HYDROLOGICAL MODELING FOR THE REGIONAL STORMWATER MANAGEMENT PLAN: AN APPLICATION AND INTERCOMPARISON OF EVENT BASED RUNOFF GENERATION IN AN URBAN CATCHMENT USING EMPIRICAL, LUMPED VS. PHYSICAL, DISTRIBUTED PARAMETER MODELING

by

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ABSTRACT OF THE DISSERTATION

Hydrological Modeling for the Regional Stormwater Management Plan:

An application and intercomparison of event based runoff generation in an urban catchment using empirical, lumped vs. physical, distributed parameter modeling

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Hydrologic modeling for the characterization of two Regional Storm water Management Plans is performed using both a lumped parameter, empirical model and a fully distributed, physical model. Both urban/suburban watersheds located in the Northeast United States contain impaired waters, impervious surfaces ranging from 15 to 25% of total land area and are officially un-gauged. Event based models performed on storms that range from 0.5 to 1.25 inches total depth were modeled to compare the resultant simulation hydrographs of the HEC- HMS model to the MIKE-SHE model. The results of the calibrated model predictions compared well with the observed stream flow in the lumped parameter model, but were less accurate in simulating soil infiltration parameters

and impervious surfaces in the fully distributed model. Sensitivity analysis of the lumped parameter model indicated that the empirical parameter representing infiltration and runoff had the greatest effect on the accuracy of the event hydrograph. The parameter that most affected accurate simulation of the overland flow in the fully distributed, physical model was the land roughness coefficient, Manning M. When the impervious surfaces and unsaturated zone were included in the fully distributed model, the hydraulic conductivity became the principal element of calibration.

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1. Introduction

The creation of a regional stormwater management plan has become an option in New Jersey intended to address stream water quality impairments, flooding and groundwater recharge on a watershed scale. Although municipal stormwater management plans are a mandatory requirement of the Stormwater Rules (N.J.A.C. 7:8), the option of creating a regional plan allows the area to be evaluated on a drainage basis and solutions to be prioritized for the entire watershed that is affected.

New Jersey has a large percentage of urban/suburban land use that affects these three issues of water quality, water quantity and groundwater recharge. New Jersey also has 566 municipalities that are governed by local councils. The regional plan has the capability to unite two or more municipalities for the common purpose of solving these issues that are created on a watershed level. To address these issues, a thorough understanding of the hydrology of the watershed is essential.

Urban hydrology is often characterized by higher runoff rates due to higher levels of impervious surfaces or compacted soils. The proper quantification of these and other key parameters can assist in the modeling effort that will serve to simulate hydrologic processes related to the urban watershed. A useful model of the urban New Jersey watershed is expected to be able to help in identifying critical areas that contribute to high runoff conditions that lead to flooding issues, lower water quality and a reduction of groundwater recharge.

The volume of precipitation that becomes runoff in an urban/suburban area is dependent on soil type, soil moisture, antecedent rainfall, land cover, impervious surfaces and surface retention (USDA-NRCS, 1986). This runoff has the potential to add to the volume in the stream if not infiltrated before it enters a direct connection to the stream. In order to mitigate the effects of this urbanization on water quantity in streams, land use options and stormwater best management practices (BMPs) can be used to infiltrate stormwater runoff, helping to minimize impacts on water quantity, decrease flooding, and promote groundwater recharge.

Urban and suburban land uses dominate New Jersey's landscapes. These urbanizing areas are now required by the Federal Clean Water Act to comply with non-point source loading limits under adopted Total Maximum Daily Loads (TMDLs) and the New Jersey Pollution Discharge Elimination Permits for their municipal separate storm sewer systems (MS4s) (N.J.A.C. 7:14A). The determination of the water quality and water quantity impact from these land uses is complicated by the impervious surfaces that are scattered throughout the watershed. Many of these impervious surfaces are directly connected to the stormwater conveyance system, contributing disproportionately to stormwater runoff volumes from the watershed. Other surfaces are disconnected from the stormwater conveyance systems and produce less of a water quantity and water quality impact on local receiving waters. Together with soil infiltration capacity and topography, the hydrologic character of urban features plays an important role in water quality and water quantity issues. It would be beneficial to the TMDL process and to the process of improving water quality and flooding issues to properly quantify the benefits of promoting the infiltration of the runoff from these urban surfaces.

Although traditional stormwater conveyance is necessary in urban areas to mitigate local flooding, smaller storm events can often be treated with low impact, non-structural approaches. The infiltration of precipitation closest to the area that the rain falls is the optimal situation for both baseflow maintenance and the reduction of flashy stream flows that carry surface contaminants and erode stream banks. The accurate modeling of these smaller storms will aid in detecting the characteristics that will improve the stormwater management of the area.

Existing models that are currently used for evaluation of water quantity and pollutant loading vary on the methods used to represent the urban landscape. The computer models have the ability to represent the descriptive parameters of the watershed spatially and can be grouped into a distributed format, a lumped format or a combination of the two. Calculations within these models can rely on physical or empirical equations. Spatially distributed models lend themselves to the use of physical calculations due to the use of a grid based system of input parameters. These parameters are to represent the characteristics of the urban catchment and proper quantification is expected to affect the accuracy of volume and peak flow prediction.

Technological advances in computing and spatial data representation have presented the opportunity to use a physically based fully distributed model for representing the hydrologic scenarios necessary to watershed planning. These models require the rigorous development and calibration to properly characterize their practicality.

The goal of this research is to be to apply, analyze and compare results using two prediction tools in two urban watersheds. The HEC-HMS hydrologic model, developed by the Army Corps of Engineers, is a lumped parameter, empirical model as a replacement for the HEC-1 model. The computation engine for the HEC-HMS draws on over 30 years of experience with hydrologic simulation software (Hydrologic Engineering Center, 2001).

The MIKE-SHE hydrologic model is a spatially distributed, physically based model developed by DHI Water and Environment in 2003. An earlier version, SHE, was developed in cooperation with the British Institute of Hydrology. MIKE-SHE has undergone limited verification (www.integratedhydro.com/reviews.html), but has gained attention with the ability to model the full extent of land based hydrological physical processes with the increase in computer speed and size.

2. Literature Review

An overview of the use of distributed models used in planning and forecasting efforts is presented here. A focus on the generation of runoff components and the comparison to traditional lumped parameter models together with a concise description of the uses of empirical versus physical models is intended.

2.1 Use of Distributed Models in Watershed Planning

The benefits of using a distributed model are the ability to represent land use change, spatially variable inputs and outputs, pollutant and sediment movement, and hydrological response at un-gauged sites (Beven, 1985). However, the broad use of this tool was hampered until recently by intense data requirements and the computational efforts that are required.

2.1.1 Defining the lumped and distributed parameter model

The distributed model is differentiated from the lumped parameter model in the spatial aspect that the descriptive data inputs are represented. The lumped parameter model "averages" these properties together, over a delineated area, using a weighted approach. A distributed parameter model will allot distinctive cells, usually a measured grid area, which will be used to calculate mass and momentum changes between cells. The lumped parameter model generally performs calculations using empirical based formulas, whereas a fully distributed model can employ physical calculations.

A well developed lumped parameter model using empirical representation of the watershed characteristics is the Hydrologic Engineering Center Hydrologic Modeling

System (HEC-HMS). The HEC-HMS model has been developed by the United States Army Corps of Engineers (ACOE). Evolving from the need to capture the knowledge of WWII engineers approaching retirement age, the ACOE established a division to organize and present water resources development activities, and out of that came the HEC grouping of software. Early versions of the hydrologic software component date back to the 1970's. (http://www.hec.usace.army.mil/whoweare/history.html).

The distributed models are defined by the spatial distribution of the physical data input and the calculation of the processes that occur in that space. A distributed model will produce model evaluation output (i.e. infiltration depth, overland flow) at the level of grid scale. A lumped parameter model will only produce output elements at the outlet of the delineated sub-area. The spatial distribution of data is the key to the distributed model, and the use of physical calculations within the spatial extent would be expected to best represent the hydrological processes that occur in a watershed, with excess precipitation experienced in each cell over each time step being routed to the next down-gradient cell.

Language in the literature has developed an understanding of the components of a distributed model, however, inconsistencies do exist. Two examples of inconsistencies of definition are the SWAT model (USDA and Texas A&M) and the TOPmodel. The SWAT model is considered by some to be a distributed model (Sangjun, 2007; Yang, 2008; Wang, 2008) being that there is accounting of spatial variability of land use and other input parameters. SWAT uses the "Hydrologic Response Unit" (HRU) in determining the parameterization of the model. These units can be adjusted for desired size with the ability to essentially replicate the size of the grid with the delineation of drainage areas or to perform calculations on subbasins. SWAT is basin scale, continuous-time model that operates on a daily time step. In SWAT, a watershed is divided into multiple subwatersheds, which are then subdividied into hydrologic response units (HRU's) that consist of homogeneous land use, management, and soil characteristics. The HRU's represent percentages of the subwatershed and are not identified spatially within a SWAT simulation (Gassman, et al., 2007). Also, in SWAT, the excess volume of runoff is routed directly to the stream, with no ability for this water to pass over the land of the next "cell". This is performed with the assumption that since the lag time would be less than the model time step, that this excess would become part of the stream flow in that time. This characteristic would complicate representation of the watershed hydrology at an event scale.

TOPMODEL has been represented as being distributed and semi-distributed (Peng, 2008; Takeuchi, 1999). An EPA fact sheet describing TOPMODEL begins by defining it as a physically based distributed watershed model. (http://www.epa.gov/nrmrl/pubs/600r05149/600r05149topmodel.pdf) TOPMODEL does not account for the spatial variability of hydrological important features such as climate and soil, but will only allow for the spatial distribution of topography (Franchini, 1996). The TOPMODEL has rarely been applied to large areas due to the fact that it was developed for the hillslope/catchment scale and not the drainage basin scale (Quinn et al, 1995).

It has been suggested that so-called physically based distributed models are in reality lumped conceptual models operating at the grid scale (Smith, 2004). Carpenter and Georgakakos (2006) of the Hydrologic Research Institute (United States Scripps

Institution of Oceanography, CA) differentiate the distributed and lumped parameter model by being of “high or low spatial resolution”. The method in which excess precipitation is routed has not been included in this definition.

For the purpose of these case studies, the HEC-HMS modeling system is considered the lumped, empirical model using delineations of subbasins and is compared to the MIKE-SHE model, which in using a grid scale to compute hydrologic processes is considered the fully distributed, physical model.

2.1.2 The application of distributed models

Different types of distributed hydrological models are developed in the literature. These models vary in their degrees of complexity and appropriateness.

In a collaborative effort to evaluate the use of distributed hydrological models as compared to lumped parameter models, the Distributed Model Intercomparison Project (DMIP) was initiated to “infuse new science” into the river forecasting capability of the National Oceanic and Atmospheric Administration’s National Weather Service (NOAA/NWS). The NWS is mandated to provide river and flash flood forecasts for the entire US and has forecasts being generated for over 4,000 points daily. Currently, these forecasts are being generated through the use of the lumped parameter model, the Sacramento Soil Moisture Accounting Model (SAC-SMA), which is a 2-layer conceptual model (Smith, 2004). The results of the varying distributed models that were employed for this effort were all compared to the runoff components that were generated from the SAC-SMA lumped parameter model.

The DMIP used data for eight basins that ranged in size from 65 to 2484 km^2 (25 to 959 mi^2) and simulations generally consisted of continuous (7 to 20 years) model runs in gauged streams.

Models that were considered for inclusion in the DMIP included SWAT (Agricultural Research Service), MIKE 11(DHI), NOAH Land Surface Model (Environmental Modeling Center), HRCDHM, tRIBS (MIT), VIC-3L (University of California at Berkeley), TOPNET, (a networked version of TOPMODEL)(Utah State University), WATFLOOD (University of Waterloo, Ontario) and LL-II (Wuhan University). The spatial units for rainfall-runoff calculations included hydrologic response units (6-7 km^2), subbasins (60-180 km^2) and grids (0.02- 4 km^2) (Smith, 2004).

Results of the DMIP showed that for the greatest percentage of the basin studied, the lumped parameter models showed better overall performance (Reed, 2004). However, some distributed models showed comparable results in many basins and some improvements in other basins. With the dominant land use of all the basins being agriculture, the basins were not considered urban in nature.

The goal of the DMIP was to evaluate the use of distributed precipitation databases as they are used in distributed hydrologic models for the purpose of flood prediction. The definition of distributed hydrologic model was not well defined, with the spatial characteristics of the watershed represented in varying capacity.

Although many distributed models are available, it is necessary to determine the appropriate intended use of the currently designed computer packages. The intention of the DMIP was to evaluate precipitation. Other distributed models provide detailed information on land based characteristics, such as topography. Several models were considered for use in this comparison case study for regional stormwater management planning, and samplings of those models considered are briefly described here. Of those considered, TOPMODEL and MIKE SHE were also evaluated in the DMIP.

SMDR (Soil Moisture Distribution and Routing Model):

In research at Cornell University, small agricultural watersheds were modeled to determine the optimal placement of infiltration Best Management Practices (BMPs). Using a distributed model created at the University called the Soil Moisture Distribution and Routing (SMDR) model, the effects of the saturation capacity of the soil were analyzed. This tool was used to identify areas within the watershed where saturation occurs, thus being areas that are undesirable for promoting infiltration. Researchers at Cornell University determined that this tool which was shown to accurately predict spatial runoff generation zones is critical to the proper placement of BMPs within the watershed. This model was recently adapted to urban areas that include impervious surfaces and hydraulic control structures (detention basins) (Easton, 2007). This model was applied and validated on a 332 ha (1.28 mi^2) in determining the distributed watershed response. (Gerard-Marchant, et al., 2006 and Easton, 2007). Employing physical parameters, efforts were made to represent variable source areas (VSAs), or areas located near the base of high gradient change where accumulation of runoff would be expected to saturate the area making it undesirable for the location of infiltration BMPs.

SMDR possesses a physical structure that represents well the hydrologic characteristics of the watershed with high gradient slopes. However, the model was run on a LINUX platform and used GRASS (Geographic Resources Analysis Support System) for geospatial data input. The model has not been fully maintained and is not readily available. Although SMDR is a public domain model, website information has not been kept current and model support is not available.

TOPMODEL:

TOPMODEL (a TOPography based hydrological MODEL) models rainfall-runoff in a single or in multiple subcatchments, in a "semi-distributed" way and uses gridded elevation data for the drainage area. A conceptual model, it is often considered a physically based model, with its parameters being able to be theoretically measured in situ (Beven and Kirkby, 1979, Beven et al., 1984).

The development of TOPMODEL was initiated by Professor Mike Kirkby of the School of Geography, University of Leeds under funding from the UK Natural Environment Research Council in 1974. TOPMODEL is considered a collection of concepts that can be used where appropriate, which would be considered catchments with shallow soils and moderate topography which do not possess long dry periods (Young et al., 1994).

TOPMODEL uses the spatially distributed data of the topography of a watershed to determine the key physical input parameters of $ln(a/tan\beta)$ that describes the upslope area and movement of water over the slope gradient. The model allows for multidirectional flow of excess precipitation in 8 directions (Franchini et al., 1996). Parameters such as soil characteristics and precipitation distribution are input over larger scales and are not considered fully spatially distributed.

TOPMODEL was used to interpret the relationship of catchment topography and soil hydraulic conductivity to lake alkalinity (Wolock et al, 1989), to evaluate the effects of subbasin size on topographic characteristics and simulated flow paths (Wolock, 1995) and was used at Princeton University where macro scale, dimensionless and fully distributed versions were used (Sivapalan et al, 1987; Wood et al, 1988; Familglietti et al., 1992). The use of TOPMODEL is limited due to the specific watershed characteristics previously discussed. Although a public domain model, recent use has been diminished due to lack of institutional support.

tRibs (TIN-based Real-time Integrated Basin Simulator):

tRibs is a distributed, physically based model licensed by MIT, based on a UNIX platform and is not publically available. The model emphasizes the dynamic relationship between a partially saturated vadose zone and the land surface. Initially designed to use the grid cell as its calculation basis, the model has been developed to use the "voronoi cell" which is adjusted to better fit the terrain. (http://hydrology.mit.edu/index.php/Models/TRIBS). With the focus on hillslopes, the role of topography in lateral soil moisture redistribution has been studied, with rainfall intensity and initial groundwater position strongly influencing model output (Noto, 2008).

The tRIBS model emphasizes the relationship between the partially saturated vadose zone and the land surface being affected by the precipitation event. This is performed by computing the moisture fronts created in relation to the water table. Using these operations, the model is able to produce runoff through several runoff generation mechanisms, including infiltration excess and saturation excess. However, this excess is currently routed to the outlet and not downgradient to the next cell (Vivoni, 2005).

Currently used primarily for research purposes, the model has been studied for its resulting simulations involving ecohydrology, fluvial geomorphology, hydroclimatology and watershed hydrology. The goal of the work in watershed hydrology is to utilize this model as a hydrometerological forecasting system for the prediction of the spatial and temporal response in very large basins, in the area of hundreds to thousands of square kilometers. Current projects include the evaluation of predicting soil moisture using multiple data sources and climate dynamics involved with the fully distributed hydrologic model (http://hydrology.mit.edu/index.php/Research/Hydrology).

The tRIBS model is intended for research purposes and has not been demonstrated for planning purposes of small urban watersheds. Together with the model complexity, limited availability and UNIX platform, tRIBS does not offer the easy option of investigation for use in planning purposes, but may in the future.

MIKE SHE (System Hydrologique European):

MIKE-SHE is a grid based distributed hydrological model developed jointly by the Danish Hydraulic Institute (Denmark) and SOGREAH (France) (Xevi, 1997). The MIKE SHE modeling system (Refsgaard and Storm, 1995) is a deterministic fully distributed and physically based model which can incorporate all major processes of the land phases in the hydrologic cycle. A finite difference approach is used to solve the partial differential equations of overland, channel, unsaturated and saturated subsurface flows (Thompson, 2004).

Applications of MIKE SHE include the use of the model for lowland wet grassland (Thompson, 2004) with two consecutive eighteen month periods being used to investigate the models abilities to represent the physical movement of water through this type of landuse. The conclusions found sensitivities in the land topography and macropore flow.

Christiaens and Feyen (2001) evaluated uncertainties associated with different methods used to determine soil hydraulic properties using the physical calculations of the MIKE SHE model. The four methods of obtaining soil hydraulic properties include (i)moisture retention lab measurements, (ii) prediction via pedo-transfer functions (PTFs) using field texture measurements, (iii) prediction via PTFs using USDA texture classes, and (iv) prediction through the bootstrap-neural network approach using field texture measurements, with the neural network producing the lowest uncertainties.

Vazquez et al. (2002) evaluated the effect of grid size on the performance of the MIKE SHE code. Using a 326 km^2 drainage area and daily catchment discharges and observed water levels, the grid sizes were varied from 300, 600 and 1200 m^2. It was determined that, for the given level of data input and quality, that the 600 m grid resolution was the most appropriate.

The calibration and validation efforts surrounding the MIKE SHE model have taken a variety of routes. Using the Neuenkirchen Research Catchment, researchers calibrated and validated the MIKE SHE model with a two-year time series of stream flows at the outlet of the basin, finding that peak overland flow and total overland flow were very sensitive to resistance parameters and to the vertical hydraulic conductivity of the surface soil (Xevi et al., 2007). The model output variables considered were not significantly affected by the vegetation parameters nor by the specific storage coefficient.

Using the Generalized Likelihood Uncertainty Estimation (GLUE) on a MIKE-SHE model, McMichael et al. (2006) calibrated, and provided predictive uncertainty estimation in monthly stream flow in a semi-arid shrub land catchment in central California. A focus area in this study was the representation of the remote sensing-based

Leaf Area Index (LAI) and its use in fully distributed models. Results indicate prediction uncertainties are generally associated with large rainfalls and wildfires.

As a part of the FLOODRELIEF project (Butts, 2005), the MIKE SHE model was developed to provide a flexible, hydrological modeling framework that permitted both conceptual and physics based processes to be used in a spatially explicit manner. The model was evaluated for use in a flood prone basin for operational hydrological forecasting so as to evaluate the trade off between model complexities and accuracy against the needs for rapid flood forecasts. In the evaluation of two large watersheds, the Blue River in Oklahoma and the Odra River in Poland, the spatial resolution of precipitation distribution was observed to reach a point where increase discretization would not increase model accuracy. It was concluded that there may be model limitations if the purpose is to predict flows at catchment outlets. There may also have been a limitation in one or more areas of the model: 1) the model structure itself, 2) the available calibration data, 3) the accuracy and representation of rainfall, or 4) the parameter estimation procedures (Butts, 2005).

The physical equations that the MIKE SHE model is based on are the equations that have been developed as the science of hydrology has evolved. Using these equations on a watershed scale poses several challenges to the modeler. These challenges include the proper characterization of spatial data. Although the collection of spatial data has improved with the use of GPS and GIS, it has not been demonstrated that using these data on a watershed scale with these physical calculations can provide reliable simulations of the hydrological processes.

Additional Distributed Models

Refsgaard and Knudsen (1996) compared the complex distributed model (MIKE SHE), a lumped conceptual model (NAM) and an intermediate complexity model (WATBAL) on data-sparse catchments in Zimbabwe. Their results could not strongly justify the use of the complex distributed model, although the distributed model performed marginally better for cases where no calibration was allowed. This was the conclusion after attempts at calibration actually produced simulations that were less acceptable, which made proper characterization of the input parameters more important. The three watersheds in Zimbabwe ranged in size from 98 mi^2 to 421mi^2 and no characterization of impervious surfaces were included.

Refsgaard (1997) determined that distributed models calibrated to basin outlet information did not adequately represent internal piezometric conditions. In contrast, Michaud and Sorooshian (1994) determined that a complex distributed model was able to simulate internal conditions at least as accurately as the outlet simulations. A comparison of basin attributes and input data should be considered.

Reed et al. (2004) attempted to explore the connection between conceptual and physically based models for hydrologic prediction. Using the simulations of a total basin area of 256 km^2 basin, the effect of rainfall distribution and grid size were evaluated to determine the effects on the infiltration processes, with the infiltration excess type models being the most sensitive to rainfall distribution.

Identified Limitations of Distributed Models

Input parameters to fully distributed hydrologic models include the spatial discretization of land use, soil types, topography, precipitation, land cover and man made hydraulic structures. The availability of this data is changing rapidly with the improvements in satellite acquisition and computer technology. A move toward centrally accepted data sets is taking place in order to support the collaboration of multiple users. ESRI, a company that provides Geographic Information Systems (GIS) and mapping software, has provided and created formats for spatial data since 1969. An alternative to ESRI GIS is the open source software, Geographic Resources Analysis Support System (GRASS), which is not fully supported in the United States.

The resolution of the topography, soil classifications, precipitation distribution and other key input parameters to distributed models have been evolving. Data is collected on the ground and digitized, paper maps are digitized into formats compatible with GIS systems, and remote sensing data are becoming available. As thes data evolve, distributed models improve their ability to fully represent the characteristics of the watershed and provide useful simulations of hydrologic activities that will aid in watershed planning efforts.

