URBAN HYDROLOGY MODELING WITH EPA'S STORMWATER MANAGEMENT MODEL (SWMM) AND ANALYSIS OF WATER QUALITY IN A NEWLY CONSTRUCTED STORMWATER WETLAND

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ABSTRACT

URBAN HYDROLOGY MODELING WITH EPA'S STORMWATER MANAGEMENT MODEL (SWMM) AND ANALYSIS OF WATER QUALITY IN A NEWLY CONSTRUCTED STORMWATER WETLAND

The Clean Water Act (CWA) enacted in 1972 has shaped the engineering world on ways to ensure that the laws protect the waters of the United States. In 1987, the CWA Section 319 Nonpoint Source Management Program was established. Constructed stormwater wetlands (CSWs) have gained their popularity over the years due to the realization of the natural cleansing processes that natural wetlands provide to aquatic ecosystems. The processes performed by a CSW treat the water by chemical transformation, filtration and chemical precipitation between the water and substrate, and settling of suspended particulate to mention a few.

Initial watershed dynamics were investigated by the creation of an urban hydrology model using Environmental Protection Agency's Stormwater Management Model (SWMM). The creation of this in-depth model allows the predictions of future storm events and also the sizing and design of future stormwater control measures. The model is highly sophisticated and equally depends on all of the variable parameters that need to be input. Full sensitivity analyses for both a simplified single subcatchment and the multiple subcatchment Villanova University watersheds were performed showing this high sophistication. Data from this model was then used to fill in gaps with older data that had flow instrumentation error at the CSW on Villanova University's campus.

Villanova University has recently retrofitted an existing CSW in order to see how an extended flow path and larger treatment area would affect water quality. The wetland system in its initial juvenile maturity and little vegetation provided no apparent trends in water quality improvement or degradation. Both storm and baseflow events were sampled throughout the first few months of its life where nutrients, chlorides, and solids were analyzed at locations throughout the wetland system. In accordance to Pennsylvania Department of Environmental Protection, the system discharged acceptable concentrations of pollutants for a majority of sampling events. For baseflow events, total suspended solids and chlorides had 0% exceedance and total dissolved solids had 30% exceedance. Nitrogen speciation was analyzed and no consistent patterns for baseflow samplings were observed, however, during a warmer temperature day there was obvious denitrification from inlet to outlet. Storm samples all showed the *first flush* phenomenon with high concentration during the beginning of the storms for all pollutants followed by a rapid decline in concentration.

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Chapter 1 : Introduction

1.1 Introduction

The Clean Water Act (CWA) enacted in 1972 has shaped the engineering world on ways to ensure that the laws protect the waters of the United States. In 1987, the CWA Section 319 Nonpoint Source Management Program was established. Part of this amendment identified navigable waterways that are in need of assistance and improvement of their water qualities. In this respect, watershed managers of these waterways have become stricter in the effluent water qualities from urban areas. (EPA CWA Section 319, 1987) Section 319 not only regulates, but assists in the transfer of technology and education concerning stormwater management on a national level.

> "The objective of the Federal Water Pollution Control Act, commonly referred to as the Clean Water Act (CWA), is to restore and maintain the chemical, physical, and biological integrity of the nation's waters by preventing point and nonpoint pollution sources, providing assistance to publicly owned treatment works for the improvement of wastewater treatment, and maintaining the integrity of wetlands."
>
> - EPA Clean Water Act Mission Statement

Stream degradation over past decades has been directly correlated with increased urbanization of watersheds that release into these local streams and other surface waters. Since the creation of the CWA, the National Pollutant Discharge Elimination System (NPDES) has been used to regulate the quality of the nation's waters (National Research Council, 2008). In attempts to mitigate the amount of downstream degradation, local municipalities and governments have implemented regulatory requirements of Best Management Practices (BMPs). A BMP can be structural or non-structural (i.e. education, regulation) in nature and is mandated, regulated, and enforced by their geographically respective agencies. Structural stormwater BMPs, which are now known as Stormwater Control Measures (SCMs) for a more clarified identification, include rain gardens (bio-retention or bio-infiltration), detention basins, infiltration trenches, constructed stormwater wetlands, etc. All of these SCMs use common theory of hydrology and hydraulics to slow and reduce peak flow runoff as well as improve the runoff quality before it reaches local waterways.

Constructed stormwater wetlands (CSWs) have gained their popularity over the years due to the realization of the natural cleansing processes that natural wetlands provide to aquatic ecosystems. According to the Handbook of Constructed Wetlands Volume I (1995) released by the Environmental Protection Agency, a CSW only needs water, a good soil substrate, and vascular plants to perform all the processes that allow for improved effluent water quality. The processes performed by a CSW treat the water by chemical transformation, filtration and chemical precipitation between the water and substrate, and settling of suspended particulate matter to mention a few. (EPA, 1995) Constructed Wetlands are not just used for the treatment of stormwater, but are also used in agricultural wastewater, domestic wastewater, and coal mine drainage for the same purposes.

With the growing emphasis on stormwater control, Villanova University has a number of SCMs around its campus and has been involved in numerous projects in Southeastern Pennsylvania, particularly the Greater Philadelphia area. Villanova University has a CSW which is an active research site for the Villanova Urban Stormwater Partnership; it has been supported by both the Environmental Protection Agency and the Pennsylvania Department of Environmental Protection through the 319 Non-Point Source, Growing Greener and Coastal Zone Management programs. The CSW and its watershed is the focus of the research presented.

1.2 Site history

Prior to 1999, the Villanova CSW site was a stormwater detention basin (Figure 1-1). The detention basin was about one acre in size and the locations of its boundaries were not altered to convert it to a CSW 1.0 (first designed stormwater wetland). A 12 inch underdrain was originally in place from inlet to outlet to allow the site to remain dry during baseflow events and have ponding during storm events.

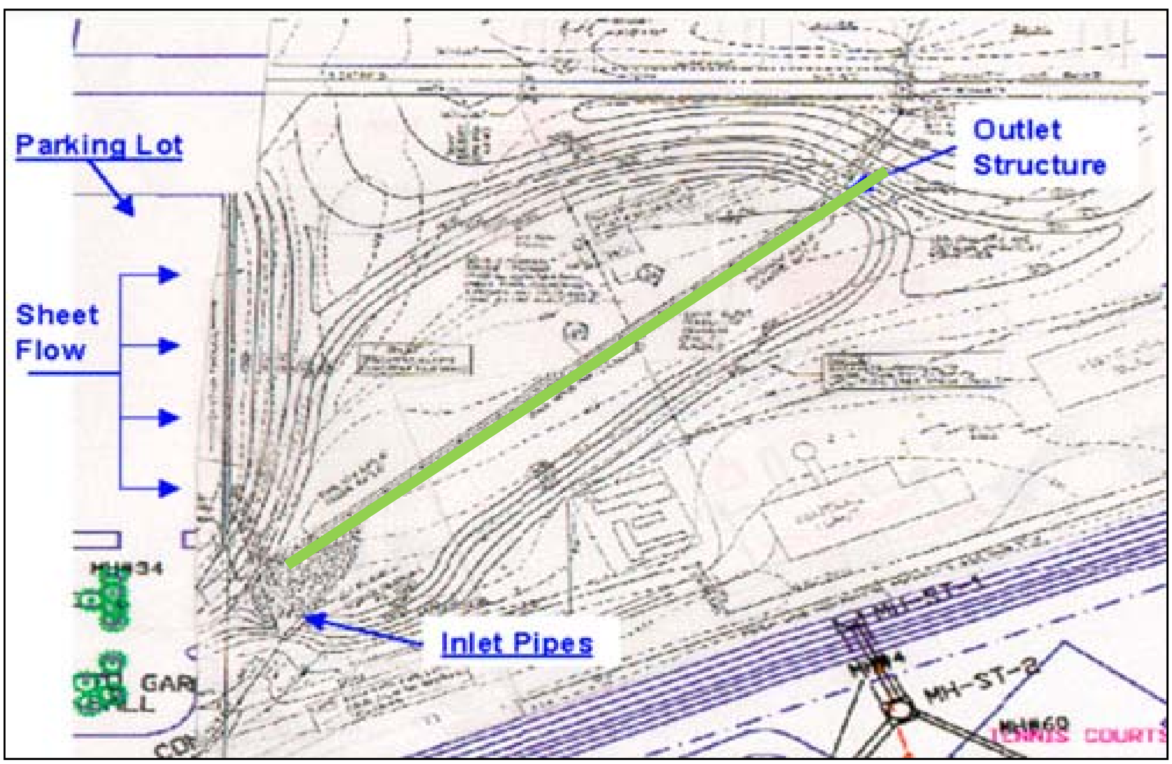


Figure 1-1 The original detention basin design

At the inlet structure, there is a headwall that allows flows to enter the SCM from two distinct geographical areas of Villanova University's campus: Main Campus and West Campus. The two inlet pipes are smooth concrete with Main and West Campus having pipe diameters of 36 inches and 48 inches, respectively. The total watershed area is 42.6 acres with 63% of this area being impervious surfaces. This percentage has been different in the past due to surveying techniques as well as averaging of land cover characteristics. With the improvement of satellite imagery land use can be viewed remotely.

After the realization that different SCMs can properly manage a range of high and low flow events, it was determined in 1999 that a dynamic retrofit of the detention basin would allow further research in stormwater management. A CSW was determined to be the most appropriate and feasible SCM to construct at this site. The design of the retrofit was done using the Pennsylvania Handbook of Best Management Practices for Developing Areas (Pennsylvania Association of Conservation Districts, 1998). The design of the system incorporated a unidirectional linear channel that ran through the first half of the CSW immediately after the headwall. The reason that the design did not incorporate an in-depth design of the first half of the wetland was attributed to possible campus expansion. This flow was then directed to the sediment forebay which allowed a longer detention time during baseflow and small storm events. The sediment forebay was a 40 feet by 40 feet concrete pad with a water depth of 4 feet which allowed for sediments within the water column to settle out during its residence in the structure. Post sediment forebay, the flow was navigated through a series of three meanders (Figure 1-2). These meanders were created using gabion baskets and earthen material to create the earthen berms that directed the flow utilizing most of the available area of the lower portion of the CSW.

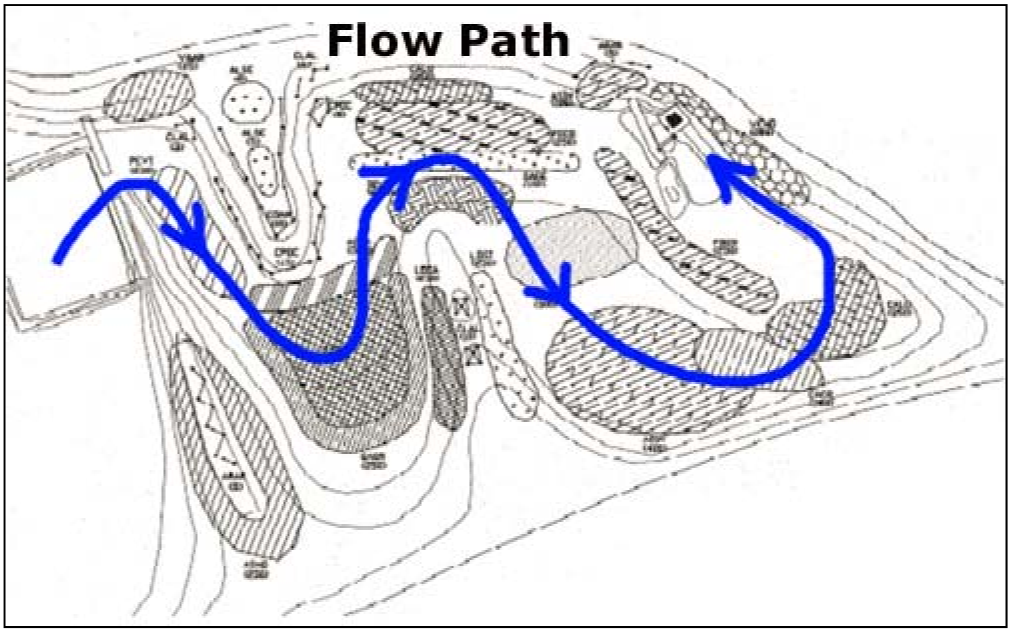


Figure 1-2 Previous CSW flow path

The outlet structure contains a multiple weir structure (V-notch weir, T weir, two rectangular weirs and a grate on top of the structure). From the inlet structure to the outlet structure was 8.2 feet elevation drop. The design also used gabion baskets to guard the structure and a vertically adjustable wooden weir to hold back low flow events as well as baseflow. Storm events up to the 100 year storm are successfully handled by the outlet structure, which has remained unchanged. This design allowed the CSW to remain saturated with different levels of water in the system. Different native species were placed in the CSW that could thrive in different water levels ranging from drought to flood conditions. The overall design allowed for different inundation of the soils to promote certain species to grow better than others.

1.3 Currently

Beginning in July of 2010, the reconstruction on the CSW began (CSW 2.0). Past research performed at Villanova University showed that if the flow path of the meanders were lengthened, better water quality as well as reduced flow rates would prevail (Jones, 2009). Since the creation of the first CSW, the Villanova School of Law was constructed directly next to the system. This negated the idea of campus future expansion taking over parts of the CSWs therefore allowing the design to incorporate the entire area within the site's boundaries. The flow path has since been extended to now incorporate the entire 0.78 acres with three meanders. At each meander, adjustable sluice gates were also installed. These structures allow different levels of pooling to exist and quantification of water quantity and quality improvement.

In addition to the extended flow path, the sediment forebay was relocated to a location closer to the inlet structure and expanded in size (Figure 1-3). Low flow events fill the larger sediment forebay and follow the channelized course to reach the meanders, however the larger events fill the entire forebay of the CSW short circuiting the first meander and entering in the meander prior to the second sluice gate.

The flow channel in the system was also redesigned to incorporate a stepped design (3 steps) across the cross-section that allows for plant life that requires different amounts of water to exist in specific locations in the channel.

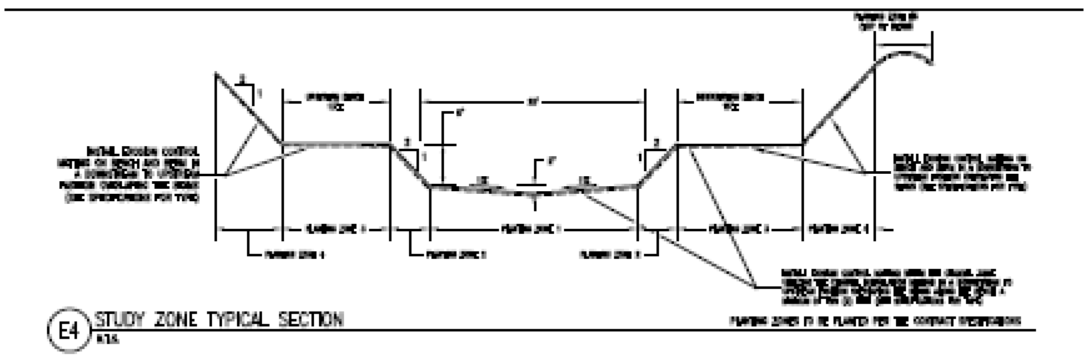


Figure 1-3 Cross sectional view of the wetland channels

This design allows for different inundation levels and limits the growth of the planted species to specific locations. Initially the CSW had a high velocity geotextile in place over the berms for erosion control until the vegetation becomes established that biodegrades over time and allow the soil to compact. With the geotextile, grass seed was planted to assist in the stabilization of the soil. There was and will continue to be chemical and physical control to rid the area of the invasive species, *Phragmites australis*, which had previously taken over the entire wetland area. The goal is to permanently remove the invasive species from the area. The CSW was planted with herbaceous and woody native plants in March 2011. Before the planting and a mature vegetative state, the site had multiple erosion control measures (ECMs). The geotextile acts as an ECM, but also there is a filter bag at the outlet for collecting any sediment that may still leave the site. This filter bag stayed on site until grass vegetation grew in.

Figure 1-4 New sediment forebay with water at baseflow (circled in red). The first meander is to the left in the picture, and the second meander to the right.

1.4 Plan of study

Throughout this study, there are two scopes of work. The first is to create a continuous simulation model that will allow accurate prediction of future storm event flows and volumes entering the CSW from the two distinct geographic locations on Villanova University's campus (i.e. Inlet Main and Inlet West). In addition, validation of past inflow data recorded for the system will be performed. The Environmental Protection Agency's Stormwater Management Model (SWMM) will be used to meet this first goal due to its ease of access and supreme popularity among hydrologists.

The second scope of work will be the more complex of the two. Since the newly constructed wetland has no planting and also a high velocity geotextile, the system can be treated as an open channel. The system will be analyzed with both no plant life and after planting is done to see if plants within the system add to water quality and quantity improvements or if it just adds aesthetics to the system. Both water quality and quantity data will be used to achieve this goal. This is discussed to more extent in Chapter 5 with in-depth procedures given in Appendix A in the Quality Assurance Project Plan (QAPP) for water quality.

Chapter 2 : Literature Review

2.1 Introduction

In this chapter, a discussion of research pertinent to the present study is given. Different methodology and modeling systems are compared to give the reader an understanding of the different platforms that are available for watershed managers. Water quality studies are also reviewed for information on pollutants that are found in the Villanova University Constructed Stormwater Wetland and its respective watershed. Finally, stream degradation is discussed along with restoration projects; future research will analyze the CSW 2.0 through its maturing to relate natural stream degradation.

2.2 Background

Watershed management took its strong hold after 1972 with the passing of the Clean Water Act by the United States Congress. This Act clearly stated its purpose is “to restore and maintain the chemical, physical, and biological integrity of the Nation's waters” (U.S. Supreme Court, 2006). Initially, the Act focused its main efforts of controlling point sources; “end of pipe” management (Goonetlleke *et al.*, 2005). Recently the management of U.S. watersheds has adapted the revision of the latest amendment, the National Pollutant Discharge Elimination System (NPDES); this is the latest legislation that requires permitting and specific pollutant reductions from point and nonpoint sources that discharge directly to surface waters (i.e. facilities, municipalities, industry) (U.S. EPA, 2009). The NPDES helped to permit the requirements of water quality leaving watersheds that eventually release into the countries lakes, streams, and rivers.

In addition to water quality, stormwater management plans typically specify peak flow control for one or more discrete events. Regulations for both quality and quantity are regulated at the point of discharge; previously mentioned “end of pipe”. Peak flow control, maintaining times of concentration, groundwater recharge, runoff volume, and flow duration control are all of interest for water resource planning. (Palhegyi, 2010)

2.3 Watershed Modeling with Geographic Information Systems

Growing emphasis from governing agencies on peak flow reduction and water quality improvement have led to the wide use of surface water hydrology models for the design of engineered control measures within a watershed. One of the most widely used watershed data processors with hydrologic add-ons is known as Geographic Information Systems (GIS). (DeVantier *et al.*, 1993) These immense computer software programs allow different data layers to be merged to create a detailed physical model of a geographic area. Inventory performed by Singh *et al.* (2000) proved that the best models for watershed planners to use take into consideration all aspects of the hydrologic cycle, but with emphasis on surface water hydrology. With the use of GIS models, such as HEC-GeoHMS released from the Army Corps of Engineers, surface water hydrology has been modeled with ease in watersheds around the country and the world. The benefit of using GIS models is that many different sub-models, such as environmental/ecological, water quality, ground water, and coastal processes, can be incorporated into one detailed model. Some of the surface water hydrology GIS models, however, cannot incorporate storm sewer networks as part of the system (e.g. HEC-GeoHMS).

The different types of data layers that can be brought in to a GIS model for manipulation range from topography to topology. Topography incorporates the use of elevations and land features to create drainage paths. The topology of the site incorporates different hydrologic parameters such as soil type and land cover. With the combination of these parameters, analysis of a watershed can be done that incorporates flooding, as well as transportation of different pollutants through mechanisms such as overland flow. (DeVantier *et al.*, 1993) A majority of modeling projects gather these data layers from highly sophisticated satellite imagery sources, however, the spatial resolution can sometimes be incorrect and cause inappropriate identification of topography and topology attributes (Savary *et al*., 2009).

2.3.1 GIS Flow Path Data

Within the discipline of GIS hydrologic modeling, there are three different ways to represent flow path data. Raster/Grid data uses evenly spaced grids that compiles and averages all necessary information into a single point that is in the geometric center of the respective square. The raster/grid method is often used in creating digital elevation models (DEMs), which was the first GIS method for watershed modeling. (Pentland and Cuthbert, 1971) The end result of the raster/grid method is the creation of the raster image with all pertinent flow path information that can be used in a GIS programs such as ArcHYDRO. Small scale modeling projects (i.e. a few acres in size) have employed laser scanners using triangulation to measure surface elevation for creation of the DEM (Dermisis and Papanicolaou, 2009). According to the Center for Research in Water Resources at University of Texas at Austin, the raster/grid approach is the most commonly used flow path method and is the basis behind the add-on tool, ArcHYDRO within the ArcGIS software (www.hydroeurope.org).

Contour lines are also commonly used for modeling of flow paths. The contour method creates vectors perpendicular to the contour lines of similar elevation; vectors connected in series are named the flow path. The vector flow path can also be referred to as digital line graphs (DLG) (DeVantier *et al.*, 1992). The contour method uses computer procedures to perform basic geographic principles.

Triangular Irregular Networks (TIN) is the third method for determining flow path in GIS software. The TIN method incorporates computational methods to take different elevation points and minimize angles of triangles that connect three points. The minimized connecting angle in turn creates the flow path that would form in the valley of two crests. Creation of TINs is also known as Delauney triangulation. In a summary report done by Moore *et al.* (2005), officials reviewed the use of TIN methodology for hydrologic model in watershed planning. Researchers used digital elevation data gathered by digital photogrammetric procedures to determine flow paths for 30 different watersheds in Fairfax County, Virginia using the TIN method. Once the TIN dataset was created, it was possible to export the data for creation of cross-sectional evaluation in hydraulic modeling software (e.g. HEC-RAS).

Use of each of the flow path methodologies requires different conditions. When performing a model using the raster/grid approach, a large memory is required due to the procedure condensing large amounts of spatially dependent data into one concise point. One of the common problems that exists with the use of the raster/grid method is that scaling and adjustment of elevation between each cell can be user varied, however it can be varied incorrectly causing terrain features to be terminated (DeVantier *et al.*, 1992). The TIN method is algorithm based and is commercially available for any user.

2.4 SWMM Modeling

Watershed planners and developers over the past few decades have tried to examine the use of simple models over those that take much time and manpower to create. One of the most in-depth yet simplistic models was created by the United States Environmental Protection Agency (EPA) in 1969-71; the Storm Water Management Model (SWMM). The original purpose of SWMM was to ease the analysis and design of combined sewer systems. (Huber, 2003) Since SWMMs creation, many additions to the platform have allowed for continuous simulation, statistical analysis of input/output time series, metrication, snowmelt, subsurface flow, and best management practices (Huber, 2003). With the many users of SWMM worldwide, third party companies have since created pre/post processors that provide easy to use Graphical User Interfaces (GUIs) (e.g. PCSWMM, XPSWMM, etc.)

The application of SWMM has ranged from waste water treatment facilities to watershed modeling and design. Heier *et al*. (2005) describes SWMM as "comprehensive and time consuming due to the different inputs that exist within its core, but still user friendly". One of the most beneficial components of SWMM is that both single events and continuous simulations can be performed and analyzed (Heier *et al*., 2005). Further, SWMM has become popular in the modeling world due to its capabilities in incorporating infiltration, snow cover, parameter of evaporation and urban drainage features. (Huber, 2003) The SWMM output can easily be manipulated in other software, such as Microsoft Excel.

While impervious cover reduction becoming a large part in urban planning, watershed managers are looking to computer modeling software that can simulate different ranges of urbanization. Davis *et al*. (2006) performed a catchment modification study using SWMM 4.4 to see the affects of altering catchment percent impervious cover, slope, width, and infiltration on stormwater runoff. Rainfall data was simulated for 50 years to limit error caused by extremely dry or wet years. Out of all of the afore-mentioned parameters, the percent impervious cover change showed the greatest runoff response. The other respective parameters only affected larger, less frequent storm runoff events and not the small, frequent events. (Davis *et al*., 2006) Overall, the increase in percent imperviousness caused the flow frequency curves to have: 1) an upward shift, 2) a "smoothing out" of the curve, 3) a decrease in space between curves, and 4) a decrease in curve slope. (Davis *et al*., 2006) These results can be found in Figure 2-1.

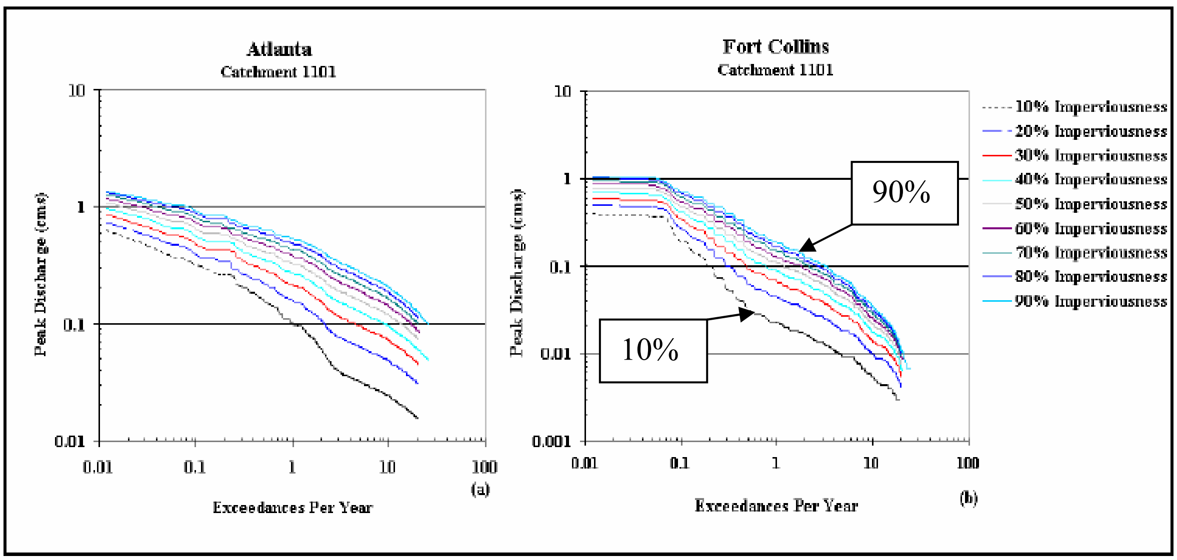


Figure 2-1 Effects of increasing percent imperviousness of subcatchments on flow frequency curves (Davis *et al.*, 2006)

When calibrating a SWMM model or any other hydrologic model, it must be made sure that enough data is generated. Gaging data of an adequate period and temporal density and/or the use of long-term continuous simulations are essential to adequately elucidate changes in the full range of geomorphically important flows produced (Bledsoe, 2004).

2.5 Model costs and Selection

Although certain models can be expensive, there are many non-propriety models freely or available at low cost. According to Moore *et al.* (2005), watershed managers should focus their modeling efforts on using GIS based systems due to most municipalities holding many years of geographical data. Integration of a watershed model should easily integrate with management firm's existing software, most often GIS systems (Borah and Weist, 2008). A review of different models containing data such as soil type and land use was performed. The overall goal of each of the models were to assist watershed planners and officials to limit the pollution and degradation of downstream water resources and bring a number of streams to meet the CWA Section 303(d) regulations on water quality. (DeVantier *et al.*, 1992)

Model selection should be based on not only cost but benefit received with ease. Borah and Weist (2008) studied a total of twenty-one stormwater management models and four matrices: 1) model summaries, 2) model complexities, 3) relative accuracies, and 4) ease of model. The overall study analyzed these models for cost-benefits, model diversities, accuracies or uncertainties against details, sharing models with other entities, operation and maintenance using internal staff or consultants, and effective communication with stakeholders. Analysis was for both end-users and water resources managers to make responsible and appropriate model selection. (Borah and Weist, 2008)

2.6 Direct Runoff Calculation

Within different hydrologic modeling programs, direct runoff can be calculated by one of three methods. The three methods that are commonly used for direct runoff are: Curve Number, Green-Ampt, and Horton.

2.6.1 Curve Number

The United States Soil Conservation Service (SCS), now known as the National Resource Conservation Service (NRCS), developed the Curve Number (CN) method with the onset of the Small Watershed and Flood Control Act of 1954 (Eli and Lamont, 2010). The direct runoff flow through the CN method is based on precipitation depth, initial abstractions from the system and the maximum potential retention. The CN is found based upon available storage determined by watershed conditions, land use, and cover density of the study area to produce values that range from 30-100 (Eli and Lamont, 2010, Rietz and Hawkins, 2000). A higher CN value indicates there is little storage in the catchment whereas a smaller CN value means there is substantial storage in the catchment. Rietz and Hawkins (2000) studied the use of CN and land use on three different spatial scales (i.e. local, regional, national) and concluded that there was more variation of CN for smaller spatial scales (higher geographic definition) than that done over a larger region when analyzing land use. Using Analysis of Variance (ANOVA), 95% of small scaled watersheds showed significant difference in their CN based on land use and 50% of regional scaled areas showed to be affected by the land use. (Rietz and Hawkins, 2000)

2.6.2 Infiltration Methods

Two other methods in calculating the direct runoff from a watershed are the Green-Ampt and Horton’s infiltration methods. The infiltration methods, particularly the Green-Ampt method uses soil properties such as unsaturated hydraulic conductivity, capillary pressure head, and moisture content as a function of time. (Eli and Lamont, 2010) The Green-Ampt model is based on Darcy's law of continuous groundwater flow. The Horton method for infiltration is a three parameter model and incorporates the minimum/maximum infiltration capacity, time, and a decay coefficient which are watershed specific. The Green-Ampt method is more commonly used because it is physically based and there being not as much guessing involved in parameter selection. (Davis *et al.*, 2006)

2.6.3 Runoff Calculation Comparison

Eli and Lamont (2010) used SWMM to compare the CN method and Green-Ampt method on a golf course (pre-development) and a housing development (post-development) for modeled runoff. The CN runoff calculation ranged from 61% to 80% of the Green-Ampt runoff calculation indicating that the Green-Ampt method tends to overestimate direct runoff. However, Eli and Lamont (2010) did state that due to the watershed being smaller in size, there may be more runoff than if the watershed was larger as was described by Rietz and Hawkins (2000).

In a study addressing the relationship between the land cover and simulated annual runoff, land cover showed a strong indication of affecting the total runoff (R-^{2}=0.97-1.00) (Savary *et al.*, 2009) Historic meteorological data (30 years) was simulated with tracking changes in land cover in a urbanizing watershed in Québec. Savary *et al.* (2009) noted that the land cover changes affected the runoff more in the drier climate years than the average climate years however; actual and simulated flow data match extremely well.

2.7 Water Quality

With population growth and urban sprawl, development within watershed boundaries has a large impact on natural water systems. As stated by Goonetilleke *et al.* (2005), urbanization within watersheds incorporates "removal of vegetation, replacement of previously pervious areas with impervious surfaces and drainage channel modifications invariably result in changes to the characteristics of the surface runoff hydrograph." That is, water quality is compromised.

Being the sole focus of the Clean Water Act, water quality focuses on phosphorus, nitrogen, total suspended solids, biochemical oxygen demand, metals, oil and grease, as well as fecal coliform that are positively correlated with development (Carle *et al.*, 2005). Examining patterns in urbanization, Carle *et al.* (2005) determined that development density affected water quality more than other individually studied "indicators" of urbanization (i.e. average household age, impervious surface cover, stormwater connectivity). Principal component analysis (PCA), a statistical reduction technique, was used to analyze patterns in the variable distributions and form a new set of linear composite variables that are products of these original distributions. GIS software was used to relate a multitude of 14 different variables as well as elevation of the watershed to come to the bold conclusion that water quality of a particular watershed is not dependent on one variable alone. (Carle *et al*., 2005)

2.7.1 Impervious Surfaces and Degradation

As defined by Chabaeva *et al.* (2009), impervious surfaces are "artificial features, such as concrete, pavement, and building rooftops that replace naturally pervious soils and prevent precipitation from infiltrating the soil." Impervious surfaces are one of the main culprits behind stream and watershed degradation both in quantity and quality aspects. Spencer *et* al. (2009) and Savary *et al*. (2009) agree that land use change and impervious surfaces can have significant impacts on hydrologic processes within a watershed system such as evapotranspiration and surface runoff routing. Palhegyi (2010) has used the term *hydromodification* to describe urbanization. Hydromodification intensifies the erosion and sediment transport process of receiving channels causing them to adjust their geometry, slope, and planform (Palhegyi, 2010).

Watershed surfaces can be either disconnected (draining to a surface with some capacity for infiltration such as bare soil, grass, lawn, or swale) or connected via a pipe or other conveyance system. (Shuster *et* al., 2008) One particular study states that runoff volumes from impervious surfaces can be as much as 16 times greater than those leaving natural areas (Thurston *et al*., 2003). Cunningham *et al*. (2009) performed a suburban stream study that showed chlorides and nitrates (Cl^- and NO_3-N) increase directly with increases in impervious cover and concluded that watersheds show impairment at 10% or less impervious cover. Li and Fan (2010) argue that if a watershed is urbanized beyond 40% of imperviousness, it becomes impossible to return the system to pre-development flows even with the wide use of stormwater control measures. Cunningham *et al*. (2009) examined five Hudson River streams throughout the year during baseflow events. The study solidified that with varying degree of urbanization, watershed impairment was seen with even low development along the streams. Shuster *et* al. (2008) explains impervious surface typically shifts the landscape from a net infiltrative sink for rainfall to a net source of runoff. A counter point however, is that soil studies from before urbanization should be examined. Spencer *et al*. (2009) states "When lands covered by more permeable soils (soil groups A and B) are urbanized, they are prone to more drastic changes in streamflow than urbanizing an area covered by less permeable soils." With a drastic change in flow characteristics along with urbanization, it is anticipated that streams may erode or aggrade which both alter the environment (Li and Fan, 2010).

