Hydrologic Modeling of the Little Crum Creek Watershed with SWMM

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E90 Senior Design Project
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May 08, 2009

Contents

Abstract…………………………………………………………………………………...3

Acknowledgments………………………………………………………………………..4

Introduction……………………………………………………………………………5

1.1 Overview of the Hydrologic Cycle and Hydrologic Modeling…………………………...5

1.2 Choosing the SWMM Model for the Case of the Little Crum Creek Watershed………...6

1.3 Sources of Data………………………………………………………………………7

1.4 Objectives of the Project……………………………………………………………..8

The SWMM Model……………………………………………………………………8

2.1 Subcatchment Properties……………………………………………………………10

2.1.1. GIS-defined Properties……………………………………………………10
2.1.2. Properties Defined from Tables……………………………………………...13
2.1.3. Infiltration………………………………………………………………15

2.2 Conduit Properties………………………………………………………………….15

2.3 Junction Properties…………………………………………………………………16

2.4 Non-Visual Objects and their Properties………………………………………….....16
3.4.1. Time Series………………………………………………………………..17
3.4.2. Land Uses………………………………………………………………17
3.4.3. Pollutants……………………………………………………………….17

Hydraulic Theory……………………………………………………………….….17

3.1 Choosing the Kinematic Wave Method……………………………….…………18

3.2 The Green-Ampt Method…………………………………………….………..19

3.3 Assumptions……………………………………………………………………...21

Field Data……………………………………………………………………………..21

4.1 Function of Auto-sampler and Rain Gage……………………………………...……23

4.2 Analyzing Data……………………………………………………………………..24

4.2.1 Hyetographs and Hydrographs…………………………………………………..24
4.2.2 TSS Loading……………………………………………………………………..24

Simulation Output………………………………………………………………………...26

5.1 Results for Selected Rain Events……………………………………………………...26

5.2 Assessment of Model Accuracy……………………………………………………….30

Applications of SWMM…………………………………………………………………...38

6.1 Uses of Model…………………………………………………………………………38

6.2 Development Planning…………………………………………………………………38

6.2.1 Scenario 1: Springfield Square Shopping Center………………………………..39
6.2.2 Scenario 2: Home Depot…………………………………………………………42
6.2.3 Scenario 3: Entire Watershed……………………………………………………44

6.3 Upgrading the Model…………………………………………………………………45

6.4 Conclusions……………………………………………………………………………46

References…………………………………………………………………………………47

Appendix A: Green-Ampt Parameters……………………………………………………..48

Appendix B: Depression Storages…………………………………………………………..49

Appendix C: Manning's n Values…………………………………………………………..49

Appendix D: Roughness Coefficients………………………………………………………50

Appendix E: Project Summary……………………………………………………………50

Abstract – The development of a watershed area can strongly impact the natural flow in a stream network during periods of rainfall because of an increase in surface runoff. Urban runoff increases the concentration of sediment in the stream and can also erode stream banks. This sediment, or total suspended solids (TSS), is classified as a pollutant by the EPA because water with high concentrations of TSS has a diminished ability to retain oxygen necessary to support aquatic life. By developing a hydrologic model for the Little Crum Creek watershed using SWMM (Storm Water Management Model), surface runoff can be calculated for a given period of rainfall. The results of these calculations can then grant insight into the environmental impact development has on the watershed.

Acknowledgments

This study is a continuation of an ongoing project to ameliorate the environmental quality of the Little Crum Creek watershed. The work done on that project has been invaluable for our study, and we would like to strongly thank those involved:

Professor Arthur McGarity, Ph.D

Susan Willis

We'd also like to thank our assistants who helped gather field data for this study:

David Burgy

Zach Eichenwald

Dan Perelstein

For giving us access to the Suburban that allowed us to make the necessary field measurements and for providing the auto-sampler enclosure plan, we'd like to thank Grant Smith.

For his guidance in helping us complete our sensitivity analysis of the model, we'd like to thank Professor Nelson Macken.

Finally, we'd like to thank the Swarthmore borough manager, Jane Billings, for her support of our study.

Introduction

1.1 – Overview of the Hydrologic Cycle and Hydrologic Modeling

Understanding how pollutants travel in an environment is dependent on analyzing the underlying hydrologic processes of that environment. Generally, the movement of water in an environment can be illustrated with the hydrologic cycle. As the name suggests, water never leaves or enters the system, but rather is circulated with the power of the sun according to several processes that can be observed separately. The hydrologic cycle, or water cycle, and the processes that comprise it are shown in the diagram below.

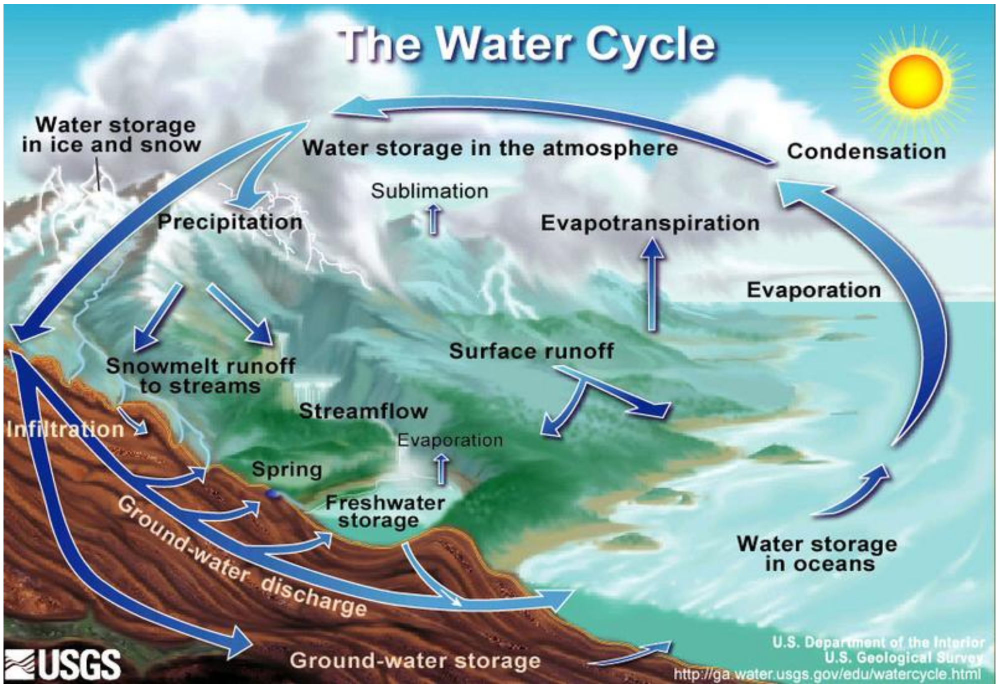


Figure 1. Diagram of the movement of water on the earth (U.S. Geological Survey).

The previous work of hydrologists has yielded several mathematical models that can analytically describe some of these processes. Additionally, a variety of hydrologic computer models based on these mathematical models have been continuously developed since the Stanford Watershed Model (SWM) was first completed in 1966. The basic system for which these models operate is called the watershed, which is the land where precipitation drains into a water body whose boundaries are defined by the terrain elevation that causes the precipitation to eventually enter that water body.

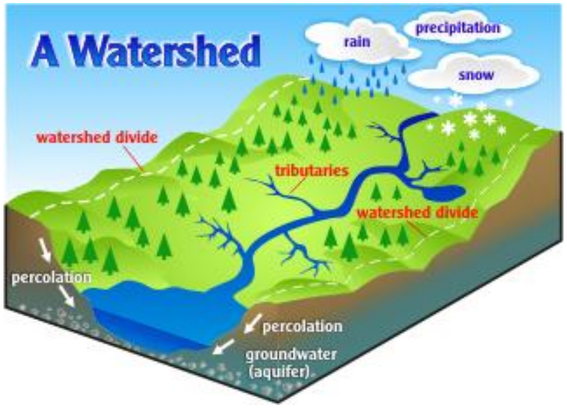


Figure 2. Diagram of a typical watershed.

There are a range of hydrologic models whose appropriateness may vary depending on the characteristics of the watershed and the objectives of the user. For instance, the SWMM (Storm Water Management Model) model first developed by EPA in the 1970's has features that make it more useful for modeling urban watersheds while another model HSPF (Hydrologic Simulation Program – FORTRAN) is more useful for modeling rural or agricultural watersheds (Wurbs).

1.2 – Choosing the SWMM Model for the Case of the Little Crum Creek Watershed

The purpose of this project is to use an existing hydrologic computer model to analyze the quantity and some characteristics of the quality of the water in the Little Crum Creek watershed for various periods of rainfall from summer 2008 to spring 2009. The Little Crum Creek watershed is a small area encompassing 3.2 square miles with parts of several municipalities in southeastern Pennsylvania, including Swarthmore, Ridley, Rutledge, and Springfield. The stream network drains into the Delaware Estuary. The land is occupied mainly by suburban residential zones.

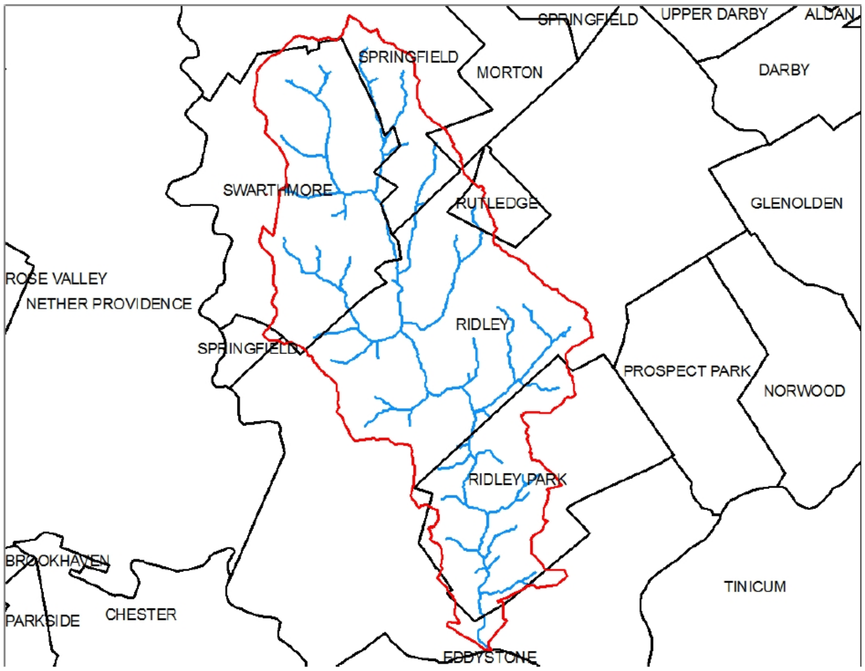


Figure 3. Boundaries of the Little Crum Creek watershed overlaid with the boundaries of neighboring municipalities (courtesy of Arthur McGarity, Ph.D).

Because of the widespread usage of SWMM in modeling urban watersheds and its water quality analysis capabilities, we chose SWMM to model the hydrology of the Little Crum Creek watershed. SWMM has a further advantage over other models like AVGWLF (ArcView Generalized Water Loading Function) in that simulations can be run for time steps of as little as one minute, making it useful for analyzing flow over a single rain event. Though the SWMM model is deterministic – it requires rainfall data for the simulation to run – these data can be obtained by using a rain gage.

1.3 – Sources of Data

In general, the accuracy of hydrologic models depends on reliable and complete data for the parameters involved in the equations governing hydrologic processes in the model. The task of acquiring these data can be difficult, expensive, or both depending on the size of the watershed. Fortunately, the data for several necessary parameters are freely available in the form of GIS (Geographic Information System) raster data layers derived from satellite imagery, which can be downloaded on the PASDA website (Pennsylvania Spatial Data Access). These layers can be processed in the GIS program ArcGIS so that particular parameter values can be extracted and inputted to SWMM.

Though several types of crucial data can be accessed in this GIS data repository, other necessary data must either be estimated in a table or measured in the field. Three students enrolled in an engineering statistics class at Swarthmore College helped make field measurements that were necessary for defining some of the properties of the hydrologic network.

Still more data cannot or are prohibitively difficult to obtain from either GIS data layers or field measurements. Some of these data can be estimated based on tables of typical values that EPA provides in the SWMM manual.

All of the kinds of data that are necessary for SWMM take the form of properties of visual and non-visual objects. These objects and their properties will be explained in a following section.

1.4 – Objectives of the Project

SWMM is a comprehensive hydrologic model that can show several outputs. Besides implementing the SWMM model, this project intends to examine those outputs that are affected by human activity. As will be demonstrated, the development of an area is a significant factor in both the amount of surface runoff that is directed into the stream network and the concentration of pollutants in the stream network. This excess runoff from developed areas is considered nonpoint pollution since the pollution enters the stream at a variety of points or areas. Results of the simulation showing the extent of the relationship between runoff and development can thus be used as a guide for development that is in accordance with environmental quality standards.

This project, however, will limit the scope of water quality analysis to a single pollutant – total suspended solids (TSS), or the total sediment that enters a stream either from runoff or from the erosion of stream banks. This single pollutant will be treated in subsequent analyses as an indicator of water quality. Also, the EXTRAN module in SWMM, which is useful for calculating flow in periods of intense rainfall, will not be utilized since this project will focus more on the problem of runoff rather than the problem of flooding.

The SWMM Model

This project utilizes the program SWMM, version 5.0.014 (the most up-to-date version of SWMM since January 21, 2009) downloaded from the EPA website. SWMM provides a GUI (graphical user interface) where visual objects can be added to form a hydrologic network. There are a large variety of visual objects that can be added to a map that include both human artifacts like weir gates, pumps, and reservoirs and natural features, like drainage basins and streams. The storm runoff in the Little Crum Creek watershed is almost exclusively diverted into its streams, so only the visual objects that represent natural features will be used to form the hydrologic network. Those areas where the runoff is redirected via storm sewers from the Little Crum Creek watershed to other watersheds are excluded in the SWMM hydrologic network. This type of area includes parts of Swarthmore College property.

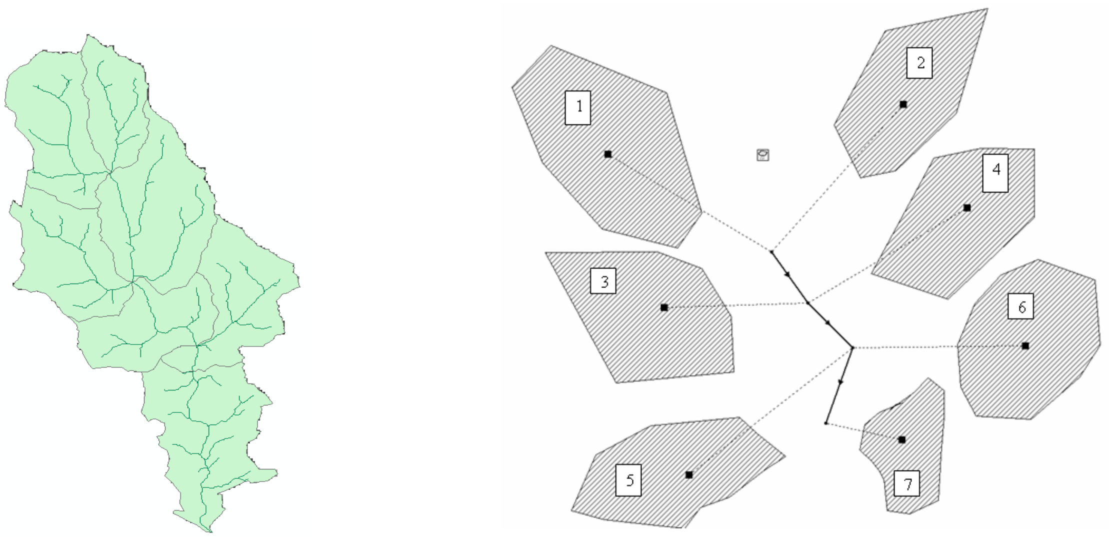
There are four types of visual objects that will comprise the model of the Little Crum Creek watershed:

- Subcatchments
- Conduits
- Junctions
- Rain gage

The first step in creating the hydrologic network is to determine the number of subcatchments that will comprise the watershed. Subcatchments are defined as subdivisions of the larger watershed. As in the larger watershed, elevation defines the boundaries of the subcatchment. Therefore, an elevation map is required to determine the number of subcatchments. Rather than using a standard hard copy elevation map, a digital elevation model (DEM) of southeastern Pennsylvania in a raster data format was downloaded and inputted into ArcGIS.