2.1.3 Physical vs. Empirical data use

Flow governing equations have developed for both empirical and physical models. Borah (2003) provides the physical flow governing equations used in the distributed model, MIKE SHE, as well as other physical models. Empirical models have taken many formats, with the NRCS/TR-55 methodology presenting a simplified procedure to calculate storm runoff volume, peak rate discharge, hydrographs and storage volumes. The TR-55 format is applicable to small urbanizing watersheds (USDA NRCS, 1996). Equations used in this study are documented in the following section.

The physical parameters observed in spatial databases commonly used in GIS can be used as descriptive data, or they can be used to determine the empirical parameter that is generally accepted to represent the data.

Strategies for the calibration of empirical models are better defined than for physical models. Truly “calibratable” parameters in the physical model are limited, as physical parameters are intended to be measurable in the field or derived from field measurements (Storm and Refsgaard, 1996). Given that parameter adjustments are used for improved model performance, the distinction between physically based parameters and empirical parameters become distorted.

The SWAT model, a public domain model, enjoys large support from the USDA and Texas A&M and therefore has been able to revise code to implement modifications necessary for optimal hydrologic processing. The MIKE-SHE model is supported by DHI, an independent, international research and consulting firm that is globally dispersed.

2.2 Modeling and the Regional Stormwater Management Plan

The Regional Stormwater Management Planning Process was promulgated by New Jersey by statute in February of 2004 (36 N.J.R. 670). Although municipal stormwater management plans became mandatory with this document, the regional plans remained voluntary, yet recommended and well guided. The basis for this recommendation lie in the fact that watersheds cross municipal and/or county boundaries, yet solutions to water quality and water quantity issues should be formulated over the area of the watershed in question.

The author of this text participated in the development and hydrologic modeling of four Regional Stormwater Management Plans in New Jersey (Goodrow, 2005; RCE WRP, 2007 (a), (b), (c)). Three of these plans, including the Troy Brook Watershed in Morris County and the Pompeston Creek Watershed in Burlington County were accepted by the New Jersey Department of Environmental Protection as official watershed plans. The hydrologic modeling performed for these plans used the lumped parameter model, HEC-HMS. The implementation of the NRCS TR-55 CN method provided valuable information about the rainfall-runoff capabilities of the watersheds and served to aid in the planning efforts regarding infiltration and the reduction of water quantity and quality issues.

As planning efforts in these watersheds continue, it is desirable to evaluate distinct land areas for their contribution to the water quality or water quantity issues. To this end, the implementation of a spatially distributed model was undertaken.

2.2.1 Event Based Modeling

In a study of the frequency and intensity of rainfall events in the Mid-Atlantic region, it was determined that up to ninety percent of all storm events produce less than one inch of rain (Claytor & Schueler, 1996). These storms contribute diffuse source pollution and flashiness to the streams to which the land drains. The correct characterization of these storms in a hydrologic model is expected to aid in the resolution of issues addressed in Regional Stormwater Management Plan.

Event based modeling is a common practice for semi-arid watersheds (10-20 inches of precipitation per year) where runoff is restricted to short periods after a storm

(Maneta, 2007). Event modeling can also be used if continuous data are not available or if the results from specific events are required (Haiping, 1998).

A boundary condition that represents the watershed characteristics before the storm event is necessary. In the case of the lumped parameter, empirical model, the 5-day antecedent moisture condition is implicit in the selection of curve numbers, according to the NRCS TR-55 method. An average antecedent moisture condition is assigned according to the location of the watershed (USDA NRCS, 1996). The boundary conditions for the distributed model were a “hotstart” file obtained from the modeling scenario of a one year precipitation record taken within New Jersey. With the small storm event greatly contributing to the stormwater issues experienced by urban/suburban watersheds, it is essential that these storms be accurately characterized for planning purposes.

2.2.2 Urban Concerns

The parameters used in the hydrologic models are expected to be altered due to the effect that urbanization has on the watershed. This urbanization could take the form of increased impervious area or soil compaction, in addition to constructed hydraulic structures including traditional stormwater conveyance.

In a lumped parameter model, these attributes are “weight averaged” and assigned a descriptive empirical value. This empirical value is used for the calibration purposes of this watershed model, and is expected to be altered in poorly characterized urban areas. In urban areas, the process of weight averaging increases uncertainty due to the level of connected or disconnected impervious areas (Althouse, 2007).

Disconnected impervious area (DCIA) has disproportionately contributes to the total runoff volume of the watershed. Lee (2003) determined that DCIA covering 44% of the watershed contributed to 72% of the runoff volume. Increasing the accuracy of connected versus disconnected impervious area resulted in a lower percentage of directly connected impervious area and therefore caused reduced modeled output volume.

However, in the modeling of most planning scenarios, it is difficult to determine the absolute amount of connected and disconnected impervious surfaces. In many situations, a range of scenarios can be implemented to evaluate the potential effects of alterations in the amount of connection/disconnection. In lumped parameter models this may be performed with a calibration effort. Physical parameters are not intended to be calibrated, and therefore need to be properly characterized as input data.

Soil attributes are similarly represented in the lumped/empirical and distributed/physical models. Infiltration and runoff due to soil characteristics are represented by a calibratable parameter in the HEC-HMS model, but physical properties are necessary input to the MIKE-SHE model. Conventional soil maps use a 1:24,000 mapping scale with a minimum mapping unit of 2.5 to 5 ha (Quinn, 2005). Combined with the unknown physical alterations due to urbanization, the physical soil attributes are thought to vary from reported values (Rodriquez, 2008). Characteristics of urban soil can also contribute to the flow rate in the form of subsurface flow (Berthier et al., 2004). This further complicates the physical parameterization of the urban environment where heterogeneous soil characteristics are present.

Best Management Practice Predication Tool

Stormwater management includes the proper placement of "Best Management Practices" (BMPs) that can be used to enhance the infiltration properties of the watershed or slow the direct addition of runoff to the receiving streams. Using a general spreadsheet model and HRUs, the optimal location to place a BMP within a watershed was determined to be complex function of watershed network connectivity, flow travel time, land use, distance to channel and contributing area (Perez-Pedini, 2005). In an urban area, the placement of any stormwater management practice is dependent on available land area. These restrictions make the use of an accurate fully distributed model for stormwater management planning more desirable.

2.3 Review Summary

The fully distributed physical model can play a valuable role in the planning process and in stormwater management scenarios. A well parameterized distributed model can provide reliable scenarios in un-gauged streams. (Refsgaard and Knudsen, 1996).

Several distributed modeling efforts have focused on continuous based modeling or flood prediction modeling. The DMIP focused on flood forecasting for the NWS. The distributed model can aid in the planning efforts necessary to address watershed impairments due to diffuse source pollution that is dependent on the urban hydrology better than the well developed lumped parameter model. To do this, small storm events must be characterized properly.

Urban and suburban areas would benefit greatly from the use of distributed hydrologic models, and spatial data that currently exists should be evaluated for their ability to characterize the input for the physical calculations that will predict overland and outlet flows. In urban watersheds, the spatial distribution of impervious surfaces in urban land use and the urban nature of soils must be well differentiated.

These New Jersey watersheds do contain a range of connected and disconnected impervious areas that are expected to affect the volume and peak flow of the resultant hydrograph. Calibration of these models will help determine if these models can be used to provide a basis for the adaptive management of the use of these models in future planning efforts.

2.4 Purpose of this research

This study will apply the distributed, model, MIKE-SHE to two urban/suburban watersheds in New Jersey, in the Northeast United States. Both of the urban watersheds considered in this study generally have a low gradient land elevation change and therefore are not expected to replicate the drainage that is present in variable source areas, as was determined with studies involving the SMDR model. And with limited distributed models being used in urban/suburban areas, this study will provide applications for two case studies as well as an intercomparison of those models to their lumped, empirical counterparts currently being used in planning efforts.

This study will seek to determine if the fully distributed physical model can be utilized in a watershed planning effort with current levels of existing spatial data. A sensitivity analysis will compare and contrast the distributed model with the lumped parameter model and provide a guide to increasing optimal parameterization in future scenarios, using a calibrated model and event based scenarios.

3. Methods

3.1 Modeling for the Regional Stormwater Management Plan

There can be several reasons for creating hydrologic models for regional stormwater management planning. Each watershed may experience different stormwater issues, including flooding, nonpoint source pollution, or the degradation of the freshwater biota. The issues experienced in urban watersheds have been related to the percent of overall impervious surface (Hatt, 2004; Lee, 2003) and the traditional methods of stormwater conveyance that routes the stormwater quickly to the nearest stream.

Accurately predicting the overland flow and stream flow caused by the smaller storms that dominate precipitation events is the key to protecting the water quality of the stream. It has been observed that storms less than 0.5 inches can be significant in the mass loading of diffuse pollution, but storms from 0.5 to 1.5 inches are thought to be responsible for most bacterial pollutant mass discharges (Pitt, 1998).

The designation of an accurate drainage area is necessary for a stormwater evaluation. For the initial hydrological modeling for the Regional Stormwater Management Plans, the watershed delineation and subbasins delineation was determined using the HEC-GeoHMS pre-processing software. This program allowed for a subbasin delineation which could incorporate the user defined outlet desired for each drainage area. This process permits not only the use of knowledge regarding the land use in the watershed and stream morphology, but can achieve subbasins of similar size. Algorithms within the program determined the flow paths expected with the input of the 10-m digital elevation model (DEM) representing the topography at a 10-m resolution. These data are available from the New Jersey Department of Environmental Protection GIS database, using sources originating at the USGS.

3.2 Governing Equations

The modeling for the stormwater management plan has been carried out using two different hydrologic models. The first model, HEC-HMS, is considered a lumped parameter, empirical model. The lumped model assumes that the watershed can be broken down into units and described by a set of empirical parameters that will be weight averaged over the delineated subbasins and will ultimately define how that watershed is mathematically represented.

The second model, MIKE-SHE is considered a fully distributed, physical model. The calculations of the hydrologic processes are determined primarily with the use of physical equations using watershed characteristics. This is performed on a grid level basis, with the characteristics found in each grid cell used for calculation purposes.

Input data from Geographic Information Systems (GIS) data layers (shapefiles) have been used in both model types. The important GIS layers that are considered essential to regional watershed hydrologic modeling are the land use, the soils, and the topography. These digital components of the model can come in varying resolutions, but layers based on the 7.5 minute, 10-m X 10-m DEM were readily available and used in this project.

HEC-GeoHMS was used to prepare the input shapefiles for use in the HEC-HMS model. This preparatory function derived the necessary geometric features (slope, length, area, centroid location) from the base topography data input. The preprocessing of GIS data is necessary for the physical model, since the model calculates the hydrologic output on a grid level.

3.2.1 Empirical, Lumped Parameter Model: HEC-HMS

HEC-HMS provides several options from a collection of methods to simulate the processes of rainfall-runoff, such as infiltration losses, runoff transform and flow routing. For the purpose of this study, the Soil Conservation Service (SCS) Curve Number (CN) Loss Model was used to estimate the precipitation excess and determine runoff volume from each watershed. The Snyder unit hydrograph was used as the runoff transform method, and the Muskingum-Cunge method was used to simulate stream flow routing. HEC-HMS provides as a final result the hydrograph (flow vs. time plot) and peak flow for model elements such as junctions, reaches and reservoirs.

For the purpose of modeling for this study, the next sections present the components chosen for use in the lumped parameter, HEC-HMS model.

Basin Model Setup

HEC-GeoHMS was used to process the available digital data. The digital input files to the HEC-GeoHMS program are the 10-m digital elevation model (DEM) that defines the topography of the area and the stream definition shapefile. Through the algorithms contained in the program, files were created that served as the input for the basin model set up in the HEC-HMS model. The processing of these input files allows the delineation of the watershed boundaries and subbasin boundaries. The program also quantifies the lengths of the rivers, longest flow paths, slopes, centroid locations and the lengths to the centroids. The basin schematic and map file used to represent the watershed are also created here.

Runoff volume (Loss Rate)

Using the SCS Curve Number Loss Model, the precipitation excess is determined by the following equation:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S}$$

Equation 1: HMS Precipitation Excess (USDA, 1986)

where P_e = accumulated precipitation excess at time (in) t; P = accumulated rainfall depth (in) at time t; I_a = the initial abstraction (in) and S = the potential maximum retention (in). The initial abstraction is intended to represent the portion of rainfall that is intercepted by vegetation and is accumulated as depression storage. The maximum retention is the quantification of the ability of a watershed to abstract and hold storm precipitation. The empirical relationships reported in the TR-55 manual have been determined through the study of many agricultural watersheds. The initial abstraction is related to the potential maximum retention (S)(in) in the watershed, which is empirically related to the CN as in the following equations:

$$I_a = 0.2S$$

Equation 2: Empirical relationship of Ia and S (USDA, 1986)

$$S = \frac{1000 - 10CN}{CN}$$

Equation 3: Empirical relationship of S and CN (USDA, 1986)

Estimation of the Curve Number

This method employs the assignment of a “curve number” (CN) to represent the empirical relationship that relates soil and the land cover with total runoff volume. The curve number method has been developed by the National Resource Conservation Service (NRCS), Technical Release 55 (USDA, 1986). The CN ranges between zero and 100, with the higher numbers denoting the higher runoff capabilities. Low curve numbers generally do not fall below 30, with a soil assigned a CN of 30 being considered a permeable soil with a high infiltration rate (HMS technical manual, p. 41).

The curve numbers that were assigned for the watersheds in this study were derived from the CN tables in TR-55. The GIS databases containing the soil hydrologic attribute (hydrologic group) (http://www.nj.nrcs.usda.gov/) and the land use/land cover (NJDEP, 2002) attributes (Type 02) were joined to produce a single GIS database that would provide individual polygons (i) which each had the attributes necessary to assign a single value (Table 1) of a curve number (CN_i).

Table 1: Curve Numbers for unique combinations in study watersheds

LAND USE	HYDROLOGIC SOIL GROUP A	B	C	D
Agricultural Wetlands			98	
Altered Lands	76		91	94
Artificial Lakes		100	100	100
Athletic Fields (Schools)	49	69	79	84
Commercial Services	89	92	94	95
Coniferous Brush/Shrubland			94	
Coniferous Forest (10-50% Crown Closure)			73	
Coniferous Wooded Wetlands		98		98
Cropland and Pastureland	72	81	88	91
Deciduous Brush/Shrubland	35	56	70	77
Deciduous Forest (>50% Crown Closure	30	55	70	77
Deciduouos Forest (10-50% Crown Closure)	43	65	76	82
Deciduous Scrub/Shrub Wetlands	98	98	98	
Deciduous Wooded Wetlands	98	98	98	98
Disturbed Wetlands (Modified)	98	98	98	
Extractive Mining	81	88		
Former Ag Wetland			98	
Freshwater Tidal Marshes	98	98	98	98
Herbaceous Wetlands		98	98	98
Industrial	81	88	91	93
Managed Wetlands			98	98
Mixed Deciduous/Coniferous Brush/Shrubland		60	73	79
Mixed Forest		55	70	77
Mixed Urban or built-up land		92	94	
Natural Lakes		100	100	100
Old Field (<25% Brush Covered)	48	67	77	83
Orchards/Vineyards/Nurseries/Horticultural Areas		88	91	
Other Urban or Built Up Land	49	69	79	84
Recreational Land	49	69	79	84
Residential, High Density, Multiple Dwelling	77	85	90	
Residential, Rural, Single Unit	46	65	77	82
Residential, Single Unit, Low Density	54	70	80	85
Residential, Single Unit, Medium Density	61	75	83	87
Transportation		69	79	84

(USDA, 1986)

These curve numbers were then area-weighted, or composited, to produce an overall curve number for the subbasin of interest ($CN_{composite}$) (USACOE HMS Technical Manual, p. 41). This composite curve number is calculated as shown in Equation 4.

$$CN_{composite} = \frac{\sum A_i CN_i}{\sum A_i}$$ **Equation 4: Composite Curve Number (USDA, 1986)**

Where A_i= area of polygon with single assigned CN (CN_i).

Impervious Area

A third component of the runoff volume computed by the HEC-HMS model is the percent impervious area. Although there is an available option to denote this element separate from the assigned curve number, if the CN tables for urban districts, residential district and newly graded areas are used, it is not necessary to separately denote these impervious areas (USACOE, 2000, p. 41).

Direct Runoff (Transform)

In the HEC-HMS model, the transformation of precipitation excess to runoff was accomplished by using the empirical model of the Snyder Unit Hydrograph (UH) (Chow, 1988, Snyder, 1938). This parametric UH provides for relationships that estimate UH model input data from watershed characteristics. Snyder selected the lag, peak flow and total time base as the critical components of a UH. After parameterizing data for many watersheds, Snyder used the following empirical equation to relate the parameters to measurable watershed characteristics. For the lag time, the following equation is used:

$$t_p = CC_t (LL_c)^{0.3}$$ **Equation 5: Snyders Basin Lag (USDA, 1986)**

Where C_t = basin coefficient (unitless, derived from gauged watersheds, represents variations in watershed slopes and storage characteristics); L = length of the main stream from the outlet to the divide in miles (kilometers); L_c = length along the main stream from the outlet to a point nearest the watershed centroid in miles (kilometers); and C = a unitless conversion constant (0.75 for SI and 1.00 for foot-pound system). C_t is not a physically based parameter and can be adjusted with calibration. A range of 1.8 to 2.2 is suggested for initial simulations (Bedient and Huber, 1992).

For the standard case, Snyder determined that the UH lag and the peak per unit of excess precipitation per unit area of the watershed are related as in the following equation:

$$\frac{U_p}{A_r} = C\frac{C_p}{t_p}$$

Equation 6: Relationship between lag and peaking coefficient

where U_p =peak of standard UH (cfs); A =watershed area (ft^2); C_p=UH peaking coefficient (unitless); and C =conversion constant (2.75 for SI or 640 for foot-pound system). The peaking coefficient, C_p is best determined during calibration, as it is not a physical parameter. Bedient and Huber (1992) report a range of 0.2 to 0.8 for values of C_p. The sensitivity of the HEC-HMS model to alterations in this parameter is shown in Figure 1.

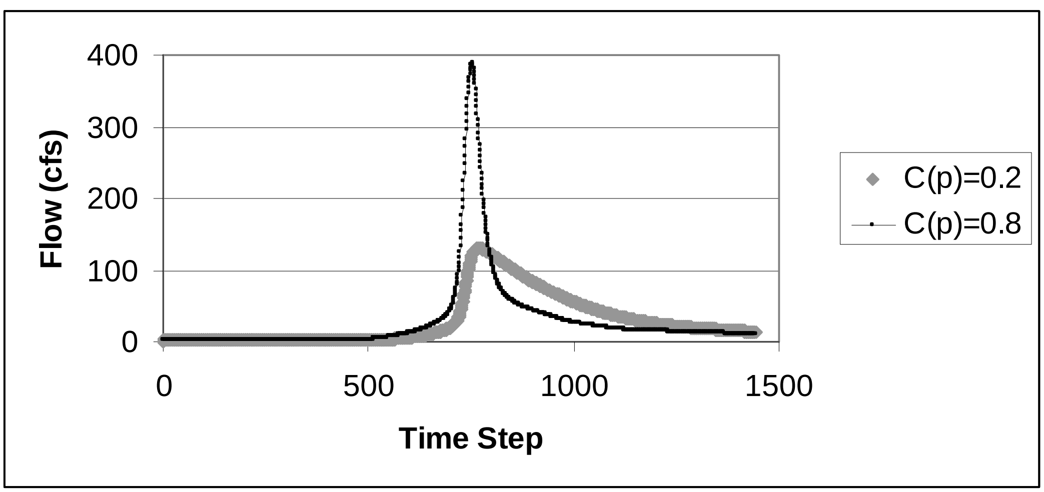

Figure 1: Model Sensitivity to Peaking Coefficient (For t(p)=0.5 hrs, A=0.541 mi2, 2 year design storm)

Baseflow

The baseflow for the HEC-HMS model was based on an average baseflow observed at the outlet. Each subbasin was provided a single value for the constant monthly baseflow that differed depending on the month and is used as a boundary condition for the simulation.

Routing Method

Hydrologic routing was performed using the Muskingum-Cunge Standard method. The Muskingum-Cunge standard section method is based on the continuity equation and the diffusion form of the momentum equation. Standard cross-sections were characterized as trapezoidal. The input parameters include channel shape, length, energy slope, bottom width, channel side slope, and Manning's n roughness coefficient. The channel slope, length and energy slope were determined through HECGeoHMS 1.1 basin processing and the Mannings roughness coefficients were assigned from available tables (Chow, 1988). Bottom width and channel side slope were assigned default values based on a prism shape consistent between models.

Precipitation and the Meterologic Model Setup

A tipping bucket rain gage was installed in a central location to record precipitation depth at intervals between two and six minutes. This tipping bucket was programmed to tip once for each 0.01" of rainfall. A pulse was sent to a data logger to record each tip of the bucket. Rainfall data were downloaded from the logger on bimonthly basis. Both total rainfall depth and a time series distribution were determined from the rainfall data.

The rain data representing depth over time were provided to a meteorological component file in the model. This could be used, with a control specification file, to provide the time steps that the model calculates the rainfall runoff processes.

3.2.2 Physical, Distributed Parameter Model: MIKE SHE

The MIKE-SHE model provides for the integration of the full hydrologic cycle, including groundwater movement, evapotranspiration and soil water. It is a physically based model, solving basic equations that govern the flow processes within the model domain. The model is a fully distributed model, meaning that the spatial and temporal variation of all input data are represented on a grid scale.

Basin Model Setup

The MIKE-SHE flow model set up requires the input of geographically similar spatial databases. The model domain is determined by a watershed boundary created outside this program. Preprocessing is an internal step of the MIKE-SHE program that is undertaken immediately prior to a water movement simulation. The preprocessing does not calculate distances or lump descriptive parameters, it simply organizes and overlays the data input that is necessary to the model run. This step determines if all inputs are in the same projection and if all the information for a model run is available. Spatial databases that are required for hydrologic simulations include, at a minimum, topography and roughness coefficients. Additional information on soil characteristics and evapotranspiration are used for the modeling of the unsaturated zone. Aquifer yield, hydraulic conductivity and storage are necessary input parameters if the saturated zone is to be modeled. Surface water is routed using the MIKE 11 Rivers and Lakes dialogue and characteristics of the stream may be obtained from GIS spatial data layers.

The movement of water is controlled by the simulation specifications input to the MIKE SHE flow model. Since it was the intention of this research to compare the lumped parameter model with this distributed model, every effort was made to maintain similar inputs. However, the modeling structure of the distributed model limited exact duplication. Two modeling structures were developed to bracket the data input that was necessary for the HMS model.