As previously described, impervious surfaces lack the ability of infiltrating therefore causing surface runoff. A downsized model study performed by Shuster *et al*. (2008), analyzed the time of concentration differences between different combinations of impervious and pervious surfaces. The overall finding of the study was that the time of initiation of runoff was significantly regulated by impervious area extent ($p<0.001$) and an interaction between antecedent soil moisture and connectivity ($p<0.001$). Researchers also found that increased moisture, as expected, reduced the infiltration and acted more like an impervious surface than drier soils. (Shuster *et al*., 2008)

The relationship between impervious surfaces and their negative effects on water quality has continuously been studied however; watershed planners and modelers continuously struggle with quantifying impervious cover throughout larger watersheds. Chabaeva *et al.* (2009), while using GIS software and different land use data sets for Connecticut, examined the processed impervious cover value using JMP Statistical software to create different coefficients to be used in the Impervious Surface Analysis Tool (ISAT) released by the National Oceanic and Atmospheric Administration (NOAA). This supplemental tool allowed for a GIS layer to be created with different resolutions for the different land use. The authors determined that the National Land Cover Data (NCLD) was usable; however data from the state government of Connecticut provided more detailed and precise mapping. Both the national and state data were compared to the actual impervious cover for specific geographical areas. A linear regression solidified that the Connecticut land use data performed the best in modeling with the R^2 being the closest to 1.0 as opposed to the national data set.

There have been studies on the use of a stormwater market to manage quality through tradeoffs of impervious surfaces. Principles have been set through an algorithm, in one particular study, to compare the cost of a BMP to control pollution leaving the impervious surface with the cost of having to pay capital for stormwater (Thurston *et al.*, 2003). "Those who build BMPs with greater detention capacity than their responsibility calls for (may) have the opportunity to sell the excess as allowances in the market" (Thurston *et al.*, 2003).

2.7.2 Particulate Matter

Runoff from urban and suburban areas often transports pollutants including nutrients, heavy metals, and pathogens to receiving surface water (Shaw *et al.*, 2010). A majority of these pollutants are transported via the adsorption to particulate matter for quicker conveyance (Shaw *et al.*, 2010). A recent study reported that the coarse fraction of sediment (>75 μm) accounts for the predominance of the total metal mass associated with dry deposition particulate matter and the predominance of particulate matter surface area (Kim *et al.*, 2010).

Many hydrological models, such as EPA SWMM, incorporate modules to analyze the buildup and wash-off of these particulates during dry periods and storm events, respectively. Shaw *et al.* (2010) analyzed the use of two different models; the single event mean concentration (EMC) model and the sophisticated buildup/wash-off (BUWO) model. The simple EMC model assumes that the buildup accumulates to an asymptotic value of maximum buildup without any wash-off while the BUWO model is continuous and considers intermittent storm events that adjust the buildup of pollutants. (Shaw *et al*., 2010) Both approaches have varying buildup values. The BUWO model uses equations and theories to simulate natural, complex processes making it the most widely used model in hydrology (Shaw *et al*., 2010).

Most literature classifies the sized pollutants as sediment, settleable, and suspended-bound metals. To verify modeled particulate loads, there are two methods in analyzing physically acquired water samples; the aliquot/subsample process (TSS) and the suspended sediment concentration method (SSC). The mass balance errors were higher for the TSS method than the SSC method since the TSS method does not use a highly representative sample (Kim *et al*., 2010).

A particular study performed in central Massachusetts analyzed the use of tradeoffs in regulating water quality. The study proved that a high correlation exists between sediment yield and mineral phosphorus as well as nitrates and does not correlate with the total runoff volume coming from a watershed. The importance lies in the fact that nitrates and phosphorus are leading causes of eutrophication in surface water. (Randhir and Tsvetkova, 2009) Watershed management focuses on these pollutants but treatment of them individually can be challenging. The correlations that Randhir and Tsvetkova (2009) found provide the conclusion that if planners and managers can improve the sediment yields through regulation, education, and BMPs, the nutrients loads will be reduced. Deletic (1998) found that for one third of storm events in Lund, Sweden releasing urban surface runoff had a distinct correlation for suspended solids and the first flush phenomenon.

The first flush theory incorporates three progressions throughout a single storm. First, an initial high pollutant concentration in runoff at the onset of the storm occurs. Then, a proceeding rapid decline in the concentration as the drainage areas is exhausted of buildup followed by a low pollutant concentration.

The first flush phenomenon is now a large part in the sizing of certain stormwater Best Management Practices. While studying wash off pollutant concentrations from a parking deck, researchers concluded that capturing the most volume will ensure the most pollutant load is captured (Batroney *et al*., 2010). Three primary philosophies for this phenomenon are: 1) at least 80% of the pollution load is transferred in the first 30% of the runoff volume, 2) pollution load is concentrated in the first 25% of the event volume, and 3) first flush is if the mass cumulative curve is higher than the runoff volume curve (Deletic, 1998). Many engineering practices have attempted to store runoff and slow the release with possible treatment of the first flush to reduce water degradation. Generally, most of the runoff water comes from smaller storms for a larger part of the United States and these engineered practices incorporate design for the smaller, more frequent storms.

2.7.3 Nitrogen and Phosphorus

Two of the leading causes to stream and water body degradation are phosphorus and nitrogen. These constituents make water unfit for drinking, recreation, industry and for aquatic life (Kwong *et al*., 2002). *Urban* runoff contributes to eutrophication of these water bodies and although phosphorus is the main limiting nutrient, nitrogen also has its precedence (Taylor *et al*., 2005). Nitrogen and Phosphorus are both common constituents of water quality degradation due to their abundance and mobility (Kwong *et al*., 2002).

Nitrogen can exist in either organic or inorganic form with inorganic nitrogen being primarily dissolved. Dissolved inorganic nitrogen compounds are ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-) which are all available for uptake by flora and fauna in aquatic systems (Taylor *et al*., 2005). Taylor *et al*. (2005), during a study in Melbourne, Australia determined that particulate organic nitrogen peaks at the start of a storm as a result of runoff, the lowest concentration during the storm event, and high total dissolved nitrogen after the storm ceases. The first flush phenomenon becomes important when addressing agricultural storm runoff (high nutrient loads); amount, intensity and timing of the first rainfall event after application are key factors in first flush concentrations (Kwong *et al*.,2002).

The direct correlations between pollution loadings and urbanization are continuously being made in academia as well as case studies. In a study comparing land uses, the annual yields of total phosphorus were twice as high in urban watersheds than agricultural watersheds near Rochester, NY (Kappel *et al*., 1986). Brezonik *et al*. (2002) found in a study of the Twin Cities metropolitan area in Minnesota the event mean concentrations for not only Total Phosphorus and Nitrogen, but soluble reactive Phosphorus, Nitrite, and Lead were higher during snowmelt runoff events than rainfall in most of the researched sites. This shows the emphasis that, although loadings are high during summer seasons, winter months can pose great threat to water bodies as well.

Governing bodies have quickly realized the need to regulate not only certain forms of Nitrogen and Phosphorus but a total pollution concentration. In 2008, the USEPA implemented a policy concerning the Total Maximum Daily Load that a water body can hold. This allows a water body to meet standards and improve in any combination of pollutants and not focus on just one constituent. (Randhir and Tsvetkova, 2009) Treatment of nitrogen pollution has been physically done using wetland systems due to their ability of denitrification at the sediment-water interface. This is where the aerobic water containing forms of nitrogen (NO_x) comes into contact with anaerobic sediment. (Taylor *et al*., 2005)

2.7.4 Stream geomorphology and restoration

Different stream types are affected differently with increasing levels of urbanization. Sand bed and low-gradient streams are more responsive to changes in discharge and sediment supply as transport capacity, grain size, and channel confinement decrease in the downstream direction. Stream degradation can be both sporadic and on-going, but researchers have determined that there are two time periods of concern: 1) the time for a system to react to a change in conditions (reaction time) and 2) the time taken for the system to attain a characteristic equilibrium state (relaxation time). (Bledsoe, 2004) Watershed characteristics such as i) climate, ii) soil type, iii) soil surface roughness, iv) cropping, and v) land management practices have been correlated to stream degradation. A positive non-linear relationship between soil erosion, rill development, applied rainfall intensity, and slope angle exists when analyzing watershed characteristics and processes. (Dermisis and Papanicolaou, 2009)

Increasing levels of stream degradation cause watershed managers to undertake stream restoration projects; otherwise known as urban stream syndrome. Project modeling and design needs to incorporate a wide range of flow regimes that not only represent historical flow but possible future stream flow. (MacBroom and Loehmann, 2008) All parts to the stream system should be considered in design; stream channel, riparian buffer, and flood plain. The stream hydrology which encompasses flow rates, durations, seasonality, sediment loads, scour, and deposition should be analyzed and assessed in its entirety. (MacBroom and Loehmann, 2008) Stream stability is the goal behind all stream restoration projects. Channel stability is loosely defined as one that does not aggrade or degrade. (Palhegyi, 2010)

2.8 Wetlands

A wetland is a naturally occurring system that has functions including water quality improvement, floodwater storage, maintaining water flow during dry periods, fish and wildlife habitats, aesthetics, and biological productivity (EPA, 2001). These functions prove that these systems are critical to the health of ecosystems around the world. The geomorphic classifications for wetlands are in-stream, riparian, isolated basins, and coastal wetlands (Mitsch *et al*., 2000). In-stream and riparian systems are both fed by stream flow and flooding streams respectively. Isolated basins are fed primarily by surface water runoff or piping networks such as a stormwater wetland and agricultural wetlands. Coastal wetlands are dependent on the tidal fluctuations and are important to off-shore ecosystem productivity. (Mitsch *et al.*, 2000)

A study performed by Schulte-Hostedde *et al*. (2007), analyzed the disappearance of natural wetlands in southwestern Ontario and attributed the disappearance to agricultural drainage. The reason behind the draining and filling of these natural systems is due to value not being clearly publicized. The Ontario government in 1992, recognizing the rapid disappearing wetlands, instituted a Wetlands Policy Statement with the intentions of “ensuring the wetlands are identified and adequately protected through land use planning and to achieve no loss of provincially significant wetlands (PSW).”

(Schulte-Hostedde *et al*., 2007) These PSWs are rated on their hydrology, biology, social, and special features they offer the surrounding environments. Mitsch *et al*. (2000) also came to the conclusion that the lack of worldwide protection of wetland systems is due to their value not being properly identified and that the conversion of wetland systems to other uses are often viewed as a social necessity that takes precedence. In Cameroon, Africa, many of the low-lying coastal wetlands have been used for sourcing of fuel, fishing, and human settlement and because of this these sites are perceived as waste lands and hazards to health (Chebo, 2009). Much of the world's rapidly growing populations view wetlands as constraints to urbanization and simply development road blocks.

Serving many advantages, wetlands have recently become more protected due to scientists understanding more about the loss of biodiversity in these systems. Around 46% of the United States endangered species are wetland-dependent. Therefore, both engineers and biologists have begun a movement of creating wetland systems, as well as rehabilitating damaged sites, in hopes for increasing the already declining biodiversity. These systems have also proven to operate the same in nutrient production. (Whigham, 1999) Most of the world's populations do not realize the wetlands importance does not depend on size. Whigham (1999) states "small isolated wetlands are often more important from the perspective of landscape hydrology and biodiversity." This crucial piece of information could decide the fate of the common, isolated wetlands found in most of the world. Mitsch *et al.* (2000) performed a large ecological economics study of wetlands and concluded that not only size but the geographic location of the system determine the function and value to society. Xie *et al*. (2010) performed a survey on how people perceive wetlands in China. "A total of 90 people whose education were relatively low were interviewed, among whom 29 only got primary school degrees, 4 junior school degrees, 17 high school degrees, and 1 college degree. The low education was correlated with a negative attitude against protection of wetlands." (Xie *et al.*, 2010)

Mayes *et al*. (2009) recognized that wetlands perform the below processes for treating effluent waters:

1) formation and settlement of metal (primarily Fe) hydroxide flocs from suspension
2) physical filtration of colloidal metal hydroxides from solution by plant shoots, roots and fibrous wetland materials
3) direct uptake of metals into roots and shoots, which is particularly effective for low residual influent Fe 'polishing' wetlands typically deployed after preliminary settlement lagoons
4) iron plaque formation on roots and rhizomes of wetland macrophytes through oxygenation of the rhizosphere
5) ion exchange and organic complexation

As previously mentioned, much of the processes are performed by the plant life as well as the biology of the system and not just the hydraulics. From a survey of wetland plants growing in extreme pH waters, *Phragmites australis* existed in 80% of treatment systems. (Mayes *et al.*, 2009)

In 1985, the United Kingdom's Water Research Centre (WRC) became interested in the use of wetlands to treat for both water quality and quantity and created the Water Authorities Association Reed Bed Treatment Systems coordinating group. This sparked the movement of widespread construction and reporting of constructed wetlands used to treat water across Europe. This treatment process became known as 'conventional technology'. (Cooper, 2009) The table below shows the growth of constructed wetland systems throughout the United Kingdom. The UK WRC created what is known as the *European Guidelines on the Design and Operation of Reed Bed Treatment Systems*, which states that these *Phragmites australis* beds remove Total Suspended Solids, reduce Biological Oxygen Demand (BOD_5), and provide improved nitrification. (Cooper, 2009)

Table 2-1 United Kingdom historical use of *Phragmites australis* beds (Cooper, 2009)

Year	Number of beds reported
1985	2
1989	24
1990	27
1996	>400
2002	628
2007	1012
Probable true Total	1200

The guidelines do enforce that routine maintenance is required and if done properly, these systems can have a life span greater than 20 years. Although much of the common knowledge is centered on the plant life primarily treating water, this knowledge is incorrect. Plant life does play a large role in treatment, but a majority occurs in the biofilm that grows on the media. (Cooper, 2009)

2.8.1 Coastal Wetlands

Most of the world's populations understand wetlands to be coastal wetlands which have been described as "areas of very internal relief which combine both aquatic and terrestrial environments in a dynamic system" (Coiacetto, 1996). Although there are other systems that experience immense changes, the coastal wetland is the most susceptible due to the above stated dynamic processes that occur. Coastal wetlands are greatly affected by climate change with changes in circulations of elements, energy flow, productivity, distribution and functions of these systems (Xie *et al.*, 2010). This being said, the spatial extent of wetlands fluctuates over time in response to surface water hydrological changes as well as groundwater levels (Coiacetto, 1996).

Coiacetto (1996) created a step matrix model that incorporates 31 different attributes concerning hydrology, material inputs and other attributes concerning societal and geographic principles. The author agrees that governing bodies need a comprehensive yet simple tool to facilitate decision making in wetland management that incorporate the complex set of parameters that wetland systems contain (Coiacetto, 1996).

2.8.2 Constructed Wetlands

As stated previously, constructed wetlands have been used in many respects such as secondary and tertiary sewage treatment, agricultural effluent treatment, urban runoff and circum neutral pH coal mine drainage (Mayes *et al.*, 2009).

Residence time is increased by using alterations of hydraulics in pond shape, flow paths, and vegetation distribution. This increase in residence time allows for pollutants and sediments to settle out of the water column allowing more improvement in quality. While studying such systems, it is common to integrate both tank reactor and plug flow reactor analysis to observe water quality improvement (Wörman and Kronnäs, 2005). The selected vegetation that exists in constructed stormwater wetlands supports the required bacteriological environment while still 'spreading water residence time' (Wörman and Kronnäs, 2005). Wörman and Kronnäs (2005) found that a multiple channel wetland possess slightly higher nitrogen reduction than a constructed wetland that contains one large pool. The design of these systems needs to provide enough detention time and buffering capacity to cope with different variations in pollutant loads (Taylor *et al.*, 2005).

Schaad *et al*. (2008) investigated the life cycle of constructed stormwater wetlands in highly urbanized areas; particularly receiving overland flow from a Midwestern, United States rail yard. Annual CSW effluent oil and grease concentrations dropped by 47% and the average total suspended solids dropped by 45% over the first four years after construction. An indication of the improved water quality was the presence of algae growth as well as snails at the outlet structure of the CSW. (Schaad *et al*., 2008) Extended basins and source control measures (e.g. downspout disconnection, stormwater gardens, constructed wetlands and infiltration trenches) are highly recommended for erosion control (Li and Fan, 2010).

Used in stormwater management, constructed wetlands have been widely employed as Stormwater Control Measures. It has been noted that the design and sizing of these systems be highly dependent on the amount of connectivity that exists in the watershed through swales, channels, and conduits. (Shuster *et al*., 2008)

Chapter 3 : Constructed Stormwater Wetland Watershed Model and Current Instrumentation

3.1 Introduction

In this chapter, the creation and setup of Villanova University's urbanized watershed model are discussed. The individual attributes and types of data input that created the hydrologic model for the constructed stormwater wetlands (CSW) are discussed (Figure 3-1).

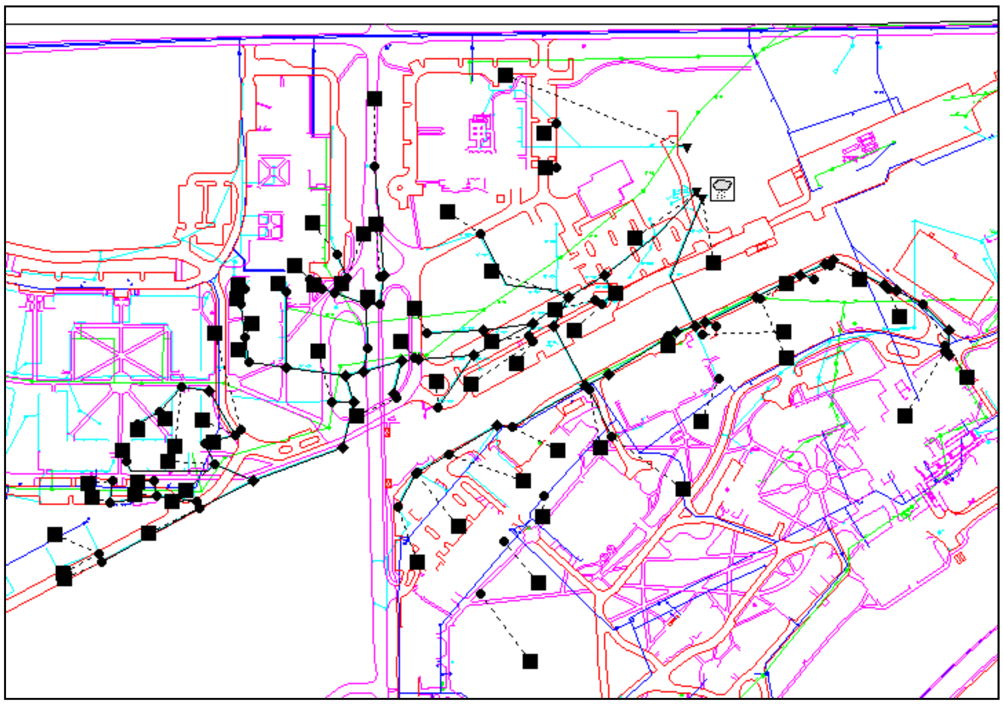


Figure 3-1 Screen print of Villanova University's hydrologic model using the Stormwater Management Model. Squares represent the centroid of each subcatchment; circles represent drainage points (storm drains), black lines represent conduit networks, triangles represent outfalls, pastel/multi-colored lines represent roads, paths, and buildings.

3.2 Stormwater Management Model

The Stormwater Management Model (SWMM) produced by the Environmental Protection Agency was selected to model the hydrology across the part of Villanova University's campus that drains to the CSW. The choice of this model over other hydrologic modeling software was due to its ability to run continuous simulations in addition to single events. Within the SWMM model itself, there are many different inputs available to make the model unique to a watershed and sets of meteorological conditions. The SWMM model has juvenile sophistication in the graphics, but it does allow the user to view a backdrop image for ease in geographic placement of different attributes to the watershed. This backdrop can be used to size attributes or the user can manually enter in the numeric values for the different attributes. In this particular model of Villanova University's CSW watershed, the backdrop image (AutoCAD drawing) was used strictly as a guide to placement of these different features and no automatic sizing functions were utilized.

3.2.1 Subcatchments

The 42.6 acre (17.2 hectare) watershed was broken into subcatchments to analyze each inlet (storm drain) to the storm sewer network (Figure 3-1). The AutoCAD backdrop image enabled easy identification of each inlet to the storm sewer network. Due to no previous model being as in-depth, the idea behind this particular watershed model was to treat each storm drain on campus as the outlet for a designated subcatchment. The subcatchments ranged in sizes from fractions of an acre to a few acres depending on storm drain location and drainage areas. Having the watershed divided into many smaller drainage areas allowed for more focus on individual features within the campus limits.

Since the backdrop image was not to size, the drainage areas could not be delineated within the SWMM program automatically. It was determined that using AutoCAD would be the best in determining the exact size of each drainage area. For the most part, the University had documents drafted with locations of all utility lines including storm drains. In AutoCAD topography layer along with the utility line layer drawing was used with the polygon function for quick delineations of subcatchments (Figure 3-2). The subcatchment tool in SWMM was used to add delineated areas and other pertinent information concerning the drainage area, such as width of overland flow found using the measuring function in AutoCAD and percent impervious cover which were determined from surveying and use of satellite imagery (Google Earth, ArcGIS). Since most of the drainage area shapes were not symmetrical, an average width of overland flow was used. Percent impervious cover was estimated using Google Earth which allowed the modeler to view the drainage area on a land use basis. All sidewalks, roofs, and roadways were assumed completely impervious.

Some of the other inputs that exist in SWMM for subcatchments are slope, depth of storage, Manning's N value, percent zero impervious, and choice of an infiltration method (Horton, Green-Ampt, Curve Number). In the initial model, these all were held constant for sensitivity analysis. Table 3-1 shows the values that were used in the initial model. The curve number values were based on land use. Chapter 4 presents comparison of model data to historical instrumentation data that helped to calibrate and verify the model.

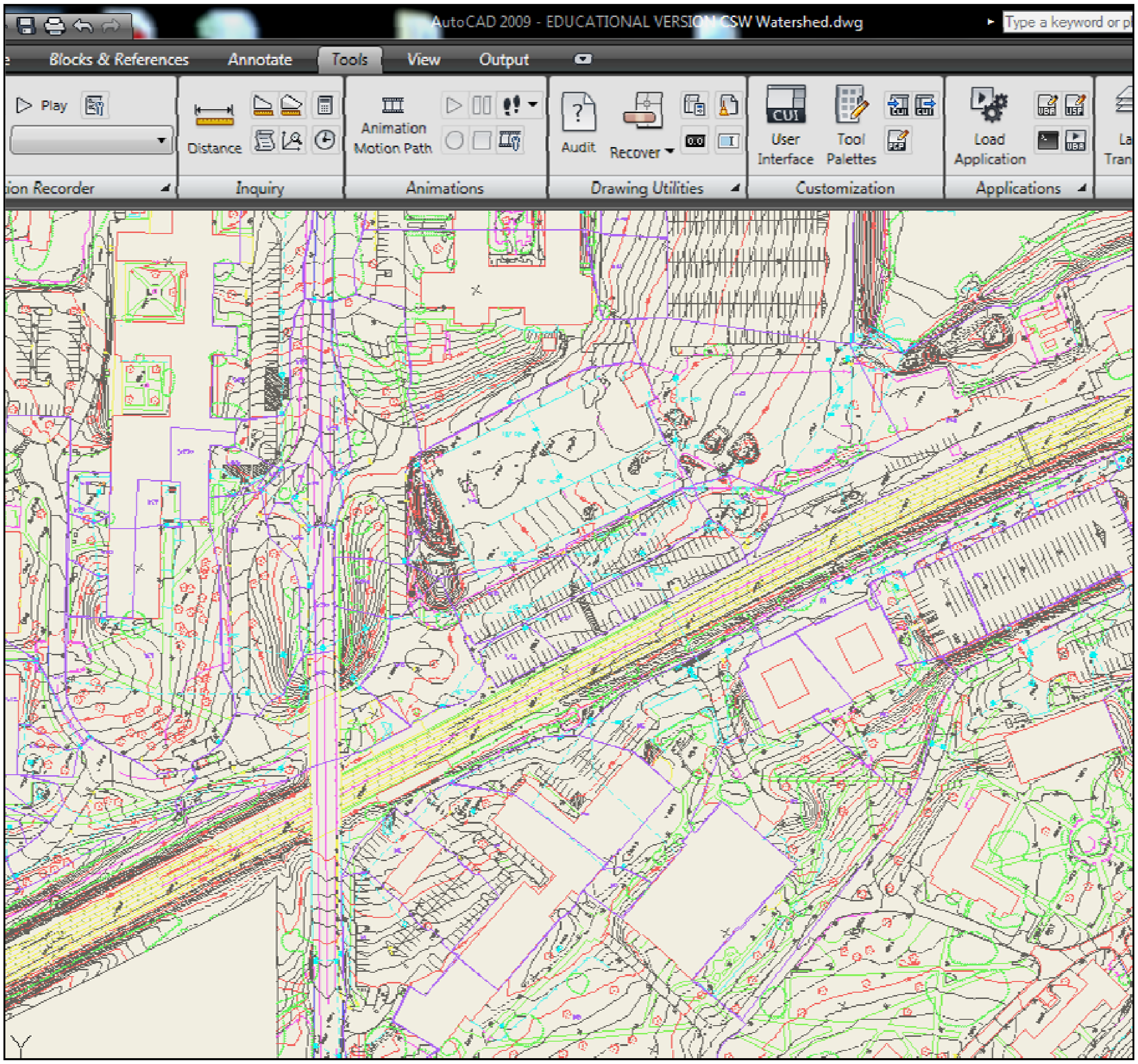


Figure 3-2 Snapshot of AutoCAD subcatchment delineations using two layers (topography and a storm drain network layer)

Table 3-1 Standard values used for the initial model

Slope	0.5%
Manning's N: Impervious Pervious	0.011 0.15
Depth of Storage : Impervious Pervious	0.0625 inches 0.25 inches
Percent Zero Impervious (%) • percent of the imperviousness with no depth storage	25
Infiltration Method	Curve Number (CN)

Once the Curve Number method was programmed, there were two variables in addition to the actual CN value that needed to be selected: drying time and soil conductivity. The drying time is the amount of time in days that a specific soil sample takes to go from completely saturated to completely unsaturated. Standard model values for drying time and soil conductivity were chosen; 4 days and 0.5 (in/hr), respectively. It is clearly stated in the SWMM model that soil conductivity "has been depreciated and its value is ignored." In this the geographical study area, the groundwater table is assumed to be deeper than the model would recognize and is therefore neglected.

3.2.2 Nodes

Within each subcatchment each storm drain needs to be represented, which is done by placing a node in the model. For the storm drain inlets a junction node is used.

The input data needed for each of the junctions was found by either survey or previously surveyed CAD drawings. One piece of information needed is the invert elevation. This is the geographical elevation of the bottom most part of the conduit pipe that enters the storm drain. If this was not given in any document, survey was done to find the distance from the road surface to the bottom of pipe and extrapolation of elevation data was done to find the approximate invert elevation. The maximum depth, which is the amount of water the node can hold without flooding, is also needed in the model. West Campus had been documented with this information in entirety however, due to the age and complexity of Main Campus, more surveying was needed. The invert elevation can be calculated by taking the road surface elevation and subtracting the maximum depth plus the vertical diameter of the pipe. Other inputs that were needed for each junction are ponded area, initial depth, and surcharge depth. For simplicity, these values for the initial model were kept at zero. For nodes, there is an additional option for water treatment for performing water quality analysis.

Most pipe networks involve intersections of multiple pipes. Within the SWMM program, it is possible to incorporate these merged pipes with a manhole, which allows for storage or just an intersection of the pipes with no storage as a divider. If the intersection does not contain storage (i.e. no manhole), no data is required except for the elevation of the invert. The same information is needed for dividers as for junction nodes (initial depth, surcharge depth, ponded area, etc.). For manholes, the maximum depth is the amount of water that can build up from the invert to the road/ground surface. For each divider, a receiving pipe is required.

The final type of node that was used in the model is the outfall. In the watershed there are two main outfalls, which are the inlet structures to the CSW (named here as Inlet West and Inlet Main for West Campus and Main Campus, respectively). The only piece of information needed for the outfalls was the invert elevation, which allows for flow direction to be computed. There is a baseflow that exists throughout the system from leaky pipes and chillers from air conditioning units on Main campus that must be represented. The inflow option of outlet parameters was utilized to input a baseline flow for Inlets West and Main, the baseline values are 0.05 cfs and 0.29 cfs, respectively. These values were found using past flow data from previous years and were the flows during dry periods of the watershed.

3.2.3 Conduits

The pipe network is mapped out connecting all the subcatchments and nodes. The pipe input variables allow an in-depth analysis of the storm sewer network hydraulics that occurs with the given hydrology.

Most of the pipe network on campus is documented so not much assumption is needed. The input data used is length, roughness, diameter, as well as entrance/exit loss coefficients. Standard values from the American Society of Civil Engineers were used for roughness (range: 0.014-0.016) depending on the age of the pipe and for the loss coefficients (0.5) for entrance and exit locations. (Mays, 2005)

Due to the age of campus, some of the inlets to the pipes from storm drains contain flapgates. These devices allow the water to only enter the pipe network once buoyancy forces lift the gate. This occurs during larger storm events and allows water to pond during smaller storm events. Primary reasons behind the use of flap gates are to prevent reverse flow through the network.

3.2.4 Rain Gage

For each of the subcatchments documented within the model, there must be a linked rain gage to convey information concerning wet weather from either time series input or *.DAT data files. The rainfall data can be in the form of intensity, volume or a cumulative rainfall. Attention must be made to matching time series *.DAT times and dates for accurate simulation.

3.3 Model Errors

One of the major benefits to using SWMM as the modeling software is its ability to check for system errors. If the user inputs data that go against basic laws of hydrology and hydraulics, the program will state “Failure to Run” and provide a list of errors in the model. For this particular model, the two largest errors were input of wrong invert elevation and inappropriately designated inlets and outlets for conduits (i.e. flow direction is incorrect). These problems were due to AutoCAD drawings containing incorrect data, therefore survey was performed to acquire new data and correct the model. Before any simulations are performed, it must be made sure that the report date and time as well as individual time steps are properly chosen to match the data being brought into the model. If the date and time does not match, the model will still run but produce no runoff.

In the event errors are produced, the SWMM model itself allows for easy altering of variables and edits. Multiple Microsoft Excel macros exist to allow input of data to be done outside of the software as well to improve the speed and validity of input. Another benefit to the editing process is SWMM's capability of editing the same parameters for multiple features of the model through the 'group edit' command. The 'group edit' feature allows the user to alter parameters of similar features with more ease and swiftness.

3.4 Input data files

Within the SWMM software, there are two different mechanisms to bring in data for analysis. These are time series and file types of data.

Time series data are input to the SWMM model through the time series module. In this module there are data cells for date, 24 – hour time, and rainfall. This is beneficial for small intense storm events or possibly a design storm where there are not many data points to the hyetograph.

File type data are used when there are many points in the rainfall data that need to be analyzed on the scale of a few days to months in one simulation run. This modeling software does not recognize the *.XLS and must be brought in using a *.DAT extension by creating a text file with the headings shown in Table 3-2, and then the modeler must convert that to a *.DAT extension.

Table 3-2 Order of data columns in *.DAT file

Rain Gage	Year	Month	Day	Hour (24-hr)	Minute	Rainfall (in)

3.5 Output data files

After the simulation is run, tables of inflow, depth, head, velocity, volume, and flooding to the two outfalls were chosen and exported to Excel. For this particular study, the flows and totalized volumes are the most important to model for comparison. One of the primary functions of the CSW is to control quantity and the modeled quantity must be compared to the field instrumentation. Figure 3-3 is a snapshot of the output table that can be copied to another spreadsheet program for computation as well as graphs for visual analysis (Figure 3-4).

Date	Time	Total Inflow (CFS)
12/07/2004	08:40:00	0.0560
12/07/2004	08:55:00	0.0560
12/07/2004	09:10:00	0.0724
12/07/2004	09:25:00	0.0787
12/07/2004	09:40:00	0.0902
12/07/2004	09:55:00	0.1128
12/07/2004	10:10:00	0.2349
12/07/2004	10:25:00	0.9726
12/07/2004	10:40:00	2.3048
12/07/2004	10:55:00	2.3858
12/07/2004	11:10:00	2.3287
12/07/2004	11:25:00	2.1969
12/07/2004	11:40:00	2.1100
12/07/2004	11:55:00	3.0469
12/07/2004	12:10:00	2.7692
12/07/2004	12:25:00	2.2362

Figure 3-3 Screen print of SWMM output table

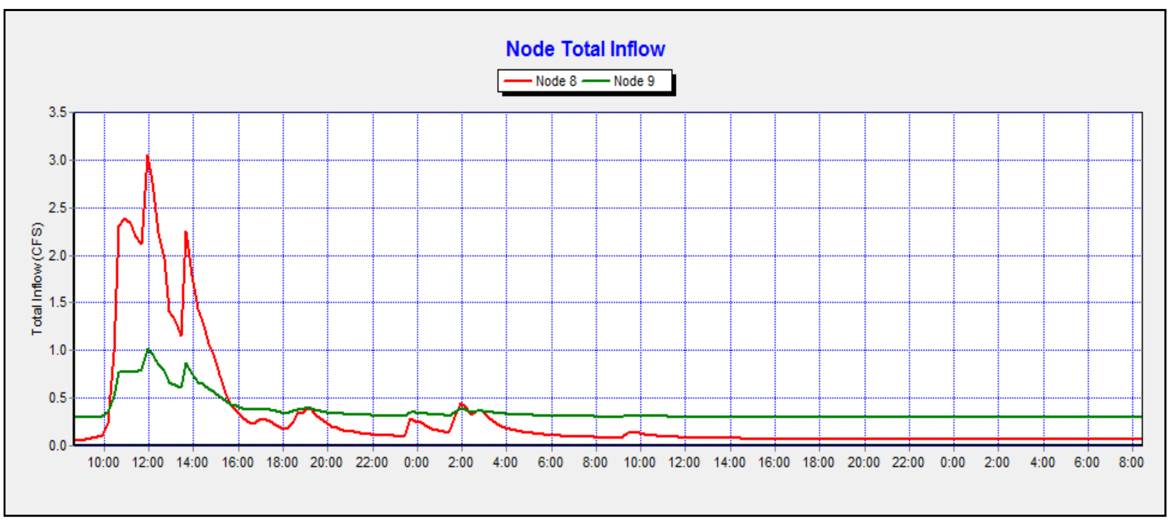


Figure 3-4 Screen print of SWMM output graph. Node 8 and 9 are inlet west and inlet main, respectively.