A terrain analysis ArcGIS extension called TauDEM was then used to delineate all of the subcatchments of the Little Crum Creek watershed based on the DEM. This involved defining the drainage outlet of the watershed represented by a GIS point feature. A series of calculated raster files that in conjunction can produce a shape file containing the subcatchments that make up the watershed. For instance, TauDEM produces a data layer that fills in pits in the DEM to simplify the elevation data, and then another data layer is produced that traces the steepest gradient from point to point in the modified DEM. This data layer is the basis for creating a stream segment data layer. Additionally, another data layer is formed from calculating the upstream contributing area to each stream segment, which can then be used to delineate every subcatchment in the watershed. However, TauDEM's initial delineation consisted of over a hundred subcatchments. In a project concerning the Little Crum Creek started in the summer of 2008 by Susan Willis and Arthur McGarity, Ph.D, these several subcatchments were grouped together into seven subcatchments. This project follows that template, and thus seven subcatchments were drawn in the SWMM GUI. Subsequent analyses focus mainly on the stream flow and pollutant concentrations of the stream segments that connect these seven subcatchments.

The following graphics show the conversion from a GIS map to the SWMM GUI:



(a) (b)

Figure 4. TauDEM outputs a GIS map shown in (a) which can then be translated into SWMM's GUI shown in (b).

The cloud icon in the GUI represents the rain gage associated with a subcatchment that provides the rainfall data that drive the simulation. SWMM allows the user to define a rain gage for each subcatchment, but because of the small area of the watershed, a single rain gage was used to provide the rainfall data for every subcatchment, assuming that rainfall intensity was comparable throughout the watershed.

Having drawn the SWMM network, the properties for each visual object must then be inputted. The following subsections will detail the processes for determining the values of these properties. A description of rain gage properties will be excluded since they relate to rainfall time series, which will be explained in a separate section.

2.1 Subcatchment Properties

2.1.1 GIS-defined Properties

Aside from simply defining the number of subcatchments, GIS data layers and ArcGIS tools can help provide the values of several other necessary properties. Those subcatchment properties for which GIS can help define are as follows:

- Area
- Width (Characteristic width of the overland flow path)
- Percent slope
- Percent impervious
- Land uses

The seven subcatchment grouping following the TauDEM delineation is in the form of a feature class. In ArcToolbox, there is an option to tabulate the area of each polygonal feature, i.e. subcatchment. These area values can then be easily inputted into the subcatchment properties screen in SWMM.

The width, or characteristic width of the overland flow path, is a property that can be estimated by taking the ratio of the length from the furthest inlet to the drainage point and the area of the subcatchment. Since TauDEM provides the stream network, the ArcGIS ruler tool can be used to measure the distance from the furthest inlet to the drainage point. It should be stressed that this is only an estimate and is thus a source of error in the model.

The percent slope can be derived by calculating the ratio of the change in elevation from the inlet to the outlet and the distance between the inlet and outlet. Again, the ruler tool in ArcGIS can calculate the distance and the elevations at any point in the watershed can be determined with the DEM.

The percent of the area of the subcatchment that is impervious can be found within a separate GIS data layer also available from PASDA. This layer is derived from satellite data of photons. An algorithm developed at Pennsylvania State University has become the standard for converting this satellite photon data into imperviousness.

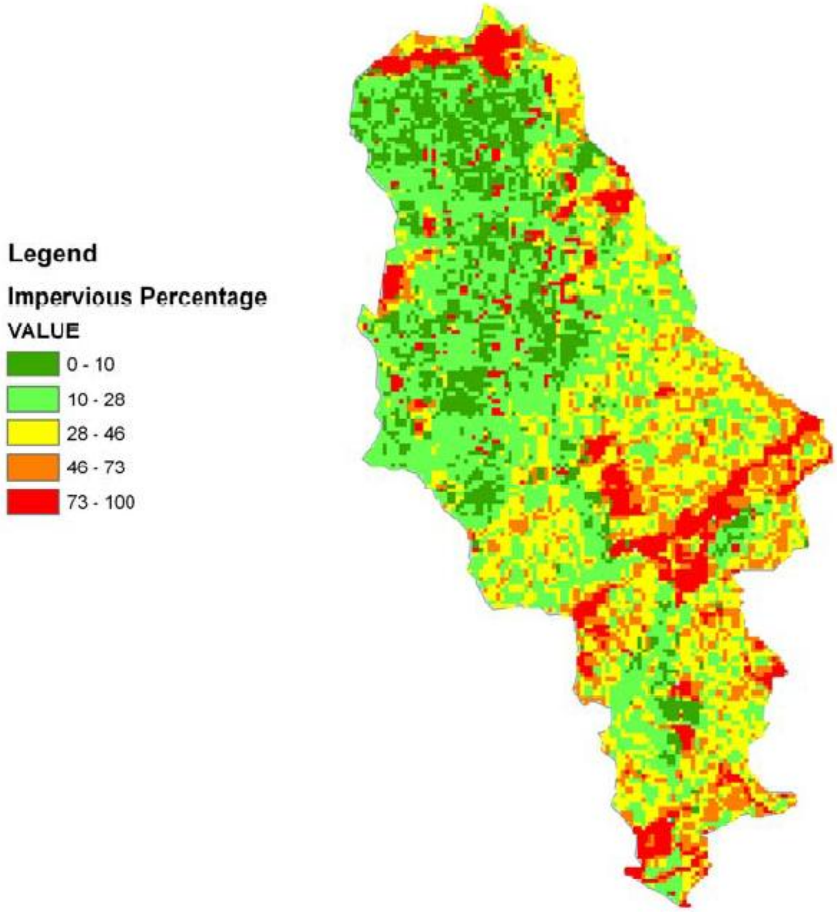


Figure 5. Imperviousness raster data for the Little Crum Creek watershed.

With this raster data, the spatial analyst extension of ArcGIS can be used to compute the mean imperviousness in each subcatchment, which can then be inputted to SWMM.

Similarly, land cover is also available from PASDA in the form of raster data derived from satellite photon data. The level of concentration of land cover can then be translated into categories of land use. Though several categories of land use can be defined, a classification system used by Arthur McGarity, Ph.D. was adopted for this model with the following categories shown in the legend:

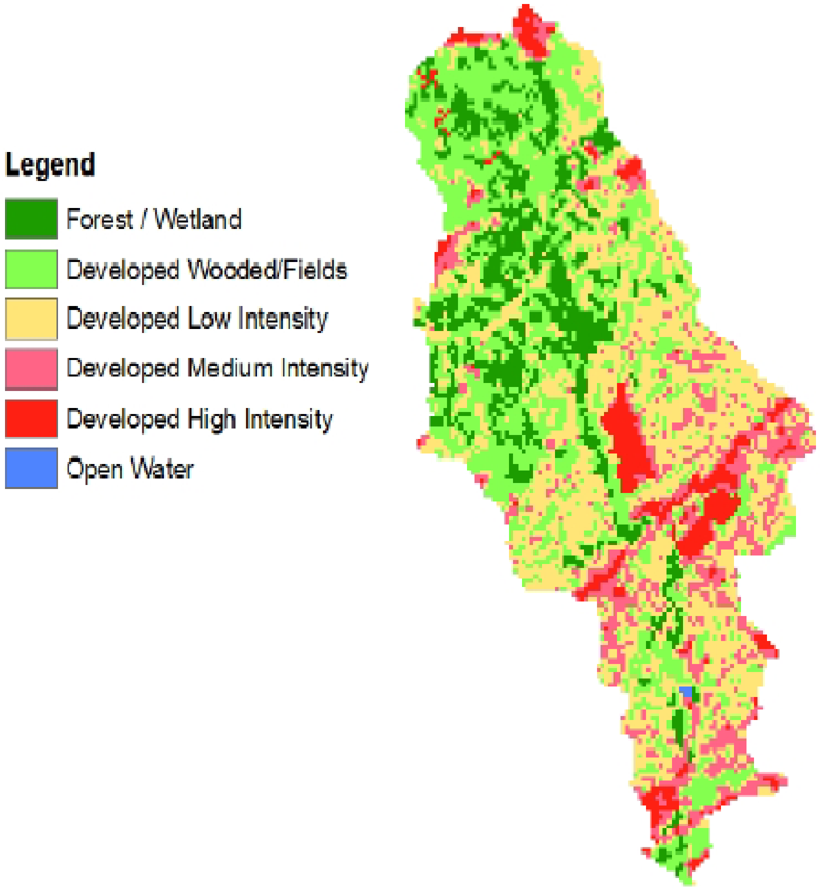


Figure 6. Land use raster data for the Little Crum Creek watershed.

Each of these land uses also have properties associated with them, which will be detailed in a following section.

Below is a table of all of the GIS-defined subcatchment properties.

Subcatchment	Area (ac)	% Impervious	Width (ft)	% Slope	% Land Use (1)	% Land Use (2)	% Land Use (3)	% Land Use (4)	% Land Use (5)	% Land Use (11)
1	353	28.9	3726	2.5	8.73	35	32	12	11	0
2	181	28.9	1905	2.5	8.73	35	32.2	12.6	11.3	0
3	294	28.9	2952	1.5	8.73	35	32.2	12.6	11.3	0
4	399	36.3	3156	2	4.03	18.7	44.2	21.8	10.6	0.56
5	248	28.9	3352	2.5	8.73	35	32	12	11	0
6	249	30.4	3141	1.5	0.49	6.3	40.3	35.3	17.5	0
7	416	36.3	3059	1.5	4.03	18.7	44.2	21.8	10.6	0.56

Table 1. Summary of GIS-defined subcatchment properties.

2.1.2 Properties Defined from Tables

Not all subcatchment properties can be defined using available raster data. However, EPA provides tables within the SWMM manual that serve as guides for choosing typical values for certain properties depending on characteristics of the watershed. These tables are appended in this report. Those properties for which tables are available are as follows:

- Manning's coefficient for overland flow over the impervious portion of the subcatchment
- Manning's coefficient for overland flow over the pervious portion of the subcatchment
- Depth of depression storage on the impervious portion of the subcatchment
- Depth of depression storage on the pervious portion of the subcatchment

Manning's coefficient (Manning's n) describes the resistance of an area to flow over it. This coefficient will vary depending on the type of surface of the area. SWMM generalizes that the impervious portions of the subcatchment will have the same Manning's n and the pervious portions will have the same Manning's n. Manning's n values must be determined empirically by testing the flow over a variety of surfaces. The cumulative results of such experiments yield Manning's n values for several surfaces summarized in a table in Appendix C. Choosing which value to use in the table is based on a quick survey of the most common kinds of surfaces in the watershed and finding a comparable n value associated with that surface from the table.

In this project, most pervious portions of the watersheds were considered to have n values between "prairie grass" and "light underbrush," though the subcatchment containing the Crum Woods was assigned an n value skewed more towards "light underbrush." The impervious portions of the watershed were considered to have the same Manning's n when considering the average impervious surface, which was chosen to be a Manning's n associated with "smooth concrete" from the table.

The depth of depression storage for the impervious and pervious portion of the watershed is the depth for which precipitation can pool. The pooled precipitation thus does not become runoff. Average depression depths for different land surfaces have been compiled by EPA and also are available in a table in the SWMM manual shown in this report in Appendix B. In the table, impervious surfaces are treated as a single entity, and so a value was chosen for the impervious depression storage that fell within the default range. The value of the pervious depression storage was chosen in the range of typical values for lawns, corresponding to the residential character of the watershed.

Another property, percent of the impervious area with no depression storage, has no table associated with it and also cannot be gleaned from raster data. Therefore, this property had to be estimated.

A summary of all the values derived from tables in the SWMM manual for each subcatchment are summarized in the table below.

Subcatchment	N-Imperv	N-Perv	Dstore-Imperv	Dstore-Perv	%Zero-Imperv
1	0.012	0.4	0.05	0.1	85
2	0.012	0.15	0.05	0.1	85
3	0.012	0.15	0.05	0.1	85
4	0.012	0.15	0.05	0.1	85
5	0.012	0.15	0.05	0.1	85
6	0.012	0.15	0.05	0.1	85
7	0.012	0.15	0.05	0.1	85

Table 2. Summary of non-GIS-defined subcatchment properties.

2.1.3 Infiltration

For areas in the subcatchments that are pervious, i.e. where the rainfall will percolate into the ground, a model must be developed that tracks how much precipitation that area can absorb over time, a process called infiltration. There are several ways to estimate the amount of precipitation that infiltrates into pervious portions of the subcatchment. SWMM allows users three options: the Horton equation, the SCS Curve Number method, and the Green-Ampt method. Each of these methods was examined to see which method was most appropriate for the information that was available. Initially, the SCS Curve Number method, developed by the Soil Conservation Service, was chosen for preliminary simulations because of its simplicity. Unlike the other two methods, the SCS Curve Number Method only requires a single Curve Number value (typical values are available in a table that EPA provides). However, the disadvantage of this approach is that the method does not conform to any physical reality and is thus purely empirical. For smaller time steps, the lack of physical grounding means that the infiltration calculations made with the SCS Curve Number are more likely to deviate from reality.

In order to increase the accuracy of the simulation, we opted to use the Green-Ampt method, which unlike the Curve Number method, does take into account various physical properties of soil. An explanation of the Green-Ampt Method is featured in the following section on hydraulic theory.

2.2 Conduit Properties

The conduits are simply the stream segments that connect the subcatchments. Like the subcatchment properties, ArcGIS tools and tables available in the SWMM manual can be used to define conduit properties. Still other conduit properties must be defined by taking field measurements. The conduit properties considered in this project are as follows:

- Shape
    - Width
    - Side slopes

    - Depth
- Length
- Roughness

SWMM has available several default channel shapes, but a trapezoidal channel shape was chosen because of its rough resemblance to a natural channel. The small-scale of the channels in the watershed necessitated field measurements to define the width of the channel, its depth, and the slopes of the sides. These properties were measured with the help of the engineering statistics students at one point in each of the stream segments. These shape properties were assumed to remain constant along the stream segments. A summary of the shape properties are shown in the table below.

Conduit	Max Depth (ft)	Bottom Width (ft)	Side Slope
1	2.583	12.083	0.4627
2	2.583	12.083	0.4627
3	4.5	16.75	1.5428

Table 3. Summary of conduit shape properties.

The length property could be determined using the ArcGIS ruler tool and tracing the length of each of the stream segments from the TauDEM derived stream network.

Finally, the roughness of the stream could be estimated with the help of a table of typical roughness coefficient values. Roughness coefficient values were chosen based on the roughness value associated with the middle of the range of a "natural channel with fairly regular sections."

2.3 Junction Properties

Only one junction property, the invert elevation, will be directly considered in this project. An option to define the maximum depth at the junction is available, but it will be assumed that it is the same as the depth of the connecting stream segment. Furthermore, initial depth will be ignored since the results will center only on the flow from runoff and not base flow.

The invert elevation is simply the elevation at the junction measured from sea level. As has been mentioned previously, elevation data are available from the DEM and can be easily inputted to SWMM.

2.4 Non-Visual Objects and their Properties

Non-visual objects do not appear in the SWMM GUI, but are nevertheless important components of the model:

- Time Series

- Land Uses
- Pollutants

2.4.1 Time Series

A rainfall time series shows the amount of precipitation that fell within a specified time interval. The rain gage used to collect rainfall data obtains rainfall data at one minute intervals. These data can be manually converted into larger time steps and saved as a .dat which SWMM can read.

2.4.2 Land Uses

Determining the extent of land uses in the subcatchments has already been explained, but each land use must have its properties defined in order to run a water quality simulation. Each land use contains a buildup and washoff function whose forms are defined by the user. An exponential function was used to model the buildup of TSS and a 10-year event mean concentration of TSS was used as a way to model the washoff.

Buildup exponential functions require a rate constant and a maximum buildup per unit area to be defined. These values were used by a previous RunQual analysis (McGarity).

2.4.3. Pollutants

SWMM allows users to define any number of pollutants, though in this report only TSS will be analyzed. For any pollutant, its properties must be defined, including the units for which its concentration will be reported and its decay coefficient. TSS is a conservative pollutant, in that its concentration does not decay over time, so the decay coefficient is 0. The units of TSS are reported in mg/L.