The first method, Method A, modeled the overland flow and channel flow only. The overland flow was simulated using a finite difference method of the diffusive wave approximation of the St. Venant equations. The second method, Method B, modeled the overland flow with the same finite difference method, and also included unsaturated flow using the 2 layer water balance method, and saturated flow using the finite difference method. Although Method B demands a greater amount of input data, these modules were necessary if the impacts of soil infiltration and the incorporation of an impervious surface grid were to be added to the model.

Overland Flow

When the capacity of the soil to infiltrate a volume of rain is exceeded, water becomes ponded on the ground surface. This excess water can become surface runoff, and will find a route downhill to the stream system. The route that this excess water takes depends on the topography of the area, and the amount that reaches the stream depends on resistance in addition to the loss of water to evapotranspiration and infiltration.

Both Method A and Method B used in this comparison study involved the implementation of the diffusive wave approximation by the finite difference method. The diffusive wave approximation simplifies a numerically challenging two dimensional equation by dropping the momentum losses and lateral inflows that are represented in the full St. Venant equations (DHI, 2008). Considering flow only in the x-direction, the diffusive wave approximation is:

$$S_{fx} = S_{Ox} - \frac{\partial h}{\partial x} = -\frac{\partial z_g}{\partial x} - \frac{\partial h}{\partial x}$$

Equation 7: Diffusive wave approximation

where S_{fx} is the friction slope in the x-direction, S_{Ox} is the slope of the ground surface. Z_g is the ground surface level, while h is the flow depth above the ground surface.

This diffusive wave approximation can be further simplified by using the relationship $z=z_g+h$. It then reduces to:

$$S_{fx} = -\frac{\partial}{\partial x}(z_g + h) = -\frac{\partial z}{\partial x}$$

Equation 8: Diffusive Wave Simplification, x direction

$$S_{fy} = -\frac{\partial}{\partial y}(z_g + h) = -\frac{\partial z}{\partial y}$$

Equation 9: Diffusive Wave Simplification, y direction

In addition, the MIKE-SHE model employs a Strickler/Manning-type law for each friction slope which governs the rate at which energy is lost due to channel resistance. Although, in the United States, the Mannings equation is frequently used for this purpose, in Europe, where this model was developed, the Strickler law is implemented (DHI, 2008). The Strickler roughness coefficient is also known as Manning ***M***, a reciprocal of the more familiar Manning ***n***. The value of ***n*** is typically in the range of 0.01 (smooth channels) to 0.10 (thickly vegetated channels), with parallel values of ***M*** between 100 and 10. The values for Manning M were determined after evaluating the land use for Manning n (Chow, 1988), then taking the reciprocal. If a land use could not be specifically identified with a land type present on accepted tables, modeler judgment that was based on a comparable land use was instituted to provide a viable assessment of the roughness coefficient that would properly represent that land use in the flow velocity equation. These values can be found in Table 2.

Table 2: Applied Manning Values

2002 Land Use Category	Manning n*	**Manning M****
AGRICULTURAL WETLANDS (MODIFIED)	0.05	**20.0**
ALTERED LANDS	0.035	**28.6**
ARTIFICIAL LAKES	0.04	**25.0**
ATHLETIC FIELDS (SCHOOLS)	0.03	**33.3**
COMMERCIAL/SERVICES	0.03	**33.3**
CONIFEROUS BRUSH/SHRUBLAND	0.07	**14.3**
CONIFEROUS FOREST (10-50% CROWN CLOSURE)	0.1	**10.0**
CONIFEROUS WOODED WETLANDS	0.09	**11.1**
CROPLAND AND PASTURELAND	0.04	**25.0**
DECIDUOUS BRUSH/SHRUBLAND	0.1	**10.0**
DECIDUOUS FOREST (>50% CROWN CLOSURE)	0.1	**10.0**
DECIDUOUS SCRUB/SHRUB WETLANDS	0.1	**10.0**
DECIDUOUS WOODED WETLANDS	0.1	**10.0**
DISTURBED WETLANDS (MODIFIED)	0.06	**16.7**
EXTRACTIVE MINING	0.05	**20.0**
FORMER AGRICULTURAL WETLAND (BECOMING SHRUBBY)	0.06	**16.7**
FRESHWATER TIDAL MARSHES	0.06	**16.7**
HERBACEOUS WETLANDS	0.07	**14.3**
INDUSTRIAL	0.02	**50.0**
INDUSTRIAL/COMMERCIAL COMPLEXES	0.02	**50.0**
MANAGED WETLAND IN MAINTAINED LAWN GREENSPACE	0.07	**14.3**
MIXED DECIDUOUS/CONIFEROUS BRUSH/SHRUBLAND	0.1	**10.0**
MIXED FOREST (>50% CONIFEROUS WITH >50% CROWN CLOSURE)	0.1	**10.0**
MIXED URBAN OR BUILT-UP LAND	0.04	**25.0**
NATURAL LAKES	0.04	**25.0**
OLD FIELD (< 25% BRUSH COVERED)	0.03	**33.3**
ORCHARDS/VINEYARDS/NURSERIES/HORTICULTURAL AREAS	0.05	**20.0**
OTHER AGRICULTURE	0.035	**28.6**
OTHER URBAN OR BUILT-UP LAND	0.03	**33.3**
RECREATIONAL LAND	0.03	**33.3**
RESIDENTIAL, HIGH DENSITY, MULTIPLE DWELLING	0.02	**50.0**
RESIDENTIAL, RURAL, SINGLE UNIT	0.02	**50.0**
RESIDENTIAL, SINGLE UNIT, LOW DENISTY	0.02	**50.0**
RESIDENTIAL, SINGLE UNIT, MEDIUM DENSITY	0.02	**50.0**
STREAMS AND CANALS	0.035	**28.6**
TIDAL RIVERS, INLAND BAYS, AND OTHER TIDAL WATERS	0.035	**28.6**
TRANSITIONAL AREAS	0.02	**50.0**
TRANSPORTATION/COMMUNICATIONS/UTILITIES	0.01	**100.0**

***Chow, 1988; **reciprocal of Manning n**

The Manning M roughness coefficient is used in the following empirical function, known as the Strickler flow velocity (Equation 10). As an empirical function, these parameters are useful during calibration.

$$uh = K_x \left(-\frac{\partial z}{\partial x}\right)^{1/2} h^{5/3}$$ **Equation 10: Strickler flow velocity**

where u=flow velocity in the x-direction, K_x=Manning M, and h=flow depth above the ground surface (z).

Determination of Runoff Volume

The hydrologic methods used in this study are represented by two ways to determine runoff volume. Method A differs from Method B in that, in Method A, there is the absence of descriptive soil attributes that distinguish the infiltration capacity of the watershed and therefore runoff volume is controlled by the amount of rainfall, minus model components called: Net Rainfall Fraction, Detention Storage and Initial Water Depth.

Net Rainfall Fraction used in Method B is used when evapotranspiration is not selected as a component of the simulation specifications. Given that this research is focused on the time period surrounding a rainfall event, it is assumed that the evapotranspiration plays a small role in the loss of water from the system and can be represented by a fractional term. A Net Rainfall Fraction of 1 would indicate that all the precipitation is made available for runoff and infiltration.

When "Overland Flow" and the "Finite Difference Method" are chosen as Simulation Specifications, "Detention Storage" used in Method B is a condition that requires quantification. Detention Storage is used to limit the magnitude of water that can flow over the ground surface. The depth of the ponded water must surpass the depth denoted by the Detention Storage before water can flow. This is equal to the effect that small ponds or depressions within a grid cell may have on the overall volume of runoff. Water trapped in this Detention Storage is still available for infiltration and evapotranspiration.

The "Initial Water Depth" quantification used in Method B is also necessary when the simulation specifications call for "Overland Flow" and the "Finite Difference Method". The Initial Water Depth is the boundary condition that must be met before overland flow can occur. The initial water depth is usually zero, but if it is present, this depth of water is not available for infiltration or evapotranspiration.

Routing Method: Mike 11

The MIKE-11 routing system applied with the dynamic wave description for non-linear storage function solves both the continuity equation and the momentum equation. The derivation of the equation of continuity and momentum, using the St. Venant equations is solved by an implicit finite difference scheme developed by Abbot and Ionescu (1967). All channel cross sections were assigned physical characteristics that best duplicated those in the routing system that is applied in HEC-HMS.

Unsaturated Flow (Method B only)

The two-layer water balance method is one module used to simulate the processes that take place in the unsaturated zone. The module includes the processes of interception, ponding, infiltration, evapotranspiration and ground water recharge. The input for the model includes the characterization of the vegetation cover and the physical soil properties. The vegetation is described by the leaf area index (LAI) and by the depth of the root systems. The soil properties that need to be quantified are the constant infiltration capacity, and the soil moisture contents at the wilting point, field capacity and saturation. The output is the actual evapotranspiration and the ground water recharge.

The infiltration volume is determined at each time step, first by filling the interception storage, then by adding to the amount of ponded water. Then the maximum infiltration volume is determined by the rate of infiltration using the saturated hydraulic conductivity. The maximum infiltration volume is limited by the amount of infiltration allowed during the time step due to the hydraulic conductivity and it is also limited by the maximum storage volume in the unsaturated zone.

The four input parameters that are required as quantitative descriptives are the 1) *water content at saturation* (the maximum water content of the soil, which is a function of the porosity), 2) *the water content at field capacity* (the water content at which vertical flow becomes negligible, where soil can freely drain, or the minimum saturation that can be achieved), 3) *water content at wilting point* (the lowest water content that plants can extract water from the soil) and the 4) *saturated hydraulic conductivity* (equal to the maximum infiltration rate of the soil).

Saturated Flow (Method B only)

The structure of the model requires the incorporation of the saturated zone module in the simulation specifications so that the spatially distributed grid representing the impervious cover in the watershed can be incorporated into the overall flow model. The saturated zone is simulated by using a finite difference method that represents the partial differential equations that explains the flow through porous media, the three dimensional Darcy equation. Default values applied are intended to simulate a groundwater table that does not interact with the unsaturated zone during a small storm event.

The impervious cover grid layer was created using the 2002 Land Use/Land Cover (NJDEP, 2004) GIS database. This spatial database with the information of percent impervious per polygon was turned into a grid type .dfs2 file for input to the MIKE-SHE model. This paved runoff coefficient defines the fraction of overland flow that drains to storm sewers and other surface drainage features in paved areas. This layer acts in two ways: 1) it instructs the MIKE-SHE model where there is paving, and 2) the value specifies how much overland flow is allowed to infiltrate and how much should be 'drained away' (DHI, 2008). This input will direct that portion of the overland flow directly to the river link that is specified in the saturated zone drainage network.

The drain flow calculation involves the use of an empirical formula. Each grid cell requires a drain level and a time constant. The values used for the Method B simulation used the default parameters of one meter below the surface and a time constant of 1 e-6 s^{-1} (MIKE-SHE User Manual, v.2, 408).

To link the paved area drainage network to the MIKE 11 model, it was necessary to create a .pfs file that instructs the model on how to interpret the input layers of the impervious areas and the drainage (Qiao, 2009).

Baseflow

The baseflow is a boundary condition that can be assigned to a specific node (chainage) in the MIKE-11 Rivers and Lakes module. This can be a quantity that is determined by a relatively longer simulation period of climate fluctuations that is considered a “hot start” for an event simulation.

Meterologic Model Setup

As with the HEC-HMS model, the data collected to represent the observed rainfall was taken from a tipping bucket rain gage that was installed in a central location to record storm depth at intervals between two and six minutes. This data was then entered into a uniform (spatial) distribution and a time varying temporal distribution file format. This was intended to provide the same input as the files in the HEC-HMS model.

3.2.3 Calibration Optimization

The models were calibrated manually rather than using the automated calibration tool that is contained in both models. This was performed in order to evaluate each perturbation of parameters and their effect on the model output. A single input parameter was modified and then later combined with a modification of another parameter or restored and another parameter was then changed. The modeled flow over time, or hydrograph, was then compared to the observed hydrograph. This comparison was performed by using the calculated Nash-Sutcliffe Coefficient.

Model Performance Evaluation Methods/Optimization

Visual analysis was a primary component to the early stages of the model calibrations of both the HEC-HMS and the MIKE-SHE hydrologic models. The intention of a high quality simulation was to represent the key aspects of the hydrograph, such as the timing of the rising limb, the timing and magnitude of the peak of the hydrograph as well as the timing of the falling limb of the hydrograph. The goal of an accurate representation of the volume and shape of the hydrograph was attempted.

To negate the subjective nature of the visual analysis, a numerical indication of the quality of the calibration was necessary. The Nash-Sutcliffe index is one of the most widely employed statistics in hydrologic literature (Jain, 2008).

The Nash-Sutcliffe Coefficient is determined as:

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2}$$

Equation 11: Nash-Sutcliffe Definition

where Q_o^t = the observed flow at time, t; Q_m^t = the modeled flow at time t and $\overline{Q_o}$ is the average observed flow. The denominator of this equation is the total variance of the observed values about the mean and the numerator is the sum of the squared residuals of the data with respect to model results. An E value of 1 represents a perfect match, a value of 0 is considered no more accurate than predicting the mean value (Jain, 2008) and values of the Nash-Sutcliffe

Coefficient less than zero ($-\infty<E<0$) indicate that the mean is a better predictor than the model.

3.3 Model Set Up: Case Studies

Hydrologic models using the HEC-HMS program were original components of the Characterization and Assessment portion of the Regional Stormwater Management Plans developed for two designated watersheds in New Jersey. Both watersheds were identified as having water quality impairments that were related to diffuse source pollution and flooding issues. The creation of a Regional Stormwater Management Plan was to provide quantitative information on how to address these storm related issues.

The location of the two case study watersheds within New Jersey can be seen in Figure 2. The Troy Brook Watershed, located in Morris County, is approximately 16 square miles. This watershed system discharges to the Whippany River and eventually to the Passaic River. The Pompeston Creek Watershed is located in Burlington County, NJ and is approximately 8.1 square miles. The Pompeston Creek discharges directly into the Delaware River.

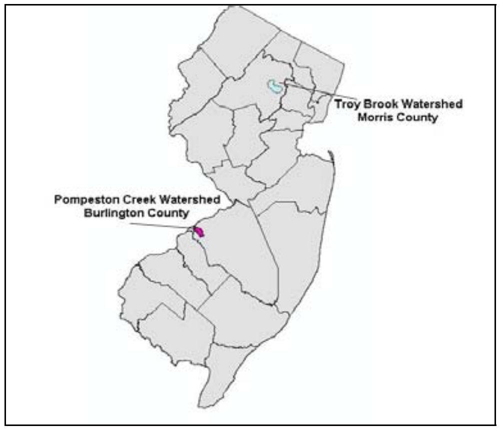

Figure 2: New Jersey Case Study Watersheds

As is the case for a great portion of New Jersey, these two watersheds contain a large percentage of developed area considered urban land use. While water quality may be a source of the impairment of the Troy Brook Watershed, water quantity and flooding issues also affect the watershed in many ways.

3.3.1 GIS Input Data

The input data for all of the models that were prepared began with readily available GIS data layers. These layers included the topography, land use, stream layers and soil layers. All layers were acquired through the NJDEP GIS download webpage (http://www.state.nj.us/dep/gis/).

The topography is represented by a 7.5 minute Digital Elevation Model (DEM) generated by USGS to describe the terrain elevation. The resolution of these standard DEMs 10-meters. The watershed boundary was delineated and further subdivided into smaller, more manageable subbasins by using this topography dataset and the HEC-GeoHMS software. The subbasins were only necessary in the HEC-HMS model, as the MIKE SHE model uses the raster DEM converted to its MIKE-SHE grid format (dfs2) for physical calculations.

The landuse of the watersheds was represented by the 2002 Land Use Land Cover dataset using the Type 02 attribute, based on the photography captured in the spring of 2002. The visual interpretation of these photographs is prepared into a digital file, with distinguishable polygons representing a distinct land use/land cover type (http://www.state.nj.us/dep/gis/lulc02shp.html). The stream network was created in conjunction with the land use/land cover 2002 dataset.

The SSURGO digital dataset represents the soil distribution of the watersheds. This dataset was developed by the Natural Resources Conservation Service (NRCS), of the US Department of Agriculture, as a part of the National Cooperative Soil Survey (http://www.state.nj.us/dep/gis/soilsshp.html).

These GIS data layers provide the necessary spatial data for these models. The preparatory step for the HEC-HMS models is the use of the Geo-HMS software that computes the metrics of input for the HEC-HMS model from the topography dataset. Using this program, the watershed and its subbasins can be delineated. All subbasin outlets are designated as hydrologic junctions where the flow is calculated. Input parameters such as flow lengths and subbasin centroids are calculated and prepared for input into the HEC-HMS model.

The MIKE-SHE model uses a .dfs2 grid file format for the physical calculations of rainfall-runoff. This .dfs2 file format is generated from the raster/grid GIS datasets. Functions within the ArcMAP GIS software allow for the transformation of a polygon shapefile into a grid format. The grid is converted to a .dfs2 format in the MIKE SHE modeling program.

3.3.2 The Pompeston Creek Watershed

Study Area

The Pompeston Creek Watershed, located in Burlington County, New Jersey is approximately 8.1 square miles (Appendix A, Map 1). The watershed system discharges to the Delaware River and contains part of the municipalities of Moorestown, Delran, Riverton, and Cinnaminson. The Pompeston Creek Watershed is comprised of 10 to 13 miles of river and more than 13 acres of lakes. The stream is tidal to about 0.75 miles upstream of its discharge point to the Delaware River which includes a freshwater tidal marsh.

The watershed was subdivided into thirteen subbasins that would represent hydrologic units for calculations in the lumped parameter model, HEC-HMS (See Figure 3 and Map 1, Appendix A). These subbasins were not used in the fully distributed, MIKE SHE model.

Note the location of the water surface elevation gage in Figure 3 at the outlet of Subbasin 12. This is the location within the watershed where the elevation of the stream was measured over time. This information was used in the calibration procedure.

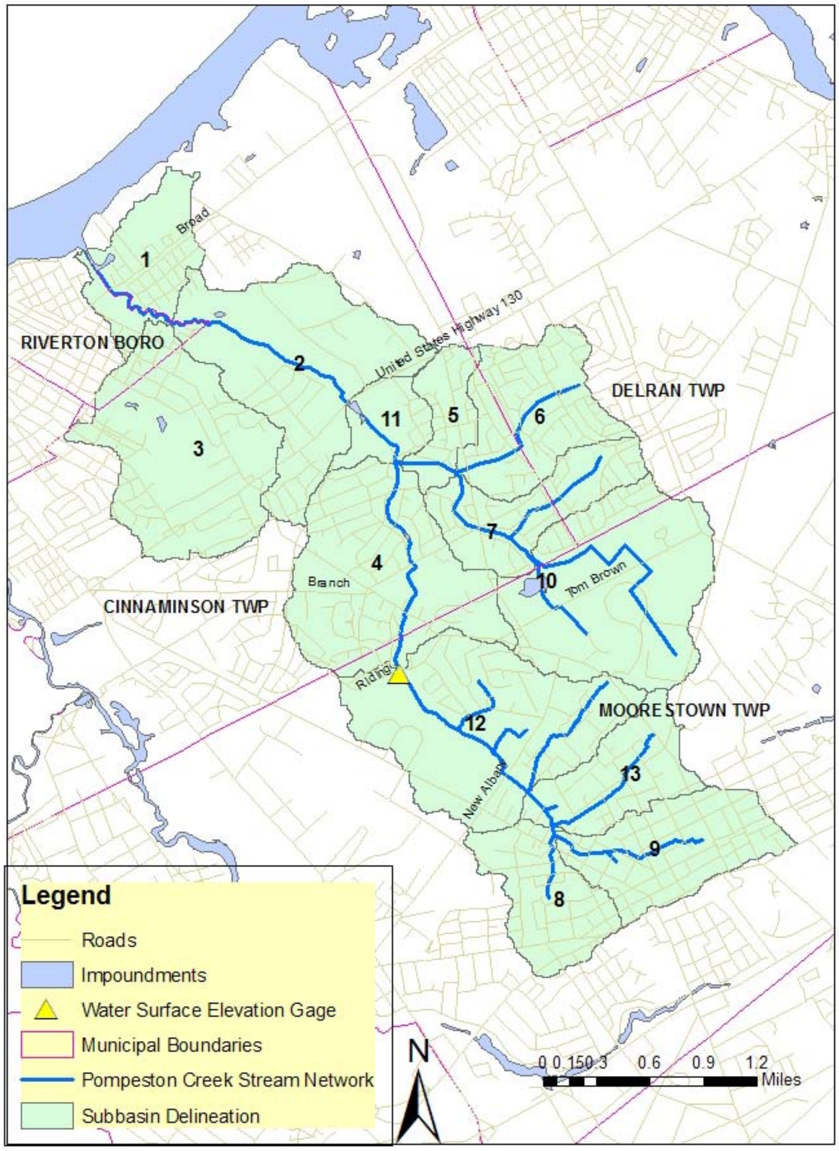

Figure 3: The Pompeston Creek Watershed Study Area

Land Use

The land use in the Pompeston Creek Watershed is composed of residential, commercial and industrial development with some minor open space. According to 2002 data collected by the NJDEP, the land use of the Pompeston Creek Watershed is 80% urbaniz. Land use information is shown in Table 3. Based on aerial photography taken in 2002, the NJDEP created a data set describing land use across the state. This land use/land cover information is available in GIS and can be useful in the analysis of a watershed.

The distribution of the land use types within the Pompeston Creek Watershed can be seen in Map 2 of Appendix A.

Table 3: NJDEP 2002 Land Use Data for Pompeston Creek Watershed

Land Use Type	Acres	Square Miles	Percentage
AGRICULTURE	173.19	0.27	3.3
BARREN LAND	86.89	0.14	1.7
FOREST	328.04	0.51	6.3
URBAN	4168.87	6.51	80.0
WATER	30.24	0.05	0.6
WETLANDS	420.89	0.66	8.1
Total:	**5208.12**	**8.14**	**100.0**

Soils

The Pompeston Creek Watershed may further be characterized by its soils (See Figure 4 and Map 3 of Appendix A). Within the Pompeston Creek Watershed, soils are predominantly in the Sassafras and Woodstown series. The Sassafras soil series, found mostly in the lower half of the watershed, consists of well-drained and very deep soils formed from sandy marine and old alluvial sediments (USDA/NRCS, 2002). The Woodstown series is mostly found in the upper portion of the Pompeston Creek Watershed and follows the stream corridor. This series consist of very deep, moderately well-drained soils in upland marine terraces and old stream terraces (USDA/NRCS 2002). The Woodstown series are characterized by their moderate infiltration rates and shallow water table (18–42 inches per year). Potential for surface water runoff is considered slow to moderate for this soil series (USDA/NRCS, 2002). Slopes can be variable, from 0 to 30 percent slopes. The Galestown series is found along the main stem of the lower Pompeston Creek. Galestown soils are characterized as very deep, somewhat excessively drained soils with deep water tables (greater than 72 inches) (USDA/NRCS, 2002). Finally, soils classified as "Made Land" are located at the mouth of the creek, where it drains into the Delaware River. Made lands are defined by the NJDEP as dredged coarse material with a slope ranging from 0 to 5 percent.