3.6 Instrumentation for field flow data

To gather flow, velocity, and head data for the inlet structures of the CSW an American Sigma 950 data logger and a Greyline AVFM-II (Area Velocity Flow Meter) are used for Inlet Main and West, respectively. The actual measurement device is an area-velocity bubbler probe that is held in each inlet pipe and the outlet pipe using a mounting bracket. Depth of water is found by the probe creating small bubbles in the water path; there is a certain air pressure required to form these bubbles and this pressure is converted into a depth using a calibrated equation within the system. Velocity is measured using the Doppler Effect, which sends a high frequency signal that bounces off impurities in the water and send a reading back concerning the transmission to the data logger.

As previously mentioned, the outlet structure contains a multi-weir structure (V-notch weir, T-weir, two rectangular weirs and a grate on top of the structure). The V-notch weir is located where water is continuously flowing over and into the outlet pipe. To use this V-notch weir, the water surface elevation is determined by a Northwest Instrumentation Pressure Transducer. This Pressure Transducer can measure depths up to ten feet and is used in a weir equation to calculate flow. The weir equation (Equation 3-1) is for typical V-notch weirs. Along with the use of weir equations, an American Sigma 950 data logger is also used at the outlet to track flow and velocity leaving the system.

$$q = \frac{8}{15} C_d (2g)^{\frac{1}{2}} \tan\frac{\theta}{2} h^{\frac{5}{2}} \qquad \text{Eq. 3-1}$$

where:
q = flow rate (m^3/s)
θ = v-notch angle
C_d = discharge coefficient
g = gravity constant (9.81 m/s^2)
h = head on the weir (meters)

This flow data from either the weirs or instrumentation will be used in the comparison to the simulation watershed hydrographs from SWMM in Chapter 4.

Chapter 4 : SWMM Results

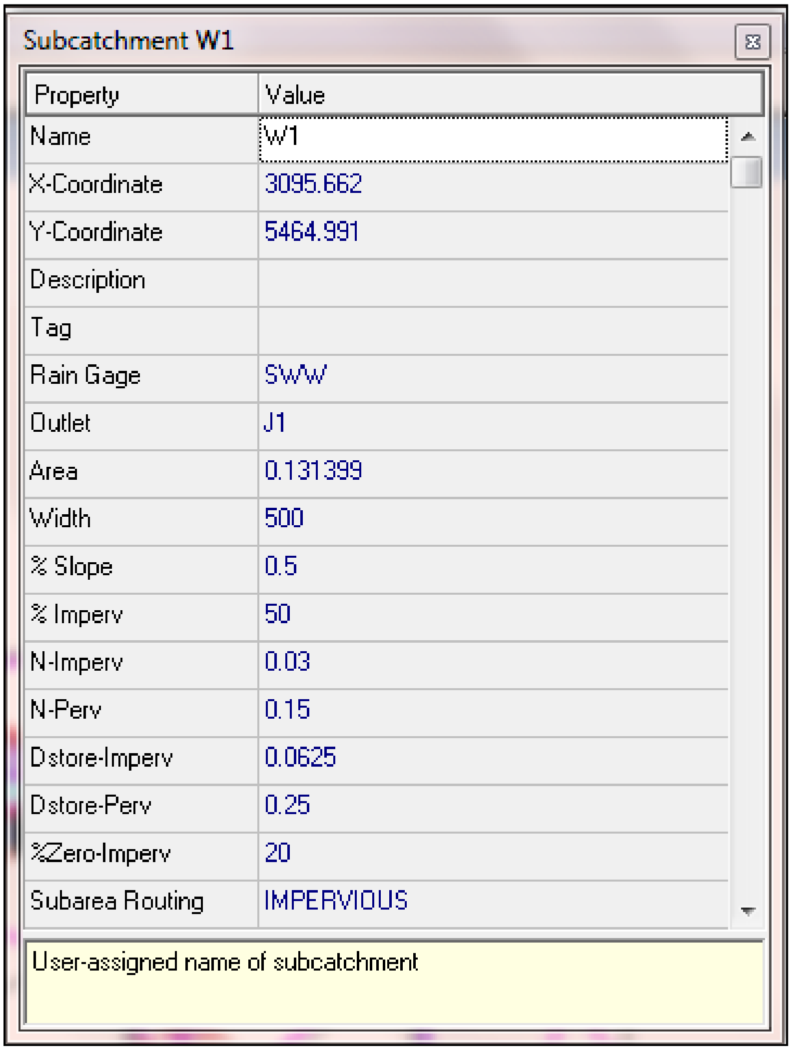


Figure 4-1 A partial screen shot of SWMM data input module for an individual subcatchment

4.1 Sensitivity Analysis – Simple Watershed

The SWMM model is a sophisticated platform and involves many different variables; therefore a sensitivity analysis on each variable was performed to see which variable tends to affect the outflow of a simplified watershed the most by simulating a 2 inch over 3 hours SCS design storm. Subcatchment parameters for individually isolated and altered to see their overall affect on peak flow, average flow, and total volume. The simplified watershed was 5 acres in area with half impervious cover and half pervious cover. Standard values for variables were used as a base reference point and can be found in Table 4-1.

Table 4-1 Standard values given initially with a new SWMM project

Overland Width	500 feet
Slope	0.05%
Manning's n **-Impervious** **-Pervious**	 0.01 0.1
Depth Storage **-Impervious** **-Pervious**	 0.05 0.05
Infiltration Method	Curve Number
Routing Method	Kinematic Wave

The curve number infiltration and loss method was chosen due to its simplicity in modeling and ease in changing variables within the model (i.e. only one input needed for single event modeling). The other infiltration and loss methods that can be used in SWMM are the Horton and Green-Ampt methods which both require multiple parameter entry (Section 2.6).The kinematic wave routing method was selected to reduce computation time. Other routing methods include steady flow and dynamic wave. The dynamic wave method involves complex calculations that allow flow to occur in both directions in the storm sewer network.

4.1.1 Curve Number

As the curve number (CN) value determines how much water is separated from the precipitation and allowed to infiltrate the soil, alteration of this parameter was the first step in the simple watershed sensitivity analysis. Acceptable curve numbers from 60 to 98 were chosen and all three variables (peak flow, average flow, and total volume) were plotted against their respective CN to determine any existing trends. (Figure 4-2)

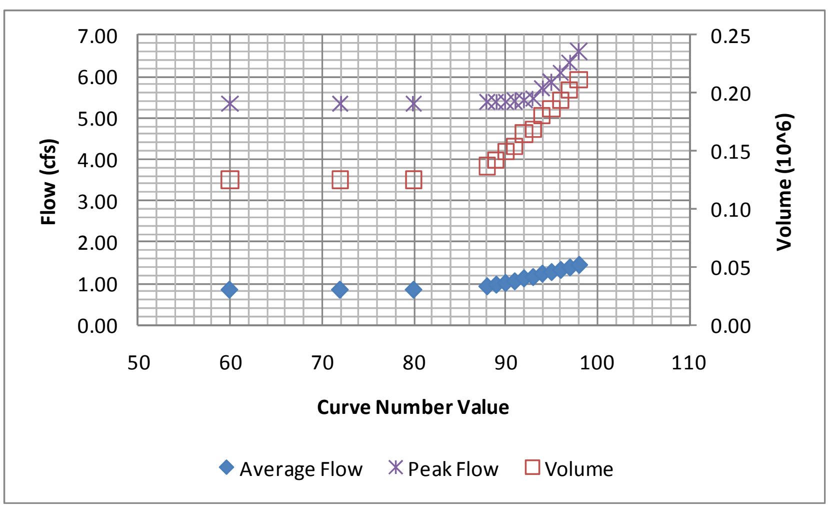


Figure 4-2 Relationships between curve number and the produces peak flow, average flow, and total volume

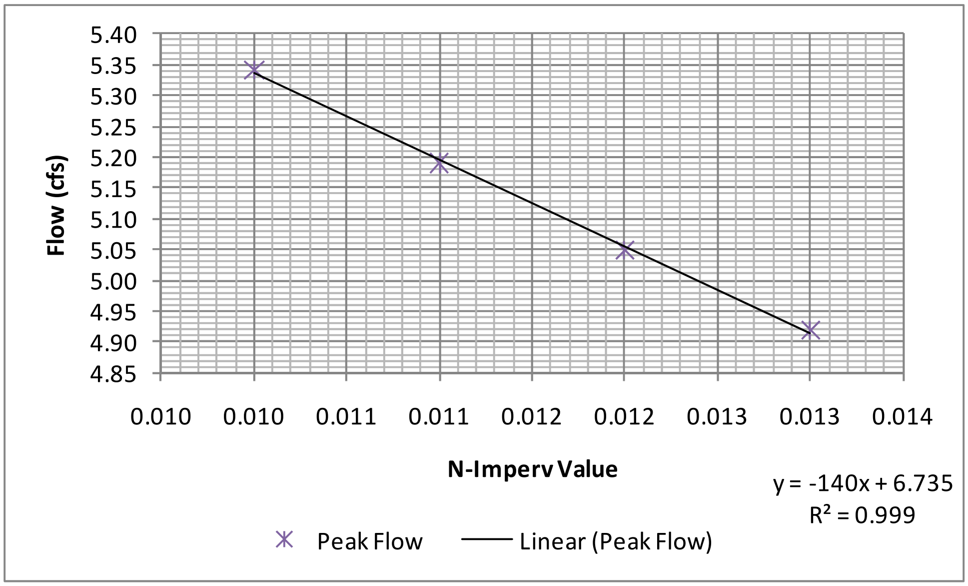
The CN value in comparison to peak flow has a non-linear relationship. Figure 4-2 shows that CN values from 60 to 92 compute a peak flow of an almost constant 5.4 cfs, as opposed to CN values of 93 to 98 producing peak flows that exponentially increase (e.g. CN of 98 has a peak flow of 6.6 cfs).

The average flow and total volume also have a constant value for lower CNs, with the increase occurring at a CN of 88 as opposed to 92. It should be noted that average flow dictates and governs the total volume leaving the watershed; this trend occurs for all of the variables altered in the sensitivity. For land areas that are not intensely urbanized, the SWMM model is insensitive to changes in CN, however for highly developed areas the model is sensitive to changes in CN.

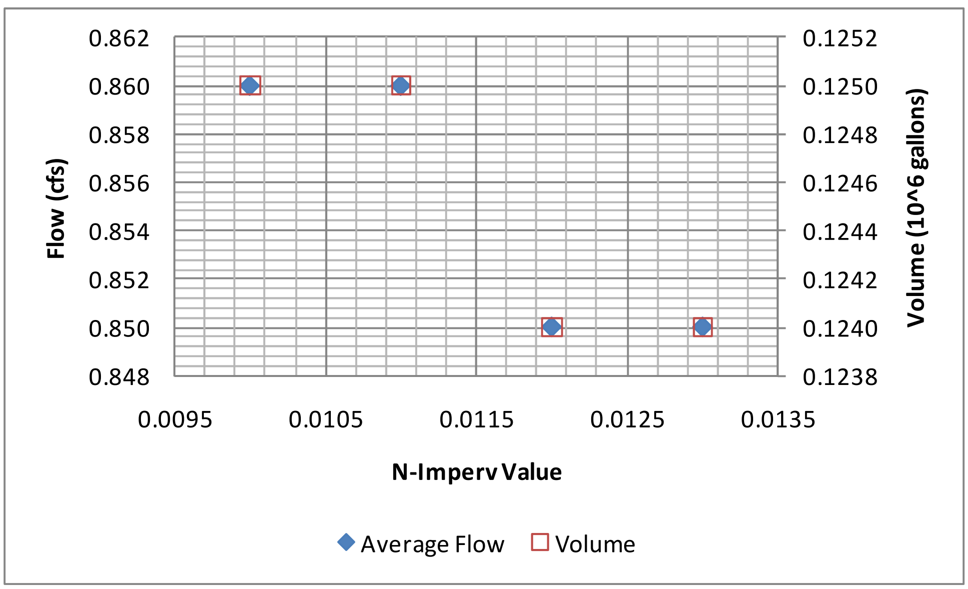
4.1.2 Manning's n

The second variable altered for analysis was the Manning's n for both pervious and impervious area. It was initially hypothesized that the altering of this value for both types of land cover would produce similar trends for both of the pervious and impervious cover Mannings's n. Standard Manning's n values provided by the American Society of Civil Engineers were simulated along with exaggerated values to see how the model handles more extreme values.

With an increase in Manning's n for both of the land covers there was an inverse relationship in the peak flow, average flow, and total volume. The impervious cover peak flow had a near-perfect linear relationship (R^2=0.999) and the average flow along with total volume decreased in a 'step-like' pattern (Figure 4-3). The Manning's n value for pervious land cover exponentially decreased all of the variables, but showed an asymptotic trend with larger values chosen (Figure 4-4). This justifies that as roughness increases, the flow decreases to a fairly constant rate.

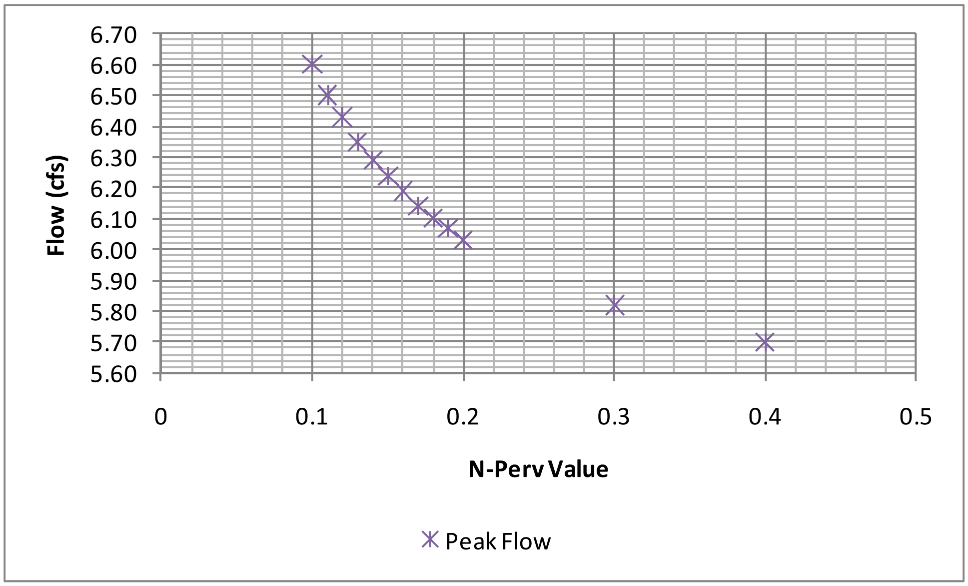


a)

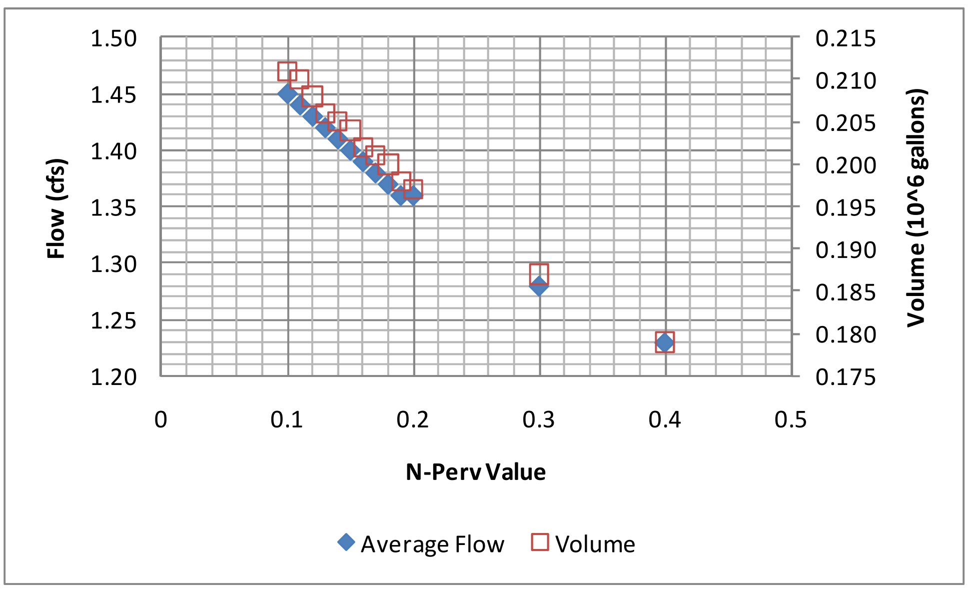


b)

Figure 4-3 Manning's n alterations for impervious cover and their affects on (a) peak flow, (b) average flow, and (b) total volume. The equation of the linear line of best fit is given in (a).



a)



b)

Figure 4-4 Manning's n alterations for pervious cover and their affects on (a) peak flow, (b) average flow, and (b) total volume

4.1.3 Slope

One of the most interesting parameter changes for the simplistic watershed sensitivity analysis was subcatchment slope. The slope of the subcatchment was initially set at 0.05% due to that being the initial setting that SWMM provides at the start of a new project model. For sensitivity analysis multiple slopes were chosen, including physically impossible slope values. The SWMM model itself allows for slope percentages to exceed 100% without producing error messages.

The overall trend for increasing slope percentage with average flow and total volume was a decreasing pattern (Figure 4-5). What became more interesting was the relationship between slope and peak flow value. No trend existed and certain increasing in slope caused a varying response (Figure 4-6). The flows do not vary over large ranges but this gives insight as to how SWMM does not depend on slope for maximum flows as much as the average flow and volume calculations.

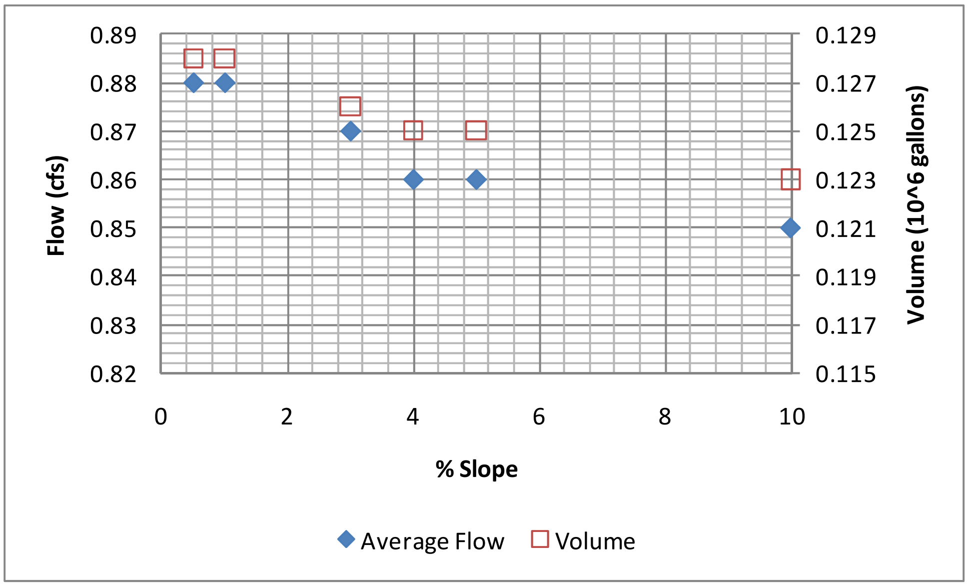


Figure 4-5 Slope alterations and their affects on average flow and total volume

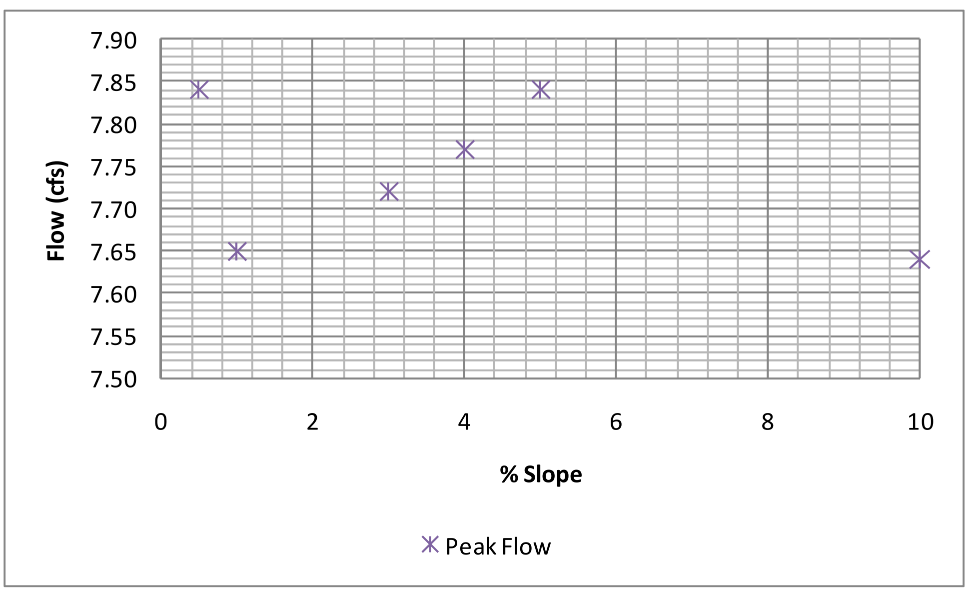


Figure 4-6 Slope alterations and their affects on peak flow

4.1.4 Depth Storage

The depth storage component of both impervious and pervious cover in the sensitivity analysis showed no real response in changing of peak flow, average flow, and total volume. The largest effect on flow was seen with changing the storage value on impervious and pervious cover producing a maximum change of +/- 0.2 cfs in average flow (Figure 4-7 and Figure 4-8). The peak flow values for changing the depth storage on both types of cover had little to no variation (Figure 4-9 and Figure 4-10) except with an extreme value of 1.0 inch storage.

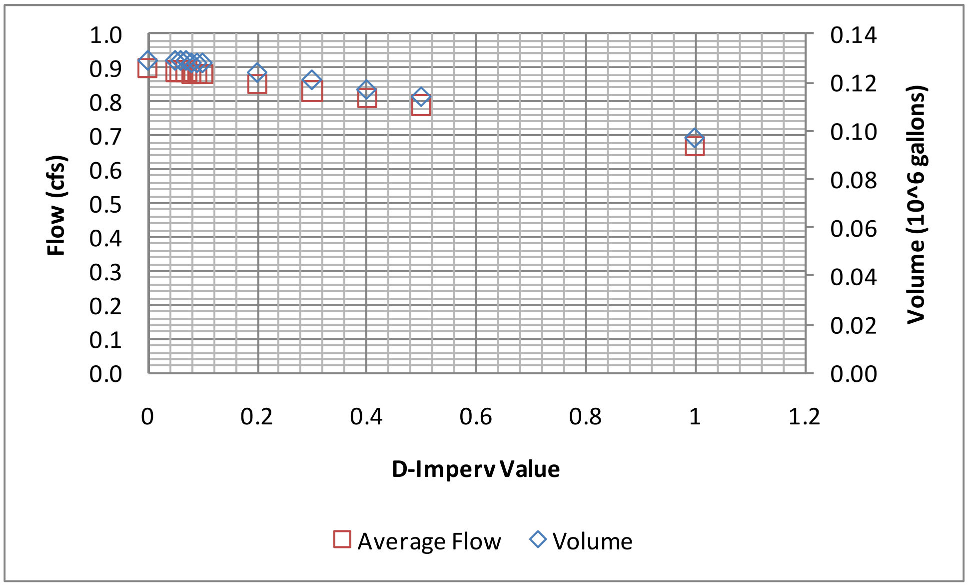


Figure 4-7 Alterations of depth storage of impervious cover and their affects on average flow and total volume

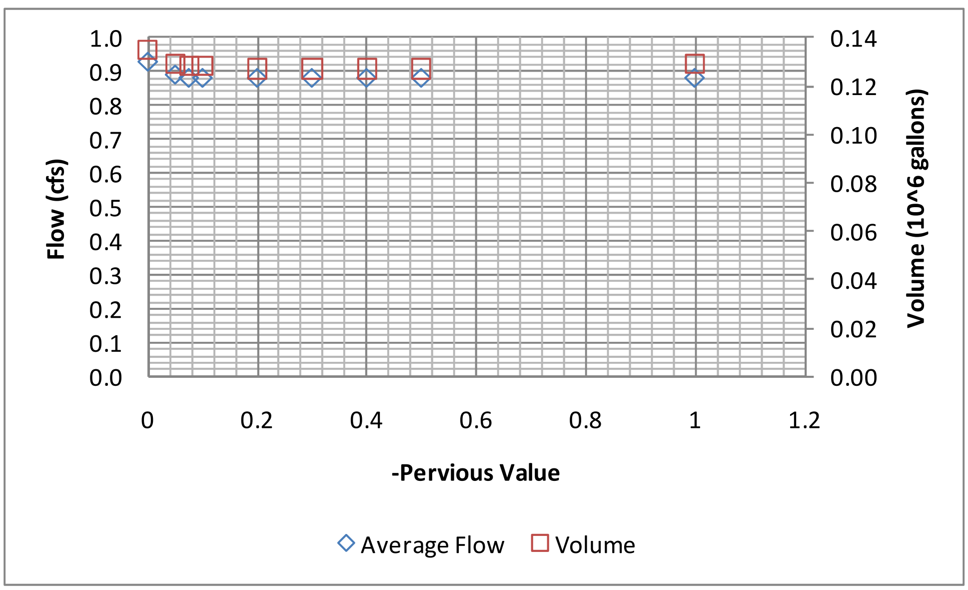


Figure 4-8 Alterations of depth storage on pervious cover and their affects on average flow and total volume

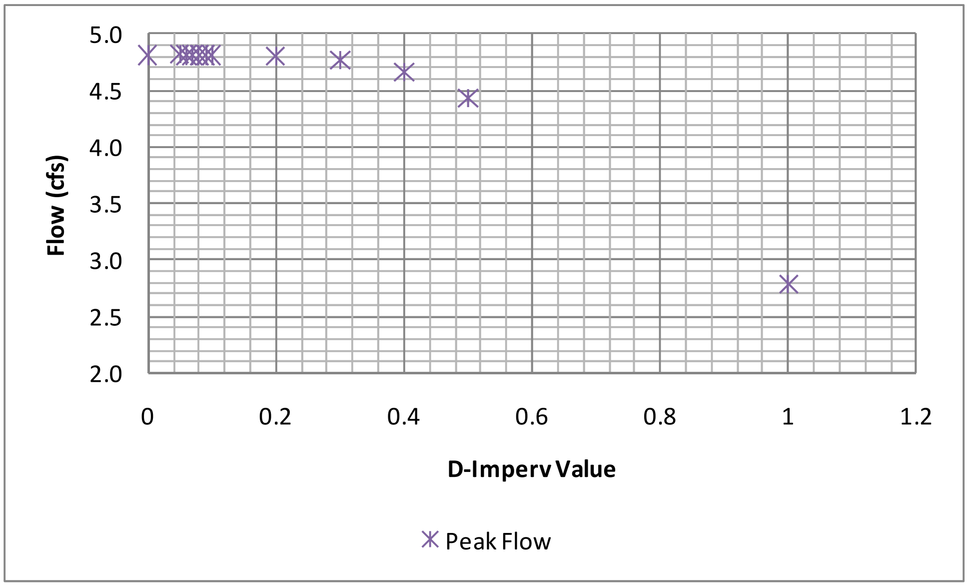


Figure 4-9 Alterations of depth storage of impervious cover and their affects on peak flow

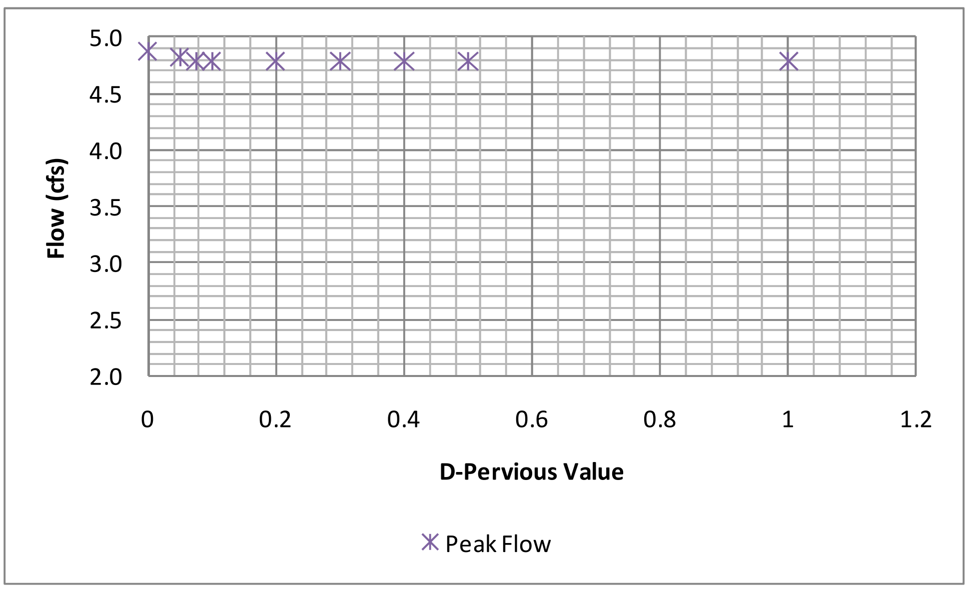


Figure 4-10 Alterations of depth storage of pervious cover and their affects on peak flow

4.2 Sensitivity Analysis- Villanova University Watershed

The model for Villanova University's watershed incorporates two distinct geographical areas of interest; West and Main Campus. Analysis was done on subcatchment (Section 4.2.1-4.2.4) and conduit (Section 4.2.5) variables. The sensitivity analysis of the more simplified watershed points to the idea that the same trends would be observed for peak flow, average flow, and total volume.

4.2.1 Curve Number

The curve number (CN) incorporates several land use and soil parameters that affect runoff; it was hypothesized that the CN for each subcatchment would alter the peak outflow from the watershed the most. The CN, Green-Ampt, and Horton infiltration methods were all investigated and analysis showed that there was no substantial change in runoff between methods. The CN method was selected due to the wide availability of data and common use in surface water hydrology.

The curve numbers used were found using Water Resources Engineering (Mays, 2005). Table 4-2 shows the different CN values that were used in each iteration.

Table 4-2 Iterations of curve number selection

Iterative 1 (A)	98 - Roofs/Roads 70 – Grass with pavement 60 – Grass/Pervious Cover (Based on Satellite imagery)
Iterative 2 (B)	98 – Roofs/Roads 86 – Grass Based on Hydrologic Soil Group C (Poor)
Iterative 3 (C)	98 – Roofs/Roads 79 – Grass Based on Hydrologic Soil Group C (Fair)
Iterative 4 (D)	98 – Entire Watershed

Simulations of design storms of different constant intensities and durations were performed for each iteration. The storms were 0.10, 0.25, 0.50, and 1.00 inches/hour for both 1 and 4 hour durations to provide both small, low intensity and large, high intensity storms. The maximum flow values were investigated to see the hydrograph peak location and magnitude for each iteration. Analysis of full hydrographs is done later in this chapter with SCS design storms and real storm events.

Note: The nomenclature used for the graphs within this chapter is given in Table 4-3 and the iteration is attached to the end of each abbreviation (A, B, C, etc.).

Table 4-3 Nomenclature used in graphs Section 4.1

Inlet West Average Flow	IWAF
Inlet Main Average Flow	IMAF
Inlet West Maximum Flow	IWMF
Inlet Main Maximum Flow	IMMF

From the output data (Figure 4-11 and 4-12), CN does not greatly affect the average flows from both subwatersheds that reach the CSW; the maximum difference in both maximum and average flow data is 0.10 cfs. The first output of flows demonstrated the different hydrology of the two geographical areas. Due to West campus being more developed, there is less infiltration and subsequently more runoff than the lesser developed Main campus. This correspondence proves that the model follows the same general flow regime that would be expected on site.