Hydraulic Theory

There are several different kinds of open channel flow, which are shown in the following diagram:

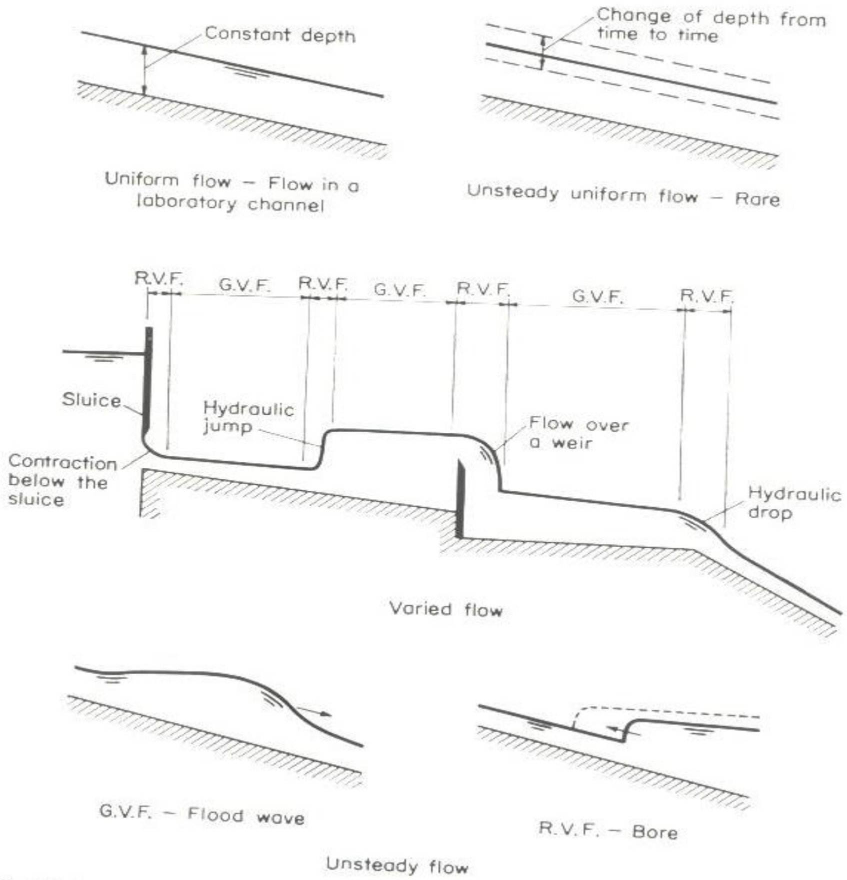


Figure 7. Different classifications of open channel flow. "RVF" stands for rapidly varied flow and "GVF" stands for gradually varied flow.

SWMM can calculate flow according to varying assumptions about flow through the channels. The different routing models that SWMM can use to calculate flow are: steady flow, kinematic wave, and dynamic wave.

3.1 Choosing the Kinematic Wave Method

Steady flow is the simplest model which does not allow flow to vary spatially or temporally within a conduit. This oversimplification is of limited utility in runoff analysis since the intensity of a storm will affect flow within a conduit. Conversely, the dynamic wave method incorporates the most number of hydrologic factors to solve the Saint Venant flow equations:

The continuity equation:

$$v\frac{\partial A}{\partial x}+A\frac{\partial v}{\partial x}+b\frac{\partial h}{\partial t}=0$$

The momentum equation:

$$g\frac{\partial h}{\partial x}+v\frac{\partial v}{\partial x}+\frac{\partial v}{\partial t}=g(i-j)$$

where

h = height
v = velocity
i = slope
j = energy loss
g = gravitational acceleration
t = time
A = area

However, this model works most accurately if several types of data are available, such as the entrance and exit loss coefficients of the stream segments, among other properties. Data on these properties were not available or were prohibitively difficult to obtain.

The kinematic wave method cannot assess flow in flooded conditions like the dynamic wave method; however, this project's scope was focused more on average rain events that would result in varied flows that the kinematic wave method could predict. Therefore, the kinematic method was chosen as the most appropriate flow routing model.

Maximum flow according to the kinematic wave model is the full-flow Manning equation value, where the Manning equation is:

$$V=\frac{k}{n}R_h^{\frac{2}{3}}\cdot S^{\frac{1}{2}}$$

where

V = velocity
k = conversion constant (1.49 for British standard)
n = Gauckler-Manning coefficient
R_h = hydraulic radius
S = slope of the water surface

The slope of the water surface is considered to be the slope of the conduit.

3.2 The Green-Ampt Method

The basic concept of the Green-Ampt method is that water infiltrates through soil of some porosity along a "wetted front." An analytical equation can be obtained if certain parameters of the soil are determined.

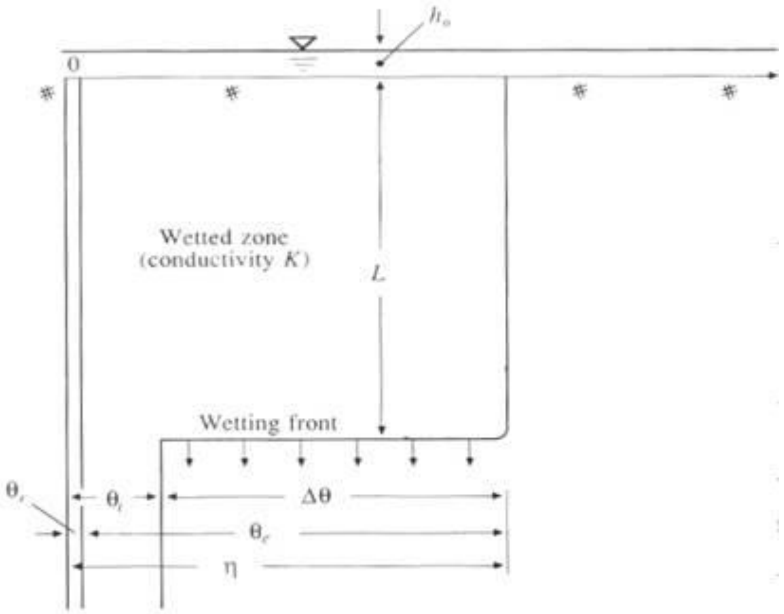


Figure 8. Conceptual diagram showing the Green-Ampt parameters and how they relate to infiltration.

Based on soil analysis (McGarity), the type of soil in the Little Crum Creek watershed could be identified as silty loam, whose soil properties as they relate to Green-Ampt parameters are in a table in Appendix A. The Green-Ampt equation is as follows:

$$F(t) = Kt + (\theta_s - \theta_i)\psi_f \ln(1 + \frac{\mathrm{F(t)}}{(\theta_s - \theta_i)\psi_f})$$

where

F(t) = total amount of water infiltrated
ψ_f = suction head
K = hydraulic conductivity
i = rainfall rate
θ_s = saturated moisture content
θ_i = initial moisture content

This equation can be solved iteratively until F converges to a stable value; however SWMM automatically computes this equation once the properties are inputted and the simulation is run.
In SWMM, some of these parameters are defined differently. One of the properties is called the initial deficit, which is the difference in the porosity and the field capacity for cases of dry soil. These properties can be looked up in Appendix A under “silt loam.”

3.3 Assumptions

Several assumptions had to be made in order for the model to conform to the data that were available. First, ponding was ignored. SWMM has the option to take into account flow effects from ponding after a flood, but this requires data on the ponded area at the junctions, or the area occupied by ponded water on the junction after a flood. These data were not available because of the rarity of flooding in the area in question. As has been mentioned, natural channels were assumed to have a trapezoidal shape, and the width of the subcatchments was calculated with an estimation technique suggested by EPA. Finally, the choice of the kinematic wave method introduces error since it relies on a simplified model of open channel flow based on Manning's equation.

Field Data

Measurements of rainfall and concurrent stream flow were collected before the beginning of this project in several locations in the Little Crum Creek watershed. The continuation of the flow and rainfall data measurements was an integral part to this project, as the field data gives a comparison for the model's outputs. The rainfall measured in the field was copied into a rainfall time series in the model, and the field data of flow was compared to the model's flow outputs to assess the accuracy of the model. The equipment also collected stream water samples during the period after a rain event, in order to analyze pollutant concentrations such as total suspended solids and phosphate and nitrate concentrations. Flow and rainfall were collected on a continuous basis by field equipment, and weekly trips were taken to download the data and collect the stream samples to be analyzed for pollutant concentrations. The sites where flow measurements were taken in the Little Crum Creek watershed were at the Little Crum Park, the Home Depot in Ridley Township, the old Virgo restaurant in Ridley Township, the Ridley Park Lake, and along Muhlenberg Avenue.

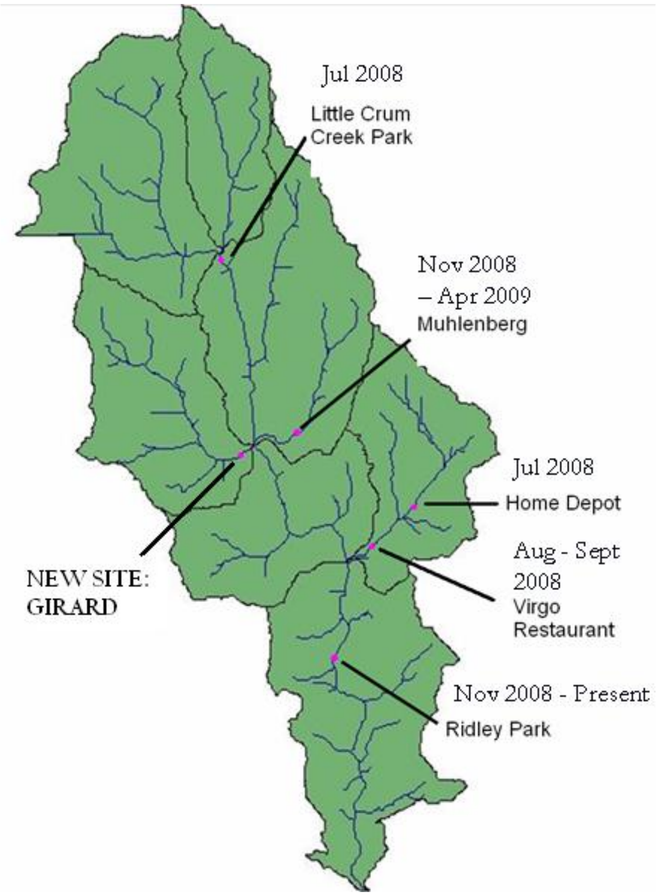


Figure 9. Little Crum Creek watershed with locations where auto-sampler data was taken and the time period for which the data were taken. Note that no new data are available from auto-sampler site Girard since it has only recently been in operation and no data have yet been downloaded from it.

4.1 Function of Auto-Sampler and Rain Gage


(a) (b)

Figure 10. Isco 6712 auto-sampler (a) powered by car battery stationed in aluminum and concrete block encasing for protection. A rain gage (b) connected to the auto-sampler is placed in an open area to measure rainfall.

The main piece of equipment is an Isco 6712 portable sampler (Figure 10a) that both calculates flow in the stream and takes stream water samples in specified time intervals after the start of a rainfall event. The auto-sampler determines that a rain event is occurring from manual inputs of minimum rainfall recorded and/or flow increases in the stream. The auto-sampler uses a flow sensor placed on the bed of the stream and weighted down by rocks or other debris to ensure it remains in the same position. The flow sensor measures velocity of the water in the stream. The sensor also contains a pressure sensor, which calculates the depth of the water using the equation for hydrostatic pressure:

$$P = P_{atm} + \rho g h$$

The pressure sensor measures the pressure at the bottom of the stream. Assuming atmospheric pressure at the surface of the stream as well as the density of the stream water to be equal to the density of pure water, the height of stream water can be calculated and used as depth of the stream at a given time. The width of the stream is measured manually and inputted into the auto-sampler. The auto-sampler assumes a rectangular channel, which was a factor in determining exact locations to measure the stream flow, and thus the cross-sectional area of the channel can be calculated by multiplying the width by the depth of the stream. As the depth changes during rainfall events, the cross-sectional area is calculated by the auto-sampler each minute that velocity data is also recorded. These two values are multiplied together to obtain flow through the stream during that minute.

When the auto-sampler realizes that a rain event has started occurring, a separate function triggers to start collecting water samples from the stream. A 500mL bottle is filled every fifteen minutes with a stream sample until the rainfall and/or stream flow reduces to values that are set to disable the program until the rain event increases in strength again. When all the bottles in the carousel are filled, they can be taken back to the laboratory to be analyzed for pollutant concentrations.

The auto-sampler is also connected to a rain gage (Figure 10b) that measures rainfall continuously. The rain gage contains an open grate at the top that allows rain into the instrument and contains a small scale that tips for every 0.01 inches of rainfall. Every time the scale tips, the rain gage attributes 0.01 inches of rainfall to that minute of data.

The auto-sampler and rain gage combination records depth, velocity, flow, and rainfall values whenever a rain event occurs. The data can be downloaded using a program called Flowlink, and is converted to a comma-separated value file.

4.2 Analyzing Data

4.2.1 Hydrographs and Hyetographs

The data taken from the auto-sampler and rain gage apparatus was graphed as hydrographs and hyetographs. Hydrographs depict flow over time for the stream. The general shape of a hydrograph for a rain event involves a steep increase in flow shortly after the rain event begins. The flow peaks as the rain event reaches its maximum intensity, and then the flow slowly recedes back to its normal flow amount after the rain event ends. The steepness of the hydrograph's peak depends on the intensity and speed of arrival. The peak of the flow increases with the intensity and duration of the rainfall.

Hyetographs depict the rainfall over time of a location. The data from the rain gage yielded a minute-by-minute hyetograph, which was converted to half-hourly data before being inputted into the SWMM model. This decreases the accuracy of the SWMM model's rainfall time series, but the model did not respond well to time steps smaller than thirty minutes.

4.2.2 TSS Loading

The bottles of stream water were taken back to the environmental laboratory to be analyzed for total suspended solids. The total mass of suspended solids found in each bottle was divided by the size of the bottle (500 mL) to find TSS concentration in milligrams per liter. The concentration was converted to English units (pounds per cubic foot) since flow measurements were taken as cubic feet per second. The TSS concentration was multiplied by the flow at the time the sample was taken to yield the load rate. The load rate was multiplied by the time interval between samples being taken to find the total TSS load for that time interval. Then the total TSS could be found by adding up the TSS load values for each interval.

The SWMM model gives TSS concentrations over time in mg/L, which can be converted in the same way to compare the model’s total TSS values to those calculated from field data.

Simulation Output

5.1 Results for Selected Rain Events

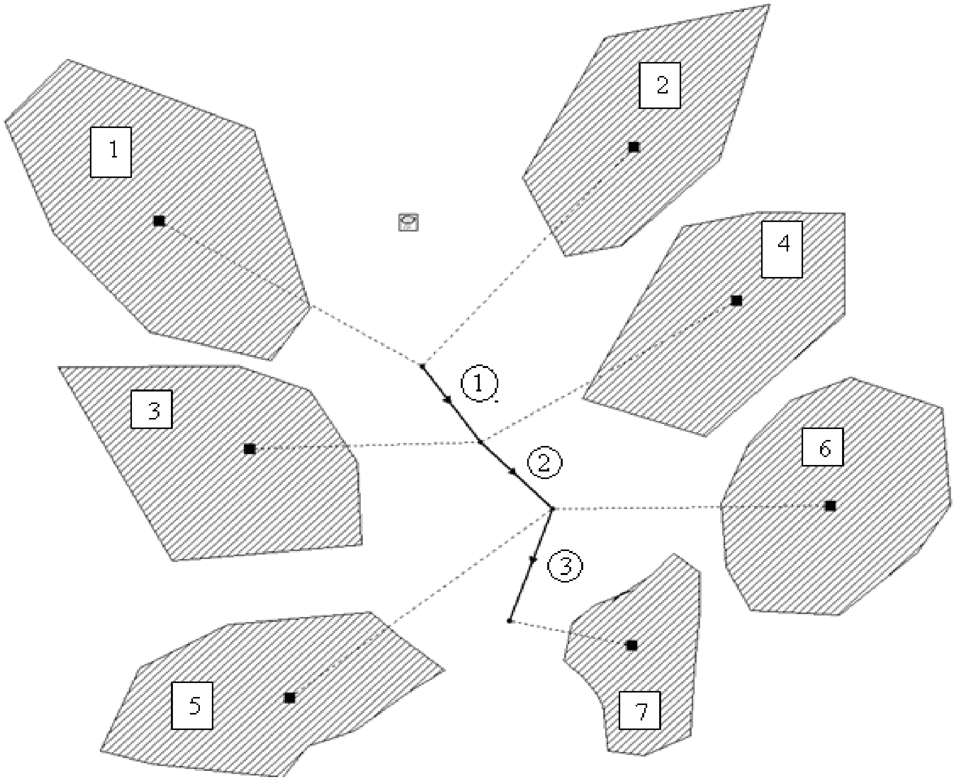


Figure 11. Little Crum Creek watershed as modeled in SWMM5 with subcatchment labels

The naming system for the conduits labels the farthest upstream conduit as conduit 1, which experiences the least amount of flow, and the farthest downstream conduit as conduit 3, which experiences the most amount of flow. Conduit 2 connects conduits 1 and 3. After inputting all the parameters to the SWMM model, a simulation can be run assuming the rainfall event inputted into the rain gage. The rainfall data can be displayed as a hyetograph over the time series of the rain event, as shown in Figure 12.