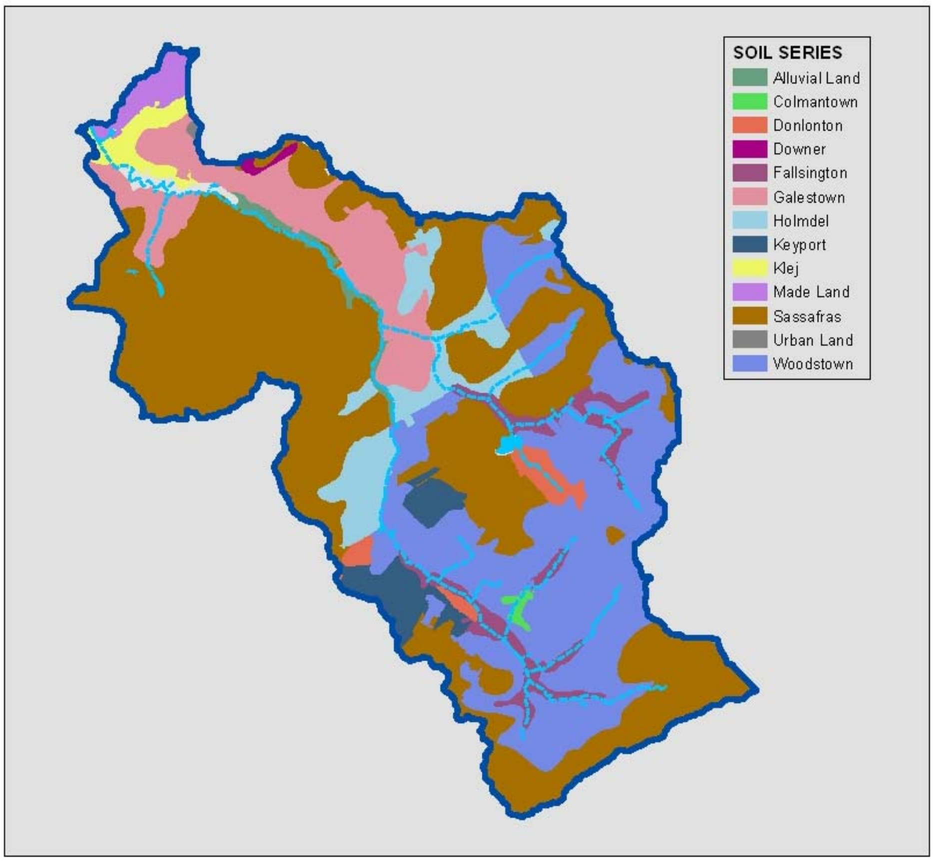

Figure 4: Pompeston Creek Soil Series

The SSURGO soil database that was used for this study provides the characteristics of these soil components. Each soil type is designated a "Hydrologic Group" based on the soil's runoff potential. There are four hydrologic soil groups, from A to D, where A generally has the greatest infiltration capacity and D has the lowest infiltration, or highest runoff capacity.

Group A soils consist of sand, loamy sand or sandy loam that has low runoff potential and high infiltration capabilities, even when thoroughly wetted. These soils have a high rate of water transmission.

Group B soils consist of silt loam or loamy soils and have low infiltration rates when thoroughly wetted. The infiltration rate is moderate when thoroughly wetted, and the soils drain well for moderately fine to moderately course textures.

Group C soils are sandy clay loam. The infiltration rates are generally low when wetted. These soils may have a moderately fine to a fine layer that slows the transmission of water.

The Group D soils have the highest runoff potential. These soils are clay loam, silty clay loam, sandy clay, silty clay or clay. These soils posses a low infiltration rate and a high swelling potential when wetted, and could have a permanent high water table or a clay layer at or near the surface making it nearly impervious.

The section of the soil hydrologic group designated “Z” are those areas that have not been classified. These areas represented relatively small areas within the watersheds, therefore the characteristics of those soils closest to the “Z” soils were used.

The soil components of the Pompeston Creek Watershed and the corresponding soil hydrologic group can be found viewed in Figure 5.

Combinations of the hydrologic soil groups denote an area that is considered of mixed attributes.

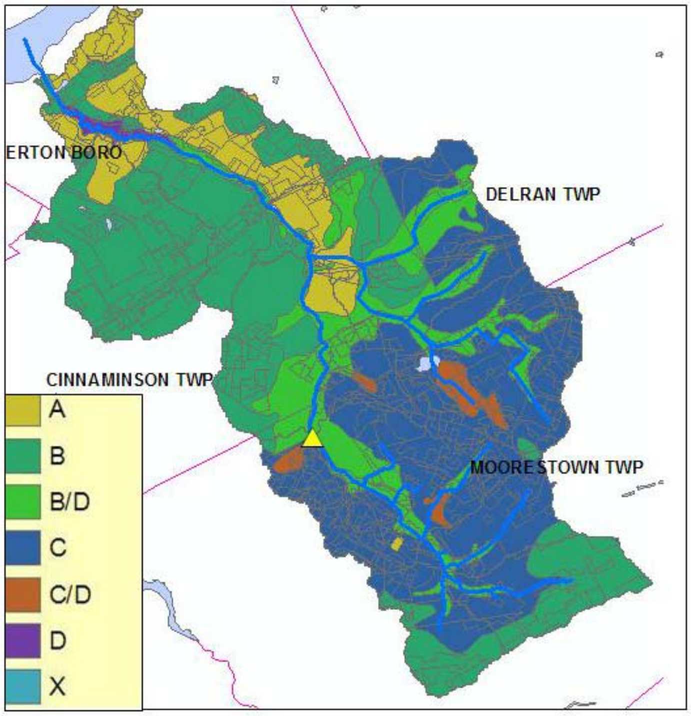

Figure 5: Pompeston Creek Soil Hydrologic Groups

Additional descriptive attributes can be found in the SSURGO database that aid in the characterization of the physical characteristics. The estimated drainage ability (poor to well), the percent of compaction, soil names and types are some of these attributes.

Impervious Surfaces

The land use shapefile includes the information on the percent of the impervious cover identified in the aerial photography. Each land use polygon is designated a percent impervious and the overall impervious nature of the watershed can be determined. An overview of the impervious coverage within the Pompeston Creek Watershed can be found in Table 4. A map showing the distribution of the percentage of impervious area throughout the watershed can be found in Appendix A, Map 4.

Table 4: Pompeston Creek Watershed Impervious Surface

IS=Impervious Surface	acres	square miles	IS acres	IS square miles	Percent IS
Overall Watershed, 13 subcatchments	5208.1	8.1	1304.7	2.0	**25.0**
Subbasin 8	261.3	0.4	85.0	0.1	32.5
Subbasin 9	345.9	0.5	142.2	0.2	41.1
Subbasin 13	253.6	0.4	52.2	0.1	20.6
Subbasin 12	698.6	1.1	108.9	0.2	15.6
Total Upper Basins	1559.5	2.4	388.3	0.6	**24.9**

The impervious nature of the entire 8.1 square miles watershed is represented in the upper four subbasins (Subbasins 8, 9, 13 and 12). Observations from these subbasins were used to calibrate both models.

<u>Observed Precipitation Events</u>

The Pompeston Creek Watershed was evaluated for the water surface elevation at the Subbasin 12 outlet site for approximately nine months beginning in April of 2005. Precipitation depths over time and flow over time were considered for model input if the distribution was somewhat parabolic and the volume of precipitation was over 0.5 inches and under 1.25 inches. This range was determined as the area of interest, given that visible runoff would be expected to begin after 0.5 inches of precipitation. Ninety percent of the rainfall events in the Mid-Atlantic region are storms of one inch or less (Claytor and Schueler, 1996) so this range would contain events that are representative of regular occurrences.

Three storm events were determined to be appropriate for use in calibration and validation in the Pompeston Creek Watershed. The storm time distribution and total precipitation depth can be seen in Table 5.

Table 5: Pompeston Creek Watershed Storm Events

Storm Date	Length of Storm (hours)	Total Precipitation Depth (inches)
10/11/2005	35.5	0.84
10/24/2005	17.5	1.06
11/16/2005	6.75	0.76

An additional data set was obtained from a surface observation station maintained by Automated Surface Observation System (ASOS) and reported through the Rutgers NJ Weather and Climate Data Network (http://climate.rutgers.edu/njwxnet/index.php). The station is located in Mount Holly, NJ, approximately ten miles from the Pompeston Creek Watershed. This data set was intended only to evaluate the sensitivity of precipitation distribution.

Observed Flow

Calibration for the four upstream subbasins was performed with the observed flow that was measured at the outlet of Subbasin 12 (Figure 3).

Given that there exists no USGS gage to measure long term flow in the watershed, this site was set up specifically for this modeling effort. A temporary pressure transducer was installed at the bottom of the stream at this location to record water depth. The depth and the corresponding flow were determined over the course of several seasons to incorporate a variety of situations. The resulting rating curve can be seen in Figure 6.

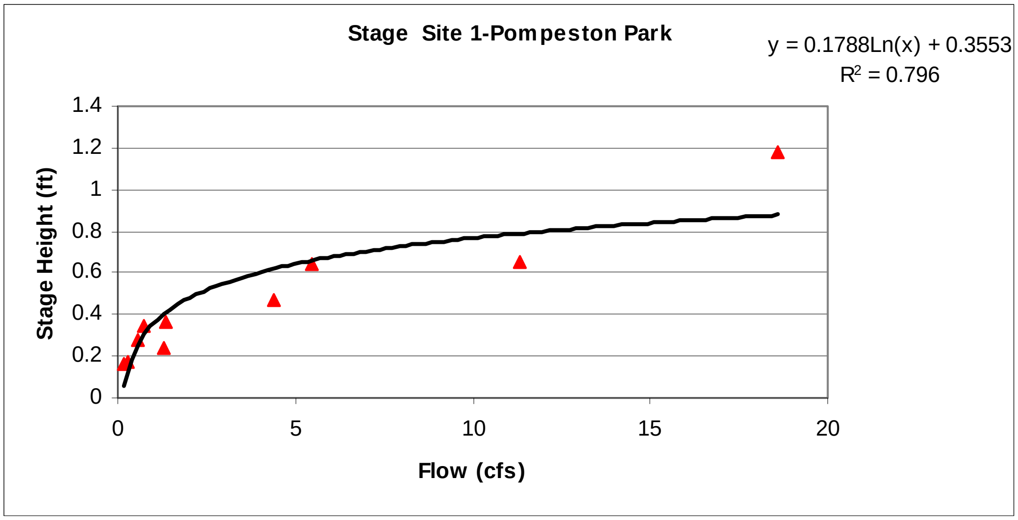

Figure 6: Rating Curve for the Pompeston Creek Watershed

<u>Pompeston Creek Watershed HEC-HMS Model Set Up</u>

Loss Rate

The GIS layers of the land use and the soils were joined into one GIS layer in the ArcGIS program. The newly created polygons contained both the attributes of the land use and the soil properties. A query process in the ArcView application was used to sort the groups of specific combinations of soil types and land use types. A curve number for that polygon could then be assigned through the use of the tables provided in the TR-55 (U.S. Soil Conservation Service, 1986). Curve numbers used for these study watersheds can be found in Table 1.

These individual CNs within each subbasin are then multiplied by the area that they cover, added together and then divided by the total area in that subbasin (see Equation 4). It was this single CN that is used to describe the characteristics of the infiltration and runoff of a subbasin in the HEC-HMS model set up.

The other loss rate input parameters for input to the HEC-HMS hydrologic model are based on the original CN, as described in Equation 2 and Equation 3.

Table 6 shows the originally determined input parameters that empirically described the loss rate for the Pompeston Creek HEC-HMS model.

Table 6: Pompeston HEC-HMS Original Loss Rate Input Parameters

Subbasin ID	Area wt CN	S	I(a)
1	73	3.7	0.7
2	76	3.2	0.6
3	74	3.5	0.7
4	78	2.8	0.6
5	76	3.2	0.6
6	83	2.0	0.4
7	83	2.0	0.4
8	79	2.7	0.5
9	81	2.3	0.5
10	84	1.9	0.4
11	67	4.9	1.0
12	84	1.9	0.4
13	81	2.3	0.5

S=Potential Maximum Retention (in)
$I_{(a)}$= Initial Loss/Initial Abstraction (in)

Transform

The volume of runoff is transformed by being temporally distributed to the stream flow (as in the shape of the hydrograph). This has been determined by using the Snyder Unit Hydrograph Method (See Section 3.3.5). The two input parameters required are the Snyder Lag time and the Snyder Peaking Coefficient. Values of the Snyder Lag time were determined using Equation 5 and the parameters derived from the GIS layers.

Table 7: Pompeston Creek Original Transform Parameters

Subbasin	Snyder Lag(tp)(hrs)
1	0.3380
2	0.4418
3	0.4320
4	0.4126
5	0.2802
6	0.3429
7	0.3732
12	**0.4437**
13	**0.3383**
9	**0.3774**
8	**0.2873**
10	0.3725
11	0.2375

The values for the Snyder Peaking Coefficient were all initially set at an average default empirical value of 0.6 (Bedient and Huber, 1992).

Routing Method

The HEC-HMS model used a Muskingum Cunge Standard Routing Method to simulate the flow in the stream. The reach length (ft) and energy slope (ft/ft) were determined from the GIS topography. The simplified cross section was modeled as a prism, with a bottom width of 5 feet in the upper watershed and 10 feet in the lower watershed (below water elevation gauge used for calibration). A side slope of 1 horizontal unit for every vertical unit was used. Mannings n values ranged from 0.02 to 0.07.

Pompeston Creek Watershed MIKE-SHE Model Set Up

The MIKE-SHE model set up does not require the assignment of an empirical number such as the curve number to determine the runoff and infiltration capacity of the watershed. This model performs the physical calculations as described in Section 3.4 using the physical data input derived from the GIS layers within the model domain. The overland flow module also uses the Manning number to represent the flow delay.

An initial grid size of 10 meters was used in accordance with the distributed resolution of the topography. This fine resolution created long simulations times. The resolution was then decreased to a grid size of 50 meters which provided simulations in a relatively reasonable time. It was determined that after the model was further developed the grid size could be reduced if desired.

The net rainfall fraction, representing the fraction of rainfall that is available for overland flow, was originally set to 1, or 100% of the rainfall was available for overland flow. This would assume that leaf interception and evapotranspiration was negligible over the time period of the event.

In the MIKE-SHE model, there are several options for modeling the rainfall-runoff processes in a watershed. For the purpose of this study, the essential elements of the model should use a fully distributed, spatial database and physically based equations. The input parameter databases, primarily those from GIS, were used to provide a base of consistency between the HEC-HMS model and the MIKE-SHE models.

Method A

Method A was comprised of three components: the overland flow module solved using the finite difference method; a “Rivers and Lakes” module, which describes the flow of the water within the channel and the climate module, which organized the precipitation distribution over time and accounts for the percent of rain available for runoff.

Input to the overland flow module (OL) consisted of the topography database, the distributed input of the Manning M values, the detention storage of the watershed and the initial water depth within the watershed depicting the initial depth of water on the ground surface, used as an initial condition.

The topographic relief (10 meter X 10 meter) was the same as used to determine the flow path in the HEC-GeoHMS model.

The Manning M was determined with the use of the land use file and empirical relations (for the reciprocal, Manning n) based on Chow, 1988. Values of Manning M could range between 100 (smooth surface, low resistance to flow) down to 10 (thickly vegetated, high resistance to flow). A spatial distribution of the original assigned Manning M values for the Pompeston Creek Watershed can be found in Figure 7.

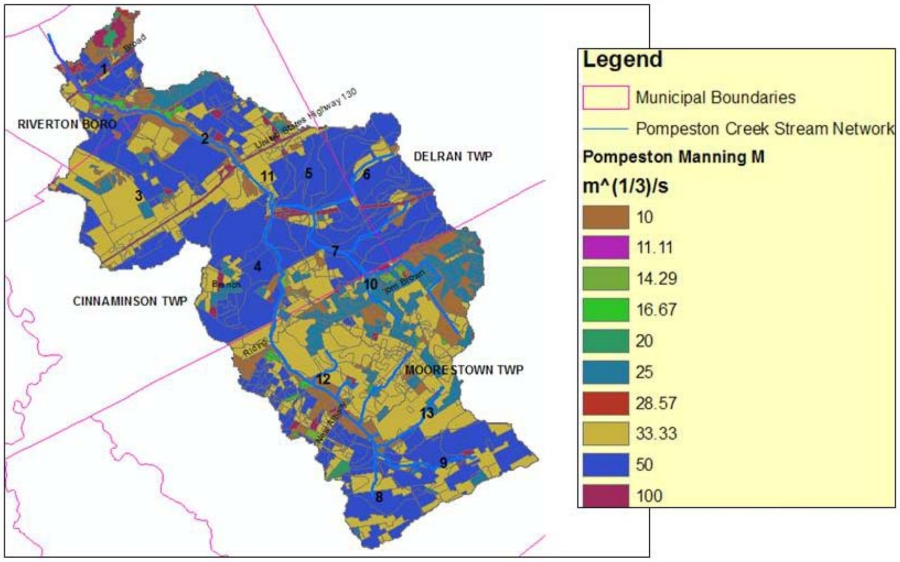

Figure 7: Pompeston Creek Input Manning M values

The original assigned value for the detention storage used a default value of two centimeters (0.787402 in). This would be the depth of ponded water allowed to accumulate on the surface of the land before flow would begin. The value for the initial water depth, the initial condition for the overland flow calculations, was set to zero.

Routing Method: MIKE 11

The "Rivers and Lakes" module of the MIKE model is the MIKE11 application software. This software has the components to provide a more detailed analysis of the hydraulic functions of the watershed than the HEC-HMS provides. However, for the purposes of this study, the stream channel was modeled to replicate the stream channel created in the HEC-HMS hydrologic model.

The stream network was created in the MIKE11 application using the ArcGIS shapefile for the Pompeston Creek. This general line network is then generated into a file that has elements where the flow is calculated (Q points) and elements where the water surface elevation (h points) is calculated. These points are spread along the network with the modeler determining the number by the amount of chainages (links of sections of streams) that are formed upon the network creation. The stream is allowed to accept overland flow input at each stream node (chainage) that is created within the model.

The cross sections used in the MIKE11 model attempted to reproduce the channel created in the HEC-HMS project. Cross Sections were of prism shaped, with a side slope of 1:1 and a bottom width of five to ten feet. The channel dimensions in both the HEC-HMS project and the MIKE-11 project were similar, assumed cross sections. This study did not examine for the model sensitivity to cross section dimension.

Method B

The "Method B" that was used to model the Pompeston rainfall runoff patterns included all of the same parameters as contained in Method A. In addition to the parameters that were used for the overland and channel flow modules, three databases were added for the purpose of gaining a better understanding of the distributed the soil infiltration function. These three databases included: a module to include water movement in the unsaturated zone; a module to include the movement of water in the saturated zone and a spatially distributed grid layer depicting the level of impervious surface.

In the MIKE-SHE model, the unsaturated zone was modeled using a 2-layer water balance method (See Section 3.4.5). This method requires the four physical characteristics of soil infiltration: the water content at saturation, the water content at field capacity, water content at wilting point and the saturated hydraulic conductivity. Table 8 provides the initial input parameters that were selected for use in the Pompeston MIKE-SHE Method B hydrologic model.

Table 8: Original Soil Property Parameters for Unsaturated Zone Model (Method B)

ID		Hydgrp*	MUSYM**	Water Content at Saturation(1) (df 0.3)	Water Content at field capacity(2) (df 0.1)	Water Content at wilting point(3) (df 0.05)	Saturated Hydraulic Conductivity (ft/day) (df 2.83465)
0	Water	X	WATER	0	0	0	0.000
1	Galestown	A	GabB	0.417	0.217	0.05	39.998
2		A	UddcB	0.432	0.232	0.05	39.998
3	Klej	B	GakB	0.432	0.232	0.05	25.998
4	Sand/Gravel	A	PHG	0.5	0.3	0.05	3.999
5		D	UdrB	0.486	0.286	0.05	0.060
6	Sassafras	B	SabB	0.401	0.201	0.05	25.998
7		A	URSAAB	0.486	0.286	0.05	39.998
8	Sassafras	C	SapkB	0.486	0.286	0.05	2.599
9	Downer	B	DocC	0.401	0.201	0.05	25.998
10		D	MamnAv	0.417	0.217	0.05	0.060
11		C	URSACB	0.486	0.286	0.05	2.599
12	Urban Land	B/D	HofB	0.4	0.2	0.05	7.999
13		B/D	FmhAt	0.486	0.286	0.05	7.999
14	Sassafras	C	SaekB	0.486	0.286	0.05	2.599
15	Sassafras	B	SapB	0.486	0.286	0.05	25.998
16	Woodstown	C	WofkB	0.486	0.286	0.05	2.599
17	Keyport	C	KeoC	0.434	0.234	0.05	2.599
18	Fallsington	B/D	WofA	0.486	0.286	0.05	0.259
19	Sassafras	C	SaekA	0.486	0.286	0.05	2.599
20	Woodstown	C	WofkA	0.486	0.286	0.05	2.599
21	Woodstown	C	WofkB	0.486	0.286	0.05	2.599
22		B/D	FanA	0.486	0.286	0.05	7.999
23	Keyport	C	KeoB	0.434	0.234	0.05	2.599
24	Shrewsbury	C/D	DobA	0.486	0.286	0.05	0.259
25	Sassafras	C	SaekA	0.486	0.286	0.05	2.599
26	Sassafras	B	SaeA	0.486	0.286	0.05	25.998
27		C/D	CoeAs	0.486	0.286	0.05	0.799
28	Keyport	C	KeoA	0.434	0.234	0.05	2.599
29		C	WofkA	0.486	0.286	0.05	2.599

*** See Appendix B; **Map Unit Symbol; (1), (2) and (3): Rawls et al., 1982/52/; Cosby et al., 1984/44/;Rijtema, 1969,/55/ (4) NRCS** http://www.mo10.nrcs.usda.gov/references/guides/properties/sathydcond.html

The model provides a default parameter for each of these features in the event that the soil is not user characterized. These default numbers are shown in parentheses under the column heading in Table 8.

The saturated zone was included as a necessary module that created the opportunity to incorporate the "paved runoff coefficient" spatial gridded database that represented the extent of the impervious area. The saturated zone was modeled to provide initial conditions that would allow the unsaturated zone to infiltrate according to its hydraulic properties. The initial default quantification of these properties can be found in Table 9.

Table 9: Default input parameters for Saturated Zone Module

Geological Layers			
	Lower Level Aquifer	-30	ft
	Horizontal Hydraulic Conductivity	28.3465	ft/day
	Vertical Hydraulic Conductivity	28.3465	ft/day
	Specific Yield	0.02	$L^3/L^2/L$
	Specific Storage	3.05E-05	L^{-1}
Computational Layers			
	Initial Potential Head	-3.28	ft

Impervious Area

The intent of the creation of Method B in the MIKE-SHE modeling format was to be able to spatially represent the amount of impervious area that the watershed contains. The 2002 Land Use/Land Cover GIS shapefile was used to determine the percentage impervious (see Figure 8 and Map 4 in Appendix A). This GIS shapefile was transformed into a GIS grid file, and then into a dfs2 file that is compatible with the MIKE-SHE modeling system.