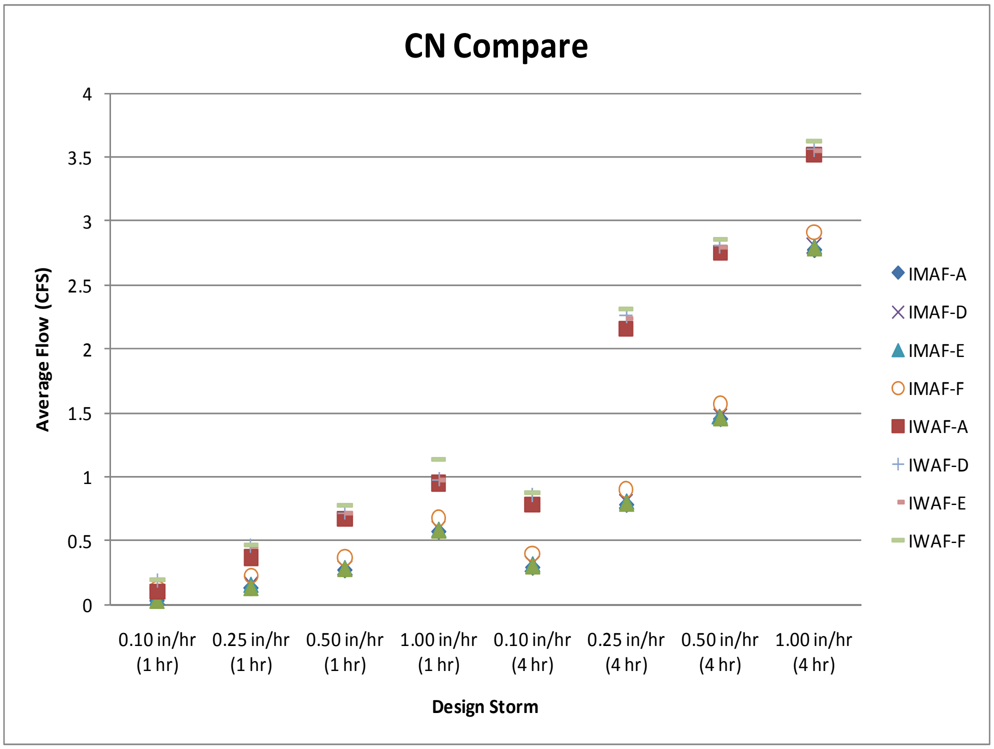


Figure 4-11 Curve number iteration comparison for average flow using different design storms

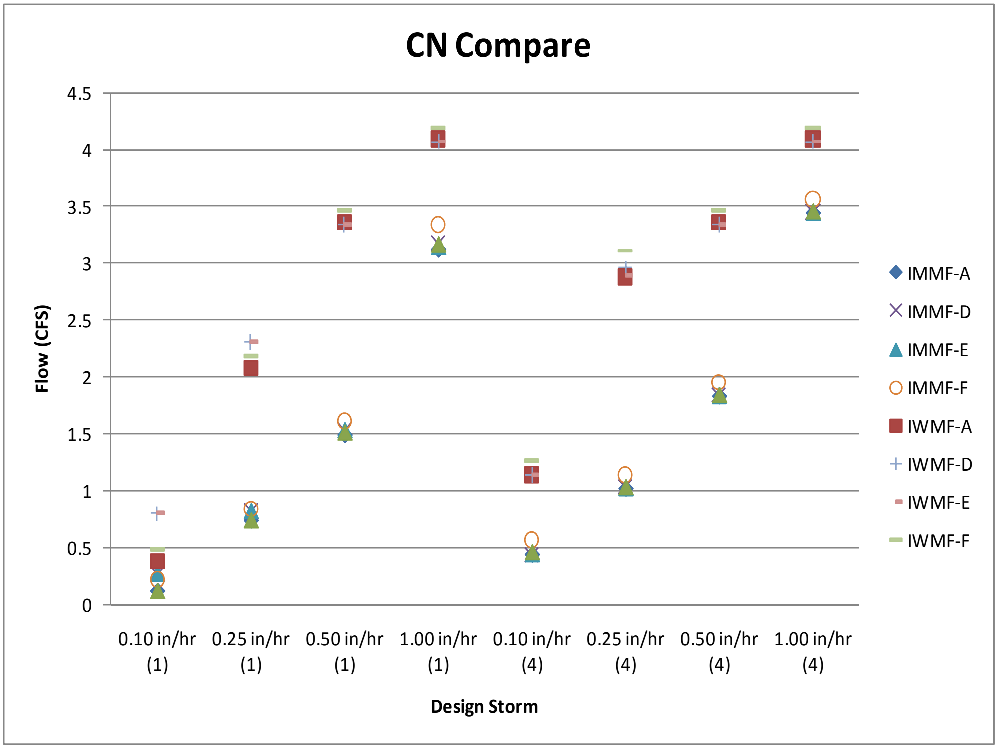


Figure 4-12 Curve number iteration comparison for maximum flow using different design storms

4.2.2 Manning's n

The Manning's n value incorporates effects of roughness, etc. In SWMM the Manning's n value is included in the Kinematic Wave routing model; other routing options include steady flow and dynamic flow routing. The Kinematic Wave method was chosen to model because of its wide use in urban watershed modeling. For sensitivity analysis, all system inputs were held constant except for the Manning's n value. Standard values for Manning's n were selected from Water Resources Engineering (Mays, 2005); the range for impervious surfaces 0.010-0.013 and the value for pervious surfaces range from 0.15-0.2. Two iterations were simulated: the first iteration consisted of impervious cover having a roughness coefficient of 0.01 and the pervious 0.15 (minimum standard values) and the second, having the same respective coefficients equaling 0.013 and 0.20 (maximum standard values). Design storms of 0.10, 0.25, 0.50, and 1.00 inches/hour for both 1 and 4 hour durations were modeled to create the graphical representation of maximum flow for the two inlets below. Average flow follows the same general pattern of the two different iterations not changing the maximum flows drastically. Figure 4-12 shows the change in maximum flows. It should be noted that Inlet West, during higher intensity storm events and different durations, the iteration has no affect on the maximum flow. It is important to note that inlet west maximum flow appears to produce the same value for both the 4.00 inch storm and the 1.00 inch storm. This becomes informative in explaining storage capabilities of the West campus watershed.

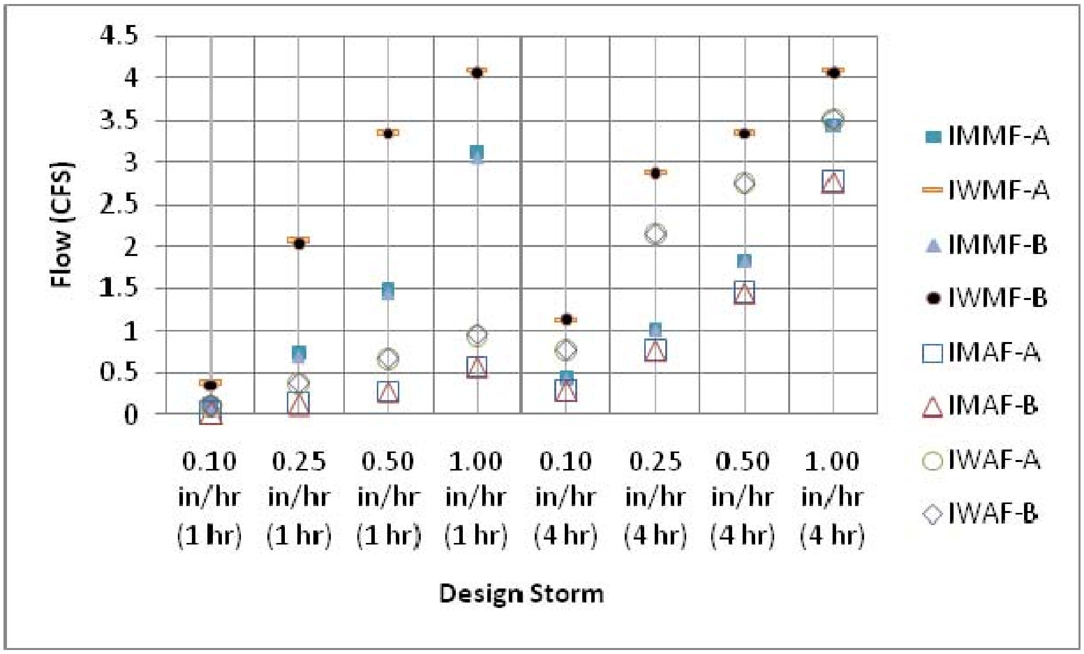


Figure 4-13 Varied Manning's n values and the effect on maximum and average flows for Inlet Main and Inlet West

4.2.3 Slope of subcatchment

The topology of Villanova University's campus is fairly constant and there are no dramatic increases in the land slope. However, a simulation of the watershed with a slope of 0.5% (Iteration A) and 1-2% (Iteration B) was done (depending on the area of campus).The CN values kept constant for these simulations were 98, 70, and 60 for roofs/roads, grass with pavement, and grass/pervious cover respectively. The two iterations changing slope had a maximum difference on the average and maximum flows of 0.02 and 0.09 cfs, respectively. Figure 4-13 shows the general pattern based on the intensity of the design storm for maximum and average flows within the system. It would be expected that the time of concentration within the watershed would decrease if the slope increases and no other variables change. This follows Manning's equation which is used to derive the Kinematic Wave method. The same production of identical maximum flow patterns values for inlet west is prevalent again as for the curve number iterations (Figure 4-14 and 4-15).

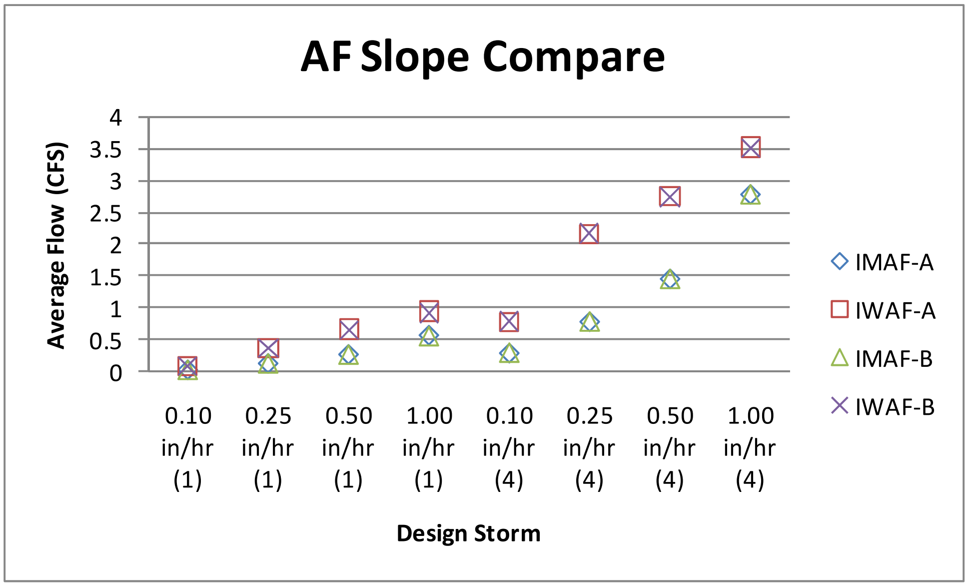


Figure 4-14 Effect of slope on average flow for both Inlet Main and Inlet West

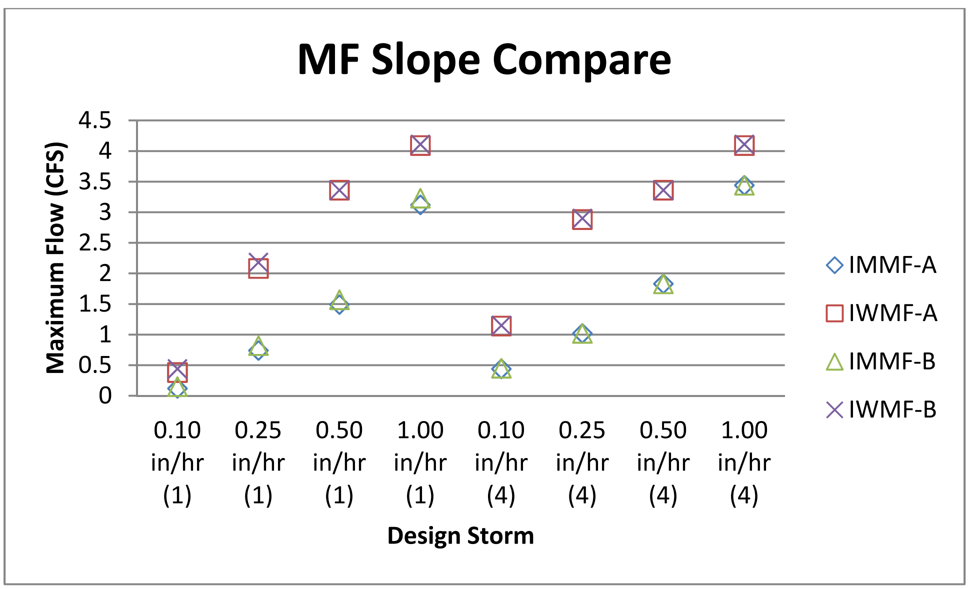


Figure 4-15 Effect of slope on maximum flow for both Inlet Main and Inlet West

4.2.4 Depth of storage

The storage on both pervious and impervious surfaces was analyzed. According to the American Society of Civil Engineers published in Water Resources Engineering (Mays, 2005); the standard values for pervious and impervious surfaces are 0.0625 inches and 0.25 inches (Iteration 1 (A)). These values along with the iterations represented in Table 4-4 were simulated.

After running through all the subcatchment variable sensitivity analysis, it was determined that each variable in the model has an equal influence on the maximum flows that come through the system. Due to the complexity of the model, each variable holds the same importance as the next.

Table 4-4 Iterations for changing the values of depth for both impervious and pervious surfaces

Iteration 1 (A)	Depth Impervious 0.0625” Depth Pervious 0.25”
Iteration 2 (B)	Depth Impervious 0.0625” Depth Pervious 0.00”
Iteration 3 (C)	Depth Impervious 0.00” Depth Pervious 0.25”

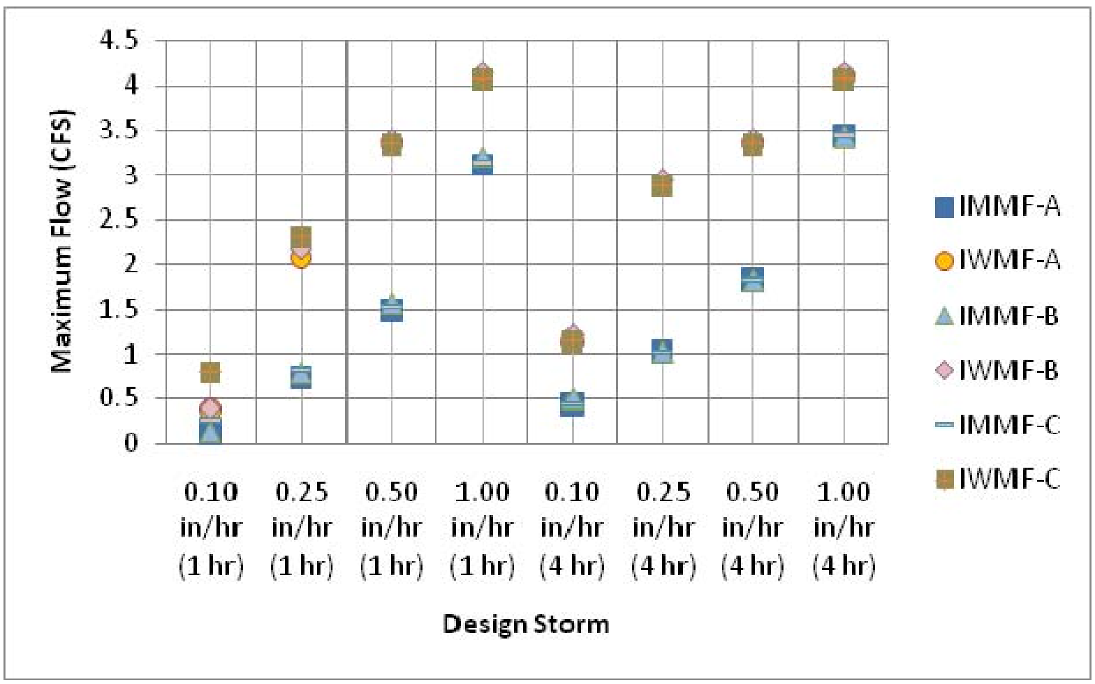


Figure 4-16 Effect of depth of storage iterations on maximum flow for both Inlet Main and Inlet West

4.2.5 Conduit Entrance/Exit Coefficients

The entrance and exit coefficients of a square entrance/exit piping to a more rounded pipe with coefficient values of 0.50 and 0.30, respectively were compared. The entrance and exit coefficient had no effect on the maximum flows of the system (Figure 4-15). All of the values produced from the model were identical. Figure 4-18 shows the affects of the different coefficients on average flows. These particular coefficients affect the hydraulics of the storm sewer network more than the actual flows and volumes.

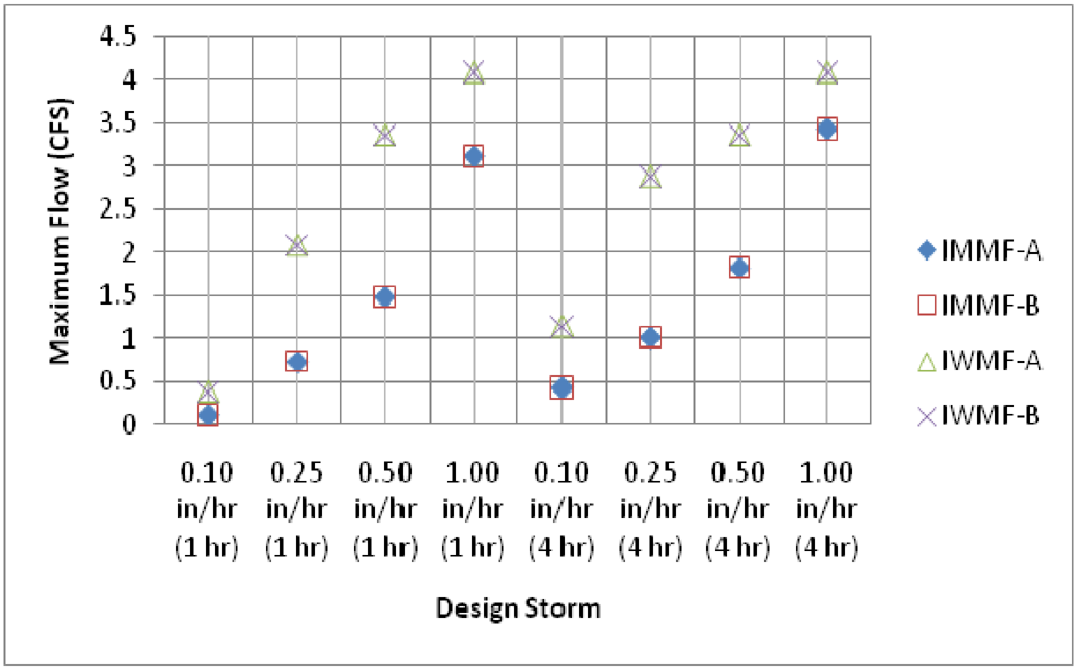


Figure 4-17 Effect of entrance and exit coefficients on maximum flow for both Inlet Main and Inlet West

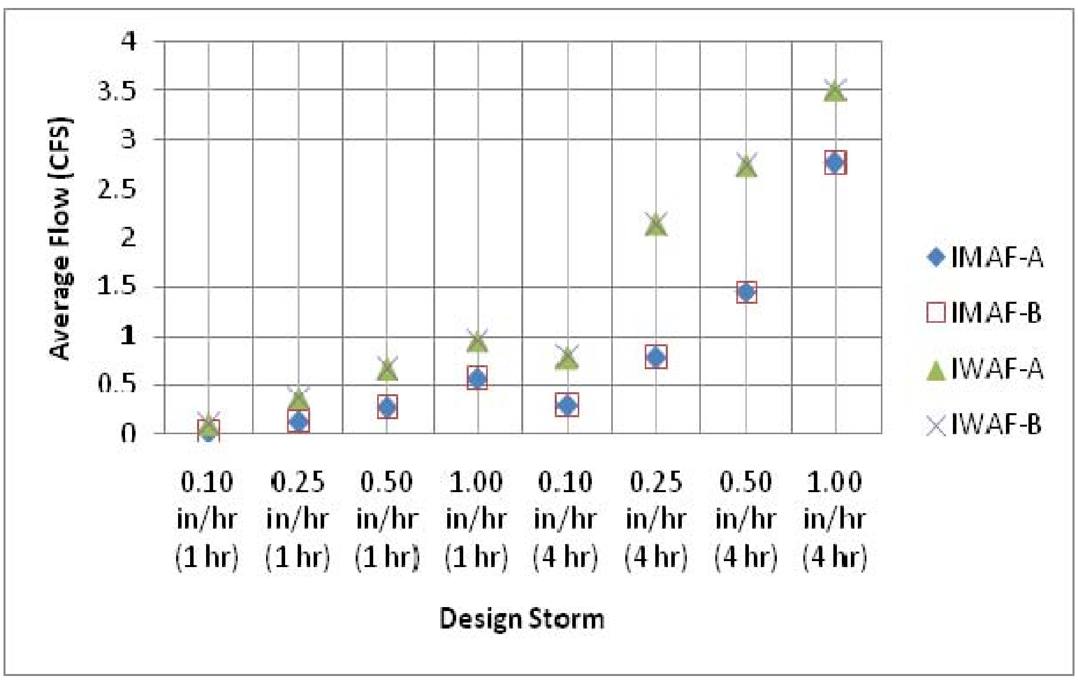


Figure 4-18 Effects of entrance and exit coefficients on average flow for both Inlet Main and Inlet West

4.2.6 Sensitivity analysis conclusions

After all of the prior statements and analyses were made, it has been determined that when using the Environmental Protection Agency's SWMM model, all variables and inputs hold the same value when individually isolated in examining the average flow and maximum flow leaving Villanova University's CSW watershed. This analysis has been done using constant intensity design storms with different durations for comparison of variables. The analysis has shown that the user can be less stringent with all the input variables within the model and the hydrology depends on the actual design of the stormwater conveyance system; it is not inappropriate to estimate unknown parameters. It is, however, insisted upon that the user define the drainage areas and the physical engineered attributes (storm drains, pipe lengths, etc.) with as much detail as possible, but can estimate the other variables based on best judgment and acceptable standard values.

4.3 SCS Design Storm

The Soil Conservation Service (SCS) design storm distribution was modeled to see if the overall model appropriately calculated outflow. The SCS design storm allowed the model output to vary temporally through the storm, as opposed to the previous constant intensity storms (Section 4.2). The hydrographs for both Inlet Main and Inlet West were analyzed for extreme flow rates to verify the parameters that were input to the model are reasonable given the hydrologic response.

The research site is near Philadelphia, Pennsylvania. An SCS Type II design storm was used (Figure 4-17).

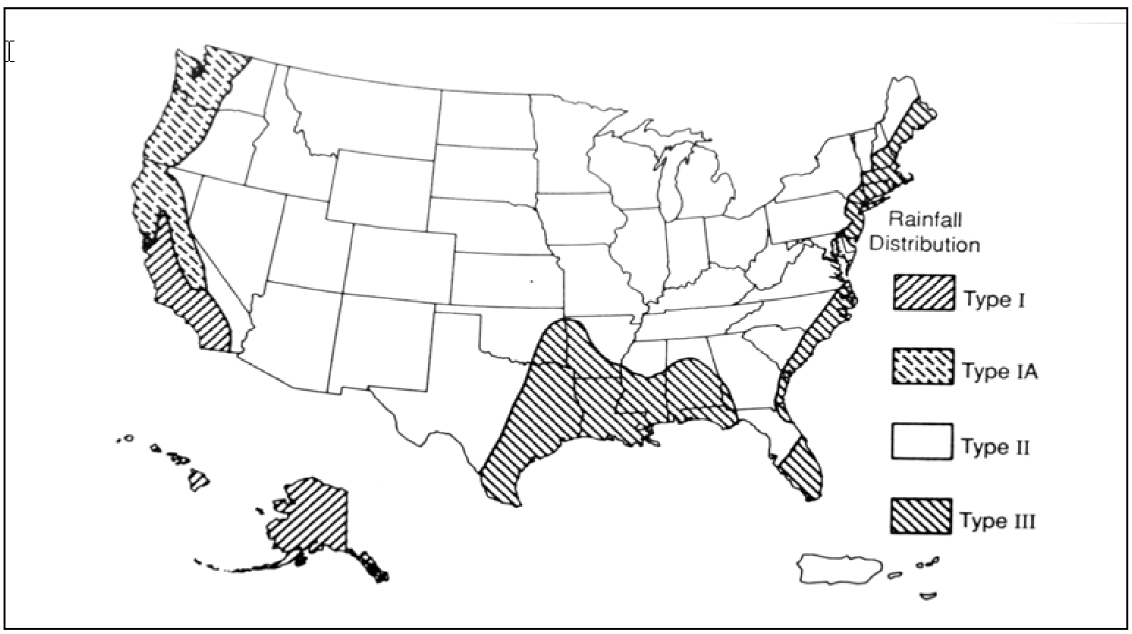


Figure 4-19 United States map containing the type of SCS design storm to use for particular regions (Soil Conservation Service, 1982)

A six hour design storm was selected to generate a hyetograph that was input to SWMM. The model simulations were set with a Manning's n of 0.03 and 0.15 for impervious and pervious surfaces, respectively, Entrance/Exit Coefficients at 0.5, slope of 0.5%, and depth of storage for impervious and pervious surfaces 0.0625 and 0.25 inches, respectively. The CN value used were values of 98 for impervious surfaces and 86 for grass cover. Two inch and three inch rainfall depth at the six hour duration were simulated. Initially, modeled storms for 0.5, 1.0, 2.0, 2.5, and 3.0 inches were done but the model did not react to the 0.5 inch rain event over the six hours. The unresponsiveness to the 0.5 inch event represents the overall storage capacity of the watershed. The model assumes the watershed is completely dry (4 days antecedent drying) before the event and all storage capacities are available in the watershed and the 0.5 inches of rainfall is abstracted completely; this demonstrates the need for more of a long continuous model. The 2 and 3 inch design storms were selected due to their ability to produce higher flows due to the available storage of the watershed. Table 4.4 shows the distributions that were used in both of the SCS design storm events.

Table 4-5 Both distributions of cumulative rainfall and individual time step rainfall for the 2" and 3" storms

Time (hours, t_i)	Time Ratio (t_i/t_{total})	Precipitation Ratio (P_i/P_{total})	Cumulative 2 inch Storm (inch)	Incremental 2 inch Rainfall (inch)	Cumulative 3 inch Storm (inch)	Incremental 3 inch Rainfall (inch)
0	0	0	0	0	0	0
0.6	0.1	0.04	0.08	0.08	0.12	0.12
1.2	0.2	0.1	0.2	0.12	0.3	0.18
1.5	0.25	0.14	0.28	0.08	0.42	0.12
1.8	0.3	0.19	0.38	0.1	0.57	0.15
2.1	0.35	0.31	0.62	0.24	0.93	0.36
2.28	0.38	0.44	0.88	0.26	1.32	0.39
2.4	0.4	0.53	1.06	0.18	1.59	0.27
2.52	0.42	0.6	1.2	0.14	1.8	0.21
2.64	0.44	0.63	1.26	0.06	1.89	0.09
2.76	0.46	0.66	1.32	0.06	1.98	0.09
3	0.5	0.7	1.4	0.08	2.1	0.12
3.3	0.55	0.75	1.5	0.1	2.25	0.15
3.6	0.6	0.79	1.58	0.08	2.37	0.12
3.9	0.65	0.83	1.66	0.08	2.49	0.12
4.2	0.7	0.86	1.72	0.06	2.58	0.09
4.5	0.75	0.89	1.78	0.06	2.67	0.09
4.8	0.8	0.91	1.82	0.04	2.73	0.06
5.4	0.9	0.96	1.92	0.1	2.88	0.15
6	1	1	2	0.08	3	0.12
			TOTAL =	2	TOTAL =	3

After the simulations, both the 2”-6 hour and 3”-6hour design storms flows were analyzed. Hydrographs for each design storm were compared at each inlet structure.

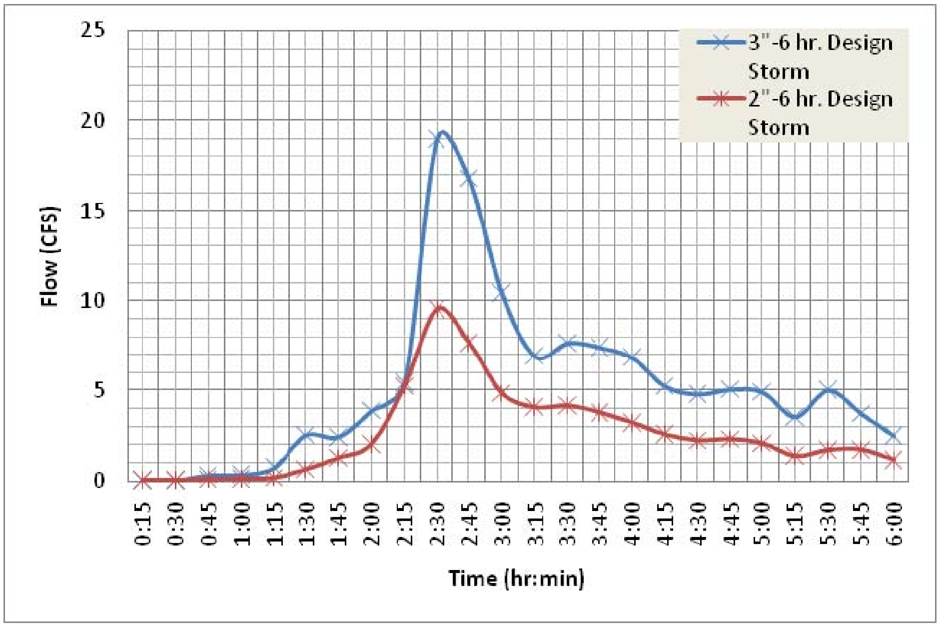


Figure 4-20 Detailed hydrographs for both the 2 inch and 3 inch design storms at Inlet West (including baseflow of 0.05 cfs). Baseflow is reached after 27.5 hours

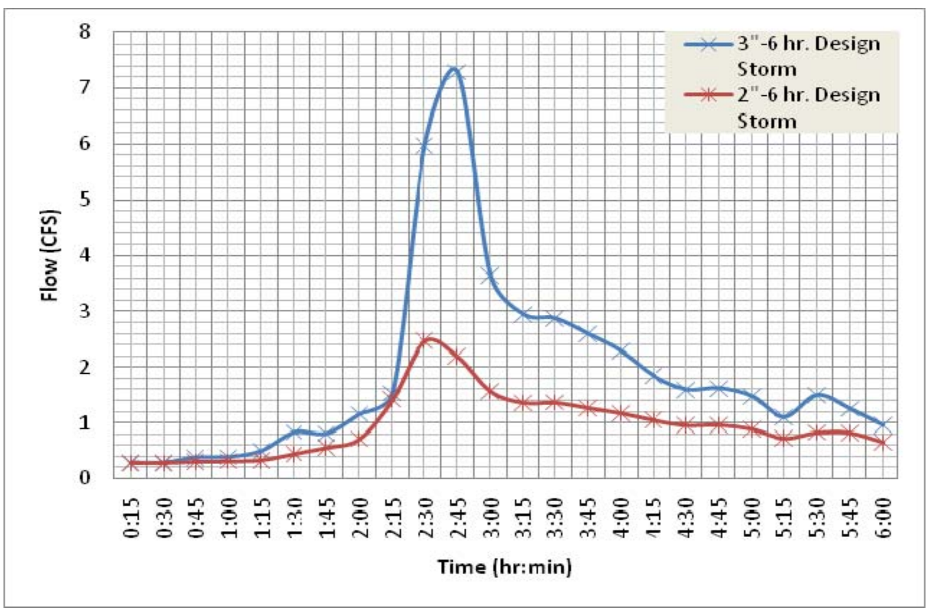


Figure 4-21 Detailed hydrographs for both the 2 inch and 3 inch design storms at Inlet Main (including baseflow of 0.42 cfs). Baseflow is reached after 27.5 hours.

Simulations were run with the design storms as the only source of water, however past observations show that there is baseflow entering the CSW in both of the inlet structures. The baseflow is attributed to old infrastructure (leaking conduits) and chillers on main campus draining into these piping networks. The baseflow values of 0.05 and 0.42 cfs is from historical instrumentation data for Inlet West and Main, respectively. These hydrographs show that the peak flow for Inlet Main is 38.4% of the peak flow for Inlet West for the 2 inch design storm and 25.9% for the 3 inch design storm. This corresponds with Main campus having more green space than West campus and provides more storage capacity. West campus contains 71.9% impervious cover while Main campus has only 50.5% impervious cover.

The simulated SCS design storms showed that the created SWMM model correctly responded to changes in precipitation. The values chosen for each parameter in the final model are shown in Table 4-5.

Table 4-6 Finalized parameter values for Villanova University's watershed

Curve Numbers	98 – Roofs/Roads 86 – Grass Based on Hydrologic Soil Group C (Poor)
Manning' N (subcatchments)	Pervious – 0.03 Impervious – 0.15
Manning's N (pipe)	0.013 – Newer Pipes 0.014 – Middle age Pipes 0.015 – Old infrastructure Based on judgment of development
Storage (subcatchments)	Pervious – 0.25 Impervious – 0.0625
Slope	0.05% for entire watershed
Entrance/Exit Coefficients	Both 0.5

After the two design storm outflows were simulated (Figure 4-20 and 4-21), there was interest in how long the system would take to recover from those particular storm events returning back to baseflow conditions. These hydrographs show different peak flows due to the SWMM software becoming more defined with longer reporting times. This is the key concept behind SWMM being used for continuous modeling.

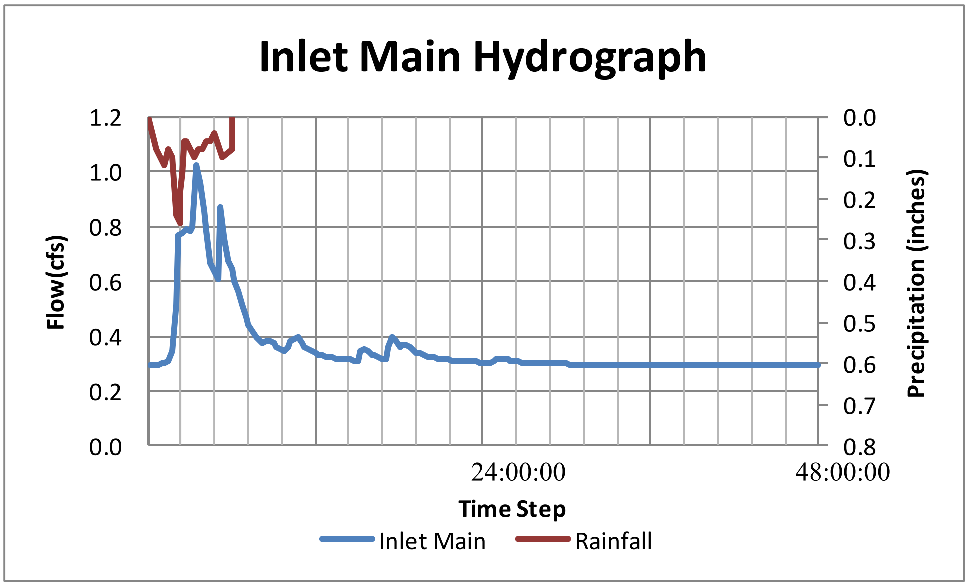


Figure 4-22 SCS 2 inch – 6hr. Design Storm extended reporting for Inlet Main (reporting interval 15 minutes)

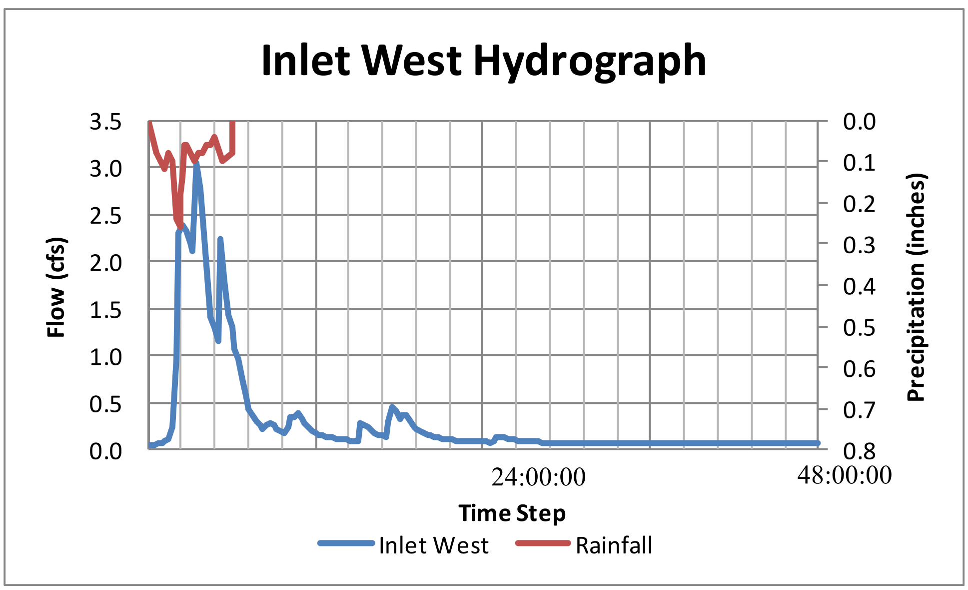


Figure 4-23 SCS 2 inch – 6hr. Design Storm extended reporting for Inlet West (reporting interval 15 minutes)

The storm runoff response is concentrated in the first 6 hours but there is a late response in the hydrograph for both of the inlets to the CSW. The system peaks again 17.5 hours after the storm event commences (SCS design storm hyetograph spikes again around 5.4 hours). Although the peak is not large, it should be noted as meaningful as it shows response to the all peaks in the design storm hyetographs. The hydrograph shows that the system begins to recover to baseflow conditions for this particular design storm

27.5 hours after the start of the storm event, which becomes important when successive storms occur during this recovery time.