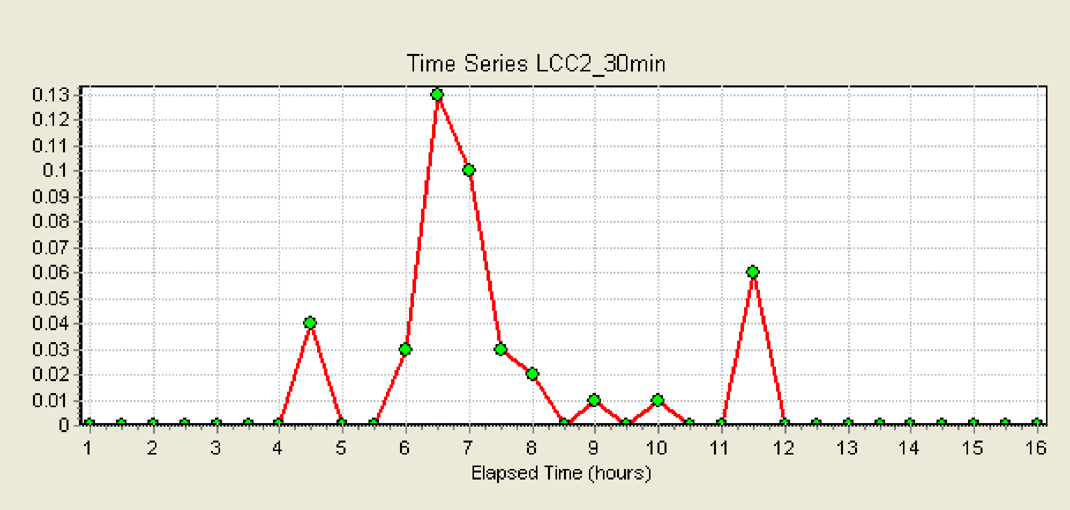


Figure 12. Hyetograph using 30 minute intervals for rain event at Little Crum Park on 07/14/08

The model simulates the increase in flow throughout the stream system, and can display outputs at any of the nodes or conduits in the stream system. At each node, the depth, head, lateral inflow, total inflow, and TSS concentration can be found over the duration of the rain event. Flow, depth, velocity, Froude number, and TSS concentration is given over time. Additionally, the outputs could be given in table form, which allowed a rough estimation of area under the flow curves for total runoff volume and the TSS concentration curves for total TSS loading.

Because the purpose of this model is mainly to determine increases in runoff and TSS loading, the only graphical outputs considered relevant to the project were flow and TSS concentration in the conduits. The model was run using the rainfall time series shown in Figure 12, known as LCC2 (the second rainfall event measured in Little Crum Park). The flow and TSS concentrations in the conduits were graphed with all three conduits on the same time scale for easy comparison.

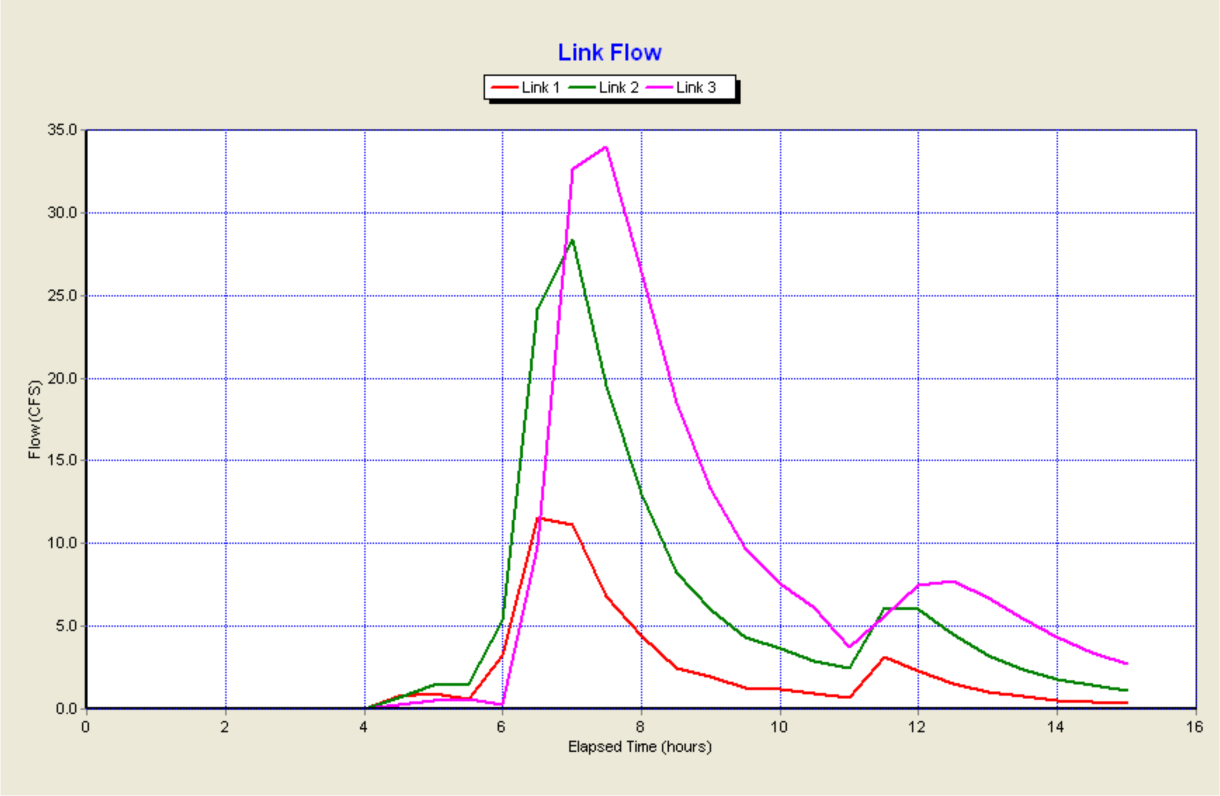


Figure 13. Hydrograph for the three stream segments in model using 07/14/08 LCC hyetograph

The flow through the most upstream conduit (conduit 1) is shown by the red line, and peaks at approximately 13 cfs. The flow through the middle stream segment (conduit 2) is shown by the green segment, and peaks at approximately 30 cfs. The flow through the most downstream segment (conduit 3) is shown by the magenta segment, and peaks at approximately 35 cfs. Conduit 1 sees the lowest flow, which makes sense because it drains the lowest area of land. Conduit 2 sees more flow than conduit 1, because conduit 1's flow moves into conduit 2, in addition to the subwatersheds that drain directly into the node that begins conduit 2. Conduit 3 sees the most flow in its channel, since it receives the flow from conduit 2 as well as runoff from the subwatersheds that drain into the node that begins conduit 3. It can also be noted that the peak flow occurs at later times for more downstream conduits. The model simulates the rainfall over all the subcatchments at the same time, but also takes into account that flow takes time to move from one stream segment to the next.

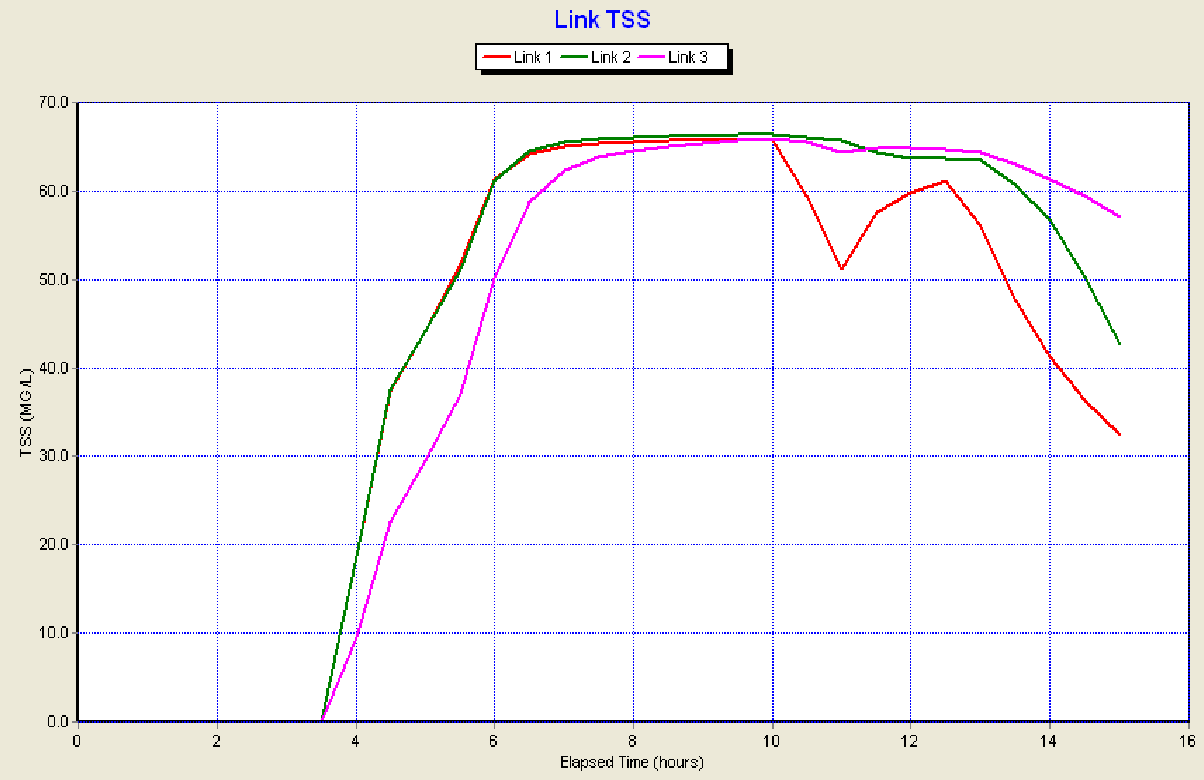


Figure 14. TSS concentrations for the three stream segments in model using 07/14/08 LCC2 hyetograph

The TSS concentrations over time for each stream segment are shown in Figure 14. The color coding for the stream segments are the same as the flow versus time graph. TSS concentrations do not increase as the runoff travels downstream. They are dependent on the land uses in the subcatchments that drain into that part of the stream.

The total runoff in each stream segment was found by calculating the area under the flow vs. time curve. The total TSS load was similarly found by determining the area under the TSS concentration vs. time curve. The areas were calculated using the trapezoidal rule, which sums the areas in each individual interval assuming each individual area is a trapezoid with height equal to the time interval and heights equal to the previous and next values for flow or TSS concentration.

Conduit	Total Runoff Volume (cubic ft.)	TSS Load (lb.)
1	119600	464
2	286500	1148
3	385700	1530

Table 4. Total runoff volumes and TSS loads each conduit in the model

5.2 Assessment of Model Accuracy

In order to assess the model's accuracy, the model's outputs needed to be compared to the hydrographs and TSS loadings taken from field data. Thus the field data needed to be taken from points along the stream system that were modeled. The data taken at the Little Crum Park site proved very valuable, as the site is located where the flow from the top most upstream subcatchments (subcatchments 1 and 2 as labeled in Figure 10) connect, and thus is a good comparison to the outputs from conduit 1. The model's hydrograph output was shown over the same time axis as the measured flow values from the auto-sampler at the Little Crum Park site. The rainfall event for Little Crum Park on 07/14/2008 was used so that each would have identical hyetographs. However, rainfall measurements taken by the rain gage were minute-by-minute, whereas the rainfall time series inputted into the model used half-hour time intervals. The model did not respond well to small time intervals, so the total rainfall for each half hour was summed and used instead.

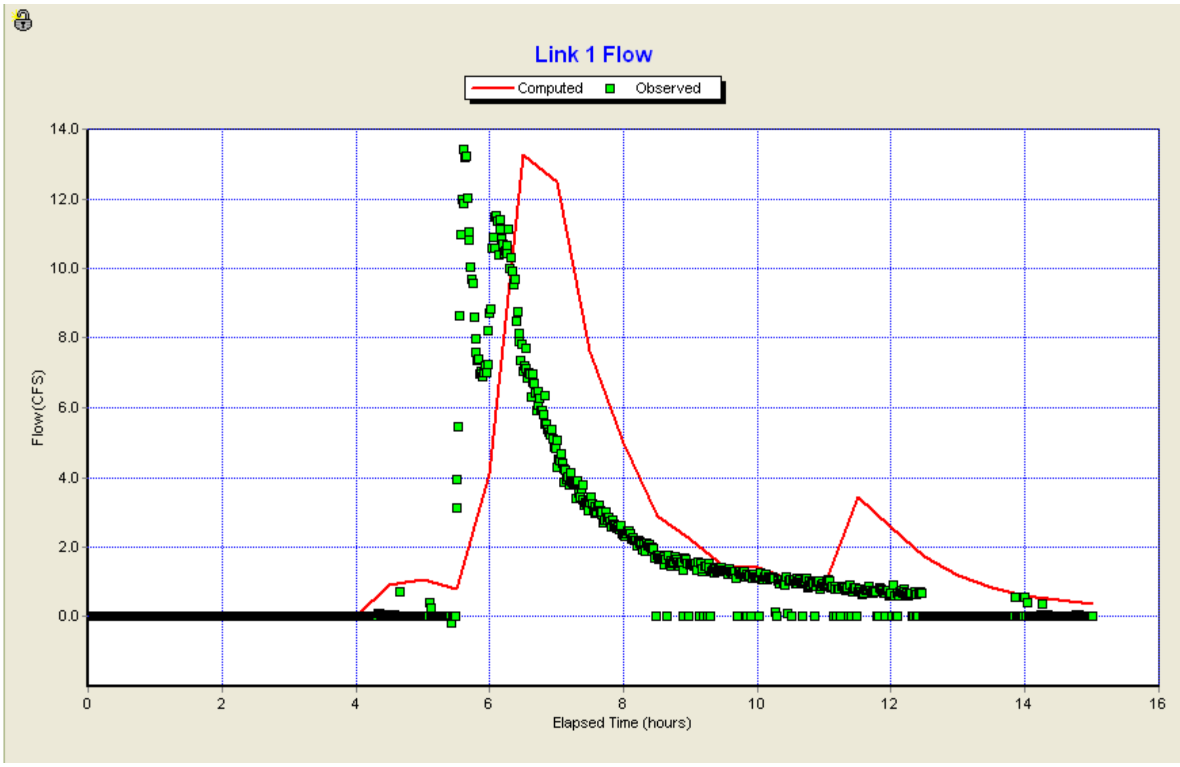


Figure 15. SWMM Model's hydrograph of Conduit 1 (red line) plotted on same axis as hydrograph calculated from field data (square points)

The shapes of the hydrographs from the model and field data are very similar. Both exhibit a sharp upward slope, and tail off in a similar fashion. One noticeable difference is that the model's flow values seem to lag around an hour behind the measured flow data. This does not make a difference in what the model will predict for peak and total flow, so it does not affect the results obtained for this report. One applicable use in which this could be a problem is if the model is set to predict flooding, as time between a storm starting and the occurrence of flooding is an important output. One possible reason for this error in timing may come from the rainfall time intervals. When the measured rainfall data was converted to 30 minute time intervals for the SWMM model, the timing of the rainfall may have become skewed. Rainfall is summed to the next half hour interval, which will delay the model's simulation of rainfall onto the subcatchments. Another difference is the secondary peak in flow present in the model's hydrograph that is absent from the field data. This can most likely be attributed to the difference in time intervals for the hyetographs. The SWMM model saw the 0.06 in spike in rainfall at the end of Figure 12 and interpreted it as a small rain event. The minute-by-minute rainfall data could have shown that it was very spread out, light rain that would have no noticeable effect on stream flow, which was most likely the case here. Quantitatively, the peak flows of the two hydrographs are very similar, but the total runoff volumes are inconsistent.