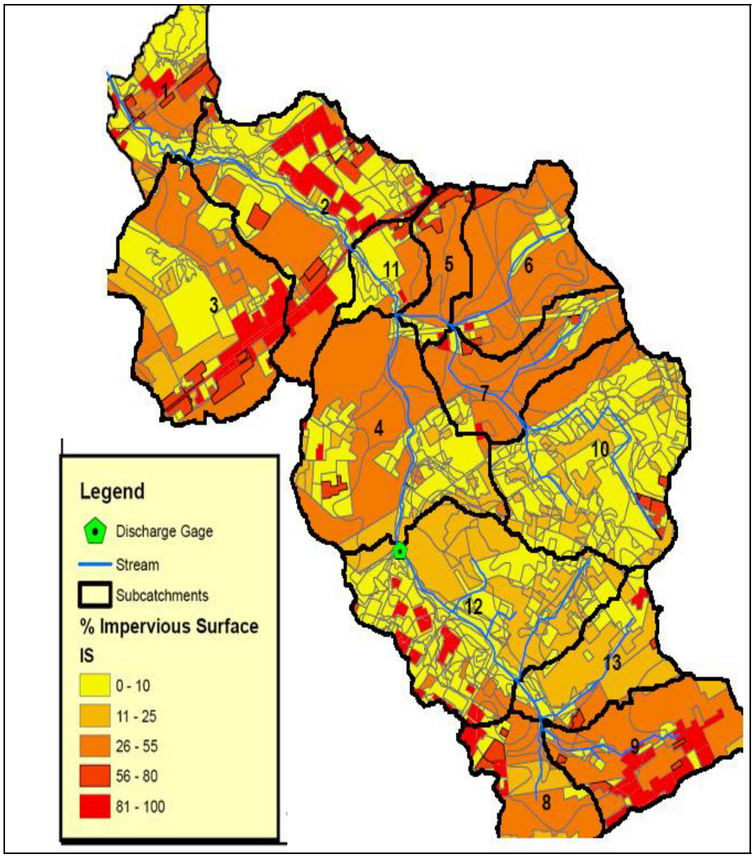

Figure 8: Pompeston Creek Impervious Area

The impervious cover dfs2 file is to initiate the amount of precipitation that is available for runoff by calculating the percentage available to the soil layer. The model will automatically route the excess precipitation from the impervious area directly to the stream nodes; this routing is based on the assumption that the time steps of the simulation are longer than the time it would take for the precipitation that hits the impervious area to make it to the stream (DHI, 2008). This assumption is not always the case, particularly in event based modeling.

The breakdown of the impervious surface distribution in the Pompeston Creek Watershed is found in Table 4. As discussed previously, the gauge for the observed data is located at the outlet of Subbasin 12 (see Map 1, Appendix A). This outlet was intended to represent the runoff from the upper four subbasins, 8, 9, 13 and 12. Together these subbasins contain 24.9% impervious area, whereas the entire Pompeston Creek Watershed consists of 25% impervious area.

3.3.3 The Troy Brook Watershed

Study Area

The Troy Brook Watershed (Appendix A, Map5 and Figure 9) is located in eastern Morris County, New Jersey. The watershed is 12 miles northeast of Morristown and approximately 25 miles from New York City. The watershed drains approximately 16 square miles with the majority of the watershed lying within the municipality of Parsippany-Troy Hills with lesser areas in Mountain Lakes and Hanover Townships. The major lakes in the watershed include Mountain Lake, Wildwood Lake, Intervale Lake, Parsippany Lake, Bee Meadow Pond, Forge Pond, the Upper Pond at the former BASF Corporation Property and the Pond at Sheraton Hotel. Major tributaries for Troy Brook include West Brook, Eastmans Brook, the tributary from Intervale Lake and the tributary from Mountain Lake. West Brook is located in the western edge of the Troy Meadows and extends from Bee Meadow Pond to its confluence with Troy Brook. Eastmans Brook is located in the south central portion of the watershed and extends from Lake Parsippany to its confluence with Troy Brook. The Mountain Lake tributary is located in the northwest portion of the watershed and extends from Mountain Lake to its confluence with Troy Brook. The tributary from

Intervale Lake is located in the northern regions of the watershed flowing from Wildwood Lake to Intervale Lake and then through Manor Lake and into Troy Brook just south of Route 46. In addition there are several smaller tributaries and ponds in the watershed.

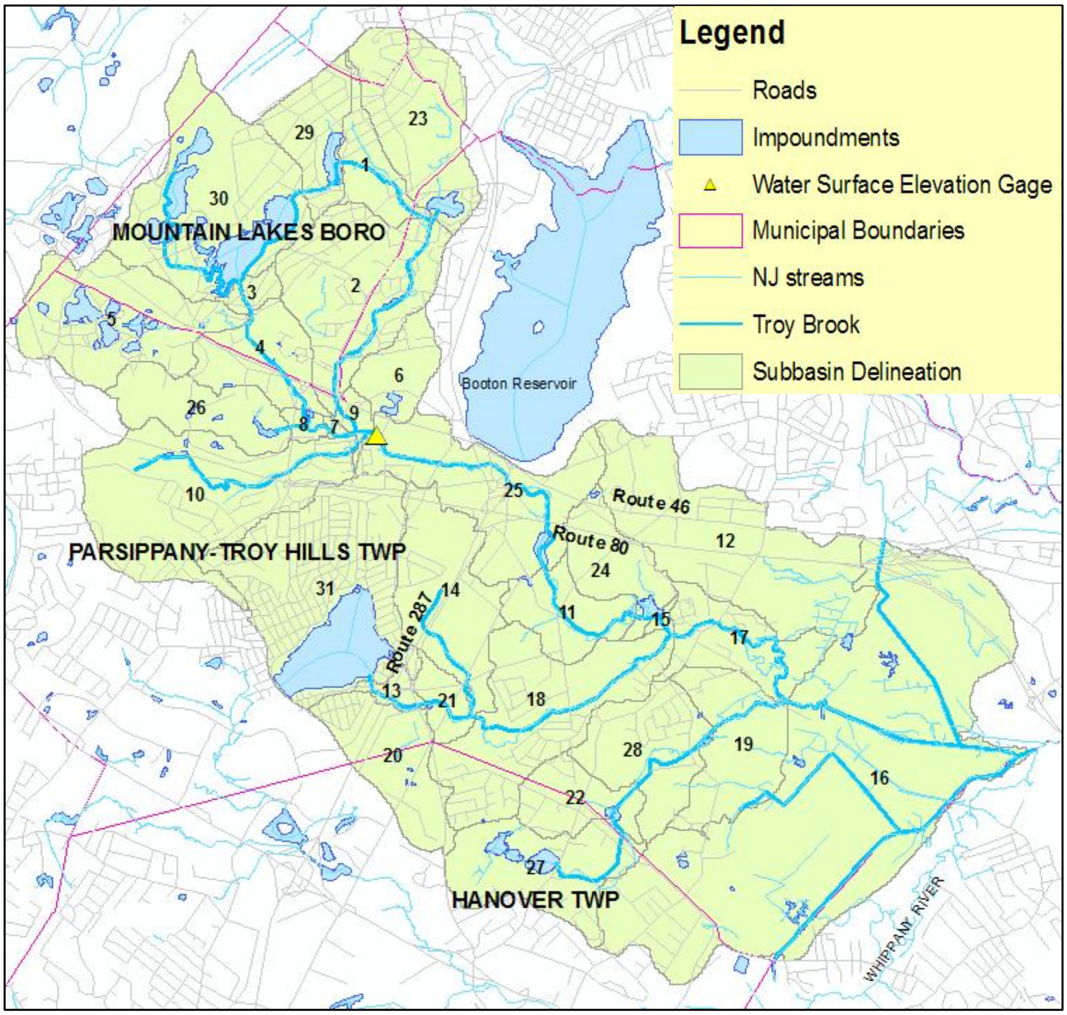

Figure 9: The Troy Brook Watershed Study Area

Land Use

The land use in the Troy Brook Watershed ranges from low density residential in Mountain Lakes, medium to high density residential through Parsippany-Troy Hills, to wetlands in the Troy Meadows section of Parsippany-Troy Hills. Hanover Township consists primarily of medium density and low density residential. Hanover Township also has a significant transitional area representing areas under development, where site preparation is present, but the future use has not been realized. Refer to Map 6 in Appendix A for the map of the Troy Brook watershed's existing land uses.

According to data collected by the NJDEP, the land use of the Troy Brook Watershed is 53% urbanized (Table 10).

Table 10: Troy Brook Land Uses 2002

Land Use	Area Square Miles	Percentage of Watershed Area %
Agriculture	0.08	0.5
Barren Land	0.05	0.3
Forest	3.37	20.9
Urban	**8.55**	**53.1**
Water	0.68	4.2
Wetlands	3.37	21.0
Total	*16.11*	*100.0*

Soils

The Troy Brook watershed may further be characterized by its soils. Within the Troy Meadows, soils are predominantly Carlisle muck. This soil series consists of very poorly drained and very deep soils formed in depressions of lake plains, outwash plains, moraines, and floodplains. The ponding duration is known to be long, from October through June, and the typical slopes range from 0 to 2 percent (NJDEP/USDA NRCS, 2004). The remaining soils of the watershed are variable. The Parsippany series are mostly found up-gradient of the Troy Meadows and follow the stream corridor. The Parsippany series consist of deep, poorly drained soils in extinct lake basins and near streams. The Parsippany series are characterized by their slow infiltration rates, shallow water table, resistance to erodibility, and are usually subject to seasonal flooding. Potential for surface water runoff is considered high for this soil series (NJDEP/USDA NRCS, 2004). The Riverhead soil series can be found in the northwest and north regions of the drainage basin. This series has been classified as having very deep, well-drained soils, derived from granitic material. Slopes can be extremely variable, from 0 to 50 percent slopes. Due to their well-drained nature, surface runoff potential is considered low to medium (USDA/NRCS, 2004). Spanning the north and middle section of the watershed are the Rockaway soil series. These soils can be categorized as being moderately well-drained, formed as till on uplands. Slope can range from 30 to 60 percent (USDA/NRCS, 2001). Finally, urban soil complexes exist throughout the center and northern regions of the watershed. Urban soils differ from soils that have formed over centuries and millenniums and thus do not have a uniform structure or known properties. Rather, urban soils range from being extremely variable in texture and structure to being uniformly heavily compacted soil material (Baumgartl, 1998). The dominant soil series within the Troy Brook Watershed are depicted in Figure 10. (RCE WRP, 2007)

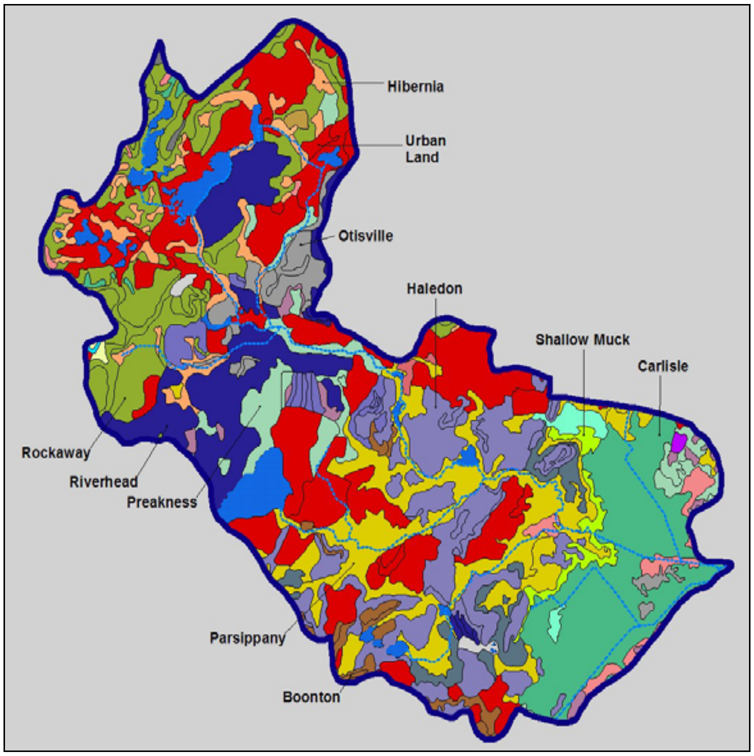

Figure 10: Dominant Soil Series in the Troy Brook Watershed

Soils can also be classified according to their potential to infiltrate water. As discussed previously, the Natural Resource Conservation Service (NRCS) categorizes soils that have high infiltration rates, "A" soils, to those that have very slow infiltration rates, or "D" soils. The soils that possess intermediate qualities are classified in a continuum. Map 7 in Appendix A shows the soils of the Troy Brook Watershed as defined by their hydrologic soil group (hydgrp).

Impervious

The land use shapefile includes the information on the percent of the impervious cover identified in the aerial photography. Each land use polygon is designated a percent impervious and the overall impervious nature of the watershed can be determined. An overview of the impervious coverage within the Troy Brook Watershed can be found in Table 11. A map showing the distribution of the percentage of impervious area throughout the watershed can be found in Appendix A, Map 8 and in Figure 11.

Table 11: Troy Brook Impervious Area Coverage

		acres	sq mi	IS acres	IS sq mi	% IS
Overall watershed		10192.66		1488.711		14.60572
Upstream Subbasins	1	133.3	0.21	23.9	0.04	17.9
	2	475.0	0.74	44.6	0.07	9.4
	3	39.6	0.06	10.1	0.02	25.6
	4	209.5	0.33	87.3	0.14	41.6
	5	436.5	0.68	80.5	0.13	18.4
	6	133.6	0.21	50.1	0.08	37.5
	7	8.4	0.01	4.0	0.01	47.9
	8	26.6	0.04	3.4	0.01	12.8
	9	35.9	0.06	15.4	0.02	42.9
	10	644.9	1.01	75.3	0.12	11.7
	23	374.7	0.59	56.0	0.09	56.0
	26	218.5	0.34	57.6	0.09	57.6
	29	183.9	0.29	23.3	0.04	23.3
	30	621.2	0.97	56.5	0.09	56.5
Total Upper Basins:		3541.7		588.1		16.6

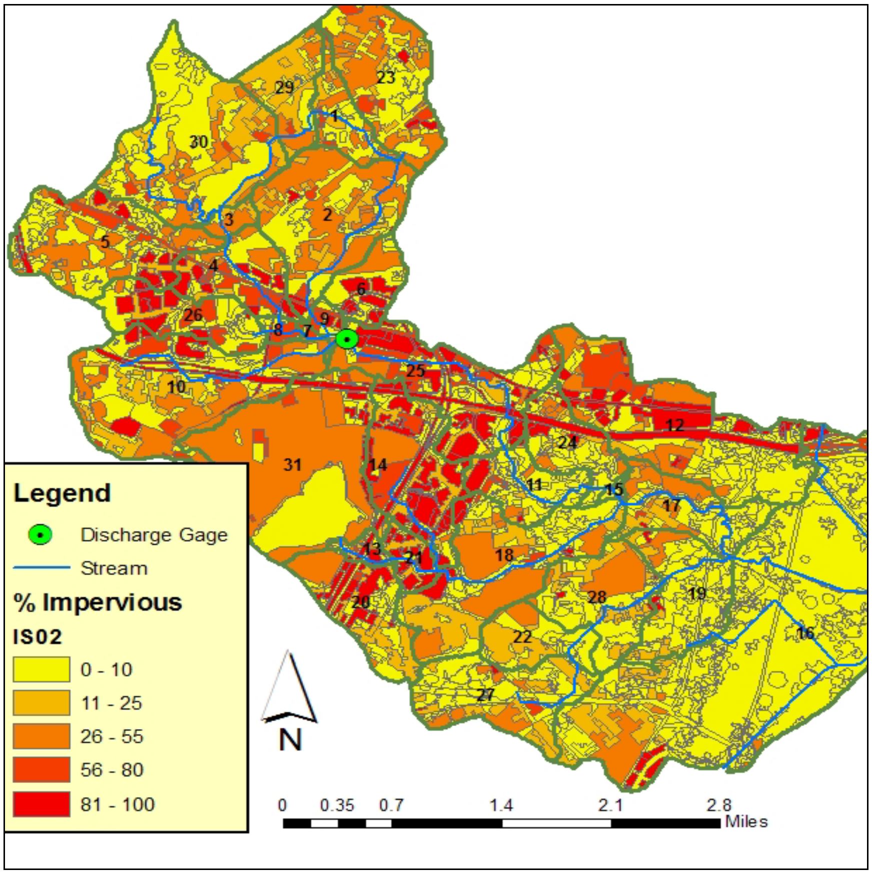

Figure 11: Troy Brook Percent Impervious Surface Per Area

The impervious nature of the entire sixteen square mile watershed is represented in the upper fourteen subbasins (Table 11). It was these subbasins that were able to be calibrated with available observed data. The overall watershed consisted of 14.6% impervious area, where the upper basins gauged for calibration purposes consisted of 16.6% impervious area.

Observed Precipitation Events: Troy Brook Watershed

The Troy Brook Watershed was evaluated for the water surface elevation at the Subbasin 9 outlet site for approximately eight months beginning in February of

2008. Precipitation depths over time and flow over time were considered for model input if the distributions were somewhat parabolic and the volume of precipitation was over 0.5 inches and under 1.25 inches. This range was determined as the area of interest, given that visible runoff would be expected to begin after 0.5 inches of precipitation and given that storms under 1.25 inches constitutes 90% of all rain events in the mid-Atlantic states (Claytor and Schueler, 1996). Storms providing over 1.25 inches of precipitation are considered above the water quality design storm that stormwater management facilities are designed to maintain.

Five storm events were determined to be appropriate for use in calibration and validation in the Troy Brook Watershed. The storm time distribution and total precipitation depth can be seen in Table 12.

Table 12: Troy Brook Watershed Storm Events

Storm Date	Length of Storm (hours)	Total Precipitation Depth (inches)
2/1/2008	**13**	**1.16**
3/4/2008	**16.5**	**0.81**
3/19/2008	17	0.94
4/28/2008	18	1.07
5/9/2008	18.5	1.15

Observed Flow

Calibration for the four upstream subbasins was performed with the observed flow that was measured at the outlet of Subbasin 9, as can be seen located in Figure 9.

Given that there exists no USGS gage to measure long term flow in the watershed, this site was set up specifically for this modeling effort. A pressure transducer was placed at the bottom of the stream at this location. The water surface elevation and the corresponding flow were determined over the course of several seasons to incorporate a variety of situations. The resulting rating curve can be seen in Figure 12.

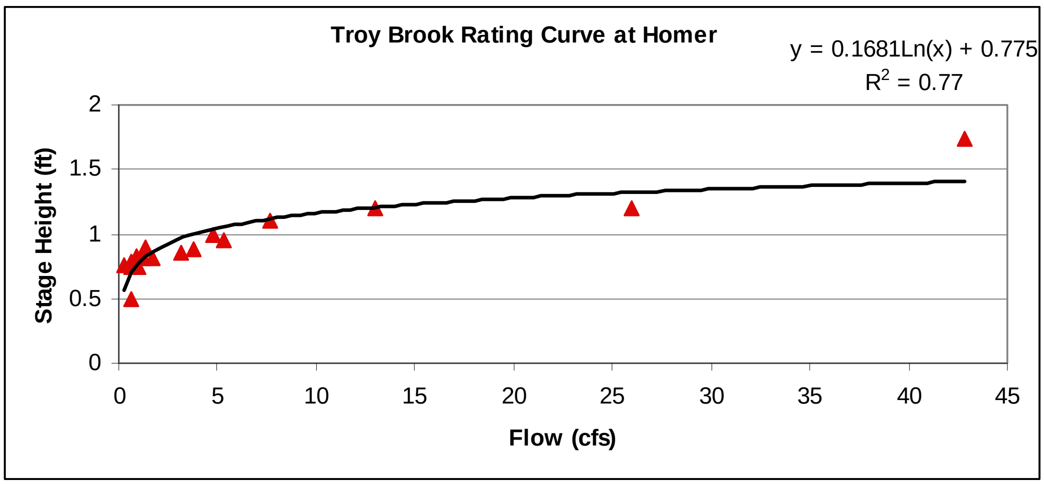

Figure 12: Troy Brook Rating Curve

HEC-HMS Set Up: Troy Brook Watershed

A HEC-HMS model was set up for the Troy Brook watershed. The simulation of precipitation and runoff processes consists of determining the amount and rate of surface runoff reaching the Troy Brook and its tributaries and routing it through a channel network. The model setup was done in two main modules: the basin model and meteorological model. The basin model contains watershed elements, properties and connectivity. The meteorological model contains precipitation intensity distribution over time.

Loss Rate

As with the Pompeston Creek HEC-HMS model, the curve number was determined as a function of land use, hydrologic soil group and available soil moisture. The 1995 land use land cover data coverage available from the NJDEP GIS database, and the NRCS SSURGO soils were used to determine average soil moisture condition curve numbers for each land use and soil combination in the Troy Brook watershed. The composite (area weighted average) curve numbers were obtained using spatial analysis techniques and spatial databases within GIS.

Areas with unique combinations of land use and soil type, and consequently hydrologic soil groups, were obtained by overlaying land use and soil datasets. These overlay processes created several polygons representing distinct combinations of these characteristics. Each of these polygons was assigned a curve number using tables published by the SCS in Technical Report 55 (USDA, 1986). The table of average soil moisture CNs used for these study watersheds was presented in Table 1.

Transform

The transformation of the excess runoff to stream flow was performed using the Synder Unit Hydrograph, in a similar manner to the Pompeston Creek HEC-HMS model. The two input parameters required are the Snyder Lag time and the Snyder Peaking Coefficient. Values of the Snyder Lag time were determined using Equation 5 and the parameters derived from the GIS layers (Table 13).

Table 13: Troy Brook Original Transform Parameters

Subbasin	Snyder Lag Time (tp hrs)
1	1.889
2	2.418
3	0.93
4	1.83
5	2.375
6	1.592
7	0.766
8	0.966
9	0.912
10	2.852
23	2.119
26	2.099
29	1.463
30	2.361

The values for the Snyder Peaking Coefficient were all initially set at an average default empirical value of 0.6 (Bedient and Huber, 1992).

Routing Method

The HEC-HMS model used a Muskingum Cunge Standard Routing Method to simulate the flow in the stream. The reach length (ft) and energy slope (ft/ft) were metrics determined from the GIS topography. The simplified cross section was modeled as a prism, with a bottom width of 5 feet in the upper watershed and tributaries and 10 feet on the main stem. A side slope of 1 horizontal unit for every vertical unit was used. Mannings n values ranged from 0.026 to 0.034.