4.4 Comparison of model and actual flow data

Actual measured storm flows were compared to simulated outflows for verification of the model. Overall the model hydrology is substantially different than the actual watershed during short periods of time (i.e. standalone events). However, long term modeling of continuous flow proves to be better, which is one of the benefits of SWMM.

4.4.1 December 8th, 2004 Storm

To model a particular storm event, storms with complete instrumentation flow data were used. The measured data for a storm is considered 24 hours before and after the actual storm which insures the model simulates the entire storm hydrograph. Measured rainfall was imported into SWMM and the model ran for the duration of the storm. The model flow data for both Inlet Main and Inlet West was compared to filtered instrumentation data. A data filter was used to remove all values larger than 4.5 cfs for Inlet West and 2 cfs for Inlet Main which is 1 cfs greater than the maximum flows given by the SWMM model. This was done to rid the instrumentation data set of unrealistic flows that could skew the total runoff volume appear higher. An unrealistic data point was considered when a flow increased by more than 200% in five minutes with no change in rainfall to explain the jump. Figure 4-22 and 4-23 are the two hydrographs for both inlet structures that compare the filtered raw instrumentation data to the modeled flow data from SWMM.

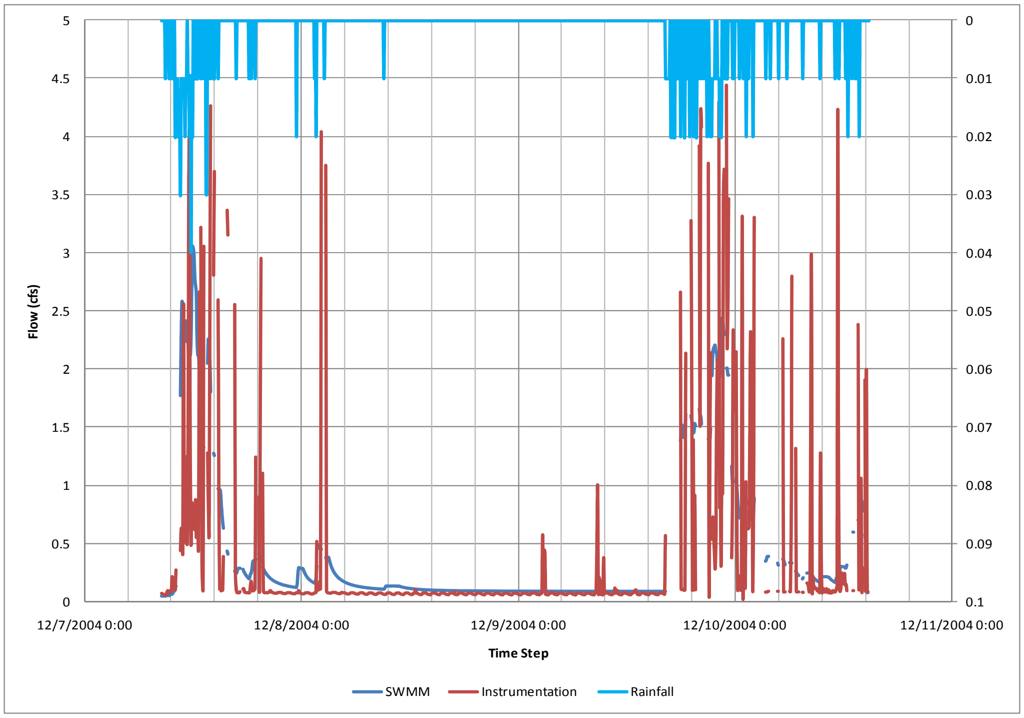


Figure 4-24 December 4th, 2004 Inlet West instrumentation and modeled data comparison

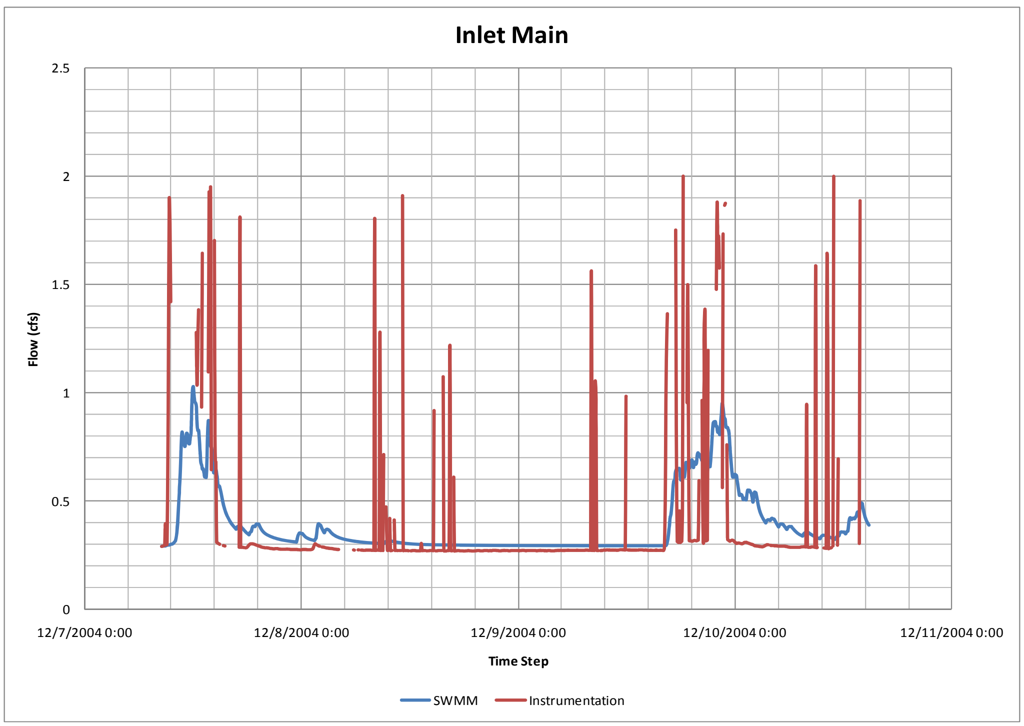


Figure 4-25 December 4th, 2004 Inlet Main instrumentation and modeled data comparison

The model has the same general pattern as the instrumentation, but the instrumentation has more scatter within its data sets and shows a larger value for peak flow. The instrumentation data is reported every five minutes and the model reported every minute. The model has more definition partly due to this user defined reporting time step producing more data than the available flow data. Another reason that the model responds with no correspondence to instrumentation is due to the rain gage potentially logging datum that actually did not occur (i.e. birds and other disturbances).

For Inlet Main, the modeled total volume is 95.4% of the observed volumes, and for Inlet West the actual volume is 90.3% of what the model predicts. The filtering of the data proves to be effective in attempting to match the volumes but also may pose error in calculation.

For this particular storm, sensitivity analysis was revisited to see how much the initial model varied from the more detailed final model. Figure 4-25and 4-26 show the initial and final model simulations, respectively. It should be noted that the peak flows increase by about 1 cfs between the two with the addition of baseflow. The finalized model contained additional survey information about subcatchments and produces a more smoothed out hydrograph for both Inlet West and Inlet Main.

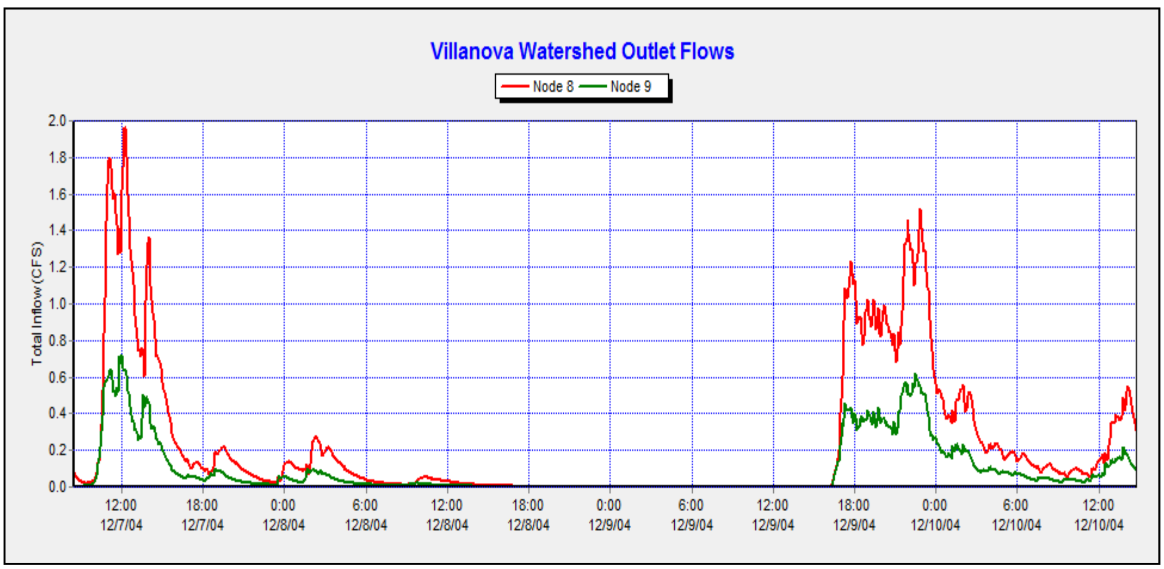


Figure 4-26 Initial rough estimation model of Villanova University's outflows (Node 8 and 9 are inlet's Main and West, respectively)

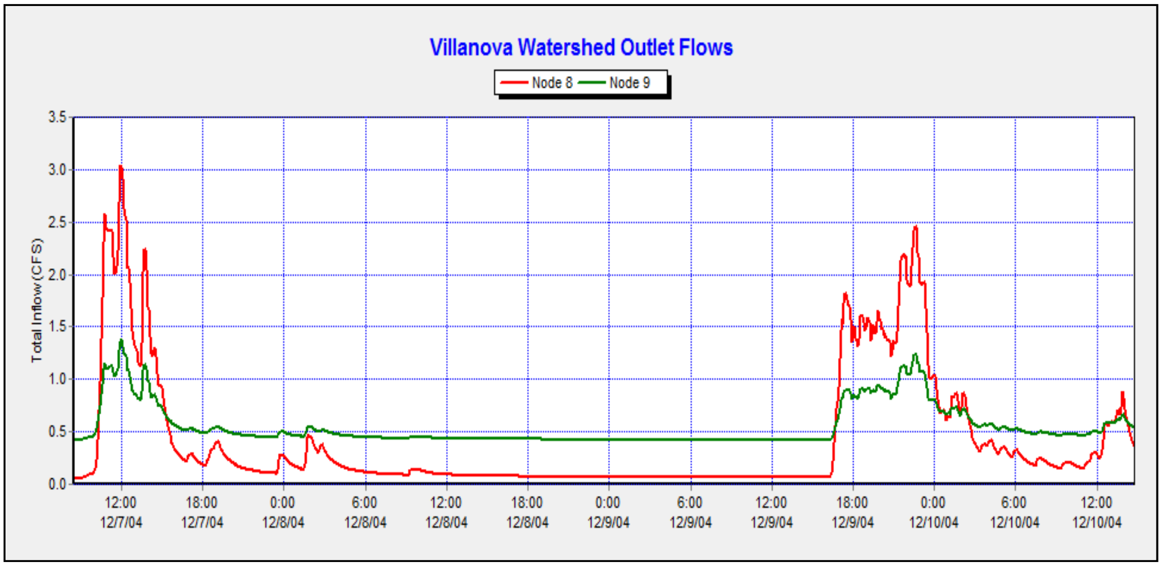


Figure 4-27 Finalization of model parameters model of Villanova University's outflows (Node 8 and 9 are inlet's Main and West, respectively)

4.4.2 October 8th, 2007 Storm

With the model working properly in terms of volume, another storm event was modeled to see if the model could produce replicated precision. In comparison to the previous storm, the hydrographs for the model and the instrumentation match in the times of the peaks but not the peak flow. No filter was placed on the data due to the instrumentation not experiencing data points extremely higher than the maximum simulated flows.

The modeled flow data for this particular storm under predicted the total volumes for inlet west (43.4%) however over predicted the volumes for inlet main (169.0%). For both inlet main and west, there is about +/- 60.0% discrepancy between the modeled and instrumentation data. The primary reason for this is due to a constant baseflow being used for each of the inlets flow and this has been observed to be a recessional limb baseflow as well as variable during different seasons. As observed, the peak flows in the model and instrument data do not match but the timing of peaks is near perfect.

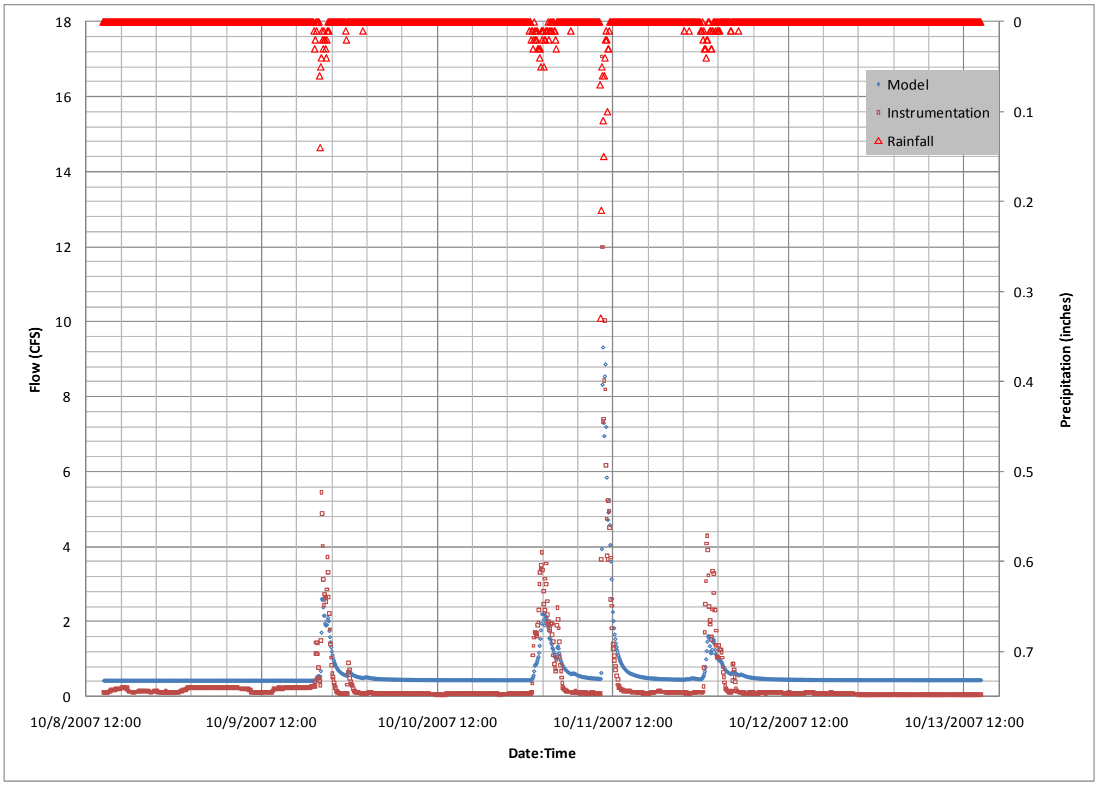


Figure 4-28 October 8th, 2007 Inlet Main instrumentation and modeled data comparison

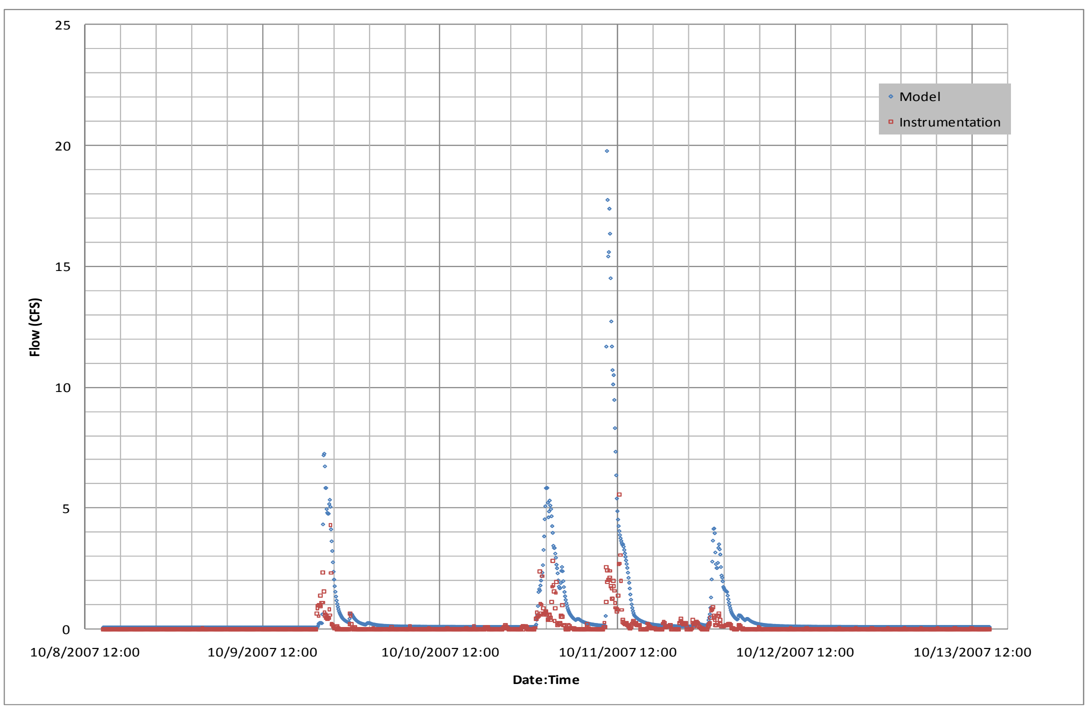


Figure 4-29 October 8th, 2007 Inlet West instrumentation and modeled data comparison with rainfall data

4.4.3 Entire months modeled – November 2008 and October 2010

An entire month containing both dry and wet weather was modeled to see if the model stabilized more over a longer period of time. The month of November 2008 was simulated because it contained multiple storm events with dry weather periods in between. Inlet Main had problems with the instrumentation; however Inlet West instrumentation matched consistently. After the model was ran, it was brought to attention that the time period modeled was when sediment buildup in the pipe was causing instrumentation problems for Inlet Main shown by the 0 CFS reading for a long period and then a scattered results toward the end of the month. The simulations were continued to be ran because Inlet West could still be analyzed in accuracy, but another time period would need to be modeled for Inlet Main (Figure 4-32).

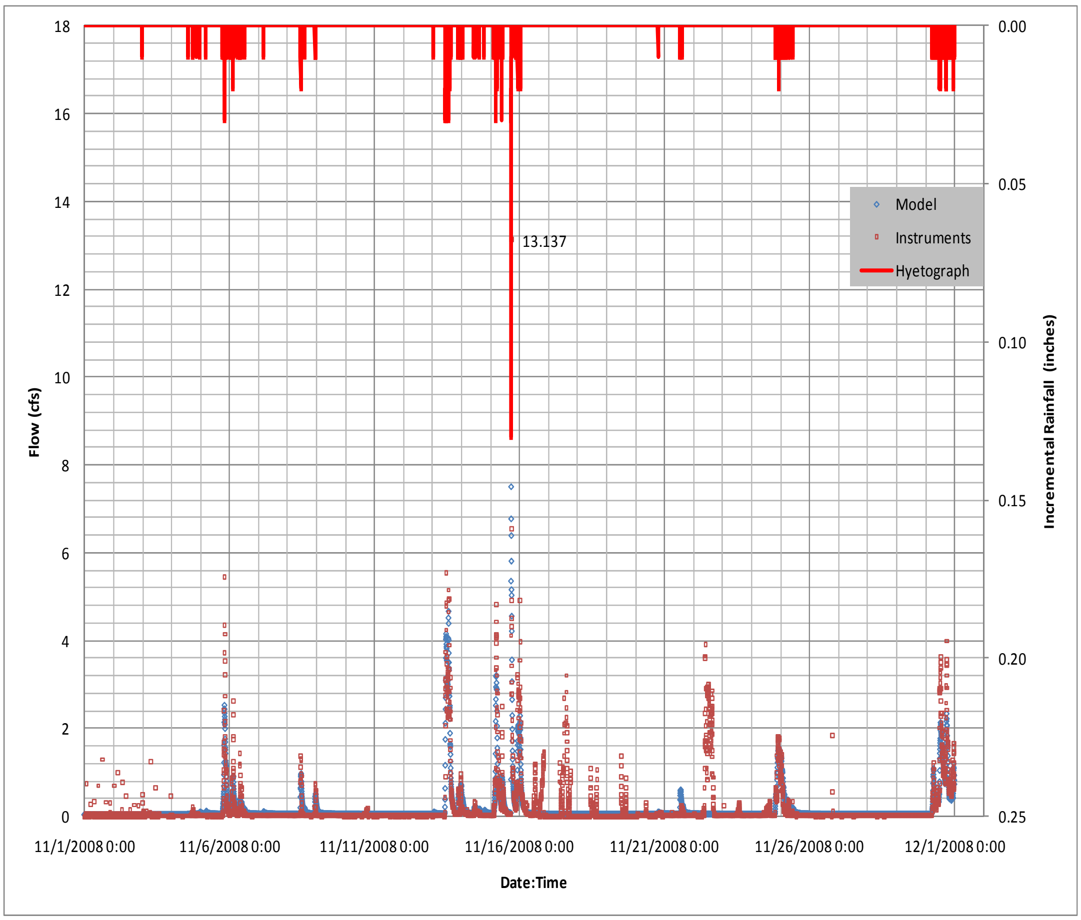


Figure 4-30 November 2008 Inlet West instrumentation-model comparison

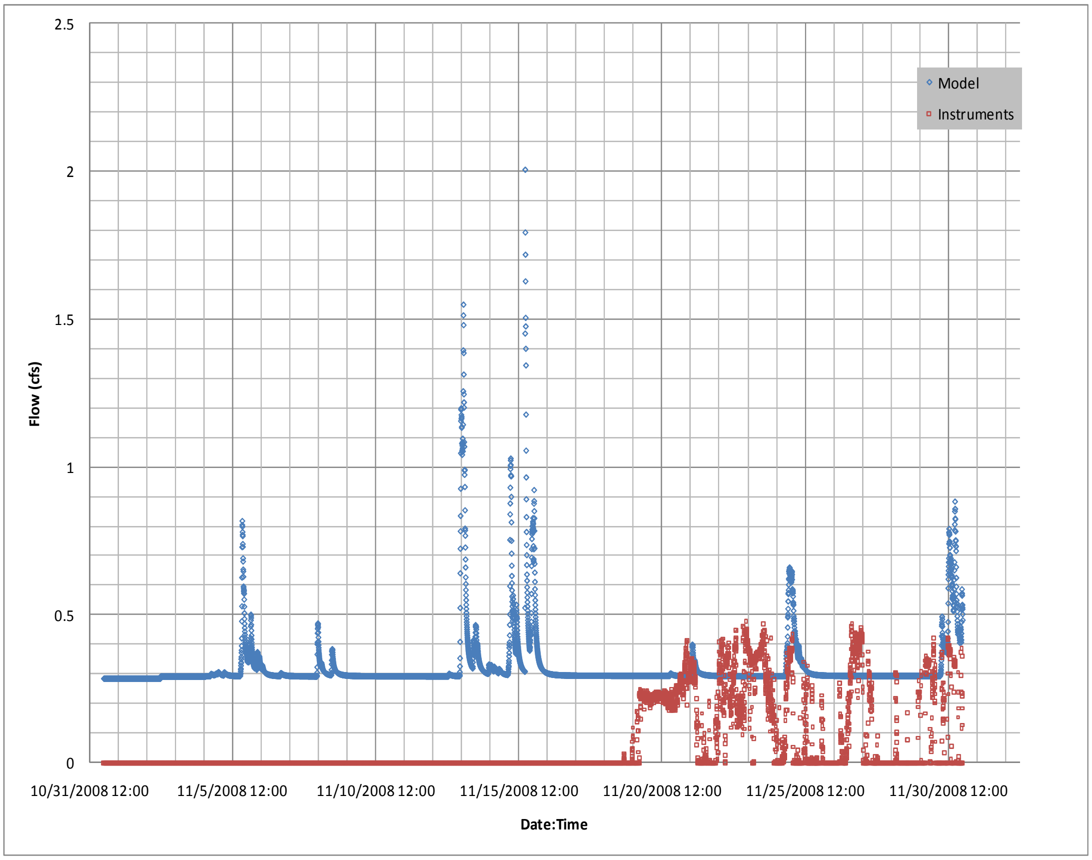


Figure 4-31 November 2008 Inlet Main instrumentation-model comparison

As Figure 4-29 demonstrates, the model behaves appropriately for Inlet West but not for Inlet Main (Figure 4-30). When the total volume was calculated for Inlet West for this particular month, the model over predicted the total volume by 3.7%. The model correlates well with the instrumentation as fluctuation between dry and wet weather patterns is present however, more recent data was modeled to attempt to confirm the model is correct for both subwatersheds.

October 2010 was modeled since instrumentation was moved in relation to the location where the sediment was building up before. Figure 4-31shows the model versus the instrumentation. The hydrographs match exactly in time and the model under predicts the total volume entering the system by 3.5%. The section of scatter (11/20/2008 – 11/30/2008) is due to the instrumentation being forced off the mounting bracket during a high flow event.

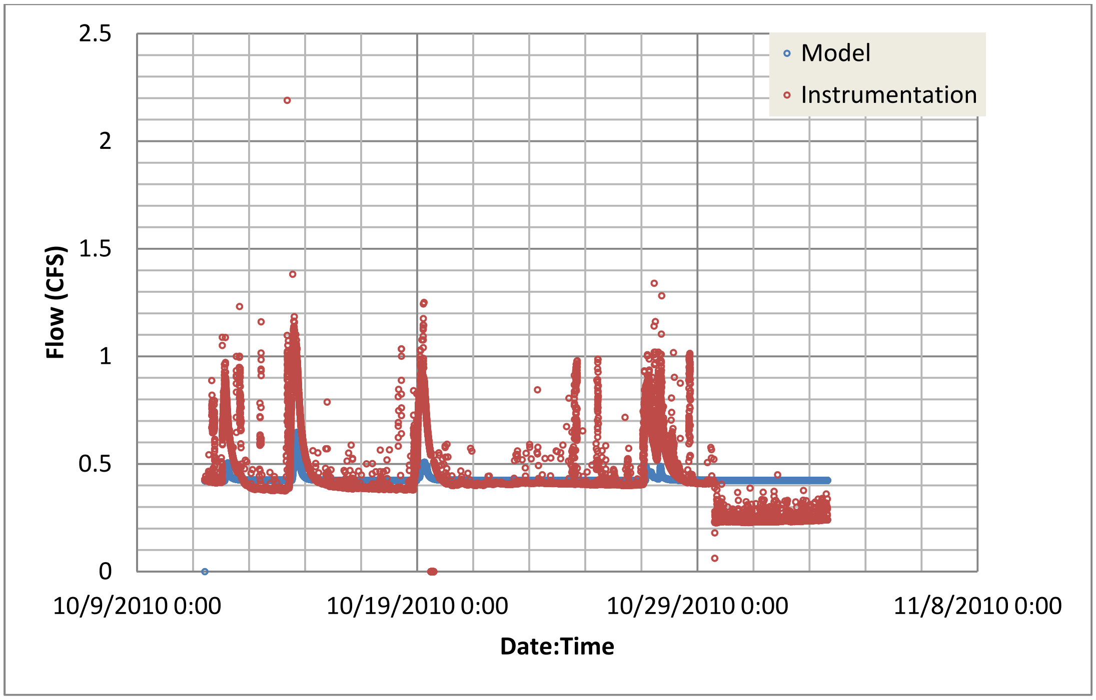


Figure 4-32 October 2010 Inlet Main instrumentation-model comparison. Instrumentation setup prevented a whole month long data set.

When the watershed hydrology is modeled over a longer time frame and more continuous conditions, the model successfully predicts total volumes within +/- 4%. The modeled hydrograph accurately predicts the peak flow temporally.

4.5 Different stages of development

The different stages of land development could be modeled and if some or all of the engineered features of the watershed were present. Four different hypothetical watersheds were used; the current design, the current design without a storm sewer network (SD), completely forested with a storm sewer network, and completely forested without a storm sewer network (NSD). Figure 4-32 and 4-33 show the hydrographs for November 2008 for each listed condition at both Inlet Main and West. As expected, the completely natural system showed no runoff and all water was stored or infiltrated in the watershed. The current design with no storm sewer network in place had a lesser peak flow value than the forested area containing a storm sewer network as seen in Figures 4-32 and 4-33. The current design does have the greatest peak flow. This agrees that a storm sewer network moves flood risk out of one particular area but translates it downstream to another location (i.e. the CSW system).

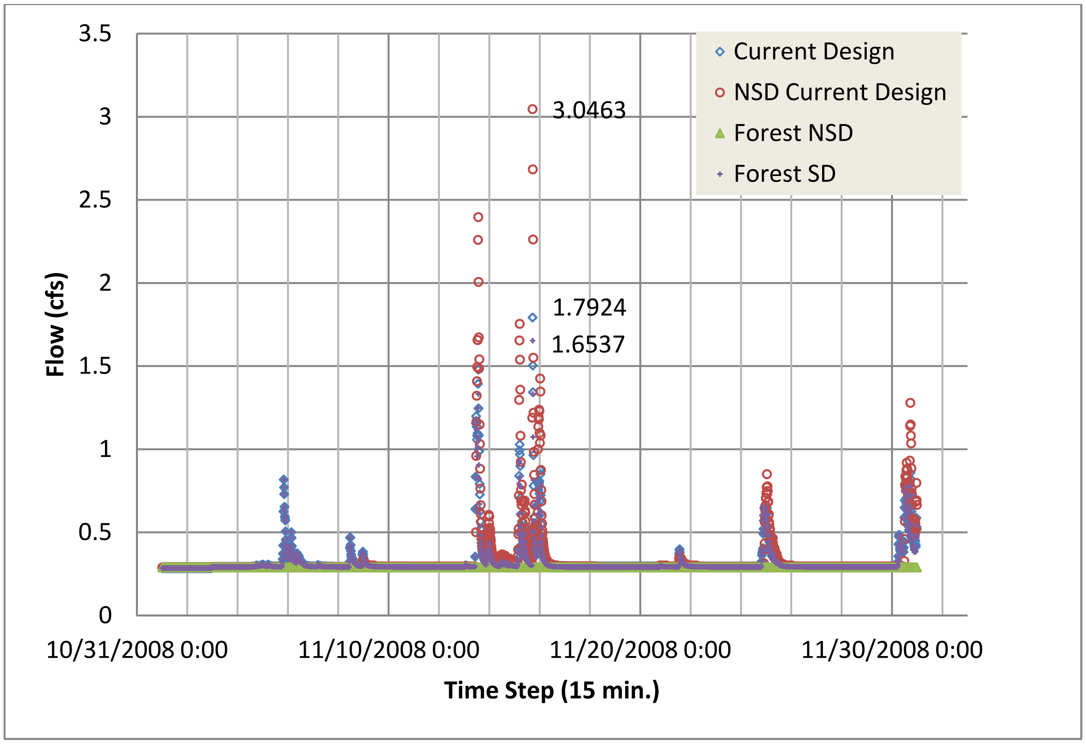


Figure 4-33 Inlet Main November 2008 hydrograph under different development conditions

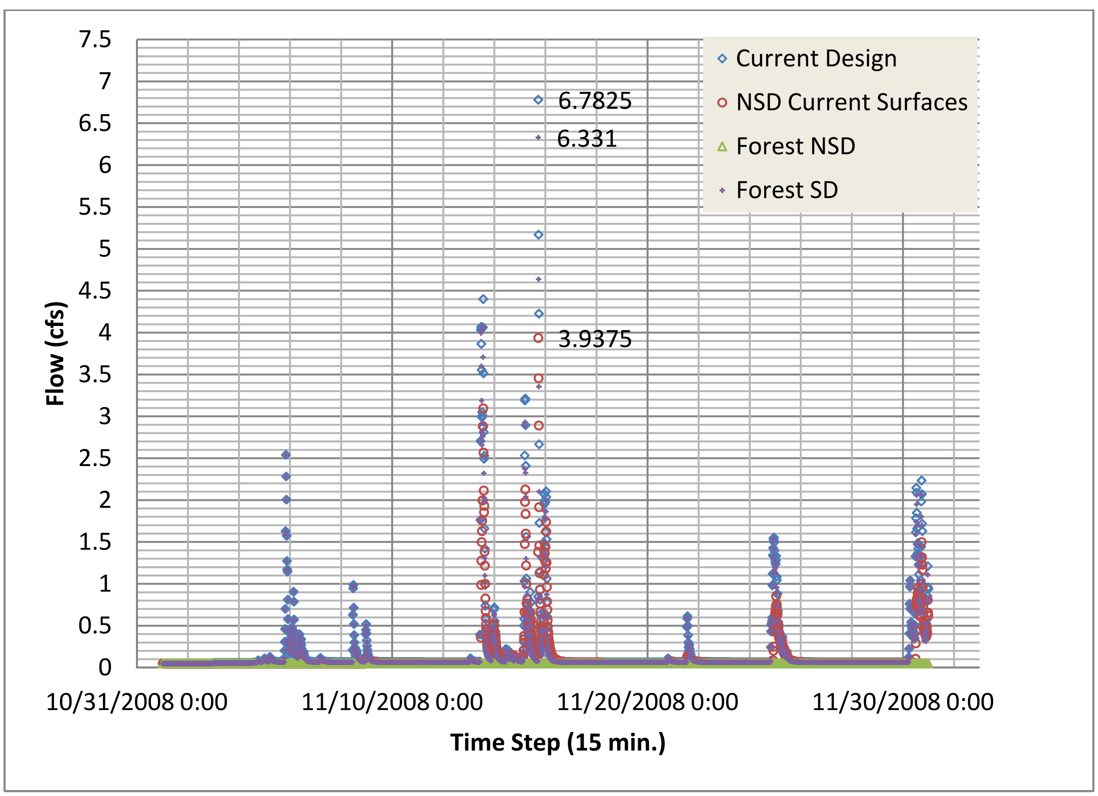


Figure 4-34 Inlet West November 2008 hydrograph under different development conditions

Chapter 5 : Water quality and stream degradation methodology

Figure 5-1 Bird's eye view of the newly constructed wetland system

5.1 Introduction

In this chapter, methods for collection of water samples with the protocols for determining the quality of runoff water entering and leaving the Villanova University CSW are discussed. The laboratory procedures that will be described are documented in the Quality Assurance Project Plan (QAPP; 2009), which was assembled for the research data in the Villanova University Water Resources Research Lab in accord with Pennsylvania's Department of Environmental Protection and United States Environmental Protection Agency standard; this document can be found in Appendix A.