Hydrograph	Peak Flow (cfs)	Total Runoff Volume (cubic feet)	TSS Load (lb.)
Field Measured Data	13.41	74119	425.2
SWMM Model	13.25	119610	463.7
SWMM Model (2nd Peak Removed)	13.25	99396	404.7

Table 5. Comparison of flow values between field data and model outputs for LCC2 event

The model's peak flow results showed 1.2% error using the field measured data as the accepted value for that particular rain event. The model's total runoff volume showed a 61.4% error compared to the field data. However, if the second, smaller peak is removed (error reasoning explained above) and the flow decays to zero instead, the error in total runoff volume decreases to 31.4%. The model's predicted TSS loading showed only 9.1% error, and decreased to 4.8% error after the second peak was removed.

There were no field measurements taken in a location that would be analogous to conduit 2, so accuracy of that segment cannot be determined. Based on its location, the auto-sampler at the new site on Girard Ave. will take flow readings that can be compared to the modeled flow from conduit 2. However, no flow data has been collected from this site, so no accuracy assessment has been performed on conduit 2.

The Ridley Park site runs along conduit 3, so flow measurements from that site could be used to determine the accuracy of conduit 3 in the model. However, problems arose in the data collection at this site, as it lies near Ridley Middle School. The rain gage was consistently found knocked over, both voiding any rainfall data and creating false rain events, causing the auto-sampler to take stream samples when there was no rain event. Eventually, the rain gage was removed and only flow and stream samples were taken during rain events. However, the rain events would not have any associated rainfall data, which is a critical input in the SWMM model. Luckily, for one rain event that occurred on 12/19/08, an auto-sampler stationed at the Muhlenberg site measured rainfall data, while the auto-sampler at the Ridley Park site measured flow. Thus, the rainfall data could be inputted into the model and its outputs for conduit 3 could be compared to the flow data taken at the Ridley Park site to assess accuracy.

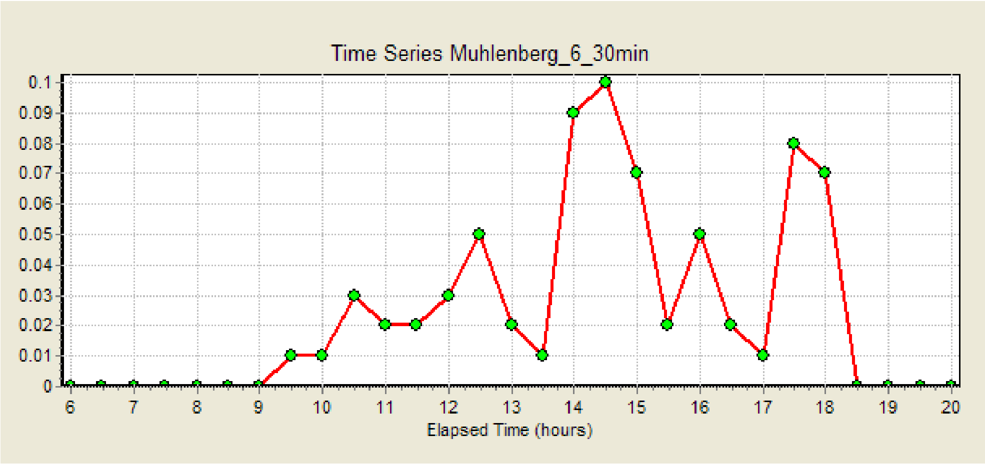


Figure 16. Hyetograph using 30 minute intervals for rain event at Muhlenberg site on 12/19/08

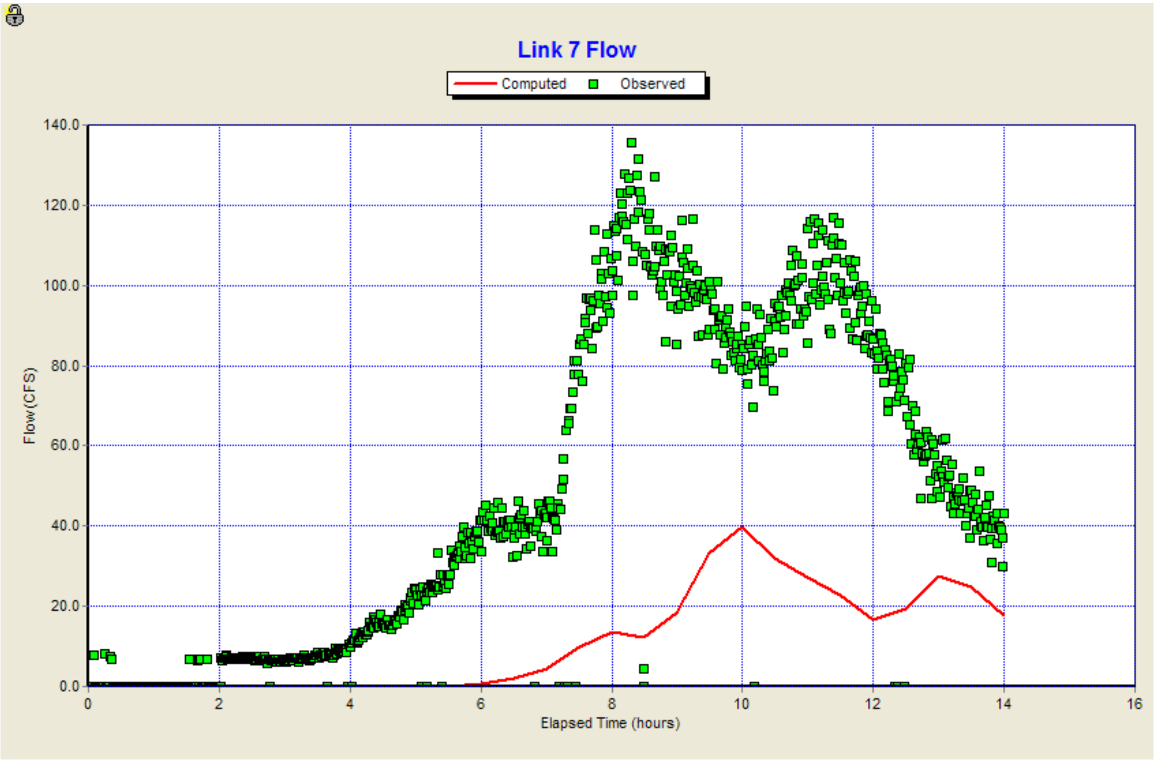


Figure 17. SWMM model's hydrograph of conduit 3 (red line) using Muhlenberg 6 rainfall data (12/19/08) as compared to measured flow during that rainfall event (square points)

The relative shapes of the graph are accurate, denoting that the rainfall data from the Muhlenberg site is consistent with what would have been collected at the Ridley Park site. However, the similarities end at the shape of the hydrographs, as the peak flow and total runoff volume predicted by the model is highly inaccurate.

Hydrograph	Peak Flow (cfs)	Total Runoff Volume (cubic feet)	TSS Load (lb)
Field Measured Data	135.54	2415914	3487
SWMM Model	39.61	580554	2367

Table 6. Comparison of flow and TSS values between field data and model outputs for Ridley Park site using Muhlenberg 6 event

The model vastly underestimated the runoff flow that would occur from this rain event. Compared to the measured flow values from the Ridley Park site, the model's predicted peak flow had 70.1% error and total runoff volume had 76.0% error. Because the model's prediction for TSS loading uses flow in the calculation, the large error in flow values renders any TSS modeling trivial.

The Little Crum Park and Ridley Park sites were the only two sites along the section of stream in the SWMM model. To use the auto-sampler and rain gage data from other sites as a comparison to the model's outputs and ultimately increase the model's accuracy, separate models were created that would simulate the flow through the same stream segments that the Muhlenberg and Virgo sites measured. These two smaller models were created with smaller subcatchments to model only the area that the Muhlenberg and Virgo sites caught. The parameters were found in the same way as the main SWMM model, with parameters relating to the entire watershed, such as infiltration, kept the same. The model for the Muhlenberg site was simulated using the same 12/19/08 rainfall data as previously used for and yielded the hydrograph below, being compared to the actual hydrograph.

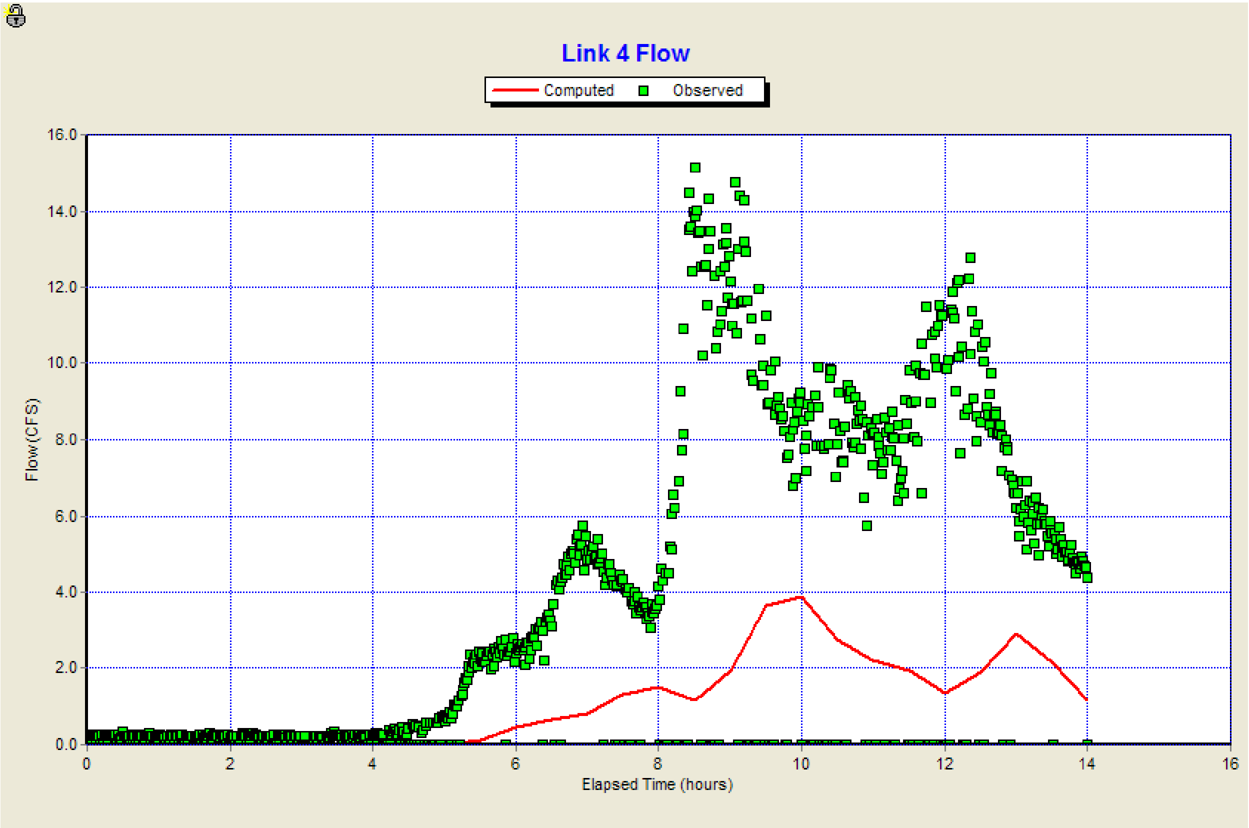


Figure 18. SWMM model's prediction of flow through Muhlenberg site (red line) graphed with measured flow at site (square points) on 12/19/08

The shape of the model's hydrograph is fairly accurate, but again, the SWMM model greatly underestimates the flow through this conduit.

Hydrograph	Peak Flow (cfs)	Total Runoff Volume (cubic feet)
Field Measured Data	15.15	187921
SWMM Model	3.88	57420

Table 7. Comparison of flow and TSS values between field data and model outputs for Muhlenberg site

The SWMM model's peak flow prediction had an error of 74.4% and its total runoff volume had an error of 69.4%. Due to the large error in flow predictions, TSS loading was not calculated because it would not have an accurate solution.

A separate SWMM model was created with only the subcatchment area that drains through the stream measured at the Virgo site. The model for the Virgo site used rainfall data from 09/06/08, when Tropical Storm Hannah passed through the area, creating a large spike in rainfall.

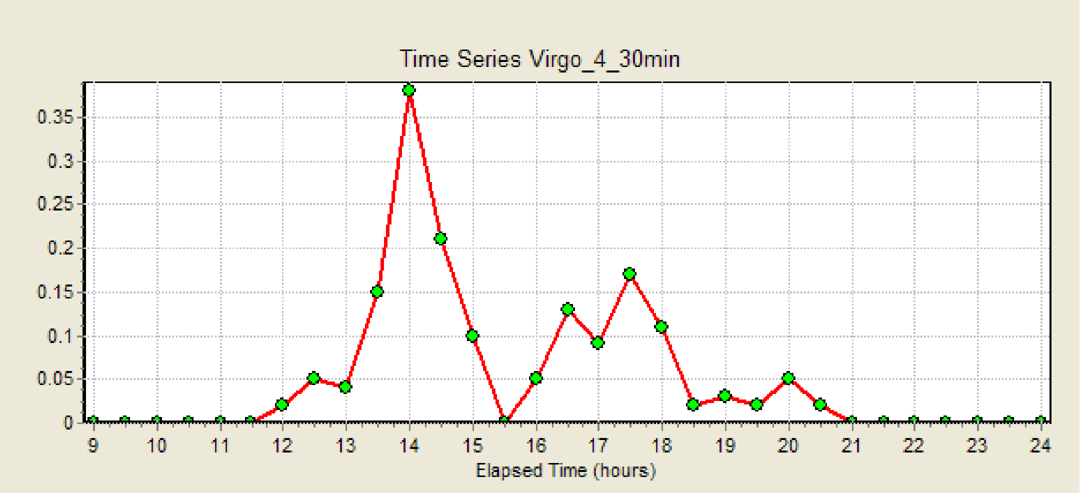


Figure 19. Hyetograph for Virgo 4 rain event using 30 minute intervals

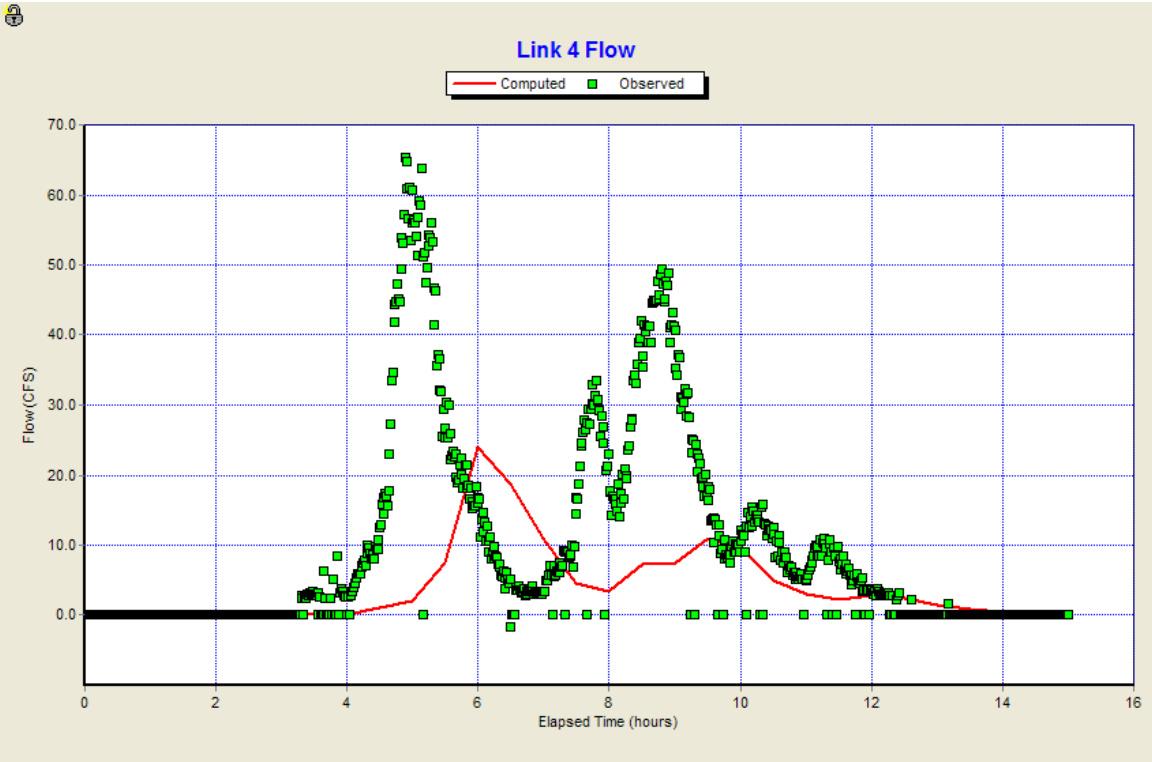


Figure 20. SWMM model's prediction of flow through Virgo site (red line) graphed with measured flow at site (square points) using Virgo 4 rain event (09/06/08)

Hydrograph	Peak Flow (cfs)	Total Runoff Volume (cubic feet)
Field Measured Data	65.39	531953
SWMM Model	24.02	227826

Table 8. Comparison of flow and TSS values between field data and model outputs for Virgo site

The SWMM model's peak flow prediction had an error of 63.3% from the accepted value measured from the auto-sampler. The model's total runoff volume had an error of 57.2%. The large error in the model's predictions suggests incorrect values of parameters. Some of the inputs had more uncertainty than others, so they were adjusted until the model became more accurate. The parameter that was changed the most was imperviousness of the subcatchment. The values obtained from ArcGIS had a high degree of uncertainty, as the program finds imperviousness by determining light reflection from the ground. It uses the assumption that more light reflection denotes a more impervious surface, which may be incorrect. The model was adjusted to minimize the error between the hydrograph from SWMM matched the hydrograph from field data.