Troy Brook Watershed MIKE-SHE Set Up

The MIKE-SHE model for the Troy Brook Watershed was set up in a similar manner as the Pompeston Creek Watershed MIKE-SHE model. There is no assignment of curve numbers for the method used for the overland flow module. All data required for slopes, centroid lengths and model domain were acquired from the GIS data layers.   This overland flow module does use the Manning number, an empirical coefficient, to represent the flow delay in this physical model.

An initial grid size of 10 meters was used in accordance with the distributed resolution of the topography. This fine resolution created long simulations times. The resolution was adjusted to a grid size of 26 meters which provided simulations in a relatively reasonable time. It was determined that after the model was further developed the grid size could be reduced if desired.

The Troy Brook Watershed rainfall-runoff was modeled in MIKE-SHE using solely Method A, the overland flow module without soil infiltration capabilities.

Method A: Troy Brook

Method A was compiled in a similar process as Method A for the Pompeston Creek modeling study. The principal process during the simulation using Method A is the overland flow, with input parameters including topography, Manning M values, detention storage and initial water depth.

The spatial distribution of the Mannings M roughness coefficients can be seen in Figure 13. Higher values of Mannings M depict the smoother surfaces expected to produce runoff more readily than lower numbers. The Manning M value has been reported to be the inverse of assigned Manning's n values, however this remains a calibratable parameter.

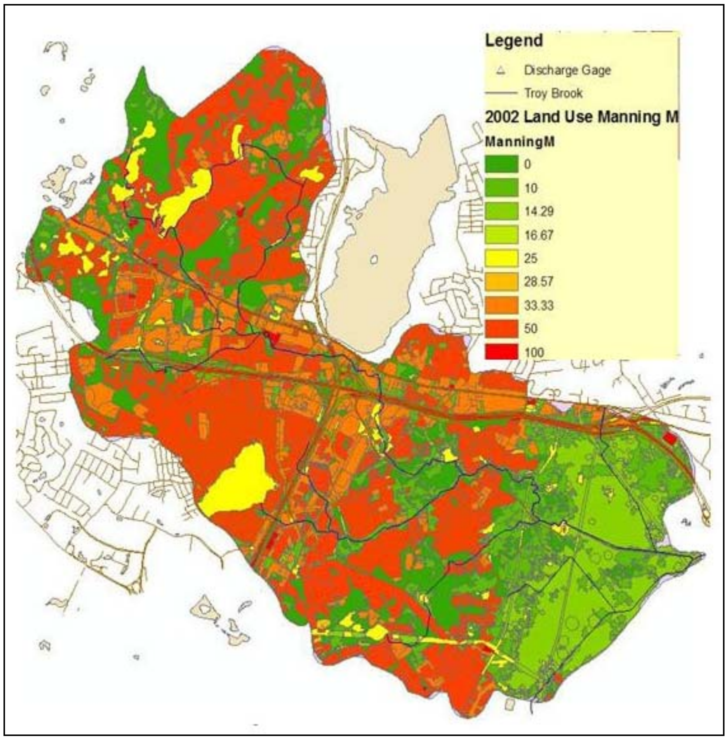

Figure 13: Troy Brook Manning M values

The original assigned value for the detention storage used a default value of two centimeters (0.787 in). This would be the depth of ponded water allowed to accumulate on the surface of the land before flow would begin.

The value for the initial water depth, the initial condition for the overland flow calculations, was set to zero.

Routing Method: MIKE 11

The routing for the stream channel in the Troy Brook was performed in a similar manner as was performed in the Pompeston Creek MIKE-SHE model.

3.4 Planning

The lumped parameter models for both the Pompeston Creek Regional Stormwater Management Plan and the Troy Brook Regional Stormwater Management Plan were the primary models used to bring the plan to completion. In both watersheds, the model parameters were adjusted to theoretically capture the change in runoff potential with the change in land use. Alterations in the curve number were used as the primary factor used to educate stakeholders in the relation of impervious cover and poorly draining soils to the effects of the stormwater volume and velocity within the stream network. Per cent in the curve number were used in the model and the resultant volumes were used to show watershed sensitivity to the curve number.

"Design" precipitation events were employed to depict potential output scenarios. These 24-hour design rain events are developed by statistical analysis of rainfall records, although the temporal distribution may not be what is seen occurring in actuality (Ubonis, 1979). Data used for the two case studies presented in Table 14 were obtained from the Natural Resources Conservation Service (NRCS) Technical Bulletin 2004-4.0 (Birckhead, 2005), based on data obtained from the statistical estimates of rainfall amounts performed by the National Oceanographic and Atmospheric Administration (NOAA).

Table 14: Design Storm Rainfall Depths

TYPE III STORM	Morris County 24-HR RAINFALL (INCHES)	Burlington County 24-HR RAINFALL (INCHES)
2-Year Storm	3.3	3.4
10-Year Storm	5.2	5.2
100-Year Storm	7.5	8.8

The distributed models were not used in the original planning efforts. The HEC-HMS was able to portray the role of infiltration as to the effects on the stream. However, the internal processes that could manage the magnitude of the runoff could not be modeled within the capacity of the lumped parameter model. The spatially distributed function, including the cell to cell calculation of the runoff processes was determined to be necessary in order to represent the management options that should be considered for a strormwater management plan. The functioning of the MIKE SHE model was evaluated on the observed data used in the calibration and validation efforts.

4. Results

Model results revealed various complexities involved in the hydrologic modeling of the urban watershed. The two urban watersheds demonstrated the importance of properly quantifying the urban nature of impervious surfaces and soils, and the two types of hydrologic models demonstrated the importance of accurate input data.

4.1 Pompeston Creek Watershed Case Study

The Regional Stormwater Management Plan for the Pompeston Creek Watershed included simulations with HEC-HMS, a lumped parameter hydrologic model. The waterways in this watershed were impaired by high bacteria and phosphorus levels and exhibited a poor overall evaluation regarding the macroinvertebrate community (RCE WRP, 2007). Although the urban land use is primarily low and medium density residential development, the overall impervious nature of the watershed is 25%. Delineating this watershed into several subbasins, the model was able to simulate the processes of runoff and the hydrologic impacts of higher volume and velocity contributions to the streams that would potentially contribute to lower water quality conditions. Much of the modeling effort revolved around properly characterizing the curve number and determining methods that would reduce the curve number and infiltrate more precipitation on site.

It became clear that these lumped models were only able to explain the processes in general and with an emphasis on an empirical parameter that is primarily used for calibration. Thus, the MIKE-SHE model was used to determine if a fully distributed, physical model could be used in an effort to identify problems and solutions with a more site specific method using the same available input data.

4.1.1 Lumped/Empirical Calibration

The Pompeston Creek Watershed HEC-HMS model was primarily calibrated by visual analysis and optimization of parameters, ultimately using an objective function for intercomparison of simulations that were visually deemed appropriate. The Nash-Sutcliffe Coefficient was the objective function used to optimize the model representation for the purposes of this.

Calibration to achieve a set of best fit parameters for the Pompeston Creek HEC-HMS lumped parameter model was performed on the storm event that occurred on November 16, 2005. The total precipitation for this event was 0.728 inches over a 3.5 hour period and the five day antecedent moisture condition was recorded to be 0.3 inches of precipitation. The resultant calibration provided a Nash-Sutcliffe efficiency coefficient of E=0.611, indicating that the model predictions are more accurate than the mean of the observed data (E=0), but skewed closer to being a perfect match (E=1). The resultant hydrograph, along with the hyetograph, can be viewed in Figure 14.

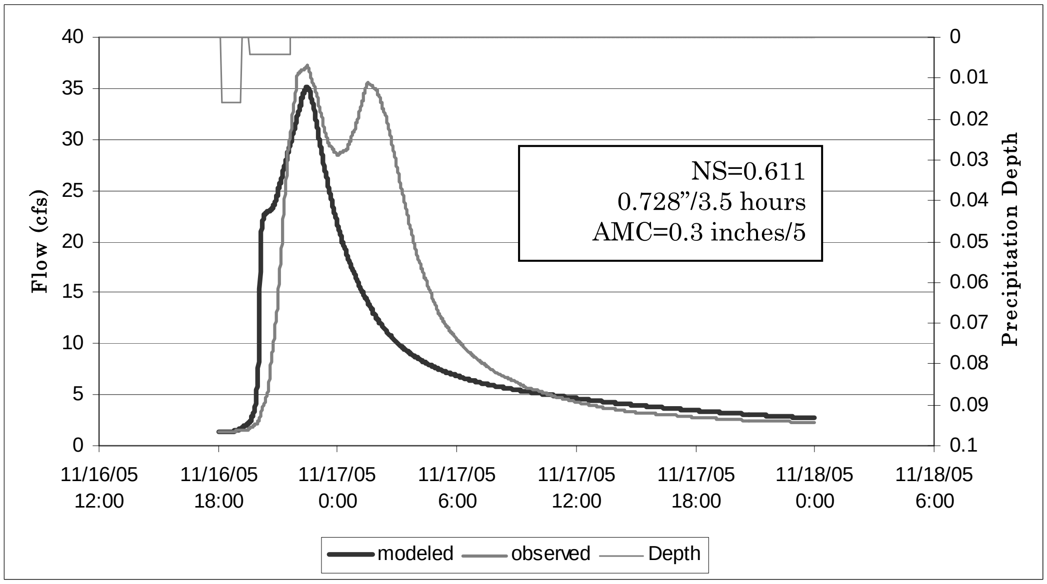

Figure 14: Pompeston Creek HEC-HMS Calibration: 11/16/ 2005

The storm distribution shows two discrete intensities of precipitation during the event. The modeled runoff demonstrates the effect from these distinct sections of rainfall, but is not fully represented in the calibration. It appeared reasonable to decrease lag time further to move the first modeled peak to begin its rise at a similar time. When this was performed, the value of the optimization parameter fell due to the larger difference between the first modeled peak and the first observed peak.

The curve numbers that were initially determined through the assignment of a quantifiable figure using the SCS method were found to be a reasonable empirical approximation of the soil and land use infiltration/runoff capacity of those subbasins. The original modeled parameters and the parameters determined through calibration can be found in Table 15.

Table 15: Parameters for Pompeston HEC-HMS

Basin	Initial CN	Calibrated CN	Initial Ia	Calibrated Ia	Initial Lag Time	Calibrated Lag Time	Initial Peaking	Calibrated Peaking
8	79.4	77	0.52	0.1	1.69	0.363	0.6	0.27
9	81.1	78	0.47	0.1	2.22	0.726	0.6	0.36
13	81.1	81	0.47	0.1	1.99	0.847	0.6	0.36
12	84.7	86	0.36	0.1	2.61	2.541	0.6	0.18

The percent change in the estimated and the calibrated curve number ranged from 0.1 percent to 3.8 percent throughout the four subbasins (Table 16), with small changes resulting in increases in runoff volume. These distinct changes should be viewed as a range of potential change, since these four subbasins are ultimately "lumped" together for the purposes of the calibration. The change in the curve numbers show the smallest percent change that was necessary to create a calibrated model that better represents this watershed.

The initial abstraction (I_a) percent change from the original parameters to the calibrated parameters showed a range of 72 to 81 percent difference (Table 16). Although the I_a is empirically related to the potential maximum surface retention (S) in the watershed, which is empirically related to the curve number, for the purpose of the calibration, these parameters moved independently. The reduction of the depth of the I_a created the situation where the maximum percentage of precipitation would be represented early in the hydrograph, to correspond to the minimal retention capacity within the watershed.

Table 16: Percent Change in Pompeston HEC-HMS Calibrated Parameter

	Percent Change in Calibrated Parameter			
Basin	CN	Ia	Lag Time	Peaking Coefficient
8	3.0	80.8	80.5	50.0
9	3.8	78.7	70.3	33.3
13	0.1	78.7	61.3	33.3
12	1.5	72.2	11.5	66.7

The Snyder Lag Time parameters were reduced during the calibration. The necessary reduction ranged between 11 and 81 percent. With the reduction in lag time, the modeled watershed response viewed in the hydrograph begins to show the movement in the rising limb of the hydrograph at an earlier time than was determined through initial estimation of parameters. The change in the peaking coefficient affected the rate of change in the rising and falling limb of the hydrograph as well as the height of the peak of the hydrograph, keeping volume consistent. The peaking coefficient was best represented by a reduction in the initial empirical parameters by a range of 33 to 67 percent.

4.1.2 Lumped/Empirical Validation

The watershed loss and transform parameters that were obtained in the calibration of the November 11, 2005 event were used in the validation analysis of the October 24, 2008 rain event. This event provided three distinct sections of rainfall intensity, but each of the sections was relatively less intense than the November 11th event. Total rainfall for this event was 1.06 inches over 22.3 hours. This event was preceded by a total of 1.03 inches of rain in the previous five days, representing a different antecedent moisture condition than that observed on the November 11, 2005 storm. As can be seen in Figure 15, many of the important aspects of the hydrograph are not well represented. All three of the observed peaks begin to rise before the modeled peaks, indicating an even lower lag time and/or lower initial abstraction. The volume is also over predicted using these model parameters, particularly in the third peak. The storm distribution, greater antecedent moisture and lower intensity could contribute to the lower Nash-Sutcliffe efficiency parameter of -3.49.

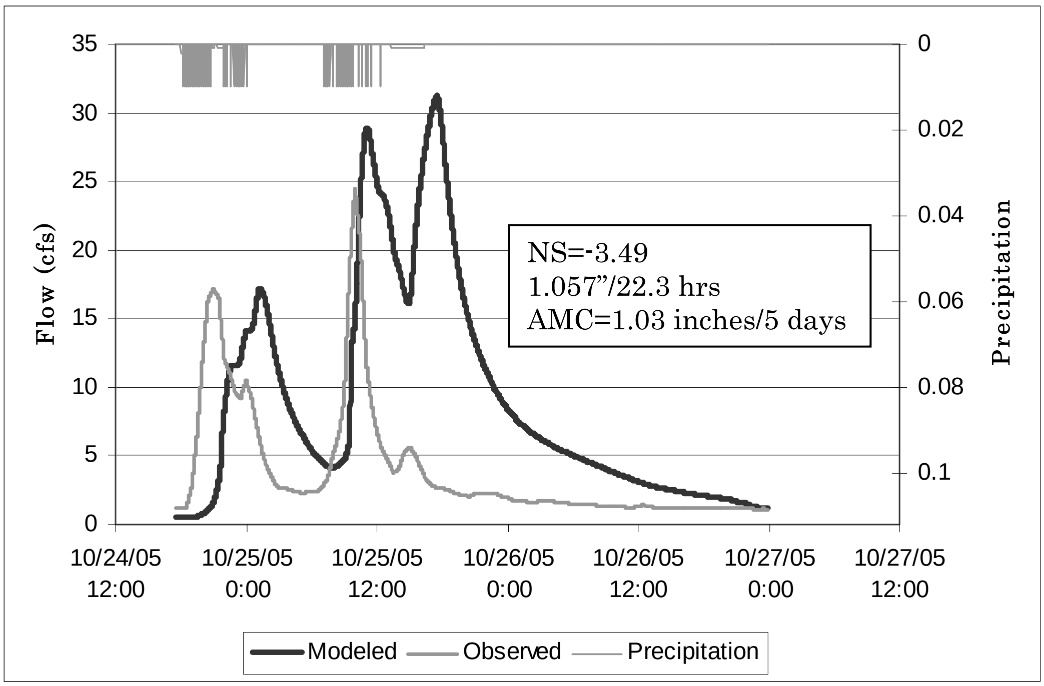

Figure 15: Pompeston Creek HEC-HMS Validation: 10/24/ 2005

4.1.3 Mount Holly Precipitation Data Set

In evaluating the potential contributions to the inaccuracies in the original lumped parameter calibration effort, an alternate input data set representing the precipitation measurements recorded at a nearby climate station was simulated against the observed data in the Pompeston Creek Watershed for the storm event on 11/16/05. This data set achieved a Nash-Sutcliffe efficiency coefficient of

0.966, matching well the rising limb, the peak height of two separate peaks and the timing of the falling limb (Figure 16).

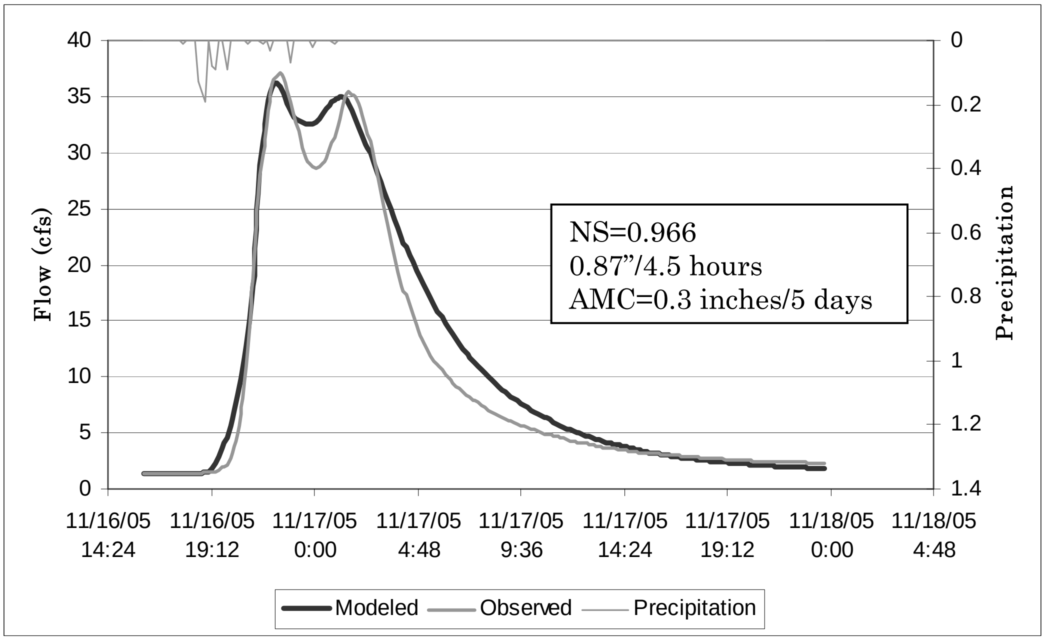

Figure 16: Pompeston Creek HEC-HMS alternate precipitation data for calibration

The best fit parameter set was then used for a validation simulation with the precipitation data collected that was also collected at this alternate site. Results were less than optimal, producing a Nash-Sutcliffe efficiency coefficient of -91. 7 (Figure 17). The effect of the varying antecedent moisture condition is evident in the timing of the rising limb, but this alternate data does not appear to represent the effect of the precipitation distribution observed in the stream as was seen in the earlier data set.

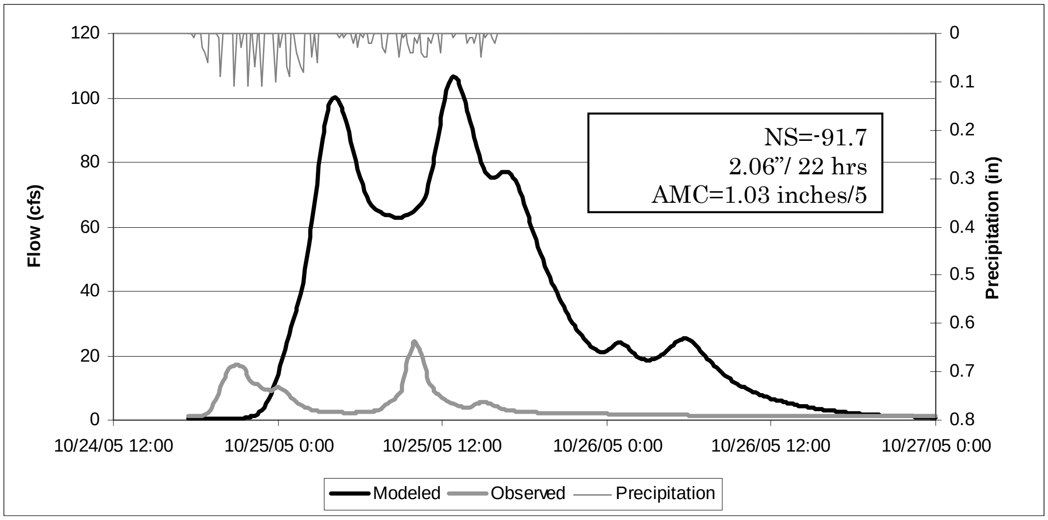

Figure 17: Pompeston Creek Alternate Precipitation Data for Validation

4.1.4 Lumped/Empirical Sensitivity

An analysis of the parameter sensitivity was performed using the October 25th storm event. The model parameters were adjusted for points greater and lesser than the optimal parameter determined in the calibration, and the effect on the optimization parameter, the Nash-Sutcliffe Efficiency Coefficient, was calculated.

Adjustment of the parameters was performed in stages on a percentage basis to allow the larger empirical parameters to fluctuate a proportional amount compared to the parameters with a smaller magnitude.

The sensitivity analysis demonstrated that small deviations in the three parameters of initial abstraction, Snyder lag time and the Snyder Peaking Coefficient produced a generally bilateral curvelinear deviation from the optimal (Figure 19, 20 and 21). The Curve Number is more reactive to percent deviations in its quantification and particularly sensitive to overestimation of this empirical parameter (Figure 18).