5.2 Water in the CSW – Where is it coming from?

The constructed stormwater wetland (CSW) receives water from two distinct geographic locations on Villanova University's campus; Main and West campus. Each of these locations has a respective storm sewer network that delivers inflows to the CSW system. Since the construction of the new Villanova School of Law in 2009, there are three additional inlet structures that are not being monitored for flow and quality because there is no baseflow and their respective drainage basins are small and relatively negligible; shaded circles in Figure 5-2.

At the site location, it is assumed that there is no interflow of groundwater into the channels of the system. Previous soil studies (Mogavero, 2008) have shown that the area has a thick layer of compacted clay that prevents seepage of water at this boundary.

Influences on or from groundwater to the system are being neglected for this particular study but could be part of future research.

5.2.1 Water quality grab sample locations

The CSW influent water sampling location is at the headwall that houses the two primary inlet structures from Main and West campus. Since this study is not comparing water qualities of the two geographic locations, a composite sample is collected, assuming that the water immediately after the headwall is completely mixed and representative of all the water entering the CSW system. The water quality samples were collected in between the two pipes at approximately a distance of four feet from the headwall (Figure 5-2).

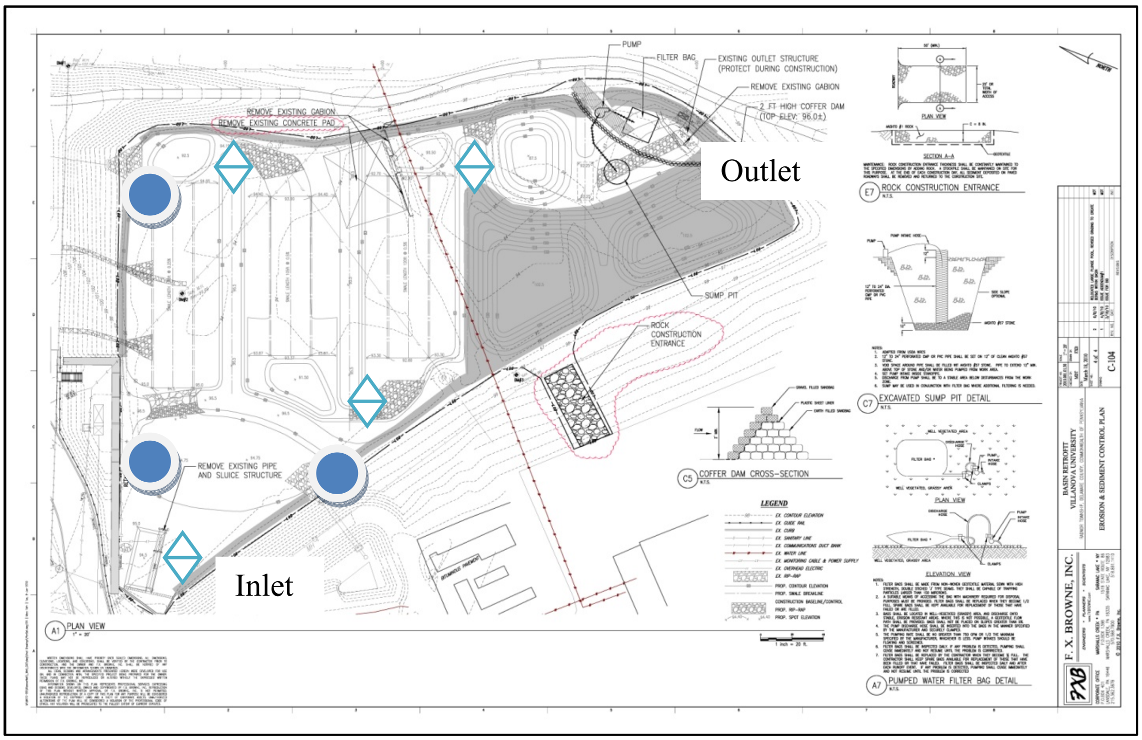


Figure 5-2 Final plan set with diamond markings to representing grab sample locations. Circles are additional inlet structures with no monitoring instrumentation.

The location where the first sample is collected is considered the sediment forebay where sizing and retention time allow for substantial settling of suspended and dissolved solids. The sediment forebay also receives influent water from the newly constructed law school from a bio-swale that was required and mandated in contract with the construction of the new School of Law as well as a new pipe connecting the building's roof down spouts. From the CSW inlet headwall and sediment forebay, water flows through a rock berm that allows large suspended particles to be removed and enters the first leg of the meandering path.

The second sampling location exists at the northern most point of the system. This is the location where one of the unmonitored inlets enters the CSW from Garey Hall and some of the Villanova School of Law parking areas. Samples are collected at the pool of water immediately before the first sluice gate weir structure. Figure 5-2 is a map showing the baseflow sampling locations.

The third location is located southwest of the second at the second sluice gate weir. Again, samples are collected immediately before the structure where the water pools. The final location is northeast of the third location at the third and final sluice gate. Once again, the sample is gathered from the pooled water just before the structure. Normally, the effluent grab sample would be collected in the outlet structure however due to the new construction and the National Pollutant Discharge Elimination System permits requiring sediment control measures, the third sluice gate sample is considered the effluent of the system; it is expected that the settling pool that exists after the third gate before the outlet improves water quality further. Possible shifting of the final grab sample location to the outlet structure will occur when the sediment control measure is removed.

From each location, a 350 milliliter American Sigma sample bottle was used to insure that enough volume was taken for complete analysis. For replication purposes, three grab samples were taken at each location.

5.3 Sampling times

Both baseflow and storm event samples were taken to ensure a represented array for quality analysis. Baseflow samples are manually collected and the storm samples are taken using an American Sigma 900 autosampler (Figure 5-3). Due to lack of instrumentation, the autosampled storm events only contain three of the four locations; inlet, first meander, outlet. These sampled storm events are composite samples over certain lengths of time throughout the storm event. Due to the retention time of the wetland, the start of collection times are lagged depending on location. The inlet starts immediately after the storm begins, the sediment forebay starts 30 minutes after the inlet, and the outlet starts two and a half hours after the inlet. A 75 or 100 milliliter sample is taken over each of the time intervals. Appendix B contains the tables with programmed time intervals and volumes. The program selections for the autosampler itself can be found in Appendix C.

Figure 5-3 American Sigma 900 Automated Sampler

5.4 Water Quality

When analyzing water samples for quality, there are many laboratory tests that can be performed to give different concentrations of pollutants and attributes the water has. One particular way to analyze the water for its general pollution level is accomplished by testing for total suspended solids (TSS) and total dissolved solids (TDS). Pollutants in a water environment adsorb to suspended and dissolved solids allowing easier transportation. Hence, a numerical value in terms of weight of these TSS/TDS values can ultimately give a general pollutant level.

5.4.1 Solids

Analysis of a water sample must begin immediately after collection. The first step in analysis was to vacuum filter a ~250 milliliter sample (Kontes Ultra-Ware ® filter apparatus) through a Whatman 934-AH™ Glass Microfibre filter (Circle 47 mmφ) placed on top of the porous glass yielding a filtered sample. Figure 5-4 shows the setup with all parts as well as the porous glass surface. The filtered sample exact volume is determined by weight using a weighing scale produced by Mettler, model BasBal (1 g ~ 1 mL) which will read two decimal places and can handle larger weights above 1000 g for the flask weight and a Sartorius scale was used for the weight of the filter papers (four decimal places).

Figure 5-4 Top) Filter apparatus   Bottom) Porous glass filter close up

Figure 5-5 Sartorius weighing scale

The filter is dried (24 – hours at 100° Celsius) using a single wall gravity convection laboratory oven manufactured by Blue M® to quantify the suspended solids.

Figure 5-6 Blue M single wall gravity convection laboratory oven

To find the amount of dissolved solids in the water sample, the filtered water must also have the water dried so only the dissolved solids remain. The filtered water is placed into an acid washed Fisher Scientific ® 350 milliliter drying bowl with a known weight (Scientech scale) then placed in a Quincy Lab Inc. ® Laboratory oven at 125° Celsius for 24 – hours.

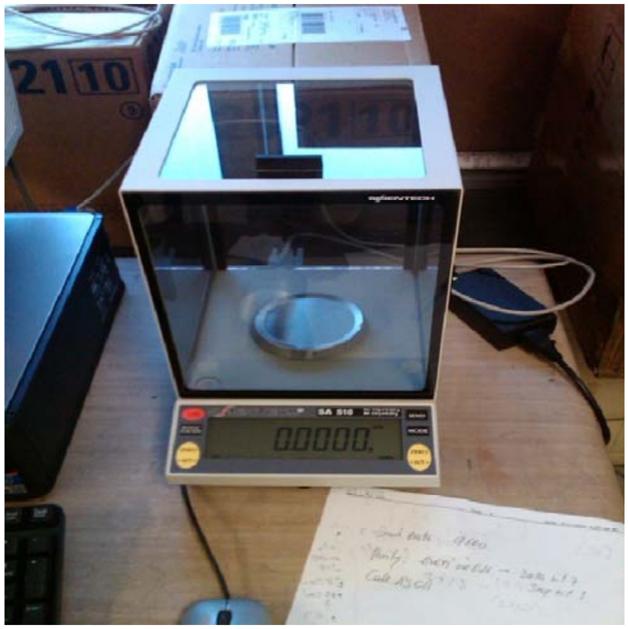


Figure 5-7 Scientech weighing scale

5.4.2 TSS/TDS Calculations

<u>Total Suspended Solids</u>

$$TSS = \frac{a-b}{c-d} \qquad \text{Eq. 5.1}$$

Where:
a = final weight of filter
b = clean filter weight
c = full flask weight
d = empty filter flask weight

<u>Total Dissolved Solids</u>

$$TDS = \frac{e-f}{c-d} \qquad \text{Eq. 5.2}$$

Where:
e = final weight of drying bowl
f = clean drying bowl weight
c= full flask weight
d = empty filter flask weight

5.4.3 Pollutants and Nutrients

The pollutants of concern in this particular study are Chlorides and Total Nitrogen (Total Kjeldahl Nitrogen (TKN) + Nitrate + Nitrite). Since the Total Nitrogen incorporates TKN, the raw sample must be chemically digested however, the other values (Chlorides, Nitrate, and Nitrite) are found using the collected raw sample.

The digestion procedure begins with adding 25 milliliters of raw sample to a VELP Scientifica® digestion tube. While in the tube 5 milliliters of a digestion matrix containing copper sulfate, potassium sulfate and sulfuric acid is added. The sample is then vortexed to insure that the sample and solution are completely mixed. Two boiling chips are added to the tubes that assist the sample to reach the required temperature. While preparing the samples, a blank as well as the standard nitrogen tubes are also mixed the same way. The Neutec® chemical digester is first brought to 160° Celsius and the samples are placed in the rack. After this temperature is reached, the samples are heated to 380° Celsius for three and a half hours.

The residual concentrated nutrients (in solid form) are diluted for analysis in an Easy Chem Plus Laboratory Analyzer for TKN. These prepared samples as well as the raw samples are all analyzed. Specific procedures can also be found in Appendix A in the QAPP.

Chapter 6 : Water Quality of the newly constructed stormwater wetland

6.1 Introduction

In this chapter, results of water quality analysis in the newly constructed stormwater wetland (CSW) on Villanova University's campus will be presented. Along with the cataloged data, manipulation and statistical analysis will be discussed and presented to statistically relate pollutant loads.

6.2 Statistical Procedures

This particular section addresses the statistical analysis procedures performed on both baseflow and storm events for water quality. The pollutants of interest are Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Chlorides, and Total Nitrogen (Total Kjeldahl Nitrogen (TKN) + Nitrate + Nitrite). Water quality results are given in terms of both mass and concentration. The reasoning behind this dual representation of data is to compare past water quality.

It should be noted that due to instrumentation malfunction in the laboratory, TKN values were not found for multiple samples. Future studies will include more TKN along with Phosphorus analysis for the constructed wetland.

6.2.1 Water Quality – Mass

The comparison of influent to effluent mass loadings is performed for both the baseflow and storm events. The loading of pollutant mass for storm events (M_s) is calculated by Equation 6-1

$$M_s = \sum_{i=begin}^{end} C_i Q_i \Delta t \qquad \text{Eq. } 6-1$$

where C_i is the concentration (mg/L) of the sample for the sampling interval (i), Q_i is the flow rate for the sampling interval, and Δt is the time interval. Likewise, the baseflow samples were also related using mass loadings (M_b) but using a slightly different calculation (Equation 6-2).

$$M_b = \overline{CQ} \Delta t \qquad \text{Eq. } 6-2$$

where $\bar{C}$ is the average concentration (mg/L), $\bar{Q}$ is the average baseflow rate and Δt is the time interval (i.e. for seasonal analysis Δt is 3 months).

Although samples for baseflow and storm events were taken at multiple locations in the CSW system, instrumentation limitations only allowed for flow data to be collected at the inlet and the outlet. Future instrumentation will allow for flow data to be collected at each of the sluice gate weirs through the use of pressure transducers.

6.2.2Water Quality – Event Mean Concentration (EMC)

According to Wanielista and Yousef (1993), event mean concentration (EMC) is "a statistical parameter used to represent a flow weighted concentration of a desired water quality parameter during a single storm event."

The procedure for the EMC method can be performed in two fashions. "If sequential water samples are collected, the EMC can be measured as the concentration in a flow-weighted composite sample with the volume of each fraction directly proportional to flow at time of collection. On the other hand, if sequential discrete samples are collected over the hydrograph, the EMC value can be determined by calculating the cumulative mass of pollutant (loadograph) and dividing it by the volume of runoff (area under the hydrograph)" (Wanielista and Yousef, 1993). Equation 6-3 is used to determine the EMC. The total volume is determined by finding the flows at eighteen hours before and after the storm and performing a flow-volume conversion.

$$EMC = \frac{\sum mass}{\sum runoff \;\; volume} \qquad \text{Eq.}\, 6-3$$

Past research projects on the Villanova University CSW have also used the EMC method for baseflow analysis but an average concentration was used instead of individually found concentrations (Wadzuk *et al*., 2010).

6.2.3 Water Quality – Exceedance probability

In conjunction with the event mean concentration (EMC), exceedance probabilities are used to track expected pollutant loadings entering and leaving the constructed stormwater wetland (CSW) system. This becomes important when determining if a stormwater control measure is operating under certain standard; in Villanova University's stormwater wetland, Pennsylvania standards are used (Section 6.3)

The exceedance probability method is performed by first finding the concentrations of certain pollutants entering and exiting the CSW. Once the data set is determined, a sorting of smallest to largest value is done for both the concentrations in and out of the system individually. The Gumbel method of ranking is applied to these values. The Gumbel method arranges all of the values from smallest to largest and ranks the smallest value as 1 and in increasing order. Gumbel values are assigned to each of the ranking numbers using Equation 6-4 where *i* is the value count.

$$Gumbel\ Value_i = \frac{ranking}{total\ ranks + 1} \qquad \text{Eq. } 6-4$$

The exceedance probability is then found using Equation 6-5 where *i* is the value count.

$$Exceedance = (1 - Gumbel_i) \times 100 \qquad \text{Eq. } 6-5$$

With the individually found exceedance probabilities for each events inlet and outlet concentration, a plot is created using logarithmic graphing paper. These graphical representations of data are useful in determining an amount of time that you can expect to see certain pollutant concentration levels.

6.3 Water Quality Standards for the Commonwealth of Pennsylvania

Regulated bodies of water in the state of Pennsylvania must meet standards in terms of pollutant concentrations (Table 6-1). It should be noted that these are the in stream water quality standards but Villanova University discharges a significant amount of water to Saw Mill Creek.

Table 6-1 Pennsylvania Water-Quality Standards (PA Code, 2009) for some of the researched pollutants discharged. Note: Pollutants of interest are starred (*).

Pollutant	PA Code (mg/L)
TSS*	25
TDS*	750
TN*	4.9
TP	0.14
RP	No Standard
Chloride*	250
Cu	1.0
Pb	0.05
E. coli (summer)	200/100 mL
E. coli (winter)	2,000/200 mL

The standards (Table 6-1) become useful in analyzing if the planting of a newly constructed wetland is required at the time of construction or if the planting may be postponed to a later time. This will be determined in the next sections discussing water quality results from both baseflow and storm sampling events.

6.4 Water Quality results and analysis

Once the construction of the new stormwater wetland was complete, water quality testing began. Results from September 14, 2010 to February 16, 2011 were gathered for both baseflow and storm events. During this sampling period, a total of 10 baseflow events and 2 storm events were taken.

Due to instrumentation error and malfunction, one of the two storm events was not fully sampled; however results will be presented as they are needed from this event.

6.4.1 Total Suspended Solids

When analyzing baseflow samples for total suspended solids (TSS), each of the sampling locations produced varying data. Figure 6-1 displays the average concentrations at each sampling location in relation to the date the sample was taken.

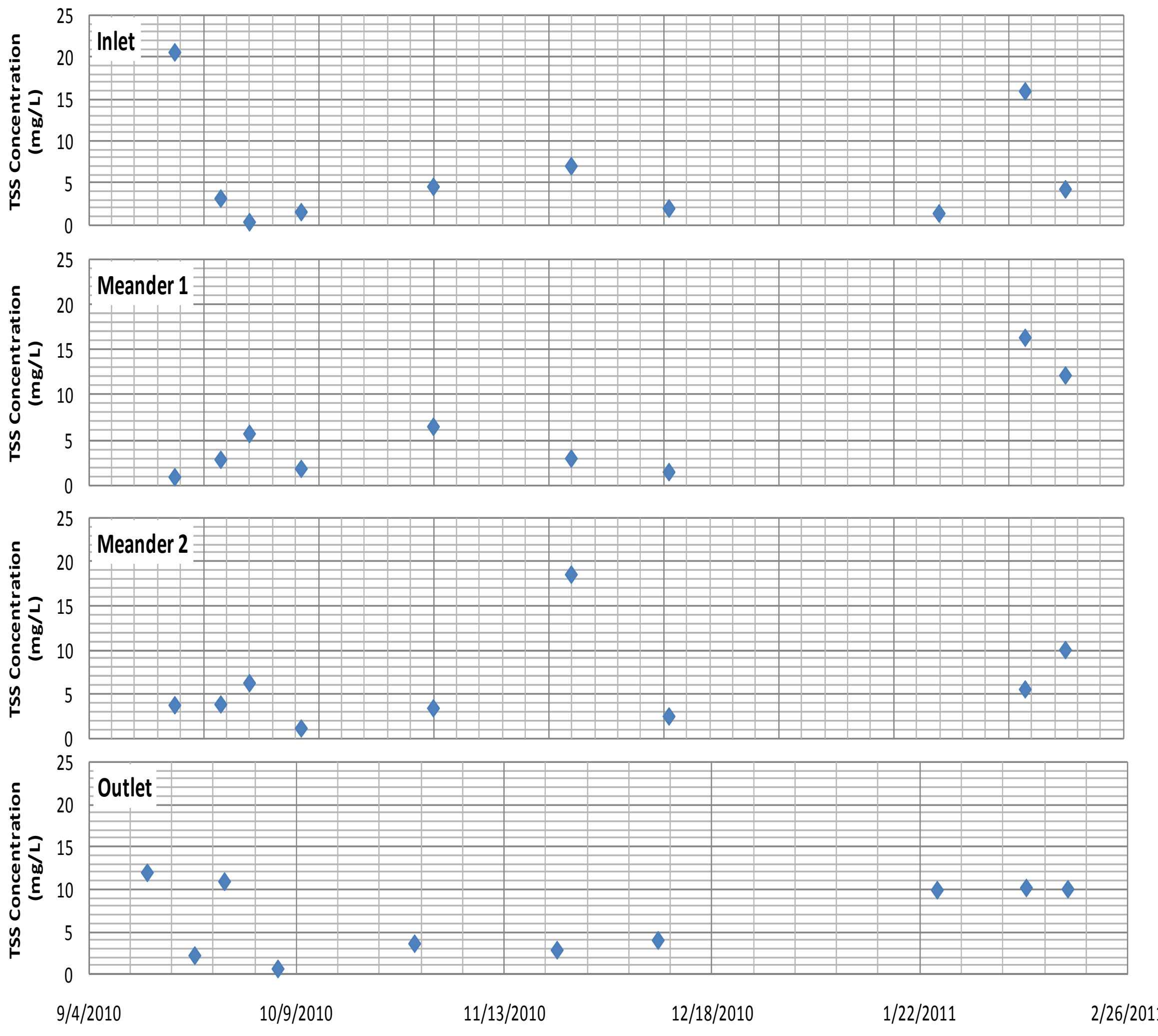


Figure 6-1 Total suspended solids (TSS) concentration at each baseflow sampling location in comparison to date

All of the TSS concentrations found provide no true pattern of treatment occurring in the wetland system. There are both increases and decreases in concentration as water moves from the inlet towards the outlet structure. Elevated TSS values occur for the system during the late fall and early winter, however all values are below the Pennsylvania standard (25 mg/L) for discharge concentration. It should be noted that the highest concentration presented was the first sampling event. This can be attributed to the fact that a single sample was collected at each location. After this point in time, the described 3-bottle sampling technique was employed (Section 5.2.1) to ensure the correct concentration was found.

Exceedance probabilities were found for all of the baseflow TSS events comparing them to the Pennsylvania standard of 25 mg/L. With analyzing the actual values of TSS, there was no exceedance percentage. Figure 6-2 shows the ranked concentration in and out of the wetland system compared to the Pennsylvania standard.

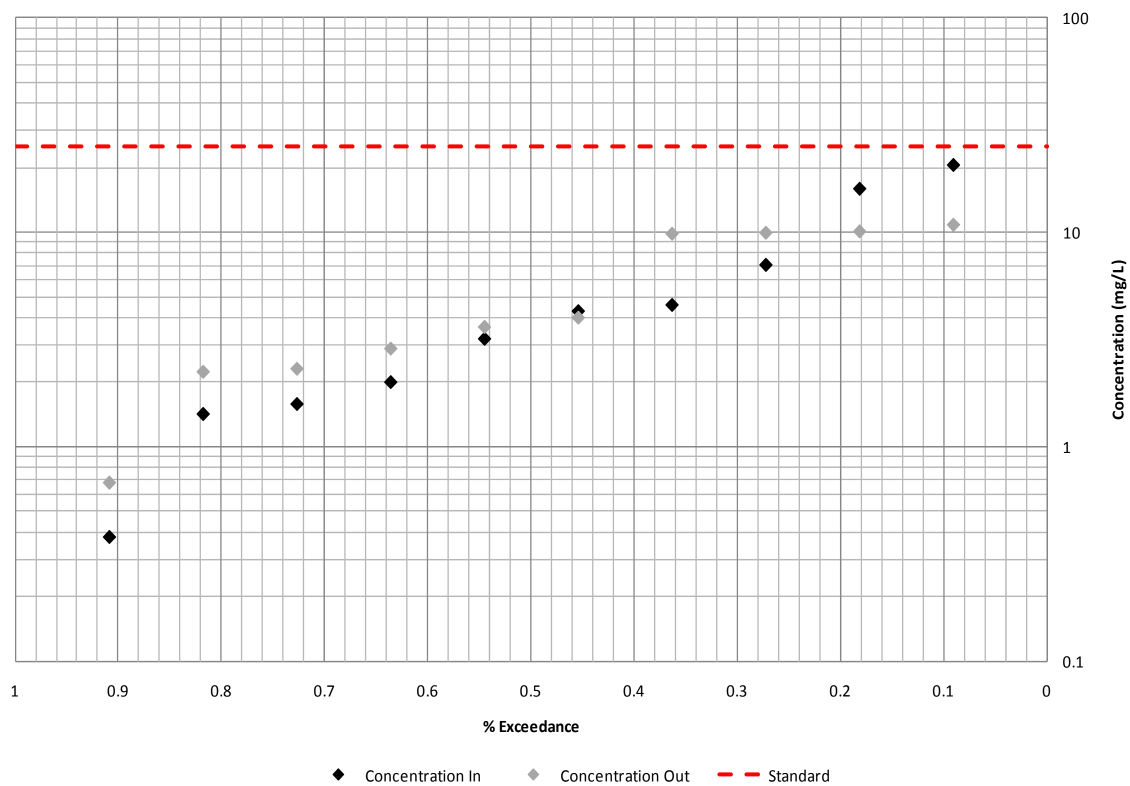


Figure 6-2 Exceedance probabilities for TSS concentration entering and leaving the constructed wetland system

When analyzing the storm events, 3 composites were taken at each sampling location (inlet, first meander, and outlet) to capture samples from the entire storm hydrograph. These sampling times can be found in Appendix B.

The first storm occurred on November 16, 2010 (0.44 inches over 36 hours; Figure 6-3) and as stated not all samples were captured. Although not all samples had been collected, one important relationship that stands out when analyzing these composite concentrations is the *first flush* phenomenon. The inlet composites show a large inflow of suspended solids followed by a rapid decline in concentration and low concentration for the remaining part of the storm. It should be noted the first flush TSS concentration is translated downstream, but the fact that highest meander concentration is the second composite and the highest outlet concentration is the third composite.

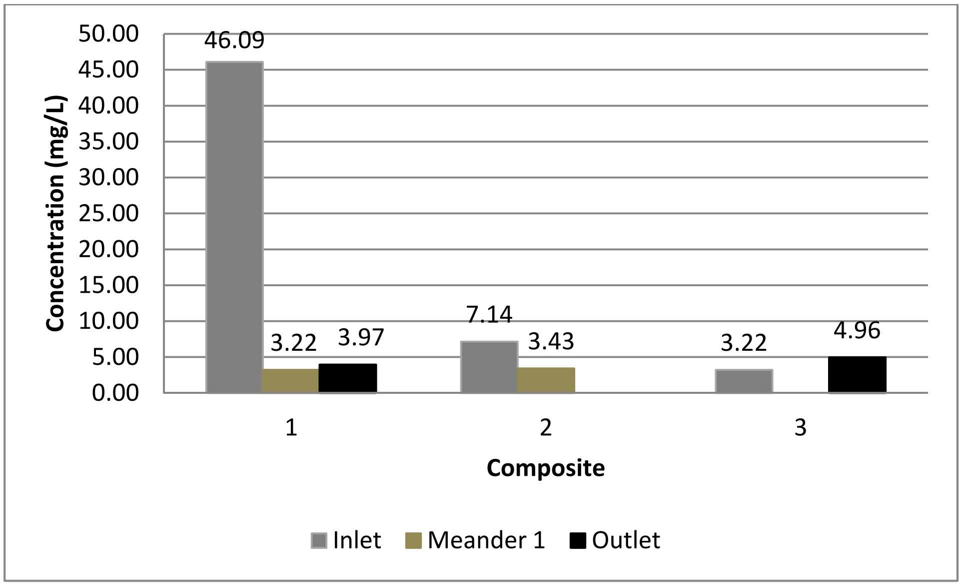


Figure 6-3 November 16, 2010 storm event TSS concentrations of composite samples

The second storm event collected contained all samples and a full description of the storm flow was able to be made. This storm occurred on November 30, 2010. This storm event had no similarities to the previous addressed event. The inlet TSS concentrations had the pattern of decreasing until after the peak of the storm and then returning to a lower concentration at the end of the storm. The meander samples throughout the entire storm were close to constant, lower value. Outlet concentrations increased toward the end of the storm decreasing to a value just higher than the Pennsylvania standard of 25 mg/L (Figure 6-4).

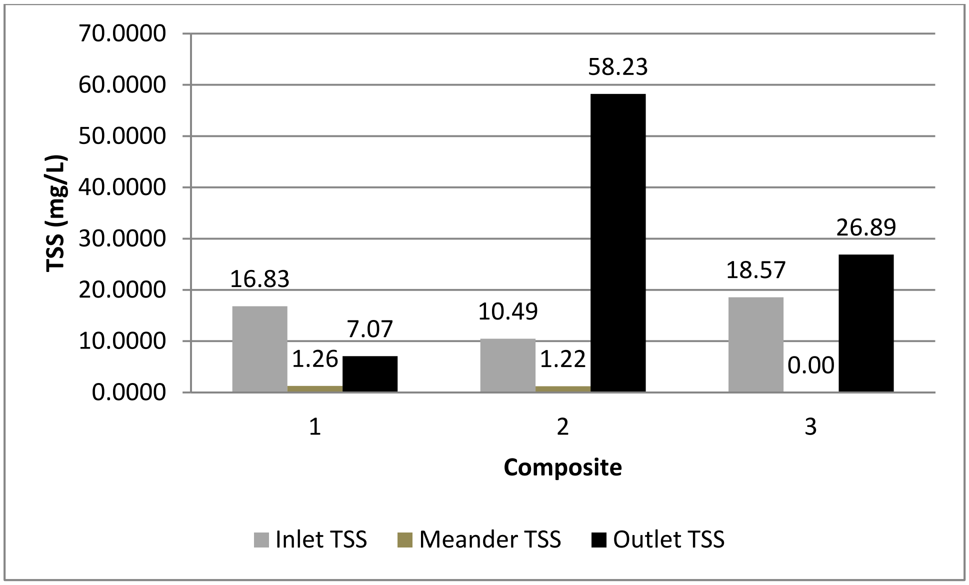


Figure 6-4 November 30, 2010 storm event TSS concentrations of composite samples

6.4.2 Total Dissolved Solids

Total dissolved solids (TDS) analysis followed the same direction as the TSS analysis presented in Section 6.4.1. The first step in analysis was seeing the overall trend of TDS in the system during baseflow events over the course of sampling times. Figure 6-5 shows the TDS concentrations at each sampling location in relation to the date the baseflow samples were taken.

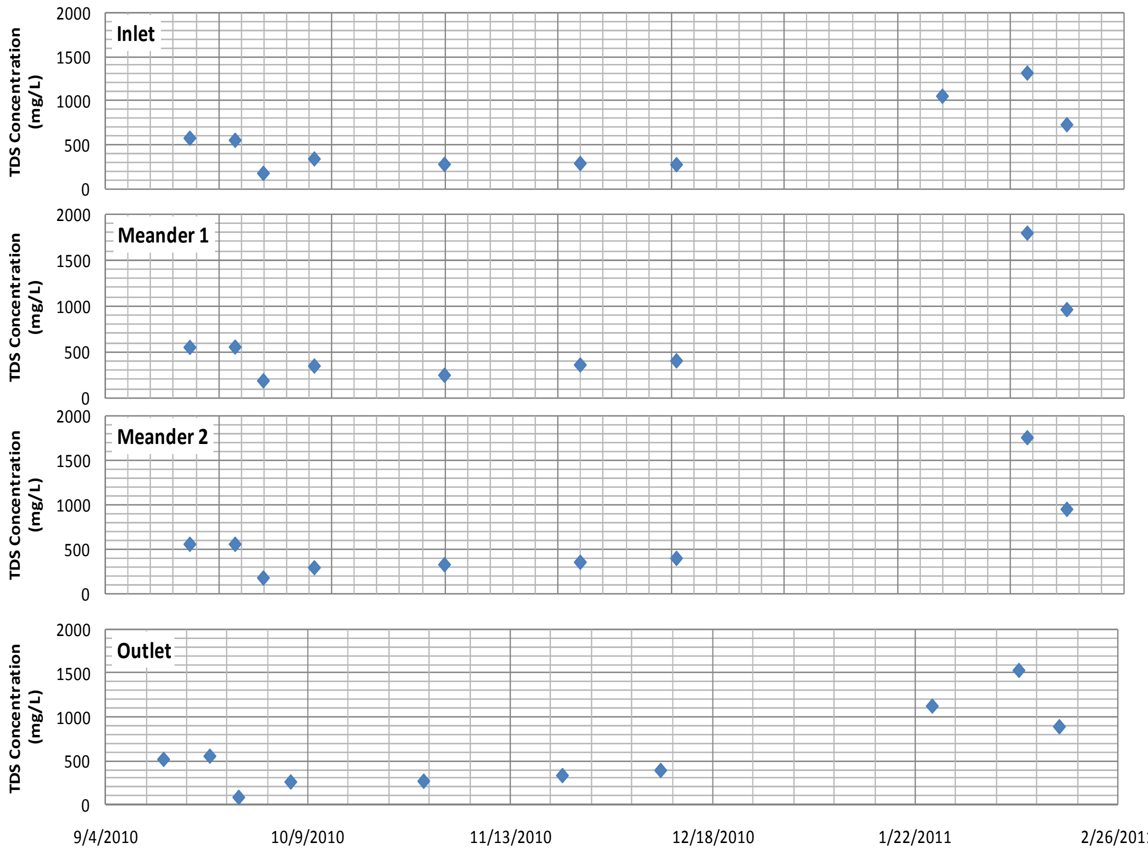


Figure 6-5 Total dissolved solids (TDS) concentration at each baseflow sampling location in comparison to date

From Figure 6-5 a few inferences can be made. As the samples are taken throughout the system, there appears to be no treatment for TDS and all of the concentrations at each location are about the same. The Pennsylvania standard for discharge of TDS is 750 mg/L. In the late summer and fall seasons, all of the concentrations of TDS are well below this standard, but the winter months are higher than the standard concentrations. This can be indicative of road salts being placed on the campus roads and parking areas. Another explanation of higher TDS concentration on site can be due to higher numbers of migratory birds using the site. The sites, being unplanted throughout the sampling events, provided a resting area for flocks of *Branta canadensis* (Canadian Geese) to feed and drop feces onsite in turn causing murky water.