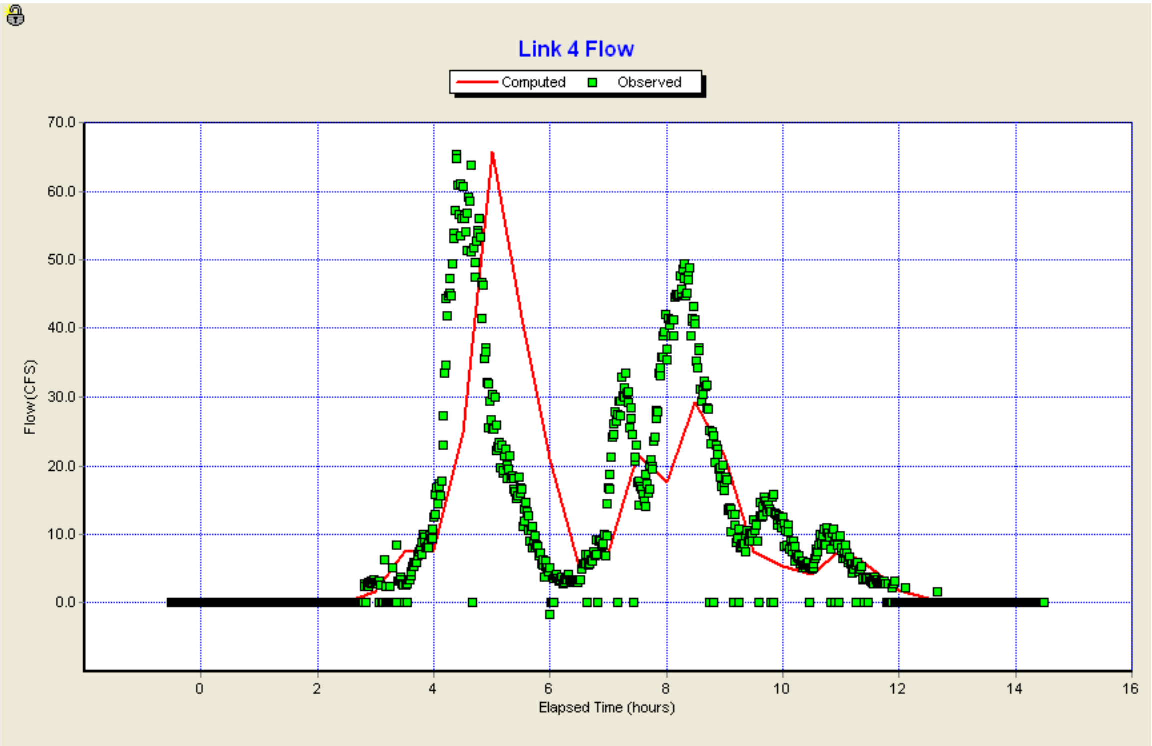


Figure 21. Calibrated SWMM model of flow at Virgo Site (red line) as compared to flow measured at the site (square points)

Hydrograph	Peak Flow (cfs)	Total Runoff Volume (cubic feet)	TSS Load (lb)
Field Measured Data	65.39	531950	249
SWMM Model	65.66	549400	722

Table 9. Results for peak flow, total runoff volume, and TSS loading for calibrated Virgo model

The calibrated model showed much more accurate results for peak flow and total runoff volume. The calibrated model's peak flow value had a 0.4% error, as compared to 63.3% from the original model for the Virgo site. The calibrated model's total runoff volume has a 3.3% error, as compared to the 57.2% error that the original Virgo model had. However, the model's TSS load value showed 190% error. Since the flow values were accurate, this shows an error in the buildup and washoff functions used to describe each land use. The washoff function is most likely the problem with the model, as an actual equation could not be found. Instead, event mean concentrations, which were given from previous StormWISE runs on the Little Crum Creek watershed, were inputted as general estimates for TSS loading over time.

The underestimations of the SWMM model for the Muhlenberg site, Ridley Park site, and Virgo site all have errors in the 60-70% range. That the percentage error is similar may be an indication that some wrong parameter or assumption by the program is causing the same error in both of these conduits. That is helpful, as one consistent error, though large, still indicates that the SWMM model's predictions are not randomly wrong. Only the Virgo site was calibrated to improve the accuracy of the model's predictions. The SWMM model for the Muhlenberg site did not reach values close to the measured data even with calibrations that were clear overestimates of some parameters. This may occur because the area that drains into the Muhlenberg site may not be large enough for SWMM to make an accurate estimate of flow. Conduit 3 was not calibrated to match the Ridley Park site flow data, because it encompasses a very large area. Several subwatersheds that have not been checked for accuracy make up the area that eventually drains into conduit 3. It is uncertain which subwatersheds should be calibrated, and by what amount. Choosing which subwatersheds to change the properties of would only be guessing, so the model was left alone. If more sites around the watershed were measured for flow, then the watershed could be calibrated piece by piece (such as the Virgo site), and results from conduit 3 could eventually be fixed in that way.

One other noticeable problem with all the hydrographs is an apparent time shift between the model's predicted flow and the actual measured data. The SWMM manual discussed this and mentioned that time shifts often occur. However, the time shift does not make a difference for the results calculated for this project, because peak flow, total runoff volume, and TSS loading should still be the same.

Applications of SWMM

6.1 Using the Model

The SWMM model was designed using the geographic parameters of the Little Crum Creek watershed primarily to assess the increase in flow in Little Crum Creek as well as TSS loading. Ideally the model would make accurate predictions of flow and TSS so auto-sampler data would not be necessary. A simulated rainstorm could be inputted into the model and it could predict the flow in the channels and determine where there were any specific areas in danger. Additionally, stronger storms that occur rarely may not have occurred since the auto-samplers were placed in the field. If the rainfall data for such a storm are available, the SWMM model could predict flow in the stream segments.

Another use of the SWMM model would be as an aide to development planners to determine the effects of further urbanization on Little Crum Creek. A model is important because the parameters can easily be changed to show their impacts on the stream system. Should any area of the Little Crum Creek watershed change its land use, development planners would need to know the effects on the environment, including any flow increases that would be harmful to the stream ecosystem.

6.2 Development Planning

Though many parameters can be determined with the land surface data, some of these data may not necessarily be static. For instance, while the topography of a watershed will probably not change over time, there is a possibility that land surface development can change. Moreover, the development of an area is strongly related to the imperviousness of that area, which is a critical property for determining stream flow. Whereas rain can percolate, or infiltrate, into the ground on areas that are pervious, rain that falls on impervious areas such as paved roads or roofs is routed to streams, which increases the stream flow beyond its natural levels. Analyzing how flow in streams may vary depending on changes in the imperviousness of the watershed area can help in making decisions to manage development and increase protection of the creek in such a way that it does not cause excessive runoff, which can lead to higher pollutant loads and damage to the stream ecosystem. Though SWMM processes other parameters that may change over time, such as depression storage, sensitivity trial runs of SWMM have shown that surface imperviousness causes one of the most significant changes in stream flow.

The model was used to assess three scenarios where imperviousness changed in different parts of the Little Crum Creek watershed. For the first case, the construction of the Springfield Square Shopping Center along the Baltimore Pike was assessed for impact on the Little Crum Creek system. The building of the shopping center affects the imperviousness of the subcatchment in which it is located. As the imperviousness increases, rainfall will no longer infiltrate into the ground, and will instead run into streams, increasing the peak flow, total runoff volume, and total suspended solids. The second case involved assessing the impact of the Home Depot built in recent years along MacDade Boulevard. A historical analysis was performed to determine the change in impervious caused by the construction of the Home Depot. The third scenario involved changing the percent imperviousness of the entire watershed. This scenario is not based off actual construction that has occurred like the other scenarios, but instead can demonstrate potential damage to the stream if development is left unchecked.

For these scenarios, it was assumed that construction only changes percent imperviousness of the subcatchment and leaves everything else constant. A sensitivity analysis was performed on the model for changes in peak flow and total runoff volume while varying imperviousness of the subcatchment or subcatchments affected by the scenario. The percent imperviousness input was varied from 0–100%, and the corresponding change in peak flows and total runoff volumes were graphed to determine a relationship using a best fit line. The changes in peak flow and runoff volume were found as a percent change from the original values used in model.

6.2.1 Scenario 1: Springfield Square Shopping Center

As can be seen in the following figure, the Springfield Square Shopping Center when completed will convert an area that can be considered “Forest/Wetland,” as is evident by the wooded area surrounding the construction site, into what will probably be a highly impervious surface. Since the SWMM simulation results matched closely with the calibration at the Little Crum Park site just downstream of the shopping center, it can be assumed that SWMM can also accurately simulate how stream flow will change to accommodate this change in the upstream imperviousness.

Figure 22. Photograph of the Springfield Square Shopping Center construction site.

The sensitivity analysis procedure mentioned in the previous section was applied to this scenario with the following results:

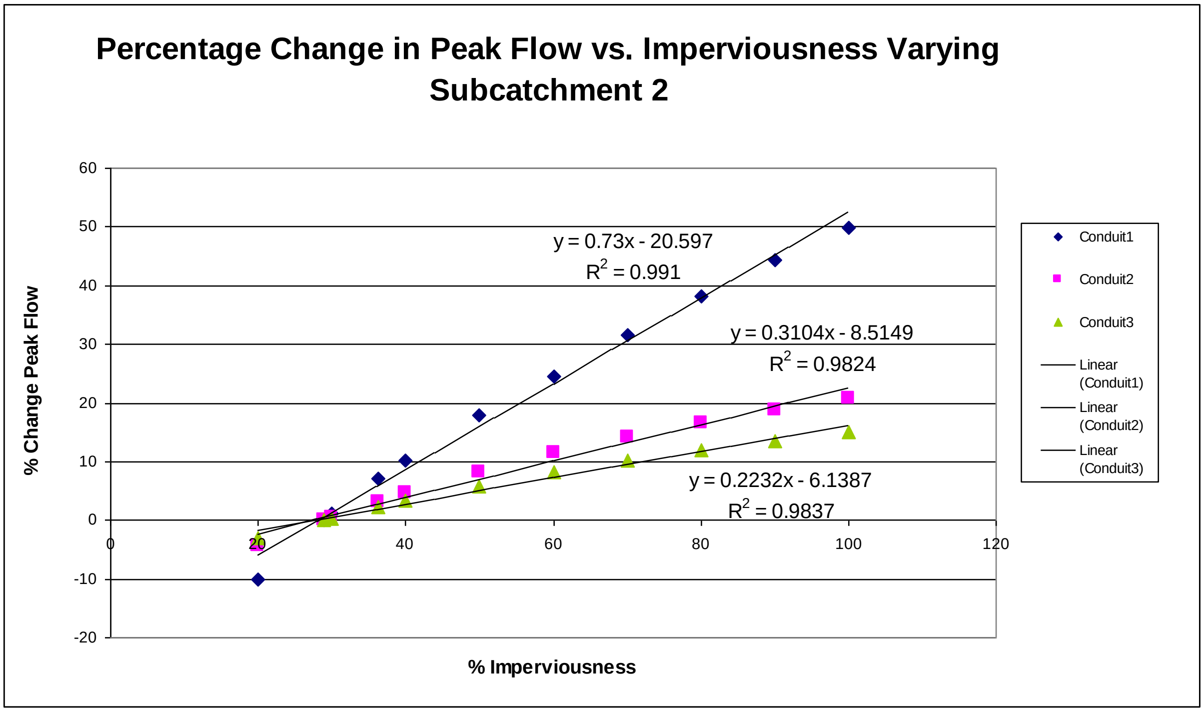


Figure 23. Sensitivity analysis and the resulting curve fit for the peak flow vs. imperviousness relationship for the first scenario.

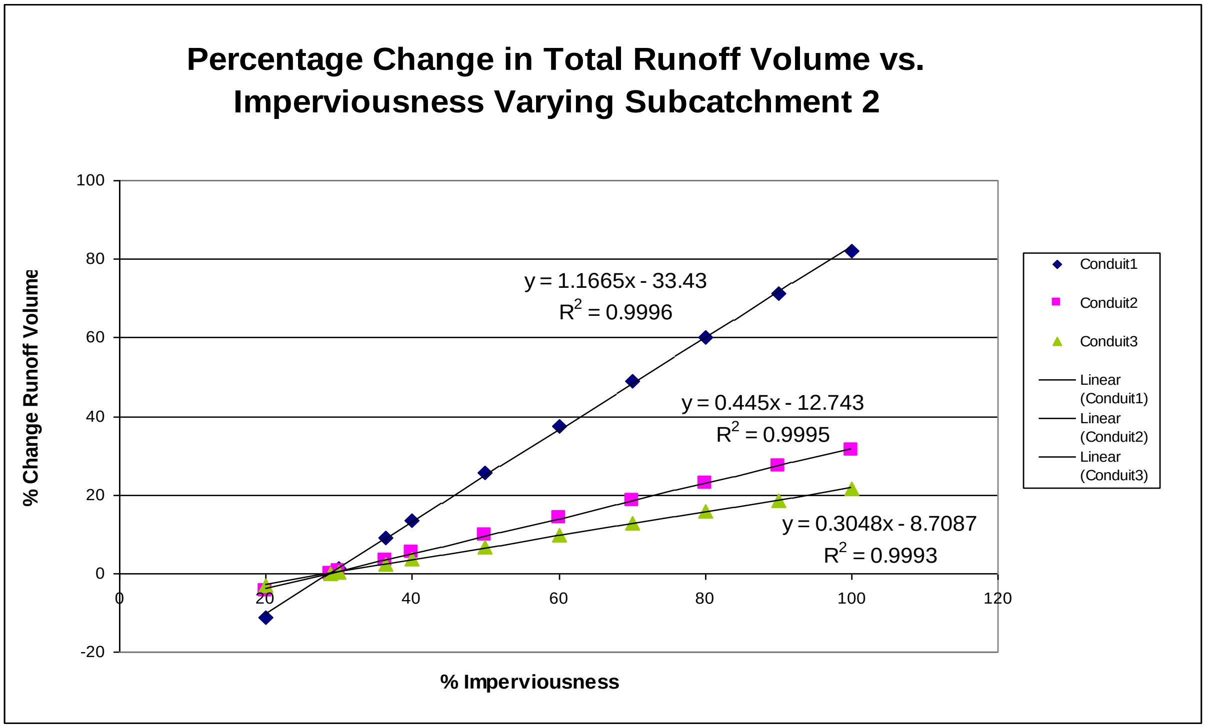


Figure 24. Sensitivity analysis and the resulting curve fit for the total runoff volume vs. imperviousness relationship for the first scenario.

In order to calculate the percent increase in total runoff volume and peak flow, the percent increase in imperviousness had to be calculated. The area of the construction site was first measured within the GoogleEarth interface. Then, the ratio of the construction site area to the total subcatchment 2 area was calculated. It was assumed that the area of the shopping center would be 100% impervious. The impervious percentage parameter was increased according to the area ratio. Finally, the percent change in imperviousness was inputted into the curve fit equation for both the peak flow and total runoff volume vs. imperviousness curve fits to obtain the percent increase in peak flow and total runoff volume. A summary of these results are shown below:

Area of Shopping Center (ac)	0.90
% Change in Imperviousness for Subcatchment	0.35
% Change Peak Flow (Conduit 1)	0.26
% Change in Total Runoff Volume (Conduit 1)	0.41

Table 10. Summary of the results of the first scenario.