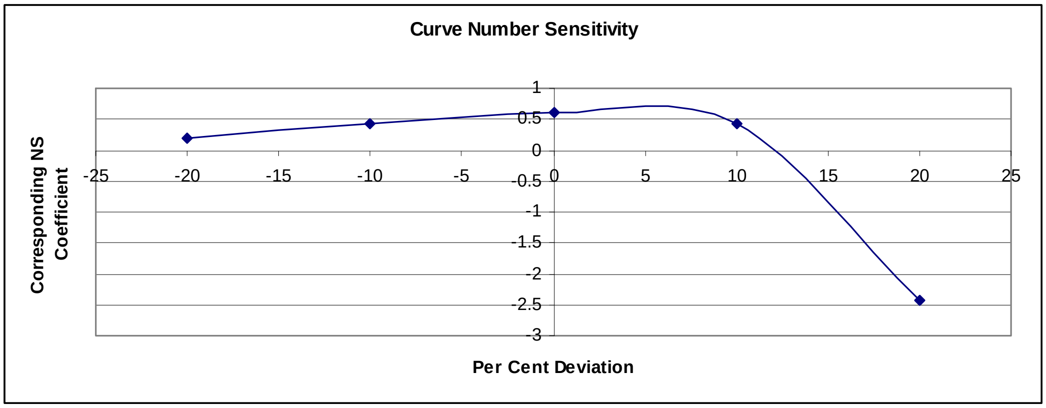

Figure 18: Curve Number Sensitivity

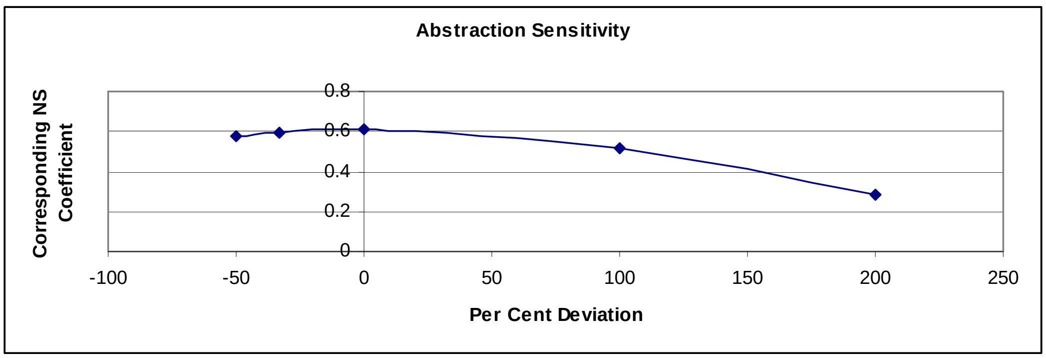

Figure 19: Intial Abstraction Sensitivity

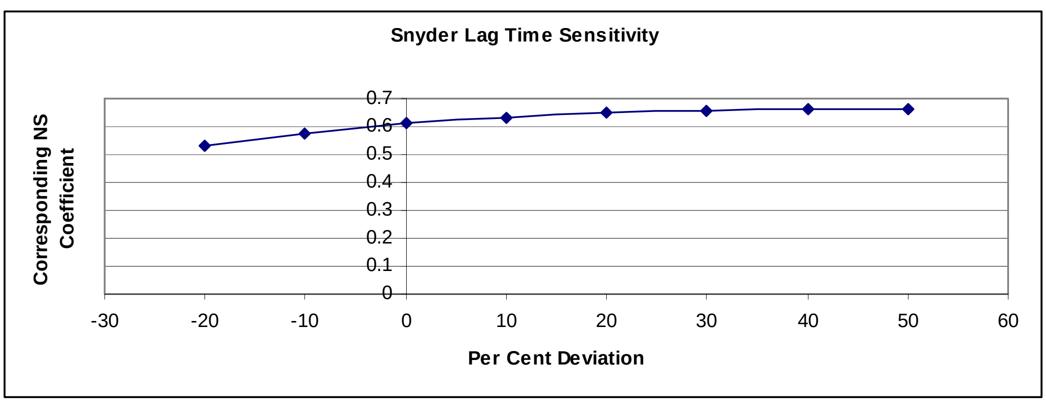

Figure 20: Snyder Lag Time Sensitivity

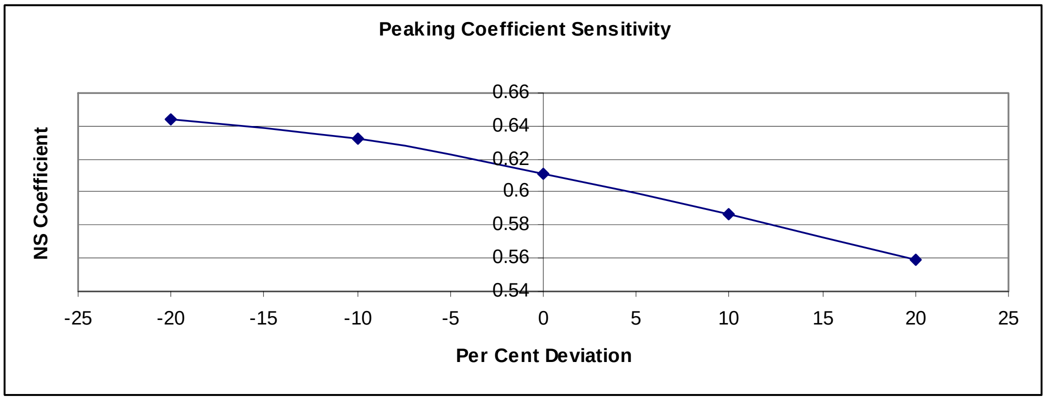

Figure 21: Peaking Coefficient Sensitivity

4.1.4 Distributed/Physical Calibration: Method A

Two variations of MIKE SHE models were developed for the Pompeston Creek Watershed, Methods A and B. The more simplistic physical model that focuses on overland flow as the primary effect on the hydrograph contains only a small number of parameters that could be calibrated. Calibration efforts for the November 16, 2005 storm event were attempted after model assemblage with data layers similar to the HEC-HMS lumped parameter model. Default values for the detention storage and the initial water depth in the watershed were reduced to their lowest levels, given the urban nature of the watershed.

Extensive alterations of the Manning's M value were necessary to provide a modeled hydrograph that showed some of the characteristics of the observed response. Original Manning's M values were assigned to land uses as the reciprocal of the assigned Manning's n values. Although Manning's n values are typically used to represent the roughness coefficient of a stream corridor, with distributed models, the entire watershed is treated like a large drainage channel. However, the Manning's M value used in the MIKE-SHE model is not well represented in the literature. Use of the reciprocal of the Manning's n did not provide a value within an acceptable range. These reciprocals required reduction by 73 to 99.5% of their original assignment to be able to provide a reasonable stream flow response to overland flow (Table 17).

Table 17: Best Fit Manning's M Values

2002 Land Use Category	Manning's n Assigned	Manning's M Assigned	**Mannings M Calibrated**
AGRICULTURAL WETLANDS (MODIFIED)	0.05	20.00	**4.5**
ALTERED LANDS	0.035	28.57	**7.5**
ARTIFICIAL LAKES	0.04	25.00	**6**
ATHLETIC FIELDS (SCHOOLS)	0.03	33.33	**9**
COMMERCIAL/SERVICES	0.03	33.33	**9**
CONIFEROUS BRUSH/SHRUBLAND	0.07	14.29	**3**
CONIFEROUS FOREST (10-50% CROWN CLOSURE)	0.1	10.00	**0.5**
CONIFEROUS WOODED WETLANDS	0.09	11.11	**1.5**
CROPLAND AND PASTURELAND	0.04	25.00	**6**
DECIDUOUS BRUSH/SHRUBLAND	0.1	10.00	**0.5**
DECIDUOUS FOREST (>50% CROWN CLOSURE)	0.1	10.00	**0.5**
DECIDUOUS SCRUB/SHRUB WETLANDS	0.1	10.00	**0.5**
DECIDUOUS WOODED WETLANDS	0.1	10.00	**0.5**
DISTURBED WETLANDS (MODIFIED)	0.06	16.67	**4**
EXTRACTIVE MINING	0.05	20.00	**4.5**
FORMER AGRICULTURAL WETLAND (BECOMING SHRUBBY)	0.06	16.67	**4**
FRESHWATER TIDAL MARSHES	0.06	16.67	**4**
HERBACEOUS WETLANDS	0.07	14.29	**3**
INDUSTRIAL	0.02	50.00	**12**
INDUSTRIAL/COMMERCIAL COMPLEXES	0.02	50.00	**12**
MANAGED WETLAND IN MAINTAINED LAWN GREENSPACE	0.07	14.29	**3**
MIXED DECIDUOUS/CONIFEROUS BRUSH/SHRUBLAND	0.1	10.00	**0.5**
MIXED FOREST (>50% CONIFEROUS WITH >50% CROWN CLOSURE)	0.1	10.00	**0.5**
MIXED URBAN OR BUILT-UP LAND	0.04	25.00	**6**
NATURAL LAKES	0.04	25.00	**6**
OLD FIELD (< 25% BRUSH COVERED)	0.03	33.33	**9**
ORCHARDS/VINEYARDS/NURSERIES/HORTICULTURAL AREAS	0.05	20.00	**4.5**
OTHER AGRICULTURE	0.035	28.57	**7.5**
OTHER URBAN OR BUILT-UP LAND	0.03	33.33	**9**
RECREATIONAL LAND	0.03	33.33	**9**
RESIDENTIAL, HIGH DENSITY, MULTIPLE DWELLING	0.02	50.00	**12**

RESIDENTIAL, RURAL, SINGLE UNIT	0.02	50.00	**12**
RESIDENTIAL, SINGLE UNIT, LOW DENISTY	0.02	50.00	**12**
RESIDENTIAL, SINGLE UNIT, MEDIUM DENSITY	0.02	50.00	**12**
STREAMS AND CANALS	0.035	28.57	**7.5**
TIDAL RIVERS, INLAND BAYS, AND OTHER TIDAL WATERS	0.035	28.57	**7.5**
TRANSITIONAL AREAS	0.02	50.00	**12**
TRANSPORTATION/COMMUNICATIONS/UTILITIES	0.01	100.00	**15**

After altering the Manning's M values to visually correspond better with observed flow in the watershed, the calculated negative Nash Sutcliffe optimization parameter depicted a model that does not predict the hydrograph better than the observed mean (Figure 22). (Refer to Figure 14 for corresponding precipitation distribution hyetograph).

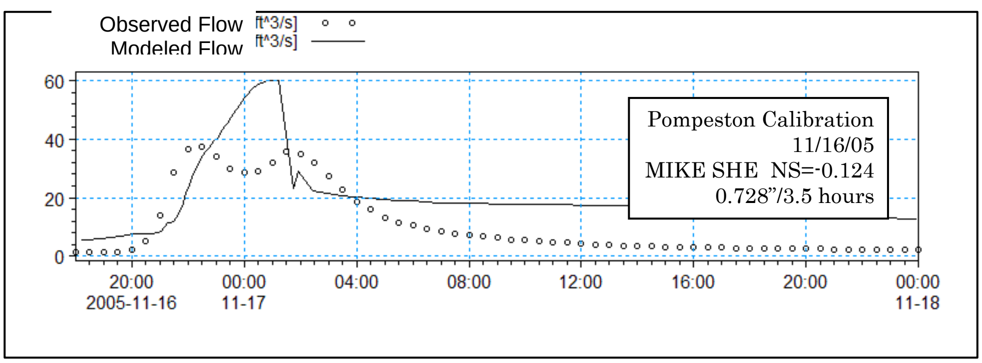

Figure 22: November 16, 2005 Distributed hydrograph

The rising and falling limbs of the hydrograph were able to be reasonably bounded with changes made to the Mannings M parameter. The height of the peak and the return to baseflow conditions was not adequately represented in this model. The response to the discrete sections of precipitation were not fully expressed and appeared to accumulate into a larger volume of excess precipitation. After the falling limb of the hydrograph returned to post-event baseflow conditions, the modeled hydrograph overpredicted flow and showed minimal reaction to the end of the precipitation event.

4.1.5 Distributed/Physical Validation: Method A

The model parameters used in the November 11, 2005 calibration run of the Pompeston Creek Watershed were used to simulate the October 24, 2005 storm event for validation effort purposes. The resultant hydrograph (Figure 23) does appear to be reacting to the various intensities of precipitation, although the timing and magnitude of runoff are of low simulation quality, as a Nash-Sutcliffe efficiency coefficient of -11.05 reflects.

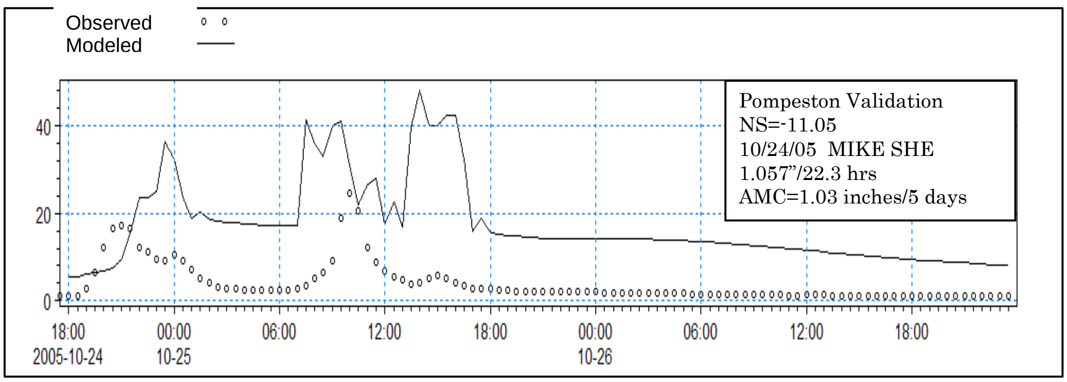

Figure 23: October 24, 2005 Pompeston Creek Watershed Distributed Method A validation Run

As in the November 11, 2005 calibration run, the modeled values are over predicted for the tail end of the hydrograph, but the multiple peaks that comprise the streams reaction to the storm are also over predicted.

4.1.6 Distributed/Physical Sensitivity: Method A

The parameters that are able to be used to calibrate a physical model are obviously more limited than those of an empirical model. The effects of magnitude changes in the Mannings M values that are used to correspond to land use have been modified to evaluate the effect on the resultant hydrograph.

Figures 24 through 27 depict the output hydrograph results of alterations to the Mannings M. During this exercise, it was determined that a 10 percent increase in the parameter would have provided a more accurate hydrograph, with a Nash Sutcliffe Efficiency Parameter, E= -0.05.

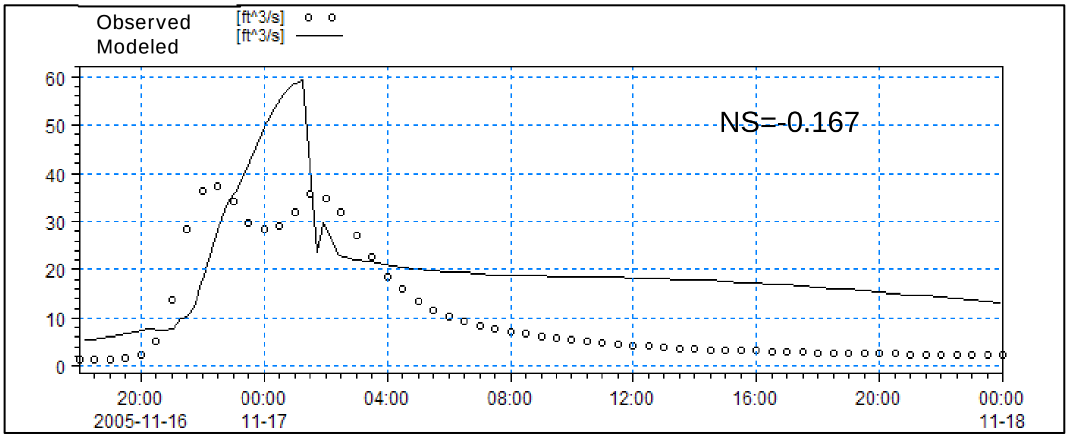

Figure 24: 10% decrease in Manning M

The reduction in Manning M by 10% appears to have only a slight affect on the hydrograph, as evidenced by the peak remaining at the same time and the same intensity. A small change in the rising limb of the hydrograph appears to have the effect of lowering the volume under the curve.

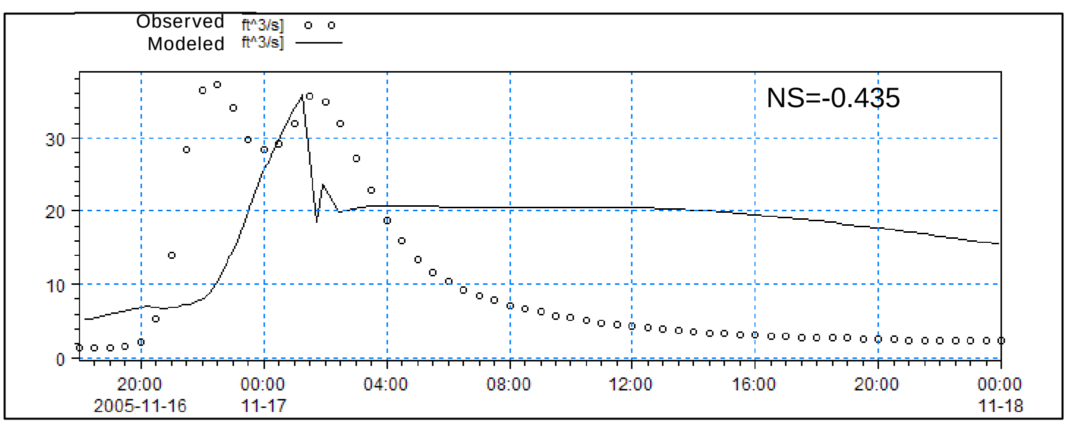

Figure 25: 20% decrease in Manning M

A 20 percent reduction in the Manning's M value decreases the peak flow, the volume of the water under the hydrograph and shortens the resultant affect that the precipitation has on the stream (See Figure 25). This appears to have little effect on the return to baseflow seen in the observed data.

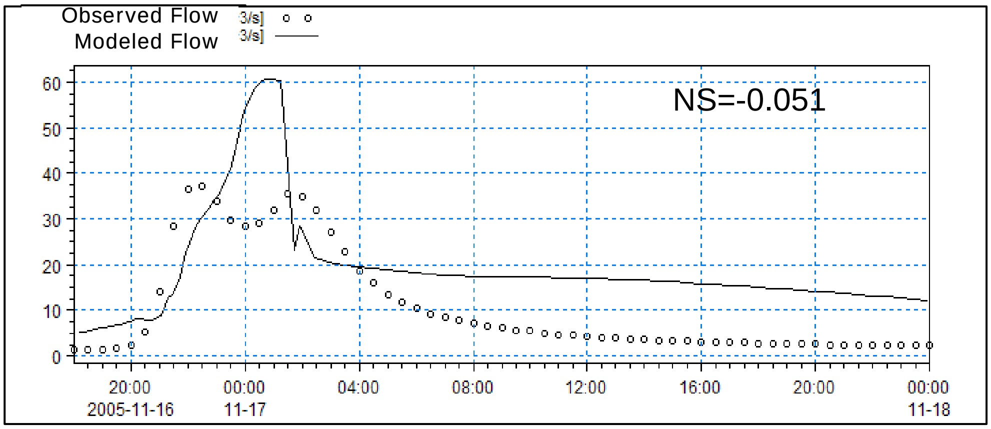

Figure 26: 10% increase in Manning M

In the scenario where the Mannings M was increased by 10 percent (Figure 26), an increase in the modeled accuracy resulted. The modeled hydrograph still failed to show the effects of the discrete sections of rainfall, as the observed and the lumped parameter model was able to show. The tail end of the modeled hydrograph showed the same slow course toward baseflow as seen in the previous distributed model scenarios.

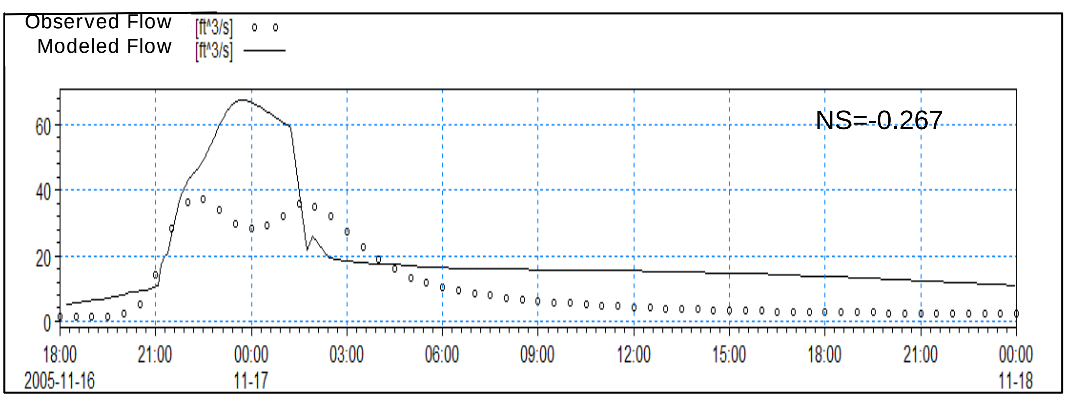

Figure 27: 20% increase in Manning M

By increasing the Mannings M value by 20 percent over the watershed (Figure 27), the peak flow of the hydrograph was higher and the volume of flow under the hydrograph increased. A smoothness of the first large peak continues to dominate in the distributed model, with the second peak being only a small artifact. It is unclear whether the second peak is a reaction to the discrete sections of precipitation or if there are other contributing factors.

The overall outcome of the Manning M sensitivity analysis (Figure 28) suggests that optimal parameters could exist within a range of values, but would likely benefit from an increase in accuracy in the spatial distribution of assigning parameters.

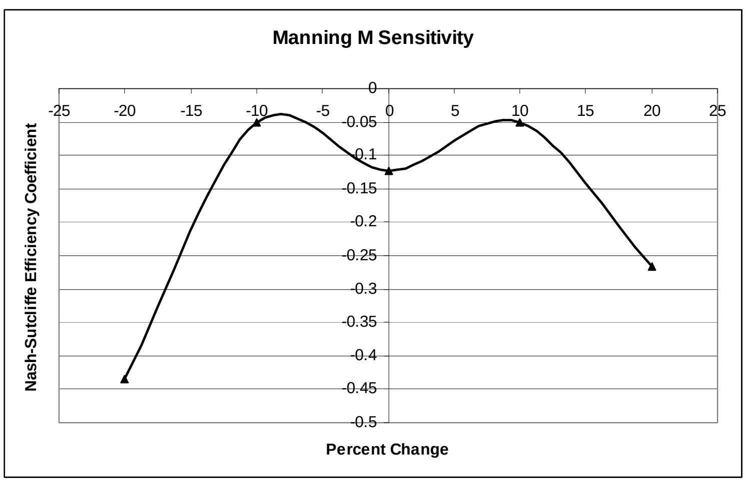

Figure 28: Manning M Sensitivity in Method A

4.1.7 Distributed/Physical Alternative Method: Method B

The MIKE SHE model offers several options for representing the hydrological response of an urban watershed. In an alternative method attempting to better characterize the urban runoff due to impervious surfaces and the effect of the infiltration capacity of the soils, additional components were added to the modeling scenario. These additional components included a 2-layer water balance of the unsaturated zone, a general/default description of the saturated zone, a drainage component and an impervious surface layer that details the percent impervious according to the land use GIS layer.

Initial input parameters necessary to represent the infiltration properties of the soils in the watershed are shown in Table 8. During calibration efforts, it was determined that these assigned parameters overestimated the infiltration capacity and therefore the hydraulic conductivity was reduced. Preliminary reductions decreased the hydraulic conductivity by one order of magnitude. Further calibration efforts adjusted these parameters with the extent and location of the soils as a contributing qualifying factor. The spatial distribution of the hydraulic conductivity assigned to the Pompeston Creek Watershed can be viewed in Figure 29.