As the TSS concentrations were analyzed, exceedance probabilities were used to determine how much of the time concentrations entering and leaving the system will be greater than the Pennsylvania standard. Figure 6-6 shows this plot along with the standard value on logarithmic paper.

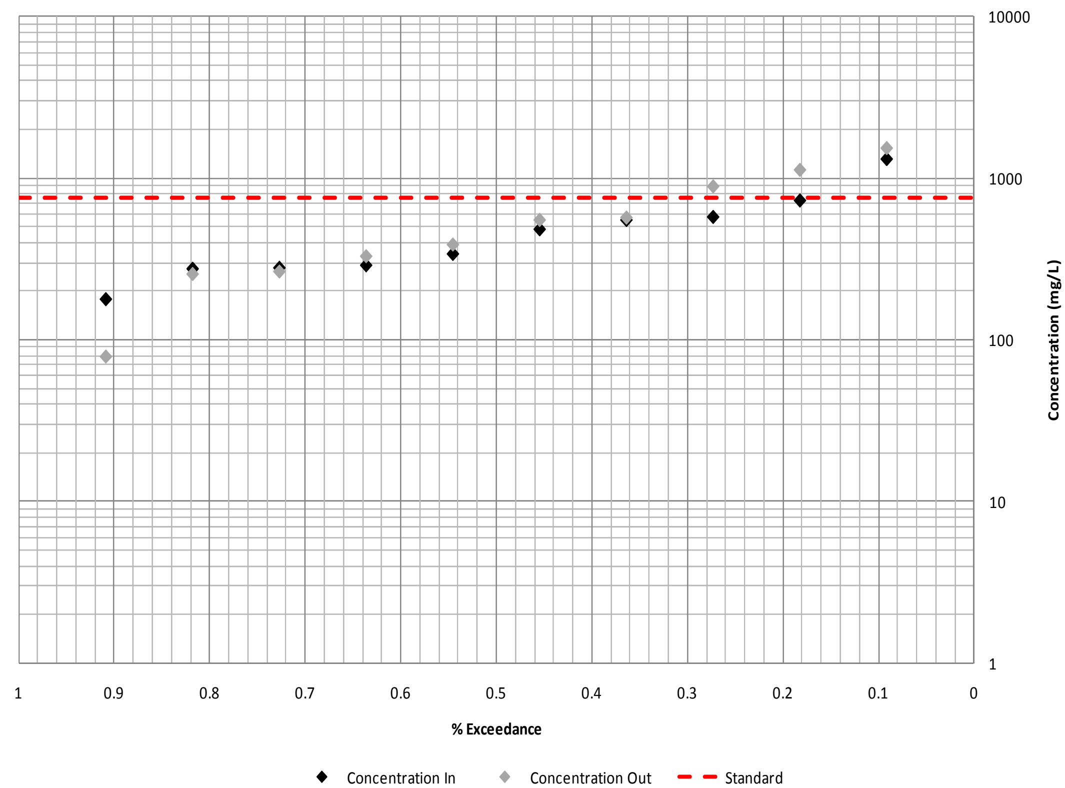


Figure 6-6 Exceedance probabilities for TDS concentration entering and leaving the constructed wetland system

From the exceedance probability chart, it can be noted that the concentrations of both incoming and outgoing flow remain under the Pennsylvania standard a majority of the time. The inlet concentration exceeds the standards about 19% of the time whereas the outlet concentration exceeds the standard about 32% of the time. What became important to note was that the three event data points that exceeded the standard were all during the winter months. The system, although no treatment is prevalent during baseflow, experiences lower TDS value during a majority of the year except for the winter months.

When analyzing TDS concentrations during storm events, 2 storm events were analyzed as was done in the TSS analysis. The first storm event was, again, on November 16, 2010. Figure 6-7 shows each of the composites for all three sampling locations and throughout the entire storm event.

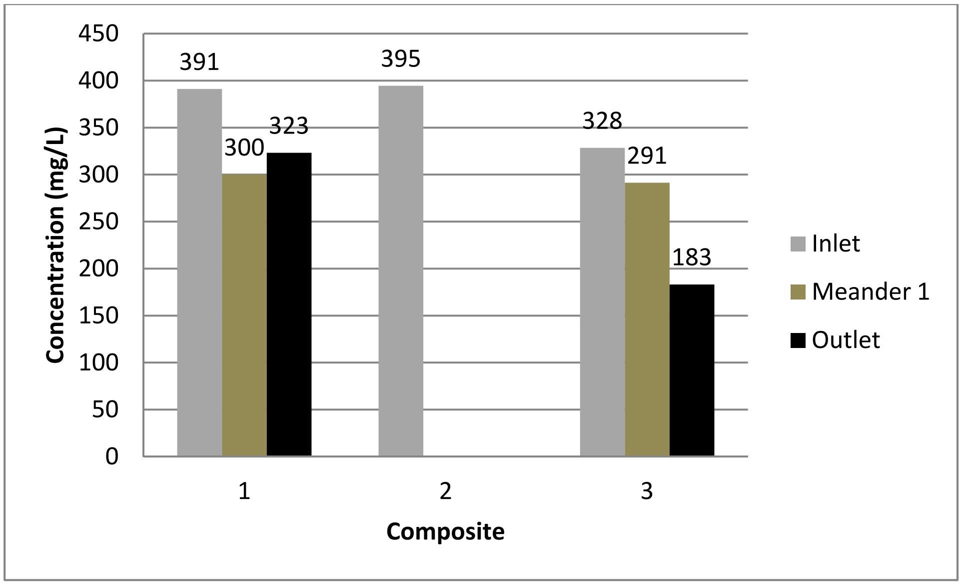


Figure 6-7 November 16, 2010 storm event TDS concentrations of composite samples

For the inlet concentrations throughout the storm experiences a fairly constant level for the first half of the storm followed by a slight decrease in concentration at the end of the storm. The meander and outlet second composites were not successfully acquired causing no analysis the center part of the storm to be performed. Both of these sampling locations experienced declines in TDS concentrations between their first and last composite.

The second storm event, again, occurred on November 30, 2010. For this storm event, all composites were acquired and a full analysis of the storm could be made. This storm event, compared to the November 16, 2010 storm experienced higher values of TDS concentration.

Inlet concentrations of TDS followed the sample general pattern of decreasing towards the end of the storm as did the previously described event (Figure 6-8). As opposed to the other storm, the highest TDS concentration existed at the first meander of the wetland system. There is an inlet structure that enters the wetland boundaries right before the first sluice gate weir that gathers runoff from parking areas near the new Villanova School of Law. As expected, the dilution from the storm flow provided the outlet structure with the lowest values. The outlet concentrations have a rapid decrease of 47.4% between the first and second composite and stabilize after this. This could be due to the first flush coming through the system followed by cleaner storm flow.

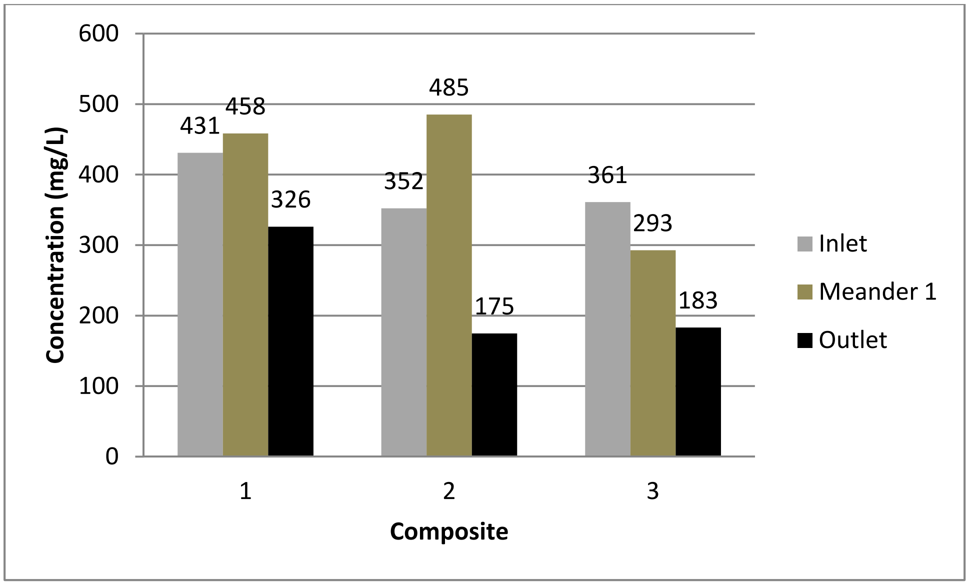


Figure 6-8 November 16, 2010 storm event TDS concentrations of composite samples

6.4.3 Nitrogen Species

A total of 4 baseflow events and 2 storm events were analyzed for Nitrite, Nitrate, and TKN. The TKN concentrations only were analyzed for two of the baseflow events. As opposed to the TSS and TDS analysis, there were not as many data points collected due to laboratory instrumentation malfunctioning.

Overall patterns in nitrogen species within the wetland system existed sporadically and were not consistent; nitrite and nitrate baseflow concentrations can be found in Appendix D (Figure D-1). As it is an unplanted system, no plant-life interactions took place. Two of the particular baseflow events were interesting to compare to one another. One of these baseflow events was during a warmer, 50° F day (Figure 6-9) and the other a wintry, 20° F day (Figure 6-10).

Analyzing the first of the baseflow plots, November 22, 2010, a distinct pattern is observed. From the inlet to the outlet of the newly constructed wetland, a decrease in nitrate (NO_3) and an increase in nitrite (NO_2) are prevalent (i.e. denitrification). However, when the next baseflow event (December 9, 2010) is plotted, no apparent trend occurs. These two events become interesting when analyzing the affects of temperature on different processes that take place in the open channel system on campus and could be included in a future study.

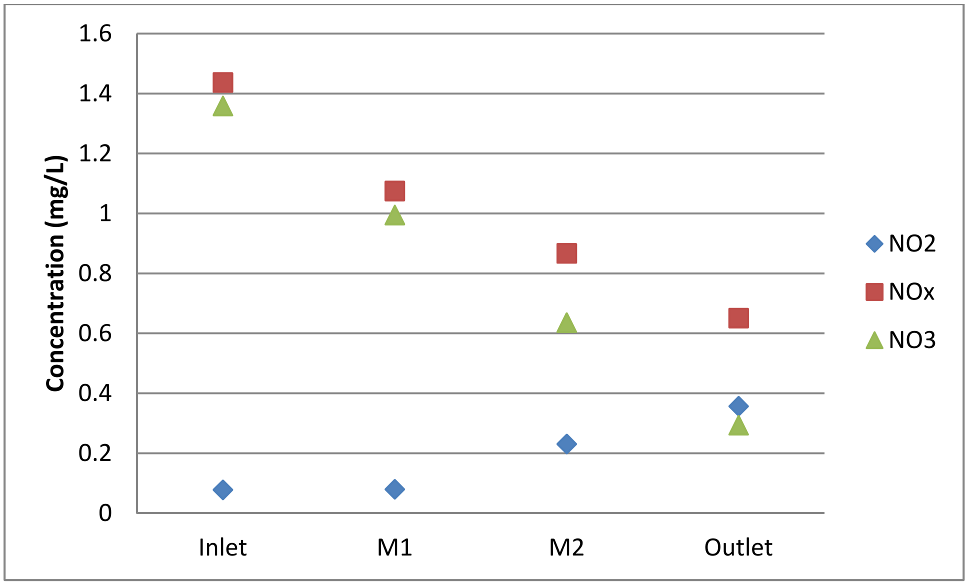


Figure 6-9 November 22, 2010 baseflow tracking nitrogen species from inlet to outlet

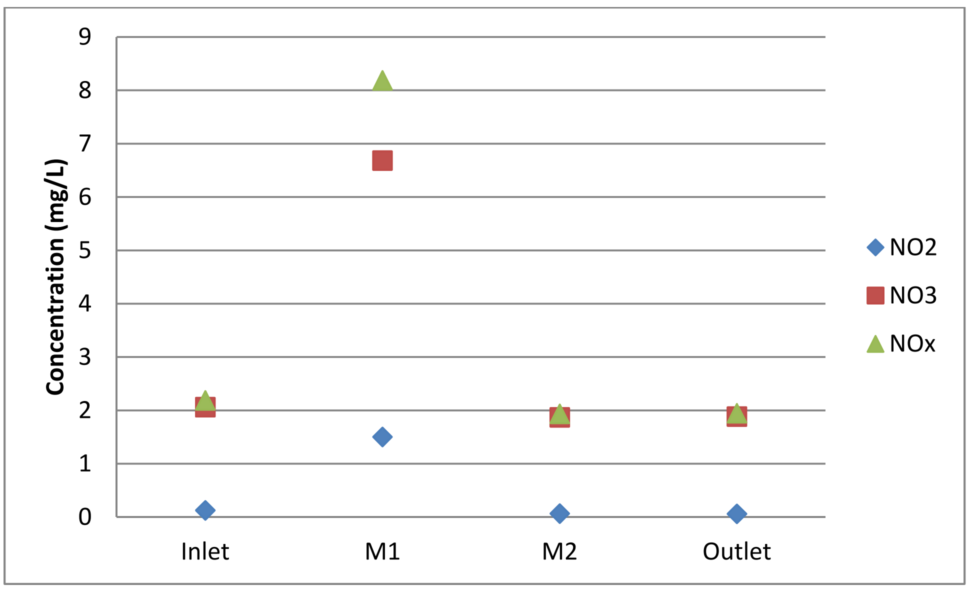


Figure 6-10 December 8, 2010 baseflow tracking nitrogen species from inlet to outlet

The TKN analysis performed on the two baseflow events had not significant trends or patterns that could be observed but it was felt that the data should be presented. This data can be found in Figure D-2 of Appendix D.

Storm events were collected to see if there were any noteworthy trends throughout the hydrograph in NO_2 and NO_3. For both of the storm events described (November 11, 2010 and November 30, 2010) the NO_3 concentrations are higher than the NO_2 concentrations throughout the storm (Figure 6-11 and Figure 6-12). As opposed to the baseflow events sampled, the system has less retention time allowing the conversion of nitrate to nitrite within the channels.

Both of the storm events show nitrate values in the system being less than 0.5 mg/L for all sampling locations (inlet, meander 1, and outlet) for the entire hydrograph. The nitrate patterns for each individual storm are slightly different. The second storm sampled shows higher values of nitrate concentration than the first storm. This could be explained by an increase in geese 'fly-overs' during the later fall.

It appears that for both storm events, the meander 1 sampling location experiences higher values of nitrates throughout the storms entirety. The sediment forebay being larger and deeper flows directly to the sampling location with limited vegetation or turbulence in the channel for treatment. A possibility of explanation for these elevated nitrate levels is the sediment forebay acting as a sink and discharging when increase flows occur through the system. It has been noted that the geese tend to flock in the sediment forebay, as well.

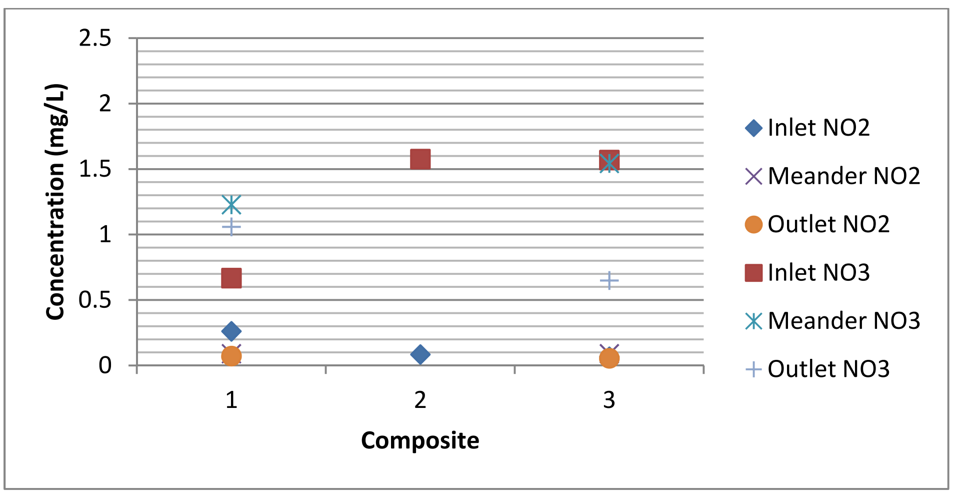


Figure 6-11 November 11, 2010 storm composites tracking nitrogen species

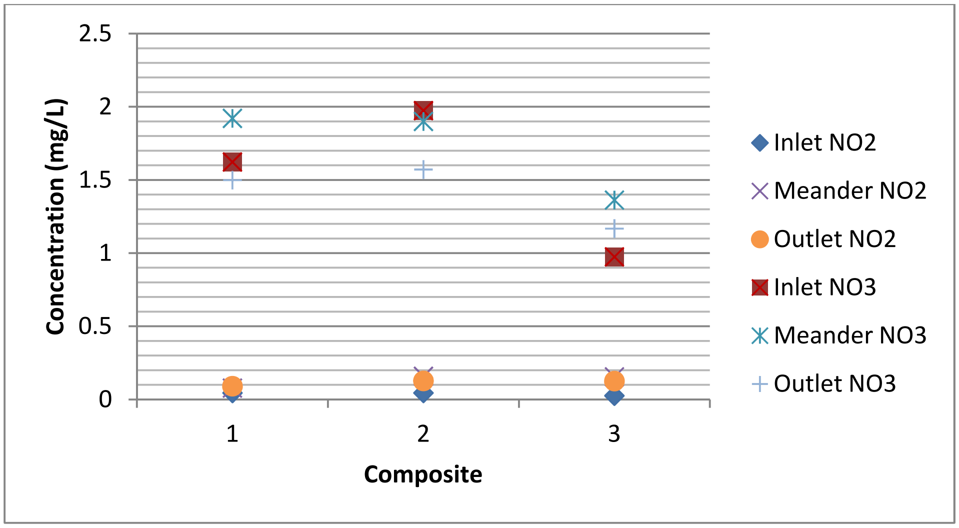


Figure 6-12 November 30, 2010 storm composites tracking nitrogen species

6.4.4 Chlorides

Chloride analysis consisted of 4 baseflow events and 2 storm events sampled to track changes in concentrations.

The baseflow concentrations observed were not consistent with each other. There were events decreasing, constant, rising and falling, and increasing from inlet to outlet (Figure 6-13). Although the patterns do not follow an obvious trend, all of the chloride concentrations being released from the unplanted wetlands remain under the Pennsylvania standard of 250 mg/L.

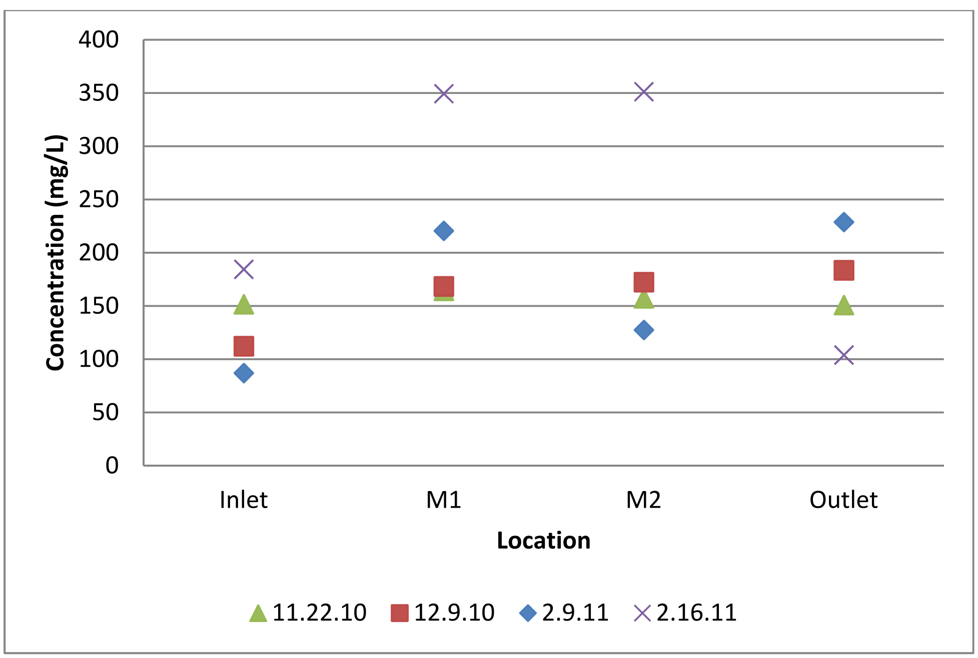


Figure 6-13 Baseflow chloride concentrations at each sampling location for each sampling event

Tracking of storm event chloride loads shows a first flush but also the process of dilution occurring with the onset of a storm (Figure 6-14). The storm event on November 16, 2010 shows decreasing concentration from the start of the sampling period till the end. The highest concentrations are for composite number 1. The storm event on November 20, 2010 shows the same decrease in concentrations from the first composite to the last however, the second composites for the meander and outlet spike during their second composite. This could be explained by the lag in the first flush due to the retention time of the system. Future studies should analyze the delay in the hydrograph throughout the system for both unplanted and planted systems.

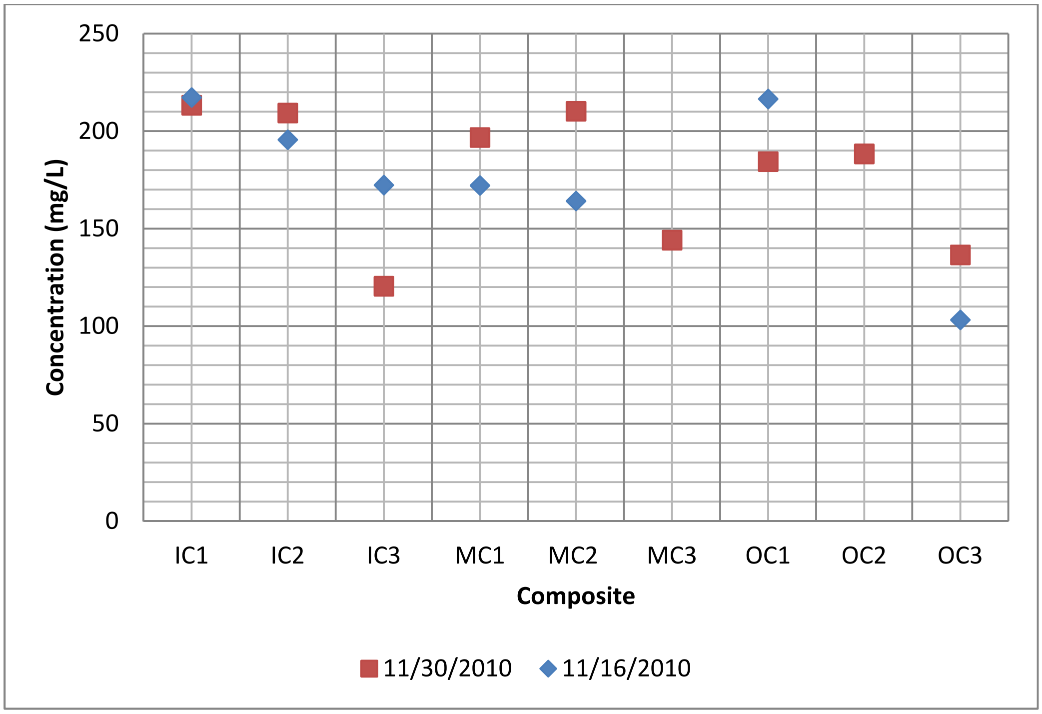


Figure 6-14 Storm event tracking of chloride concentrations (Notation: IC1 is the Inlet Composite #1)

Chapter 7 : Conclusions

7.1 Introduction

In this chapter, conclusions from both the modeling section and water quality section will be made along with recommendations for future studies. It is important to note that this study is the initial stage for ongoing pollutant tracking within the newly constructed wetland.

7.2 Modeling

In the initial planning of the watershed modeling project, geographic information system (GIS) technologies were investigated. After analysis of the HEC-GeoHMS model (Army Corps of Engineers), it was determined that a model capable of continuous simulations that incorporated urban hydrology would be more appropriate. The Stormwater Management Model (SWMM) released by the EPA proved to be the best match for the project goals.

The SWMM program can handle both the single event as well as long term, continuous modeling. Its multiple parameter input system allows the modeler to customize their model based on infiltration methods and routing techniques. Parameter input, although tedious, increases precision giving better results (based on flow comparison performed). The curve number infiltration method and the kinematic wave routing function were used for all modeling purposes.

After a full sensitivity analysis of both a simplified watershed and the created Villanova University watershed model, the SWMM model showed little alteration to peak flow, average flow, and total volume. Each individual watershed's parameters were changed individually to see their respective affects on the three stated results. It was shown that each variable was as important as the next; each value did not change drastically even with change in input value. This leads to the conclusion that the modeler can estimate parameter input for features that may not be known or quantified in the watershed. This is not to say that it does not alter hydraulics, but the hydrology remains stabile with alteration of parameters. The hydraulic modeling of the system was not analyzed however SWMM is capable of analysis of this watershed attribute.

A total of 67 subcatchments were placed within the Villanova University model, each containing specific data on their areas as well as land use, curve number (CN), and other pertinent information. Much of the Villanova University campus is developed and the CN values were on the higher end of the scale; greater than 80.

As there are many subcatchments in the presented watershed model, the model produced appropriate flow data. For the modeled single storm events, there were some problems comparing actual flow data to simulated data but solely due to instrumentation error. The simulated historic storms proved to differ in peak timing by +/- 15 minutes and the model responded acceptably for a single storm event (i.e. less than 3 days). Peak flows were within a tight range for most simulations (+/- 4 cfs), however since the system was simulated without long periods of data prior to the storm, peaks differed more than a continuous simulation. When monthly rainfall data was simulated, the model seemed to calibrate the system and the produced peak flows were within a closer, more acceptable range to the actual historic flow data. For both of the inlets to the constructed wetland (outlets of the watershed), the total volumes were within +/- 4.0%.

The SWMM modeling software proved to be accurate and model different events with ease. In terms of watershed management and urban planning, it has been an argument whether to design stormwater control measures based on peak flow reduction or total volume received. With user inputs being easy, the SWMM software is a fast and effective modeling package that should be used in urban hydrology. Its ability to incorporate hydraulics into its computations allows the user to analyze an urban watershed in its entirety.

7.2 Water Quality

The newly constructed, although unplanted during the sampling period and being in the initial stages of this ongoing study, performed well considering the conditions. The physical integrity of the site was challenged during an extremely large storm event 2 months after the completion of construction. Minor damage did occur on site with the high velocity geotextile being torn but not displaced along with some scouring of the channels and berm erosion close to the sluice gate weirs. The site did reach maximum water capacity and overtop the berms but the site operated and performed accordingly.

Water quality analysis for the first few months after construction showed some individual event trends but treatment of inflow water was sporadic. Samples were taken during baseflow and storm events then analyses were performed to determine total suspended solids (TSS), total dissolved solids (TDS), nitrite, nitrate, total kjeldahl nitrogen (TKN), and chloride concentrations.

The site, although there was not always a reduction of concentrations, did assist in keeping the concentrations leaving the system below the Pennsylvania standards for a majority of the sampling events. There were baseflow events that emitted higher concentrations of TDS, but they all occurred during the winter months where there were significant higher amounts of salt and increased migratory bird feces. This increase in TDS also correlates with increase levels of nitrogen species that could be attributed to the bird activity.

Comparison of TSS and TDS to Pennsylvania standards was accomplished using exceedance probabilities that showed on average, how much of the time higher pollutant loads would be experienced. TSS baseflow concentrations remained under the standard at the outlet structure (25 mg/L) however the TDS showed above standard concentrations (750 mg/L) in 31% of the samples (i.e. winter months). Both of the TSS and TDS concentrations during storm events demonstrated the first flush phenomenon with initial onset of high concentrations followed by a rapid reduction in concentration.

Although nitrogen species analysis was performed, a total nitrogen comparison to Pennsylvania standards was unable to be made. The laboratory equipment to determine these concentrations was intermittently operating at full performance. For some of the baseflow and storm events only nitrite and nitrate were analyzed and other sampling events only analyzed TKN. During a single baseflow, there was however a beneficial denitrification trend moving from the inlet to the outlet (warmer temperature day). This will prove important when comparison to a planted wetland on the conversion of nitrogen species. Storm events showed reduction of concentrations that can be attributed to the same first flush phenomenon that was with the TSS/TDS concentrations.

Chloride concentrations were observed to take many different patterns during the baseflow samples. There was no succinct pattern that could be determined except that all baseflow outlet concentrations were under the Pennsylvania standard of 250 mg/L. Storm events, for all of the hydrograph, produced values below the standard as well.

7.3 Final Remarks

The constructed stormwater wetland, although in its first few months of lifespan, performed adequately giving the presented conditions. Withstanding large storm events and no detrimental damage occurring showed that if a similar site is correctly designed and constructed, the absence of plants is acceptable for an undefined time span for the Philadelphia area. It is recommended that planting occur as soon as possible for just the overall integrity to begin to build.

Water quality treatment in the constructed wetland was sporadic and not many trends were observed. Although the site was unplanted throughout this study, it still assisted in keeping a majority of pollutants below the Pennsylvania standards.

7.4 Future Studies

As any research points to more ideas and theories, this study has allowed much brainstorming of future studies. After the planting of the wetlands occurs, throughout the sites maturing process flow data can be assessed to see how the development of the site contributes to flow reduction along with water quality improvement from inlet to outlet.

The site does contain the three sluice gate weir structures that will be fully equipped with pressure transducers to assist in the tracking of flow through each meander. Along with the improved flow data, it is intended to install two more autosamplers at the remaining meanders to allow a full tracking of pollutant loads and reduction through each part of the constructed wetland. Specifically, there will be an additional study concerning the wetlands ability to treat phosphorus which remains a growing concern in many urban and agricultural areas around the world.

Finally, in the near future, alteration of sluice gate elevations will be experimented with to find the best ponding characteristics to improve water quality. The benefit of having the site designed with sluice gates is the ability to alter flow conditions according to maximize water quality treatment.

The constructed stormwater wetland site is still in the initial stages of development and much research will come from this site. The wetlands system will remain a full part of the Villanova Urban Stormwater Partnership's research and future work will continue concerning many aspects of both the science and engineering of the site.

Appendix A

Quality Management Plan

For

VILLANOVA URBAN STORMWATER PARTNERSHIP

Organization

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Table of Contents

Associated QAPP'a

- **Nutrient Loading in a Mature Constructed Wetland**
    - **Approved EPA Office of Water**

- **BioInfiltration and Infiltration Trench BMPs**
    - **Attached**

- **Pervious Concrete – Porous Asphalt Comparison Study**
    - **Under Development**

1. Management and Organization

1.1 Mission and Quality Policy

The *mission* of the *Villanova Urban Stormwater Partnership (VUSP)* is to advance the evolving comprehensive stormwater management field and to foster the development of public and private partnerships through research on innovative Stormwater Management Best Management Practices, directed studies, technology transfer and education.

The *purpose* of the *Villanova University BMP Research and Demonstration Park* is to:

- determine the effectiveness of the VUSP best management practices (BMPs) in reducing stormwater runoff volumes, peak flows, and non-point source pollution to the surface water system,
- determine the volume and quality of any infiltrated runoff, and the effect to the groundwater system,
- understand how the BMPs work and develop design procedures, and
- provide data to support the EPA – ASCE National Stormwater BMP Database.

The *purpose* of the *Quality Management Plan (QMP)* is to set *policies* to insure high quality standards for all work and practices. The goal is to meet or exceed the standard as set forth in the USEPA Manual (2002) "Urban Stormwater BMP Performance Monitoring." The QMP document explains the concept of what we do, how we do it, and how we know we did it. The QMP overarches multiple projects and contracts associated with the VUSP and the Villanova University BMP Research and Demonstration Park.

Generally, research is focused on the following water quality parameters.

Temperature

pH

Total Suspended Solids (surface samples only)

Total Dissolved Solids (surface and subsurface)

Chlorides

TKN / TP

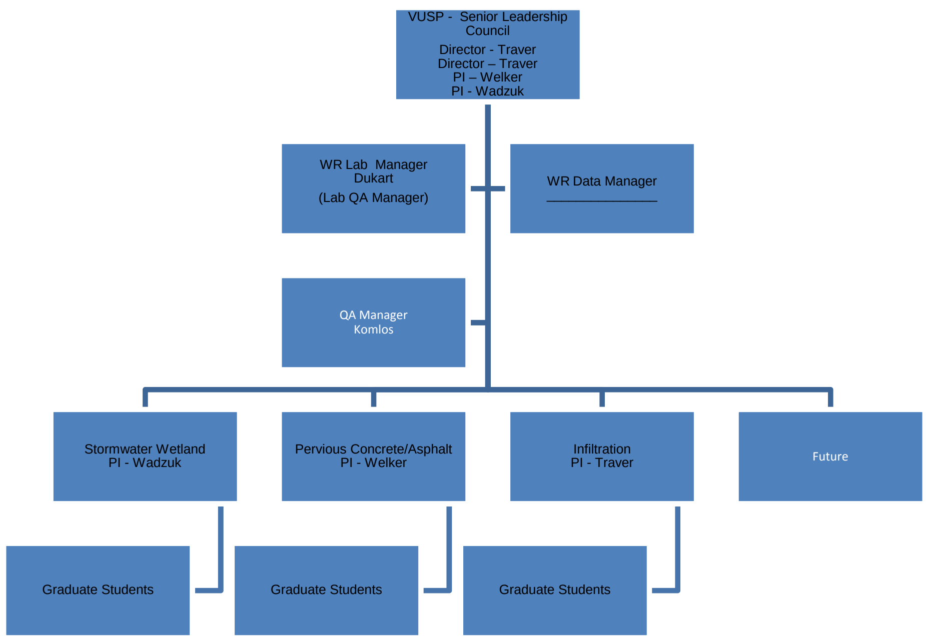
Particulate & Dissolved metals: Pb, Cu, Cd, Zn

Polyaromatic Hydrocarbons

The water quality parameters selected for study for each BMP is specified in the site QAPP. Sample collection procedures and standards for each parameter is set forth in SOP's. See Appendix A for the Target Detection Limits Table 3.1 (EPA 2002)

USEPA (2002) - "Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements"

1.2 Organizational Structure



The VUSP is housed in the Civil and Environmental Engineering Department at Villanova University. Research directions are set through the individual contracts, and / or as per the direction of the VUSP Research Partners board. Currently there are three research teams, each focusing on a specific site or sites. These sites are the Stormwater Wetlands, Pervious Concrete / Porous Asphalt, and Bio Infiltration / Retention (and Infiltration Trench). Each group is covered by a separate QAPP as required. Each team consists of a faculty PI and graduate students.

