by DC WRRI seed grant.

## 7. References

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