6.2.2 Scenario 2: Home Depot

The rectangular white building in the following GoogleEarth image is the Home Depot built on MacDade Boulevard in 2001. The black and white satellite image below it is what the same area looked like in 1989. Comparing these two images, land use has obviously changed, from approximately a developed wooded/field land use to a highly impervious surface. Unlike in the first scenario, though, instead of projecting future stream flow, stream flow was analyzed for a historical situation. The results of this historical scenario are shown below the images. There is only a sensitivity curve for conduit 3 because the subcatchment in which Home Depot is situated drains directly into conduit 3, so conduits 1 and 2 remain unaffected.

Figure 25. Satellite image of the Home Depot on MacDade Boulevard taken in the current year.

Figure 26. Historical satellite image of the same area taken in 1989.

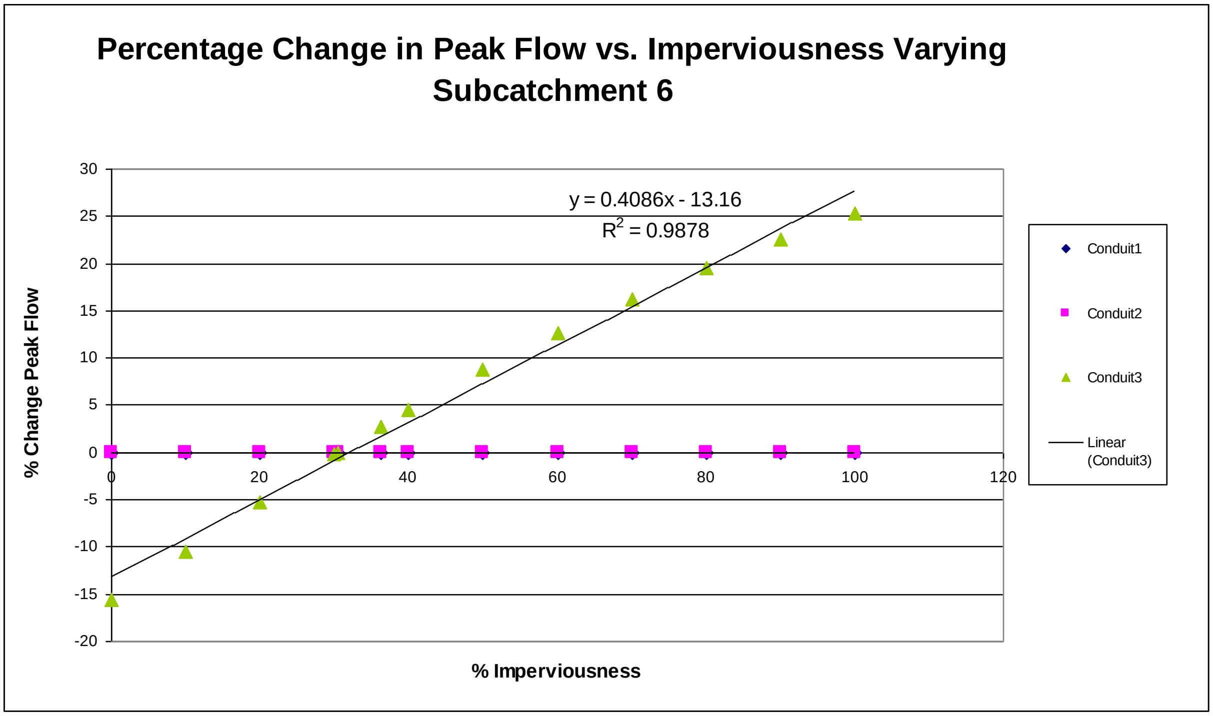


Figure 27. Sensitivity analysis and the resulting curve fit for the peak flow vs. imperviousness relationship for the second scenario.

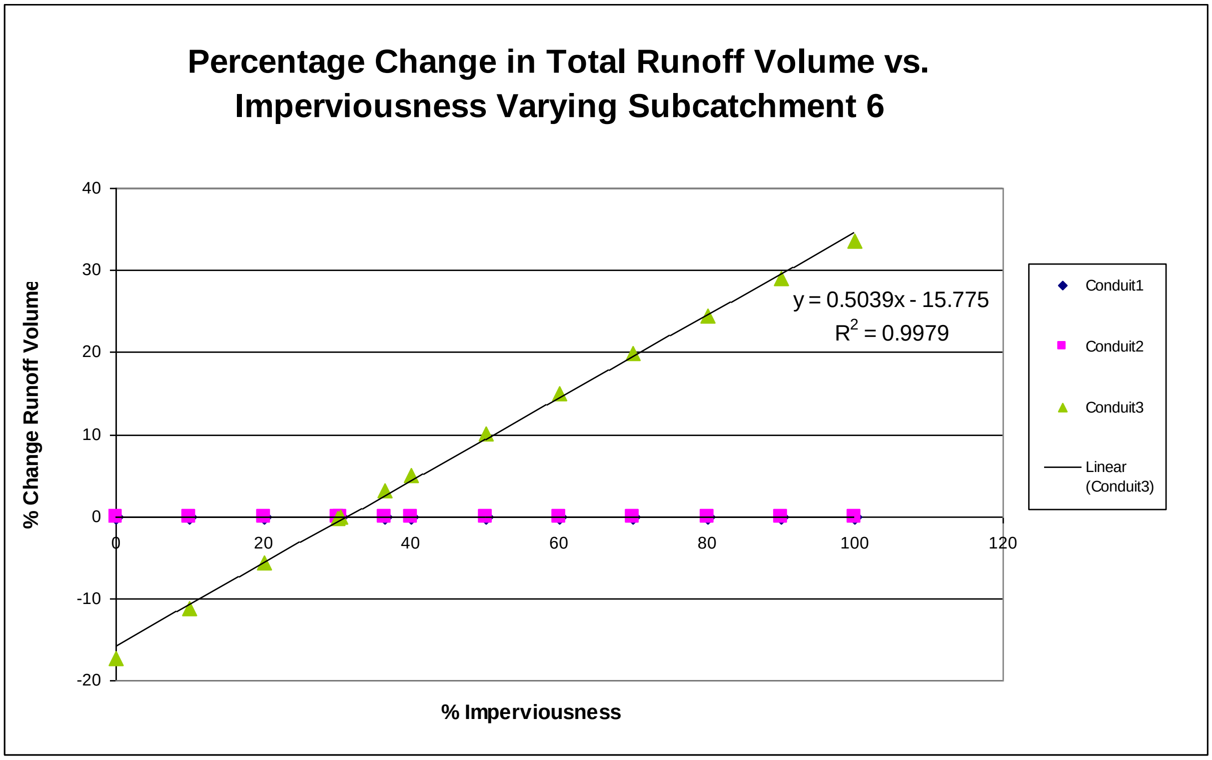


Figure 28. Sensitivity analysis and the resulting curve fit for the total runoff volume vs. imperviousness relationship for the second scenario.

The procedure for calculating percent change in peak flow and total runoff volume is the same for this scenario as in the previous scenario, except that the ratio of the Home Depot area to the host subcatchment was subtracted from the percent impervious property instead of added. The results are shown below.

Area of Home Depot (ac)	0.55
% Change in Imperviousness for Subcatchment	-0.14
% Change Peak Flow	-0.06
% Change in Total Runoff Volume	-0.07

Table 11. Summary of the results of the second scenario.

6.2.3 Scenario 3: Entire Watershed

For the case of increasing imperviousness in the entire watershed, only the percent change in peak flow and total runoff volume vs. percent change in imperviousness curves were calculated. The results are shown in the plots below.

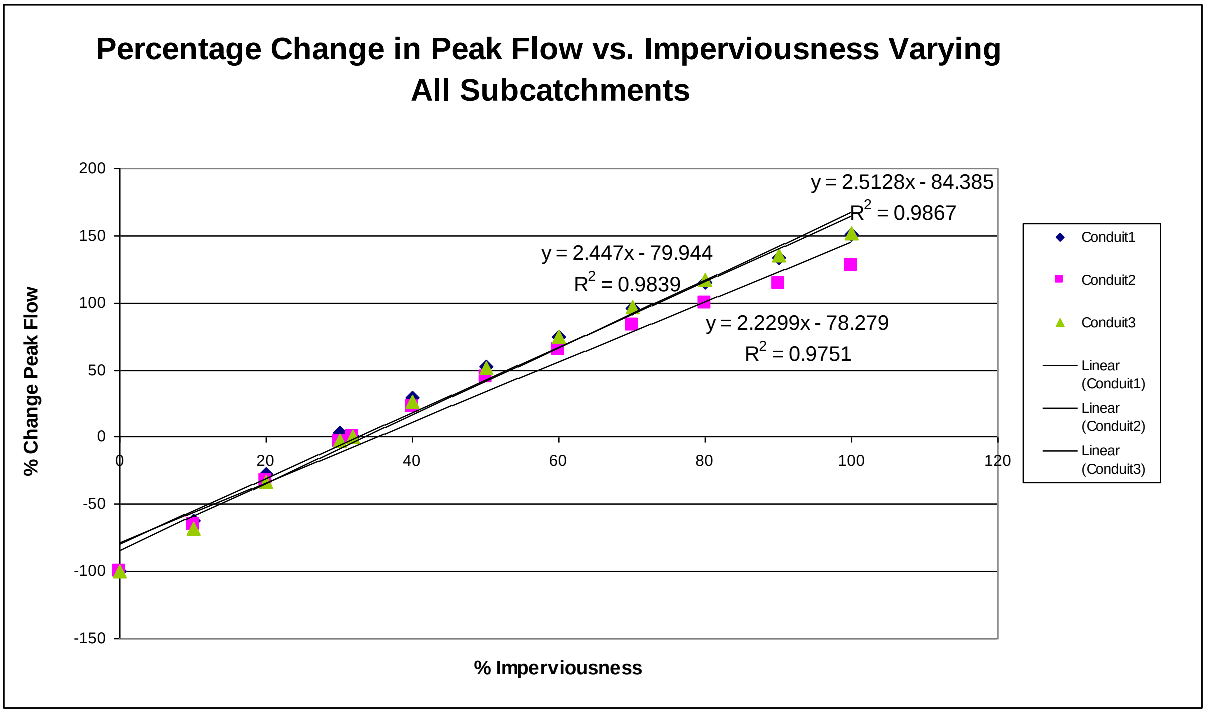


Figure 29. Sensitivity analysis and the resulting curve fit for the peak flow vs. imperviousness relationship for the third scenario.

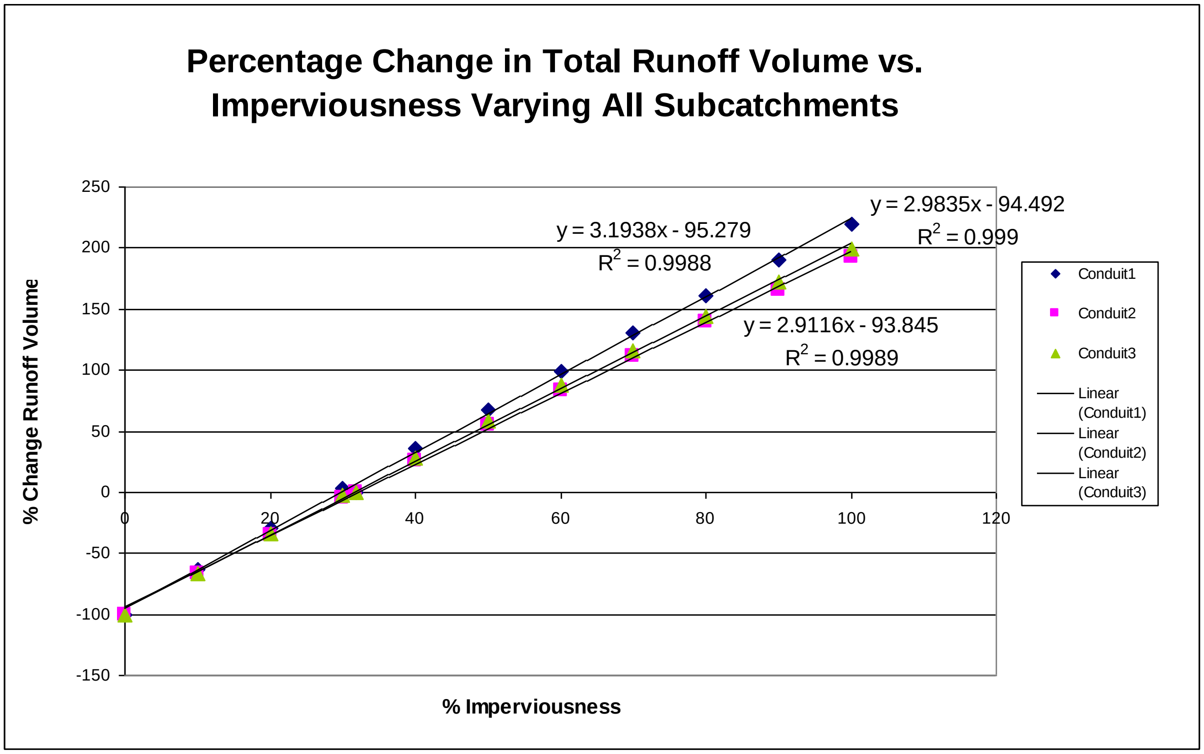


Figure 30. Sensitivity analysis and the resulting curve fit for the total runoff volume vs. imperviousness relationship for the third scenario.

By comparing the slopes of the curve fits, it is apparent how much greater of an effect increasing the imperviousness of all subcatchments has on the creek than simply increasing the imperviousness of one subcatchment. This scenario does not represent an expected change in the watershed, but shows what could happen if the land development from scenarios 1 and 2 continue without keeping contractors aware of the hydrologic conditions of the watershed.

6.3 Upgrading of Model

There are many ways that the SWMM model can made more accurate. Comparing the model to more measured flows from rainfalls will help the users get a better idea of what parameters might be causing the error in flow and TSS. This could be done by comparing the model's flow to different rain events from the sites it is already set up to predict. The most important section to get more data is the Ridley Park site, because it is located near the end of the Little Crum Creek watershed and thus receives the most flow out of all the auto-sampler sites. Also, the site has no rain gage, so the model could only predict flow at the Ridley Park site when a rain gage at another site took rain data at the same time. This only occurred once, so there is only one usable set of data for a rain event. Additionally, conduit 2 is the only conduit that couldn't be checked for accuracy. Data that will eventually be taken at the new site on

Girard Ave. can be used to check the accuracy of conduit 2. Field data from new sites that encompass parts of subwatersheds 3 and 5, where no auto-samplers have been placed yet, would also help to assess the accuracy of the model. The model could be split up and smaller sections could be calibrated, until most of the watershed has been calibrated and the Ridley Park site can then be used to calibrate the rest.

The input %Zero-Imperv is the percent of the impervious area in the subcatchment with no depression storage. There were no tables in the SWMM 5.0 manual to find what this value could be. There were no satellite data layers that could be used to determine this property, and it would be too time-consuming to conduct a land survey to manually approximate this parameter. Thus %Zero-Imperv was set to one value for all of the subcatchments. Finding a way to determine a more accurate value for this input should increase the accuracy of the model. The washoff functions for each land use were estimated as event mean concentrations, given from previous runs of the StormWISE model of the Little Crum Creek watershed. Using an actual function to describe the washoff of each land use would yield more accurate results.

6.4 Conclusions

Though there are several ways in which the SWMM implementation can be improved, the results that have been obtained from this study have shown that this model can be utilized to find changes in stream flow as a result of changes in land use. Specifically, this study has found that SWMM most accurately models runoff flow in the upper part of the watershed. This model can be used in conjunction with BMP siting models in order to find specific locations that have the greatest potential for stream rehabilitation by targeting sites with high peak flows, total runoff volumes, or TSS concentrations.