1.2.1 Responsibilities and Authorities

VUSP Director – Responsibilities for overall direction, coordination and oversight of the VUSP. Other duties include external commu.nication and outreach to the VUSP partners, and the stormwater community. Responsible for review and update of quality policies. Supervises the Water Resources Laboratory Technician (and future data manager).

Senior Leadership Council – Responsible for decisions of resource allocation, and ongoing review of operational and quality policies and procedures.

Principle Investigators (PI) – Responsible for the research performed at their respective stormwater Best Management Practices. Responsible for the Quality Assurance Project Plans (QAPP), including quality reviews. Acts as research team quality manager.

Water Resources Laboratory Manager (WRLM) – Responsible for all laboratory operations including instrument calibration and repair, QAPP quality testing SOP's, and oversight of student laboratory work. Acts as the Laboratory Quality Assurance Manager. Note that the WRLM supervises the student laboratory testing and analysis, but is not directly associated with collecting, generating, compiling or evaluating the environmental data.

Water Resources Data Manager (WRDM) – Responsible for database operation of all data streams. Position is filled as funding permits

Graduate Students (GS) – Assigned to each site for sampling, data collection and research. Note that all students share responsibility for laboratory testing, analysis and record keeping. One GS is designated weekly as "Rainmaster" to watch the weather and coordinate storm sample collection.

1.3 Technical Activities

The stormwater monitoring strategy focuses on assessing flow volumes, rates and pollutant loads for wet weather flows entering and exiting the BMPs; baseflow assessment is also performed when needed. As deemed appropriate, each site is equipped with rain gages, water sampling devices and flow or level recorders. Measurements of stormwater flows into and out of the BMP provide data on the volumetric capacity of the BMP and its ability to retain, infiltrate, or dampen stormwater flows. Water quality sampling, stormwater, infiltration, and overflow are analyzed for a host of parameters including pH, temperature, conductivity, total suspended solids, dissolved solids, chlorides, nutrients and metals. It should be noted that the extent and frequency of monitoring are presented in the project QAPP, and statements here are goals for full implementation.

1.3.1 Stormwater Wetland BMP

In the spring of 2000, the Villanova University Stormwater Project team modified an existing detention basin along County Line Rd. on Villanova's campus to create an extended stormwater wetlands. The wetlands were designed to treat runoff from approximately 41 acres of land with 16 acres being entirely impervious. Storage was maximized through the use of multiple meanders and gravel berms. A sedimentation forebay was included and designed to allow sedimentation for small to medium sized storms, but to be bypassed for larger ones. A planting scheme was selected based on various plants abilities to thrive at different inundation levels, Figure 1.3.1.

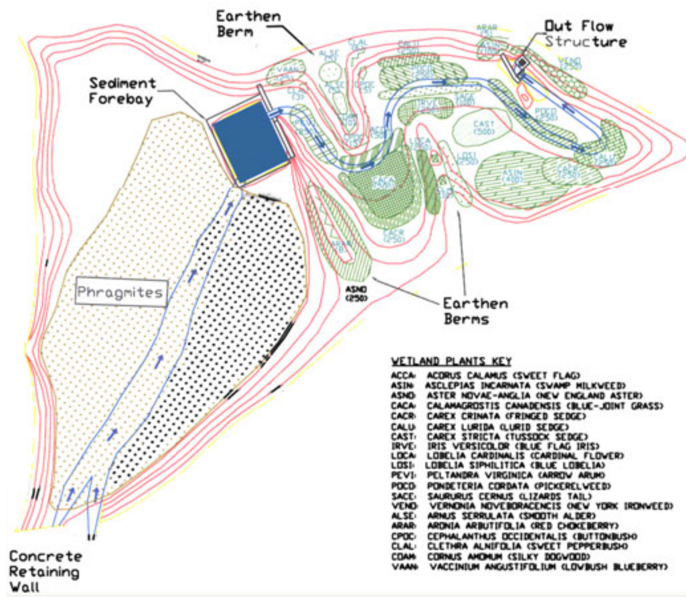


Figure 1.3.1 Original Plant Scheme of Stormwater Wetlands

In the summer of 2006, a restoration project of the stormwater wetlands was initiated. While the stormwater wetlands was initially planted with a wide variety of plants, *Phragmites australis* became the dominant vegetation over time. Herbicide was sprayed at the end of the growing season to begin the phragmites eradication plan. The phragmites were harvested in spring 2007, followed by a second spraying when new growth emerged. It is anticipated that this restoration project will take two to three years; several more spray episodes are expected at the end and beginning of each growing season.

Design Goals and Performance Criteria

The monitoring goal is for both wet weather events and dry weather base flow:

- <u>Stormwater Quantity</u>: The site has been fully equipped to monitor flow into and out of the stormwater wetlands at three designated sites (2 inlets, 1 outlet). The site is also outfitted with a raingage to properly monitor rainfall at the site.
    - Rainfall is measured in 5 minute increments by a tipping bucket rain gauge located at inlet west.

    - Three America Sigma Area Velocity flow meters located at inlets main and west and outlet pipe monitor continuous depths and velocities in 5 minute increments.

- Stormwater Quality: When samples are required, grab samples or an autosampler may be used.
    - American Sigma 900 Standard Autosamplers are located at the main and west inlets, sediment forebay and outlet. They are initiated by rainfall.
    - Baseflow quality samples are taken via grab samples after a period of at least 72 hours of no precipitation.

1.3.2 Pervious Concrete / Porous Asphalt

Villanova has developed a study to ascertain the differences between pervious concrete and porous asphalt in regards to durability, maintenance requirements, and ability to transmit or filter key contaminants such as hydrocarbons. Two nearly identical parking areas have been constructed on Villanova University's campus to establish the performance characteristics of pervious concrete and porous asphalt (Fig 1.3.2).

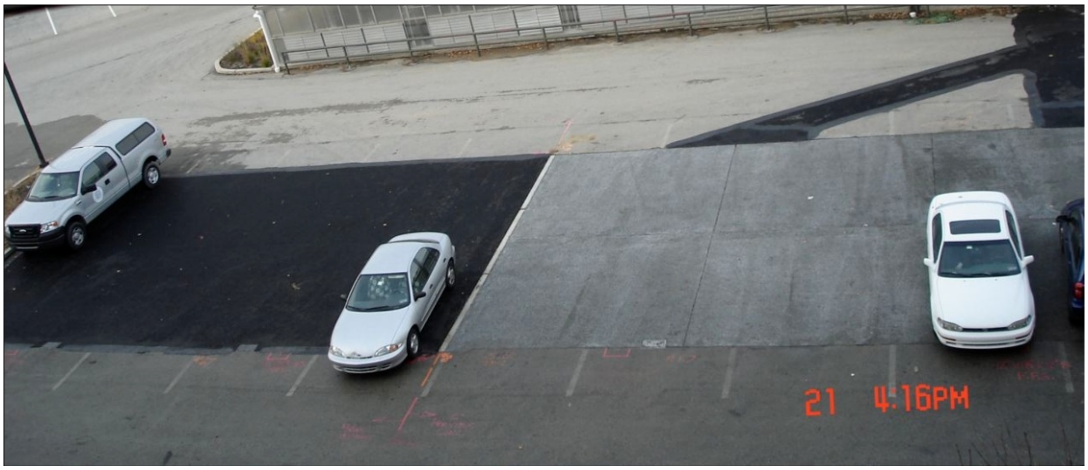


Figure 0-1.3.2 - Pervious Concrete / Porous Asphalt Comparison Site

<u>Design Goals and Performance Criteria</u>

The goals of the Pervious Concrete / Porous Asphalt BMP is to store and infiltrate stormwater and remove nutrients, contaminants and sediment. Data collection includes both water quantity and quality sampling / monitoring.

- <u>Stormwater Quantity</u>: The PC/PA has been equipped to observe runoff entering the system through the porous surface. These flows are correlated to the rainfall amounts measured by a raingage located on the premises. The site is further equipped to measure ponded depths and potential overflow.
    - Rainfall is measured in 5 minute increments through the use of a tipping bucket raingage.
    - Pressure Transducers that measure the flow in 5 minute increments are used to measure depths in each rock bed. They are also used in conjunction with a V-notch weir to measure any overflow.
- <u>Stormwater Quality</u>: Sampling is conducted based on precipitation events. The samples are representative of surface runoff and sub-surface soil moisture samples. On average, 12 -18 storms are sampled yearly.
    - Two first flush samplers catch the first two liters of direct runoff from the impervious surfaces upstream of each pervious surface.

- Grab samples are taken of runoff stored in the rock bed utilizing the portals following the storm
- Lysimeters are located at depths beneath the surface. They extract a sample from the soil through the use of porous ceramic cups placed under suction during a storm event and pressure after completion of the storm event using a pressure-vacuum soil water sampler

1.3.3a Bioinfiltration Traffic Island

During the summer of 2001, the VUSP project team converted an existing traffic island into a bio-infiltration BMP (Figure 1.3.3). The facility provides for the infiltration of the stormwater runoff from the initial first flush. The drainage area represents approximately 1.1 acres of mostly paved surface (Figure 1.3.4). Through infiltration, the BMP reduces downstream stormwater volumes, stream bank erosion and non-point source pollution to the headwaters of Darby Creek.

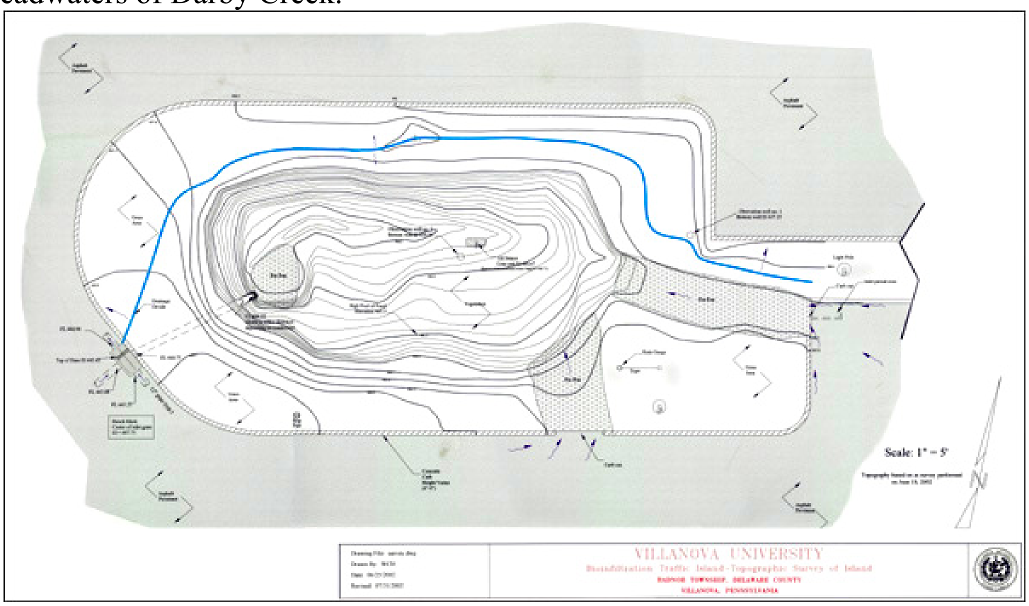


Figure 1.3.3 BioInfiltration Traffic Island

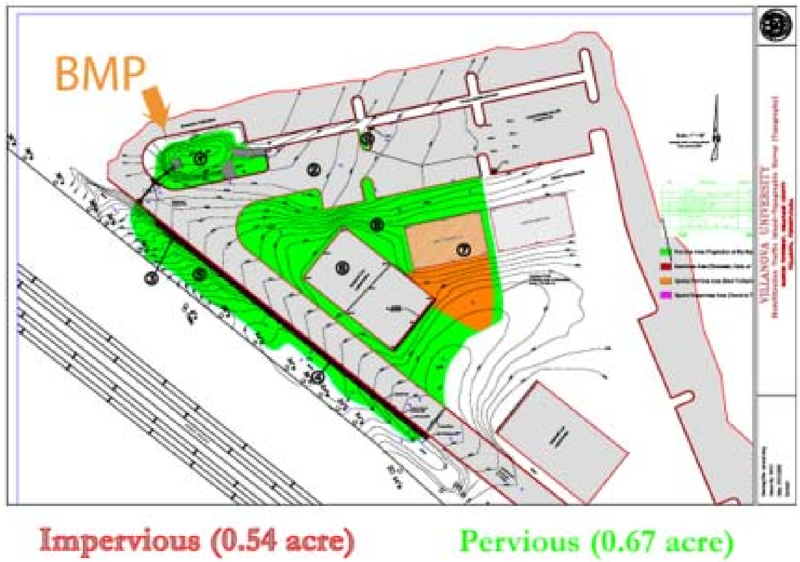


Figure 1.3.4 BioInfiltration Traffic Island Drainage Area

<u>Design Goals and Performance Criteria</u>

The goals of the bioinfiltration traffic island design are to store and infiltrate stormwater and remove nutrients, contaminants and sediment.

- <u>Stormwater Quantity</u>: The bioinfiltration traffic island has been equipped to observe runoff entering the system via two inlets (north, south). This data is correlated to the rainfall amounts measured by a raingage located on the premises. The site is further equipped to measure ponded depths. All data is recorded continuously and downloaded weekly.
  - Rainfall is measured in 5 minute increments through the use of an American Sigma Tipping Bucket raingage.
  - There are multiple pressure transducers that measure the level in 5 minute increments. One is located in the south inlet box in conjunction with a V-notch weir for surface outflow measurement. There are several transducers in a series of wells surrounding the BMP.
  - An ultrasonic transducer is located in the basin to measure the depth of ponded water in 5 minute intervals.

- <u>Stormwater Quality</u>: Sampling is conducted based on precipitation events. The samples are representative of surface runoff and sub-surface soil moisture samples. On average, 12-18 storms are sampled yearly.
  - Two first flush samplers catch the first two liters of direct runoff from the impervious surface and the grass area adjacent to the basin.
  - Two surface water samples are taken as 250 mL grab samples. The first sample is taken during the storm event and a second comes at the conclusion of rainfall, if ponding has occurred.

- Lysimeters are located at depths of 0, 4 and 8 feet beneath the surface. They extract a sample from the soil through the use of porous ceramic cups placed under suction during a storm event and pressure after completion using a pressure-vacuum soil water sampler.
- Grab samples are taken of the groundwater from surrounding wells.

1.3.3b Infiltration Trench

This project, funded through a PaDEP 319 grant, is designed to capture the first one-half inch of runoff from an elevated parking deck and infiltrates it through a rock bed into the ground. The box shown in Figure 1.3.5 contains the monitoring equipment including a V-notch weir used to measure inflow. The trench is a rock bed under the pavers shown in the figure. The project presents some unique possibilities for research. As the water is piped through storm drains to the site, filtration devices can be used and tested at this site. Of the demonstration sites being evaluated, it is the only one with a 100% impervious drainage area.

Figure 1.35 – Infiltration Trench - Tour

Design Goals and Performance Criteria

The goals of the infiltration trench BMP is to store and infiltrate stormwater and remove nutrients, contaminants and sediment.

- Stormwater Quantity: The infiltration trench has been equipped to observe runoff entering the system, storage within the system, and overflow. All data is recorded continuously and downloaded weekly.
    - Rainfall is measured in 5 minute increments through the use of an American Sigma Tipping Bucket raingage.
    - Runoff entering the site is measured using two V notch type weirs with corresponding pressure transducers.
    - Depth of runoff stored in the rock bed is measured using a pressure transducers
    - Surface Outflow is measured using a manufactured weir and pressure transducer.
- Stormwater Quality: Sampling is conducted based on precipitation events. The samples are representative of surface runoff and sub-surface soil moisture samples. On average, 12-18 storms are sampled yearly
    - An automated American Sigma sampler takes rainfall weighted discrete samples.
    - Lysimeters are located at depths beneath the surface. They extract a sample from the soil through the use of porous ceramic cups placed under suction during a storm event and pressure after completion of the storm event using a pressure-vacuum soil water sampler.
    - A grab sample collector is used to capture overflow samples.

2. Quality System Components

Specifically, the quality system supports:

- Flow monitoring
- Stormwater sampling
- Laboratory Analysis
- Data storage
- Data usage
- Modeling

The QAPP provides guidance and oversight procedures to maintain the quality for each of these components specific to each project. Internal coordination is achieved through the Senior Leadership Council. All disputes are resolved first through review of grant and applicable QAPPs and second through consensus. Disputes will be reviewed with the project sponsors, or the VUSP Research Board as appropriate.

Quality systems are implemented through planning, development of QAPP's and SOPs, personnel training, laboratory oversight, project oversight, and regular spot checks.

- A series of QAPP's and / or SOPS are developed for each of the Quality Components. Note that most of these documents have grown out of the original project QAQC plan, and predates this document.

- The WRLM trains all Graduate Students on operations within the laboratory. All graduate students are proficient in Civil Engineering (BS level). The PI's or designated qualified individuals train all GS in field sampling. All PI's are PhDs in Civil Engineering.

- After each storm sampling event, a "rainmaster" report is generated documenting any problems that occurred during the event (sampling through analysis). This report is reviewed and maintained by the WQLM. Systemic problems are reported to the VUSP director by the WRLM.

- Monthly reports are required for each site documenting the calibration and operational status of the site monitoring equipment. This report is reviewed and maintained by the project PI's.

- Laboratory oversight is the responsibility of the WRLM.

- Each Semester (3 times per year), the PI's are responsible to spot review the status of a selected storm event. This includes review of laboratory procedures, data sheets, and recording procedures. The results of this inspection will be reviewed by the Senior Leadership Council, and the VUSP Director. Review of QAPP and SOPs will occur at this time.

- As applicable, secondary data used in a project's analysis must follow specifications in the QAPP and adhere to the same stringency as newly collected data.

- As applicable, quality of model simulations is monitored according to the QAPP. Reports are generated and reviewed on a semester basis.

3. Personnel Qualification and Training

- All Principal Investigators are degreed civil engineers with experience in environmental engineering laboratories. The WRLM has an undergraduate degree in science, and is trained on each laboratory instrument used. In the event that further training is required, the CEE Technician and / or faculty from CEE, Chemistry or Biology are available.

- Safety training is required for all personnel.

- GS training will be conducted as stated earlier by the WRLM for laboratory procedures, or by the PI's or designated individuals yearly. Training will be documented on the SOPs and reviewed during the spot checks. Training documentation will be maintained for one year.

4. Procurement of Items and Services

All supplies are inspected upon arrival to the laboratory to ensure the deliverables are not physically damaged. Laboratory standards and chemicals will be purchased through established suppliers, as required by the instrument sops. The expiration dates for all reagents and standards are checked to ensure the materials are acceptable for use. This check is also performed prior to using any reagents or standards.

5. Documents and Records

Documentation and Records are required for each phase of the process. The data management goals for both the water quantity and quality aspect of this project are based on the guidelines set in the EPA manual Urban Stormwater BMP Performance Monitoring.

Water quantity data is downloaded from each monitoring device once a week or as specified in the site QAPP. The original file is maintained on the network server. The data files are then opened in Excel and converted into *.xls spreadsheets, with any required data manipulation as required by the site QAPP. Note that the server is backed up weekly and monthly (two data sets).

Water quality data is recorded in an instrument notebook as set out in the SOPs. These SOPS include the required blanks, spikes and / or duplicates. Codes for unusual events are included and defined in the SOPs. This data is also stored on the BMP site datasheets on the network, which are backed up using the same procedures discussed earlier.

Note: the documentation and recording processes are reviewed in the semester spot review.

6. Computer Hardware and Software

Computer hardware in use during the above processes are on approved machines purchased through the university information technology group. Each machine has the university anti-virus package.

Computer software is primarily Microsoft Excel, Access, the Corp of Engineers Hydrology software package HEC-HMS; EPA –SWMM; and other software as required that is project specific.

7. Planning

Organizational planning is through the VUSP Research Board, and through the VUSP Senior Leadership Council. The QAPP process is primarily planned through the Senior Leadership Council as discussed earlier. Each QAPP will cover Sample Collection, Flow Monitoring, and Laboratory Operations, Data Storage, Data Usage and Modeling, as needed. Note that common operations will be directed using SOP's, and these were previously developed and approved in a previous QAQC plan.

8. Implementation of Work Processes

PIs and the WRLM are responsible for implementation of work processes. SOPs with check lists will be used for laboratory testing. Any changes to these procedures will be reviewed with all workers immediately upon implementation of the change.

9. Assessment and Response

The WRLM is responsible to assess GS laboratory operations and make on the spot corrections. PIs are responsible to assess field operations. The VUSP Director is responsible for the overall program.

"Rainmaster Report"– Each storm event sampling will be documented by the GA "rainmaster" through a written report on the sampling event. The report reviews any abnormal circumstances or problems with the sampling and laboratory processes. This report is reviewed and maintained by the WQLM. Systemic problems are reported to the VUSP director by the WRLM for action.

Site Report – A monthly report is submitted by the GA to the site PIs. The report covers all site instrumentation, calibration, and general BMP condition. This report is reviewed and maintained by the project PI's, who are responsible for corrective actions.

Semester Spot Review – Each semester, the Project PIs or the QA Manager will review and "walk through" a specific storm event through the documentation to insure all QMP and QAPP procedures are followed. Note that this process will also be followed for secondary data or modeling if required in the QAPP.

Response – If no irregularities are found, no response is needed. Irregularities may require revising of data storage, changes to SOPs, or retraining of personnel. The senior leaders council has final say.

10. Quality Improvement

Quality improvement is continuous. The previously discussed reports and reviews are designed to identify problems, to allow correction or improvement. The GS are brought into the process, and periodic sensing meetings are held informally to discuss process improvements. It is made clear to all that this is our project, we all have ownership, and everything can and will be questioned. Quality is key.

APPENDIX A Target Detection Limits

Source - “Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements” USEPA 2002

Table 3.1: Typical urban stormwater runoff constituents and recommended detection limits

Parameter	Units	Target Detection Limit
Conventional		
PH	pH	N/A
Turbidity	mg/L	4
Total Suspended Solids	mg/L	4
Total Hardness	mg/L	5
Chloride	mg/L	1
Bacteria		
Fecal Coliform	MPN/100ml	2
Total Coliform	MPN/100ml	2
Enterococci	MPN/100ml	2
Nutrients		
Orthophosphate	mg/L	0.05
Phosphorus – Total	mg/L	0.05
Total Kjeldahl Nitrogen (TKN)	mg/L	0.3
Nitrate – N	mg/L	0.1
Metals-Total Recoverable		
Total Recoverable Digestion	µg/L	0.2
Cadmium	µg /L	1
Copper	µg /L	1
Lead	µg /L	5
Zinc		
Metals-Dissolved		
Filtration/Digestion	µg /L	0.2
Cadmium	µg /L	1
Copper	µg /L	1
Lead	µg /L	5
Zinc		
Organics		

Urban Stormwater BMP Performance Monitoring
A Guidance Manual for Meeting the National Stormwater BMP Database Requirements

Appendix B

Table B.1 Inlet autosampler program for collection

INLET				
COMPOSITE #	BOTTLE #	VOLUME (mL)	TIME AFTER BEGINNING OF STORM	INTERVAL
1	1	100	30 min	30 min
1	1	100	60 min	30 min
1	2	100	90 min	30 min
1	2	100	120 min	30 min
2	3	100	150 min	30 min
2	3	100	180 min	30 min
2	4	100	210 min	30 min
2	4	100	230 min	20 min
3	5	100	4 hr	10 min
3	5	100	5 hr	1 hr
3	6	100	6 hr	1 hr
3	6	100	7 hr	1 hr
3	7	100	8 hr	1 hr
3	7	100	10 hr	2 hr
3	8	100	12 hr	2 hr
3	8	100	14 hr	2 hr

Table B.2 Meander 1 autosampler program for collection

MEANDER 1				
COMPOSITE #	BOTTLE #	VOLUME (mL)	TIME AFTER BEGINNING OF STORM	INTERVAL
1	1	100	60 min	60 min
1	1	100	90 min	30 min
1	2	100	120 min	30 min
1	2	100	150 min	30 min
2	3	100	180 min	30 min
2	3	100	210 min	30 min
2	4	100	240 min	30 min
2	4	100	260 min	30 min
3	5	100	4.5 hr	10 min
3	5	100	5.5 hr	1 hr
3	6	100	6.5 hr	1 hr
3	6	100	7.5 hr	1 hr
3	7	100	8.5 hr	1 hr
3	7	100	9.5 hr	1 hr
3	8	100	10.5 hr	1 hr
3	8	100	11.5 hr	1 hr

Table B.3 Outlet autosampler program for collection

OUTLET				
COMPOSITE #	BOTTLE #	VOLUME (mL)	TIME AFTER BEGINNING OF STORM	INTERVAL
1	1	75	2.5 hr	2.5 hr
1	2	75	3 hr	30 min
1	3	75	3.5 hr	30 min
1	4	75	4 hr	30 min
1	5	75	4.5 hr	30 min
1	6	75	5 hr	30 min
1	7	75	5.5 hr	30 min
1	8	75	6 hr	30 min
2	9	75	7 hr	1 hr
2	10	75	8 hr	1 hr
2	11	75	9 hr	1 hr
2	12	75	10 hr	1 hr
3	13	75	11 hr	1 hr
3	14	75	12 hr	1 hr
3	15	75	13 hr	1 hr
3	16	75	14 hr	1 hr
3	17	75	15 hr	1 hr
3	18	75	16 hr	1 hr
3	19	75	17 hr	1 hr
3	20	75	18 hr	1 hr
3	21	75	19 hr	1 hr
3	22	75	20 hr	1 hr
3	23	75	21 hr	1 hr
3	24	75	22 hr	1 hr

Appendix C

Constructed Stormwater Wetlands
American Sigma 900

1. Turn the Sigma 900 Off: Press the Off button
2. Hold down the * button while pressing the On button
3. "Data is Needed. Depress * " will be displayed
4. "Enable Advanced Programming?" – Hit Yes
5. "Enter Number of Sample Bottles" – Type 8, Hit Enter
6. "Enter Units for Bottle Volume: Gallons?" – Hit No
7. "Enter Units for Bottle Volume: Milliliters?" – Hit Yes
8. "Enter Bottle Volume" – Type 350 mL, Hit Enter
9. "Enter Units for Tubing Length: Feet?" – Hit Yes
10. "Program Lock?" – Hit No
11. "Program Delay?" – Hit No
12. "Time Mode?" – Hit Yes
13. Variable Interval?" – Hit Yes (Appendix B intervals)
14. "Composite Mode?" – Hit No
15. "Discrete Mode?" – Hit Yes
16. "Bottles per sample?" – Hit No
17. "Samples per bottle?" – Hit Yes
18. "Samples per bottle" – Type 3, Hit Enter
19. "Change volume?" – Hit Yes
20. "Sample volume" – Type 75 or 100 mL, Hit Enter
21. "Calibrate volume?" – Hit Yes
22. "Auto calibrate?" – Hit Yes
23. "Ready to pump?" Hit Yes
24. "Enter actual volume pumped" – Enter correct volume
25. "Intake Rinses?" – Hit Yes
26. "Intake Rinses" – Type 1, Hit Enter
27. "Intake Faults?" – Hit Yes
28. "Intake Faults" – Type 2, Hit Enter
29. "I.D. #" – Hit Yes
30. "Clock Setup" – Enter in correct time
31. "Synchronize Time by pressing Enter" – Hit Enter

Appendix D

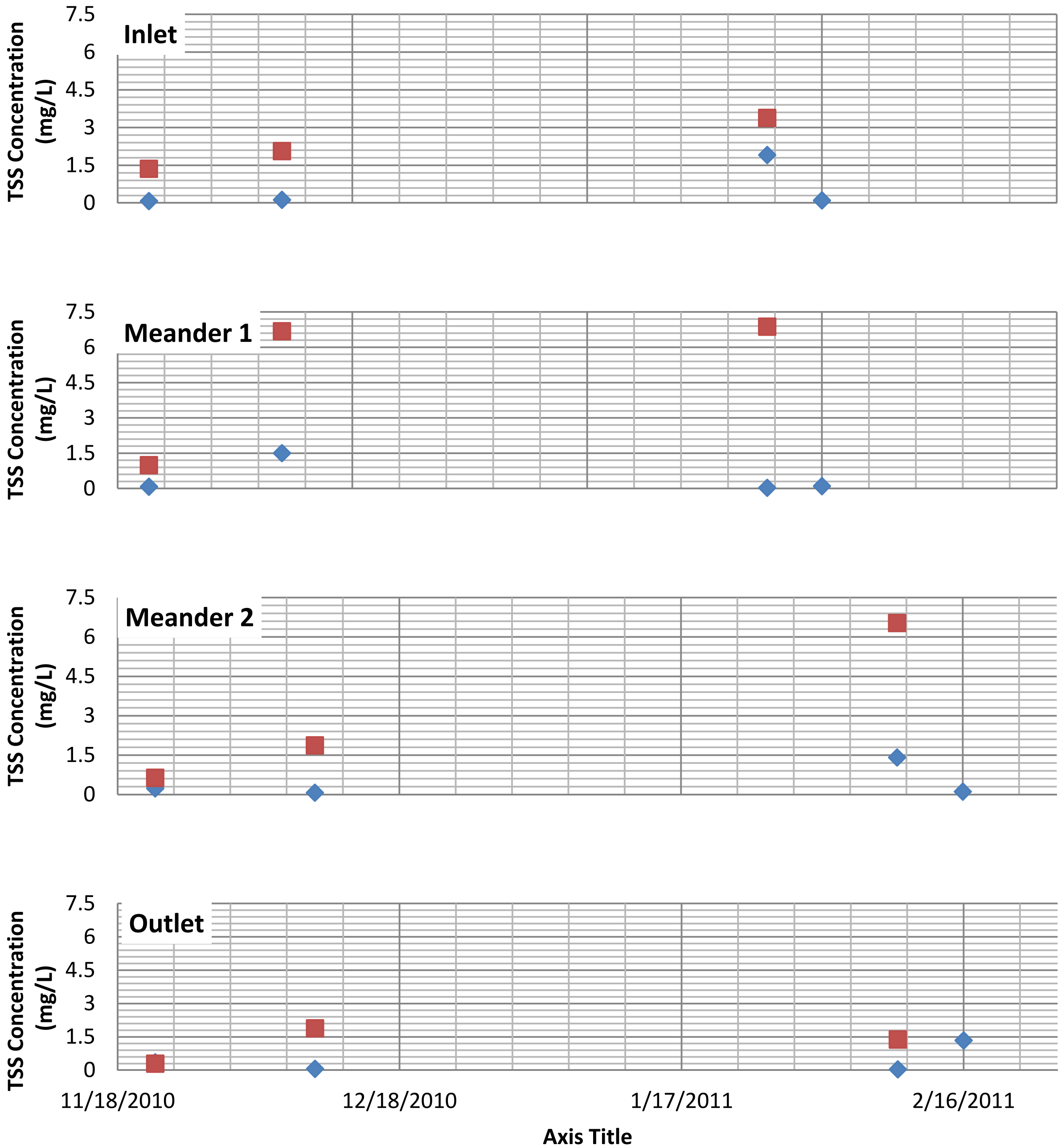


Figure D-1 Nitrite and nitrate concentration at each baseflow sampling location in comparison to date

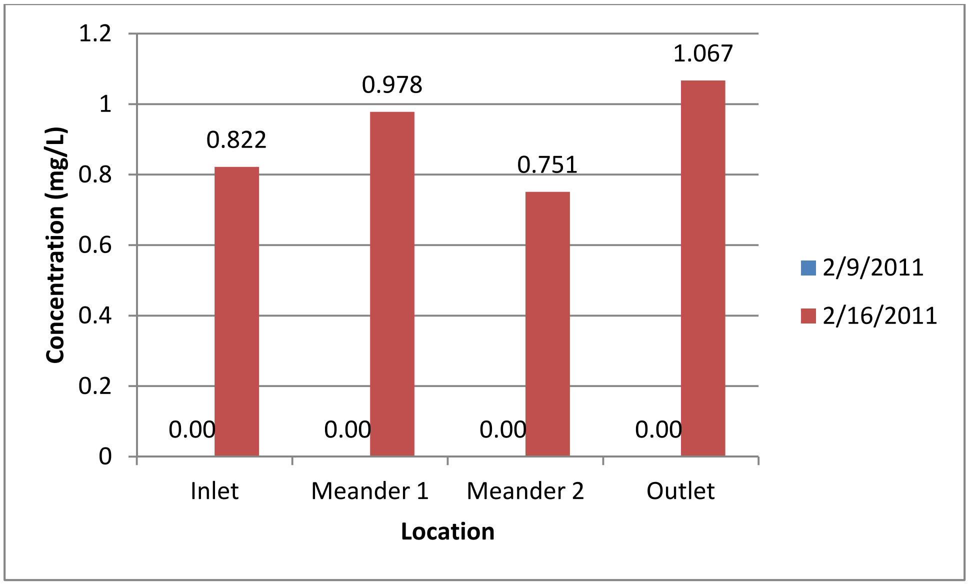


Figure D-2 TKN concentrations during two baseflow events (NOTE: 0.00 symbolizes a Non-Detect value received)

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