References

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Sleigh, P.A. and I.M. Goodwill. "The Saint Venant Equations." University of Leeds, 2000. <http://www.efm.leeds.ac.uk/CIVE/CIVE3400/stvenant.pdf>

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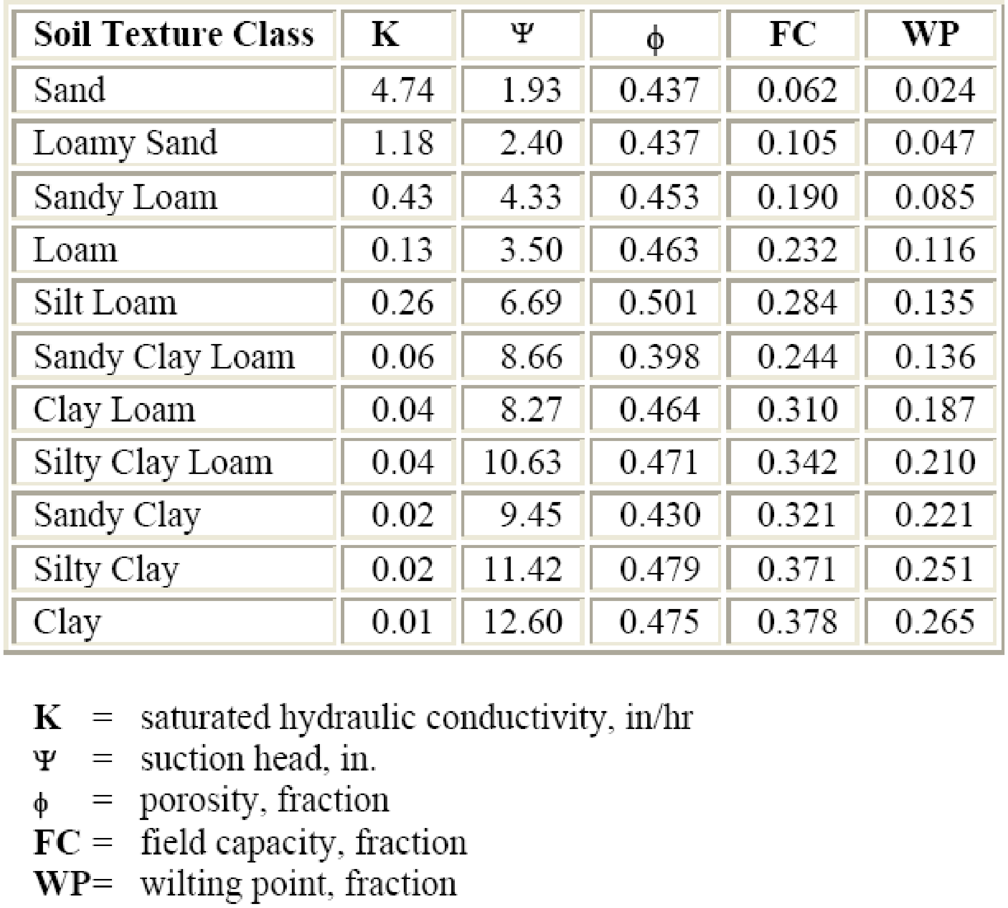
Appendix A

Green-Ampt Parameters

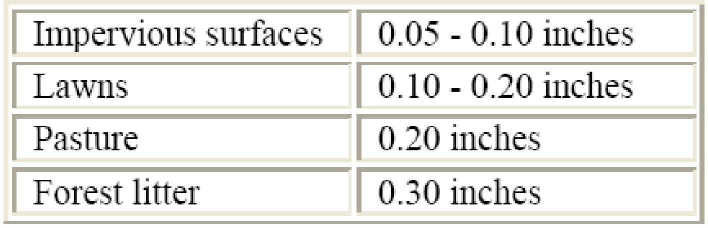


Soil Texture Class	**K**	**Ψ**	**ϕ**	**FC**	**WP**
Sand	4.74	1.93	0.437	0.062	0.024
Loamy Sand	1.18	2.40	0.437	0.105	0.047
Sandy Loam	0.43	4.33	0.453	0.190	0.085
Loam	0.13	3.50	0.463	0.232	0.116
Silt Loam	0.26	6.69	0.501	0.284	0.135
Sandy Clay Loam	0.06	8.66	0.398	0.244	0.136
Clay Loam	0.04	8.27	0.464	0.310	0.187
Silty Clay Loam	0.04	10.63	0.471	0.342	0.210
Sandy Clay	0.02	9.45	0.430	0.321	0.221
Silty Clay	0.02	11.42	0.479	0.371	0.251
Clay	0.01	12.60	0.475	0.378	0.265

K = saturated hydraulic conductivity, in/hr
Ψ = suction head, in.
ϕ = porosity, fraction
FC = field capacity, fraction
WP= wilting point, fraction

Appendix B

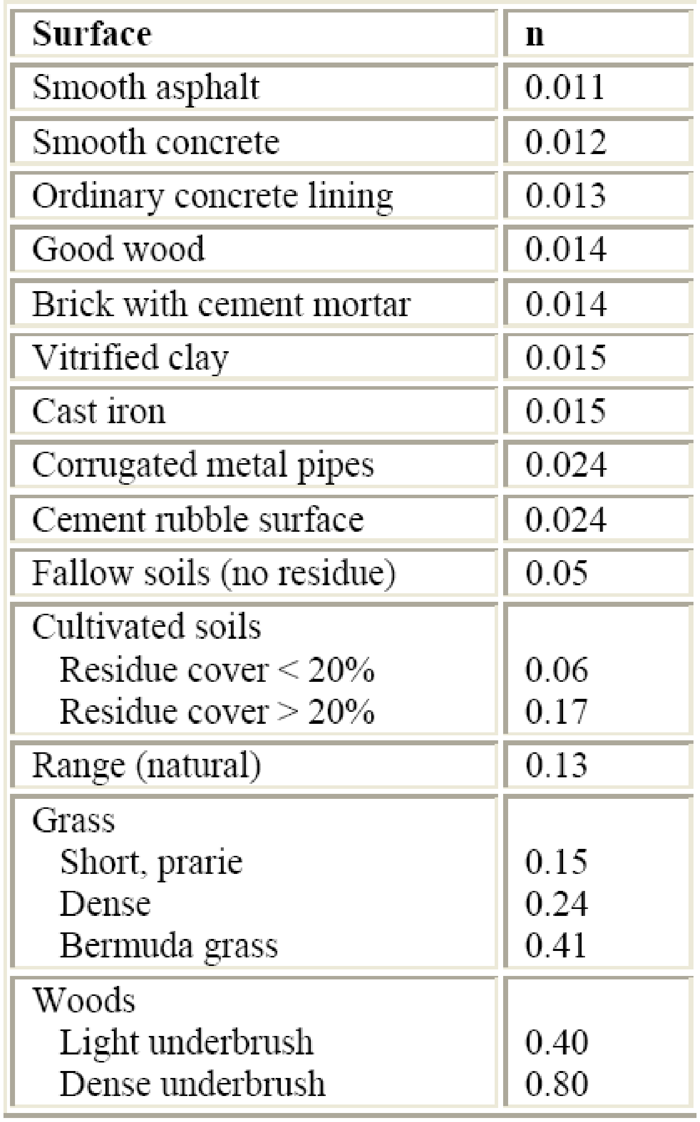
Depression Storages



Impervious surfaces	0.05 - 0.10 inches
Lawns	0.10 - 0.20 inches
Pasture	0.20 inches
Forest litter	0.30 inches

Appendix C

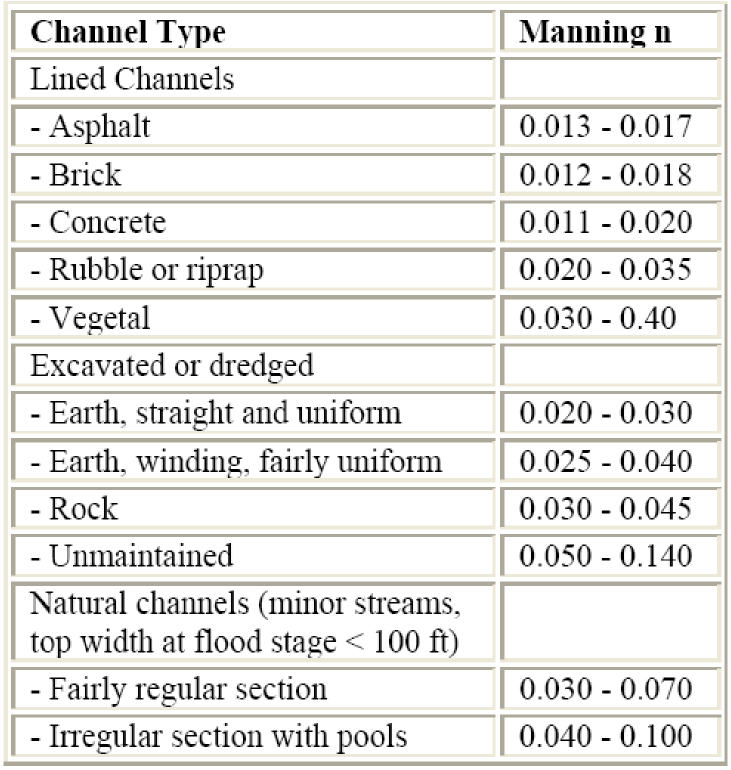
Manning’s n values



Surface	**n**
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prarie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.40
Dense underbrush	0.80

Appendix D

Roughness coefficients



Channel Type	Manning n
Lined Channels	
- Asphalt	0.013 - 0.017
- Brick	0.012 - 0.018
- Concrete	0.011 - 0.020
- Rubble or riprap	0.020 - 0.035
- Vegetal	0.030 - 0.40
Excavated or dredged	
- Earth, straight and uniform	0.020 - 0.030
- Earth, winding, fairly uniform	0.025 - 0.040
- Rock	0.030 - 0.045
- Unmaintained	0.050 - 0.140
Natural channels (minor streams, top width at flood stage < 100 ft)	
- Fairly regular section	0.030 - 0.070
- Irregular section with pools	0.040 - 0.100

Appendix E

Project Summary

```
EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.013)
  --------------------------------------------------------------

  Little Crum Creek Watershed

  ****************
  Analysis Options
  ****************
  Flow Units ............... CFS
  Infiltration Method ...... GREEN_AMPT
  Flow Routing Method ...... KINWAVE
  Starting Date ............ JUL-14-2008 01:00:00
  Ending Date .............. JUL-14-2008 16:00:00
  Antecedent Dry Days ...... 5.0
  Report Time Step ......... 00:30:00
  Wet Time Step ............ 00:30:00
  Dry Time Step ............ 00:30:00
  Routing Time Step ........ 60.00 sec


  **************************        Volume         Depth
  Runoff Quantity Continuity     acre-feet        inches
  **************************     ---------       -------
```

```
Total Precipitation ......       38.342         0.215
Evaporation Loss .........        0.000         0.000
Infiltration Loss ........       26.113         0.146
Surface Runoff ...........       11.725         0.066
Final Surface Storage ....        0.744         0.004
Continuity Error (%) .....       -0.629


**************************           TSS
Runoff Quality Continuity            lbs
**************************    ----------
Initial Buildup ..........      5411.039
Surface Buildup ..........       194.804
Wet Deposition ...........         0.000
Sweeping Removal .........         0.000
Infiltration Loss ........         0.000
BMP Removal ..............         0.000
Surface Runoff ...........      2080.081
Remaining Buildup ........      3511.801
Continuity Error (%) .....         0.249


**************************        Volume         Volume
Flow Routing Continuity        acre-feet       Mgallons
**************************     ---------      ---------
Dry Weather Inflow .......         0.000          0.000
Wet Weather Inflow .......        11.708          3.815
Groundwater Inflow .......         0.000          0.000
RDII Inflow ..............         0.000          0.000
External Inflow ..........         0.000          0.000
External Outflow .........        11.253          3.667
Internal Outflow .........         0.000          0.000
Evaporation Loss .........         0.000          0.000
Initial Stored Volume ....         0.000          0.000
Final Stored Volume ......         0.638          0.208
Continuity Error (%) .....        -1.562


**************************           TSS
Quality Routing Continuity           lbs
**************************    ----------
Dry Weather Inflow .......         0.000
Wet Weather Inflow .......      2077.002
Groundwater Inflow .......         0.000
RDII Inflow ..............         0.000
External Inflow ..........         0.000
Internal Flooding ........         0.000
External Outflow .........      1968.262
Mass Reacted .............         0.000
Initial Stored Mass ......         0.000
Final Stored Mass ........        89.335
Continuity Error (%) .....         0.934


*********************************
Highest Flow Instability Indexes
*********************************
Link 7 (1)


*************************
Routing Time Step Summary
*************************
Minimum Time Step           :    60.00 sec
Average Time Step           :    60.00 sec
Maximum Time Step           :    60.00 sec
Percent in Steady State     :     0.00
Average Iterations per Step :     1.18
```

```
***************************
Subcatchment Runoff Summary
***************************

------------------------------------------------------------------------------------------
                  Total    Total    Total    Total    Total     Total     Peak  Runoff
                 Precip    Runon     Evap    Infil   Runoff    Runoff   Runoff   Coeff
Subcatchment         in       in       in       in       in      Mgal      CFS
------------------------------------------------------------------------------------------
1                 0.215    0.000    0.000    0.153    0.060     0.580    9.922   0.281
2                 0.215    0.000    0.000    0.153    0.060     0.297    5.086   0.281
3                 0.215    0.000    0.000    0.153    0.060     0.477    7.854   0.278
7                 0.215    0.000    0.000    0.137    0.073     0.826   11.983   0.340
5                 0.215    0.000    0.000    0.153    0.061     0.411    7.151   0.284
6                 0.215    0.000    0.000    0.150    0.063     0.428    7.228   0.295
4                 0.215    0.000    0.000    0.137    0.074     0.802   12.348   0.344
------------------------------------------------------------------------------------------
System            0.215    0.000    0.000    0.146    0.066     3.821   61.571   0.306


****************************
Subcatchment Washoff Summary
****************************

---------------------------------
                      TSS
Subcatchment          lbs
---------------------------------
1                 303.632
2                 157.457
3                 257.556
7                 458.581
5                 219.403
6                 240.155
4                 443.296
---------------------------------
System           2080.081


******************
Node Depth Summary
******************

--------------------------------------------------------------------
                      Average  Maximum  Maximum  Time of Max
                        Depth    Depth      HGL   Occurrence
Node             Type    Feet     Feet     Feet  days hr:min
--------------------------------------------------------------------
9            JUNCTION    0.13     0.53    95.53     0  06:30
10           JUNCTION    0.25     0.96    67.96     0  06:32
21           JUNCTION    0.26     0.93    49.93     0  06:48
22           JUNCTION    3.45     4.50    13.50     0  03:31


*******************
Node InFlow Summary
*******************

-------------------------------------------------------------------------------
                      Maximum  Maximum                 Lateral      Total
                      Lateral    Total  Time of Max     Inflow     Inflow
                       Inflow   Inflow   Occurrence     Volume     Volume
Node             Type     CFS      CFS  days hr:min       Mgal       Mgal
-------------------------------------------------------------------------------
9            JUNCTION   15.01    15.01     0  06:30      0.877      0.877
10           JUNCTION   20.20    33.02     0  06:32      1.276      2.147
21           JUNCTION   14.38    42.56     0  06:42      0.839      2.957
22           JUNCTION   11.98    43.70     0  07:13      0.823      3.667
```

```
**********************
Node Surcharge Summary
**********************

Surcharging occurs when water rises above the top of the highest conduit.
---------------------------------------------------------------------
                                  Max. Height   Min. Depth
                      Hours       Above Crown    Below Rim
Node         Type    Surcharged         Feet         Feet
---------------------------------------------------------------------
22           JUNCTION       11.52        0.000        0.000


*********************
Node Flooding Summary
*********************

Flooding refers to all water that overflows a node, whether it ponds or not.
------------------------------------------------------------------------
                                              Total   Maximum
                         Maximum   Time of Max    Flood    Ponded
               Hours       Rate    Occurrence   Volume    Volume
Node          Flooded       CFS   days hr:min     Mgal   acre-in
------------------------------------------------------------------------
22              11.52      0.00      0  00:00    0.000      0.00


********************
Link Flow Summary
********************

-----------------------------------------------------------------------------
                         Maximum  Time of Max   Maximum    Max/    Max/
                            Flow   Occurrence  Velocity    Full    Full
Link          Type          CFS  days hr:min    ft/sec    Flow   Depth
-----------------------------------------------------------------------------
1             CONDUIT     14.35      0  06:41      2.44    0.07    0.20
6             CONDUIT     31.68      0  06:48      2.83    0.19    0.36
7             CONDUIT     36.66      0  07:16      2.80    0.05    0.17


*************************
Conduit Surcharge Summary
*************************

No conduits were surcharged.


Analysis begun on:  Wed Apr 15 20:48:04 2009
Analysis ended on:  Wed Apr 15 20:48:05 2009
Total elapsed time: 00:00:01
```