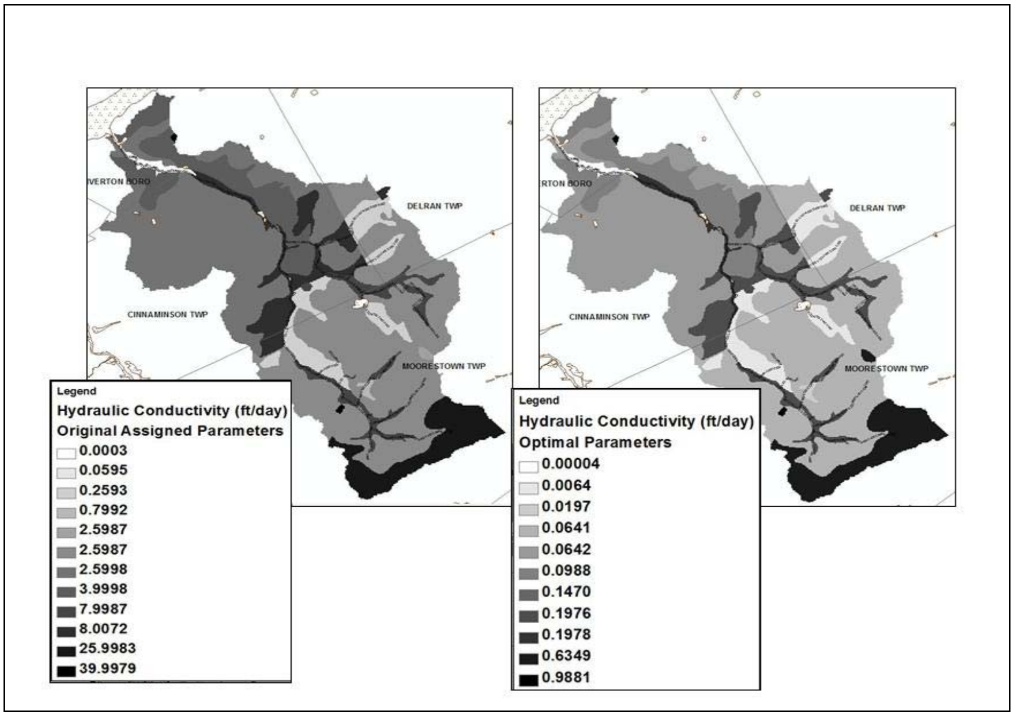

Figure 29: Pompeston Creek Distributed Hydraulic Conductivity

The November 16, 2005 and the October 24, 2005 precipitation event were simulated in order to provide information on how the model is predicts basin outflow according to the event data. The results are shown in Figure 30 and Figure 31 below.

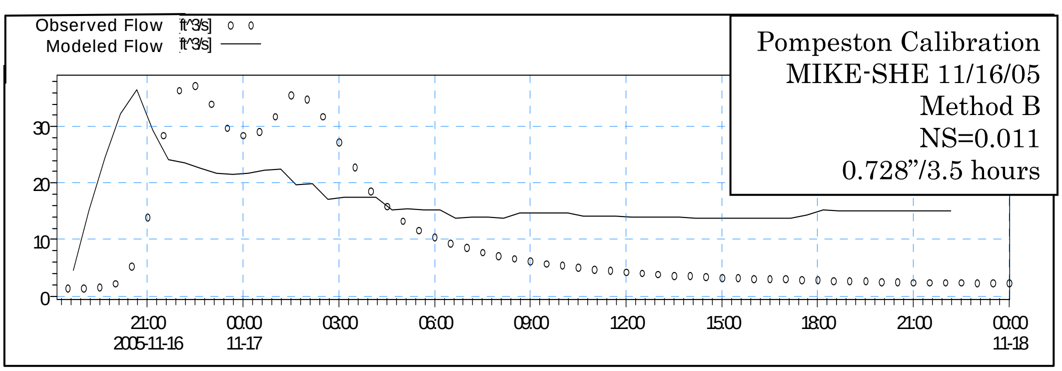

Figure 30: November 16, 2005 Pompeston Hydrograph: Method B Distributed Model

The October 24, 2005 storm event was also simulated using these added components of impervious surfaces and soil infiltration parameters. The results can be found in Figure 31 below.

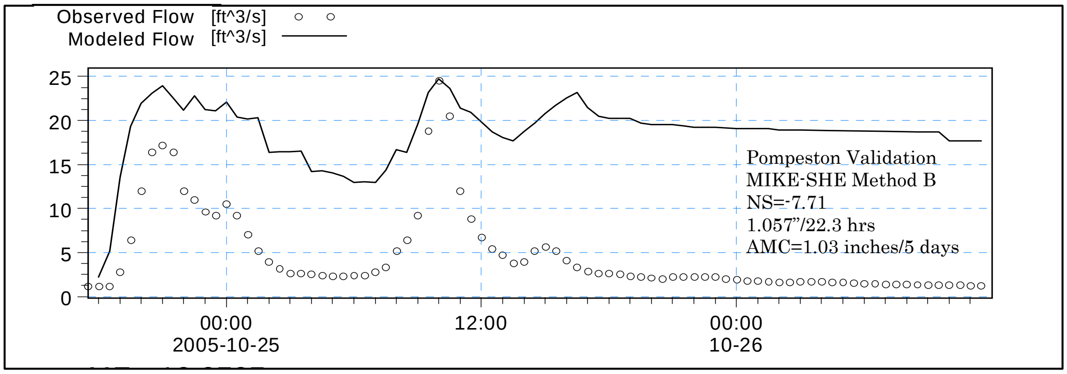

Figure 31: October 24, 2005 Pompeston Method B Distributed Model

4.1.8 Distributed/Physical Sensitivity: Method B

The overall hydraulic conductivity parameters were altered to determine the level of sensitivity that existed in the parameters used for calibration. The resulting Nash-Sutcliffe Coefficient and the resulting correlation coefficient can be seen in Figure 32.

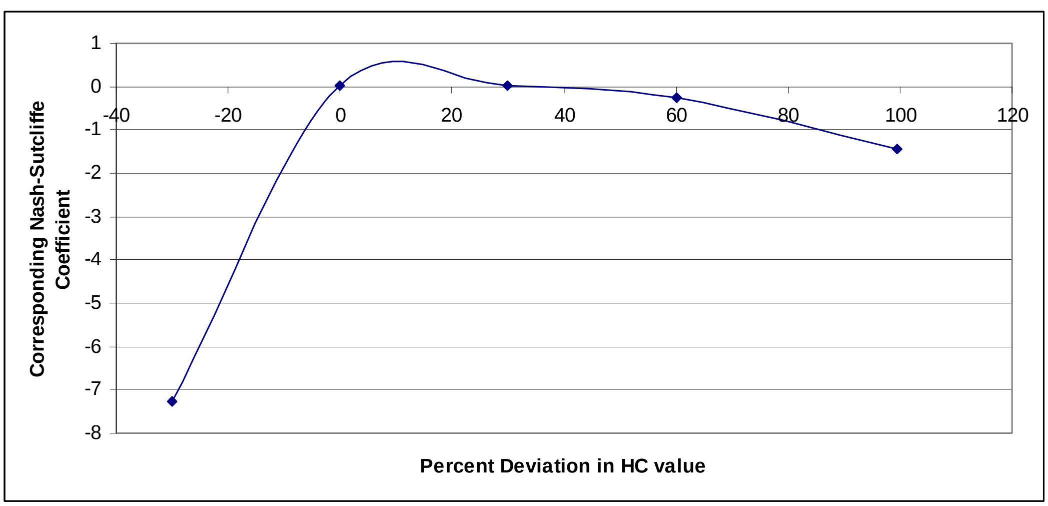

Figure 32: Sensitivity of the Pompeston MIKE-SHE model to alterations in the hydraulic conductivity parameter

However, visual analysis of these simulations shows a more comparable reaction to the precipitation temporal intensity when the hydraulic conductivity is decreased thirty percent (Figure 33). However, this reduction results in lower coefficients for the Nash-Sutcliffe.

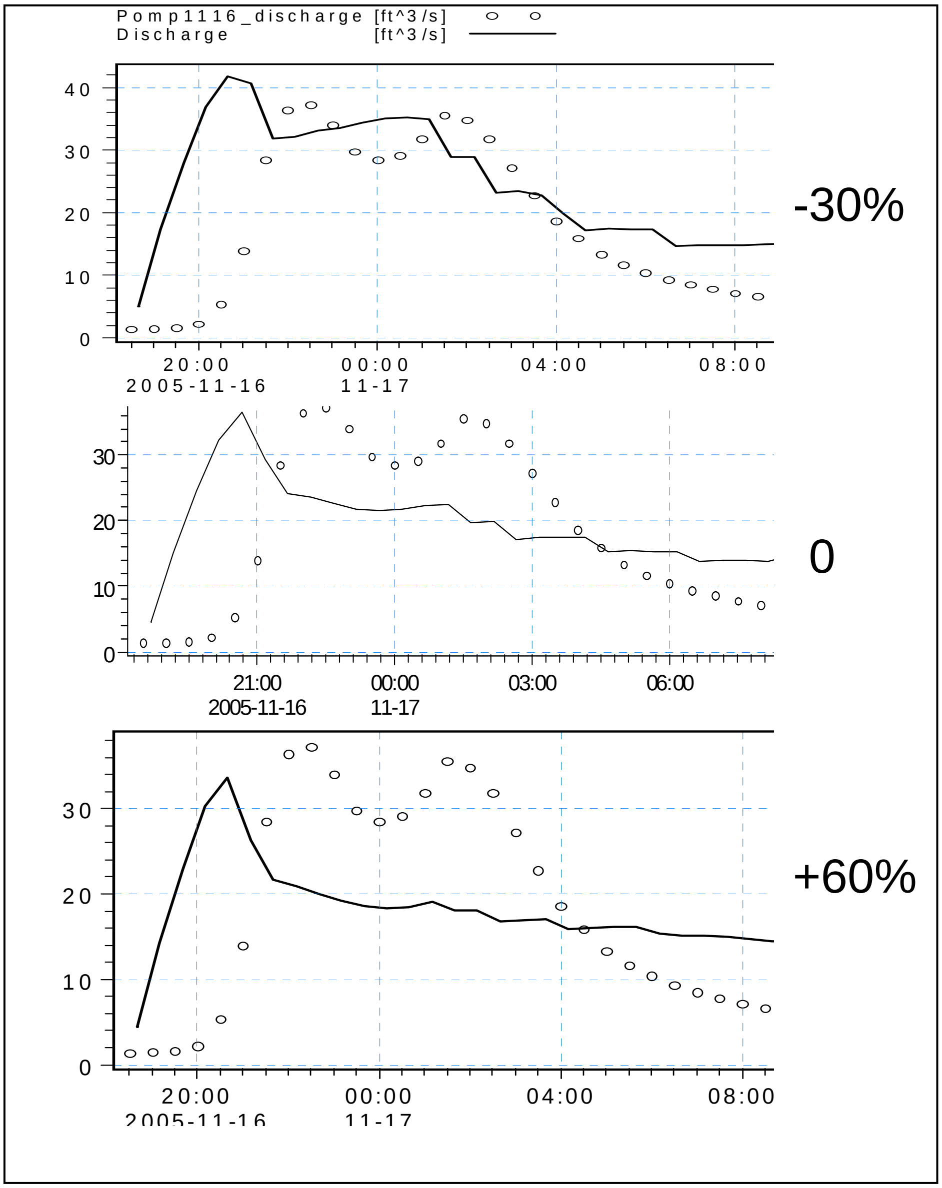

Figure 33: Hydraulic conductivity sensitivity hydrographs using Pompeston Creek calibration simulation of 11/16/05.

4.1.9 Distributed Method: Method B1

To determine the effect of the impervious cover layer on the fully distributed model with the soil infiltration capacity being represented by the 2-layer water balance, the impervious layer was removed from calculations after the validation effort was complete. This was performed on the October 25, 2005 storm event (Figure 34).

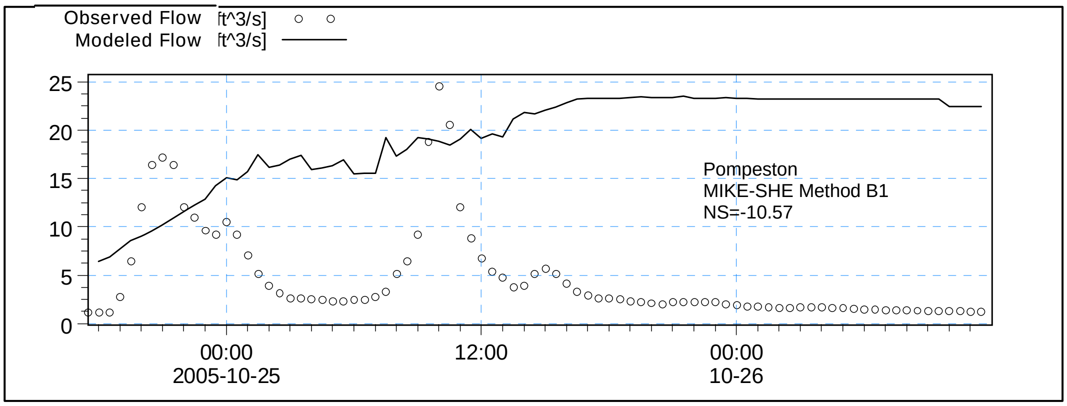

Figure 34: Pompeston Creek October 25, 2005 Method B1

When compared with the original Method B (Figure 30) which included the unsaturated zone infiltration parameters and the impervious surface coverage, the effect of the impervious area can be seen. Without the impervious area coverage inserted into the simulation, an early spike in the peak flow does not exist and the flow rises slower, and higher than that previously modeled or than that observed.

4.2 Troy Brook Watershed Case Study

4.2.1 Lumped/Empirical Calibration

Calibration for the Troy Brook HEC-HMS lumped parameter model was performed using the storm event that occurred on February 1, 2008. The total precipitation for this event was 1.15 inches over an 11.5 hour period with an antecedent moisture condition of 0.27"/5 days. The resultant efficiency assessment provided a Nash-Sutcliffe coefficient of E= -0.3051, indicating that the model predictions are less accurate than the mean of the observed data (E=0). The rainfall distribution can be seen as a hyetograph above the hydrographs of the calibration and validation efforts (Figure 35and Figure 36). The magnitude of alteration from the original assigned input empirical parameters were similar to those found in the Pompeston Creek HEC-HMS model (Table 18), showing the lowest change from the assigned curve number.

Table 18: Troy Brook Calibration of Empirical Parameters

	% Change from original parameter
CN	8
I(a)	50
Lag (hrs)	90

The February 1, 2008 storm distribution affects the observed stream flow in two stages as can be seen in Figure 35. The first peak in the observed data is underpredicted in the modeled data. This volume of excess precipitation appears in the second peak of the modeled data with an overprediction of the peak flow. The tail of the modeled hydrograph drops at a faster rate than the observed data.

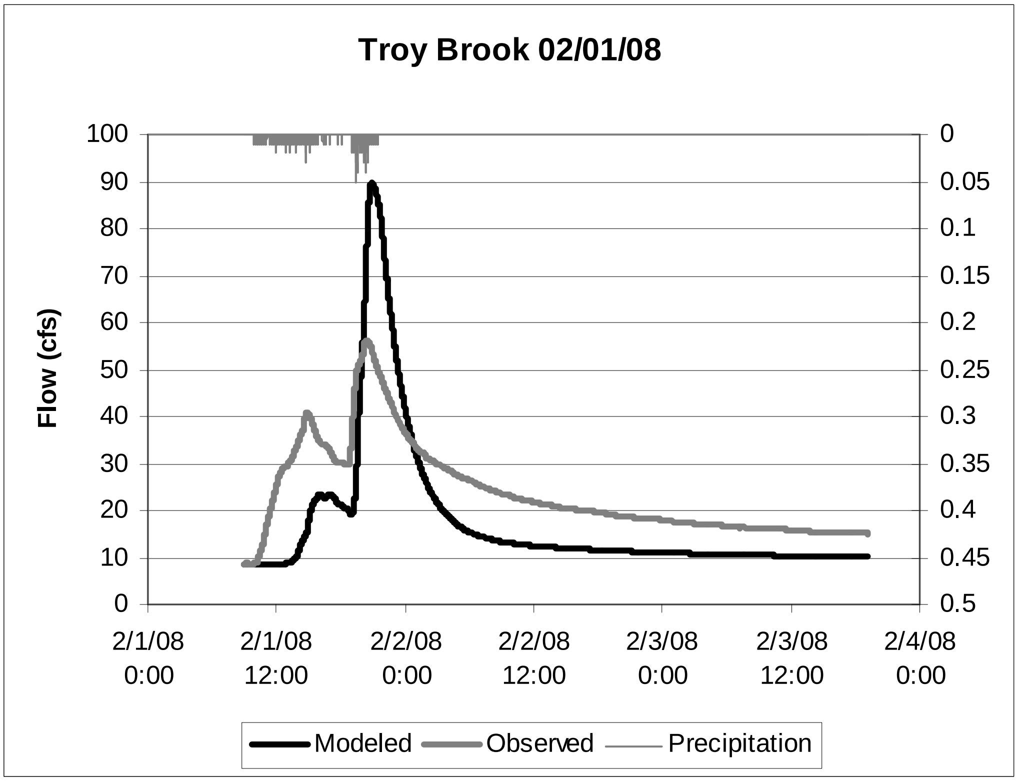

Figure 35: Troy Brook HMS February 1, 2008 Calibration

4.2.2 Lumped/Empirical Validation

Validation for the Troy Brook HEC-HMS lumped parameter model was performed on the storm that occurred on March 4, 2008. The total precipitation for this event was 0.81 inches over a 17.3 hour period and was preceded by 0.27' of precipitation in the five days prior to the event. The resultant calibration provided a Nash-Sutcliffe efficiency coefficient of E= -0.079, indicating that the model predictions are less accurate than the mean of the observed data (E=0), but a slight improvement over the calibrated model of February 1, 2008. The rainfall distribution can be seen in Figure 36.

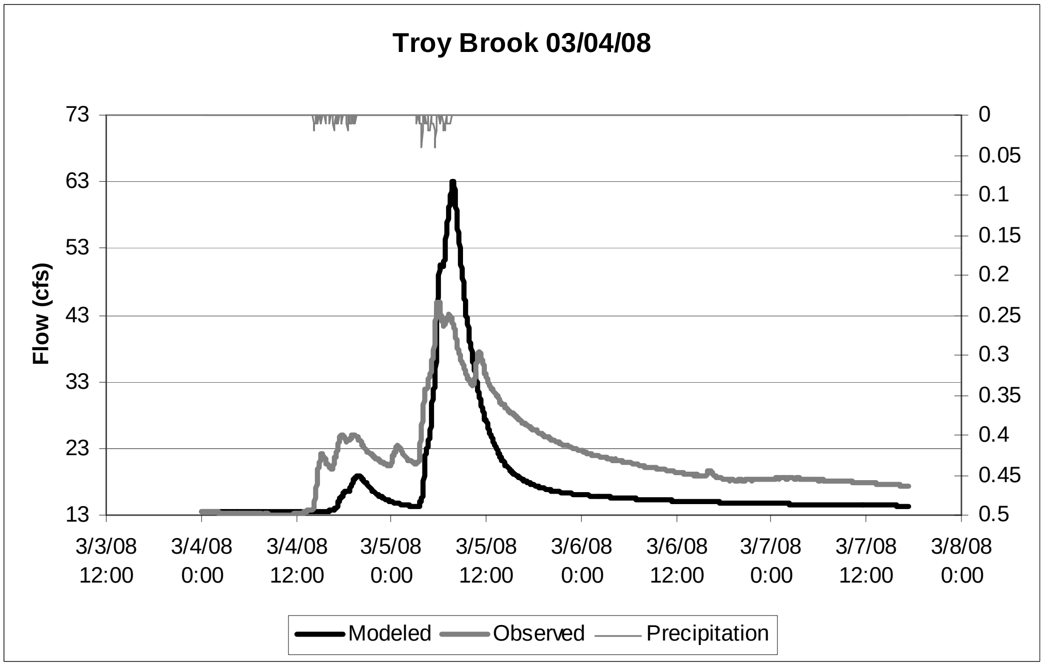

Figure 36: Troy Brook HEC-HMS March 4, 2008 Validation

The areas that are noted to be inadequately modeled in the calibration effort for the February 1, 2008 storm event are similar to the areas of the hydrograph in the March 4, 2008 validation simulation. As in the February 1, 2008 simulation, the initial peak is underpredicted by the model, and the second peak is overpredicted. Also similar to the February 1, 2008 simulation, the March 4, 2008 validation simulation effort is the fact that the tail end of the modeled hydrograph drops at a faster rate than the observed hydrograph.

4.2.3 Distributed/Physical Calibration

The MIKE SHE fully distributed, physical model was developed to represent the overland flow for the Troy Brook Watershed. This method replicated the "Method A" used in the Pompeston Creek Watershed by simulating the overland flow using Finite Difference and does not including the effects of the unsaturated and saturated zones. The storm event that occurred on February 1, 2008 was simulated and calibrated by visual analysis. This storm, 1.15 inches over 11.5 hours, was able to be simulated and achieve a Nash-Sutcliffe coefficient of E= -3.7.

The total precipitation came in two sections of intensity (Figure 37). The resultant hydrographs can be seen in **Error! Reference source not found.**.

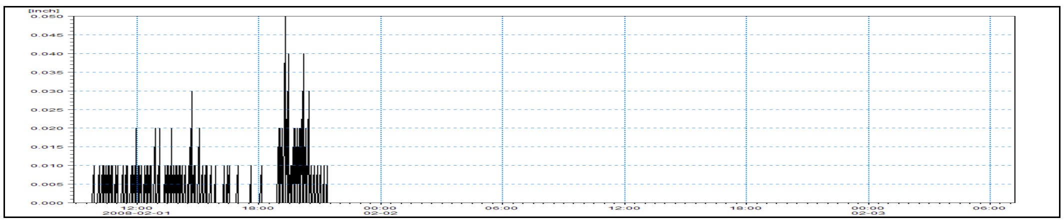

Figure 37: February 1, 2008 Precipitation

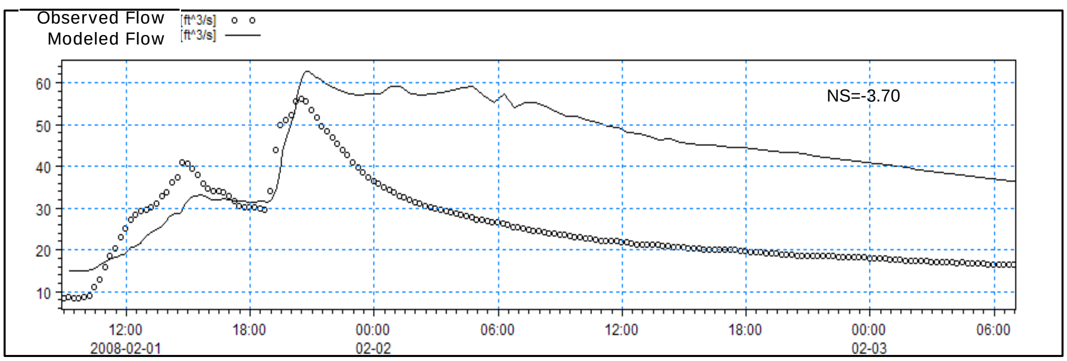

Figure 38 : Troy Brook February 1, 2008 Distributed model calibration

Calibration efforts again focused on the primary parameter that is able to be calibrated in the physical model, the Mannings M value, an empirical parameter. After reducing the Mannings M values fifty percent from their original assignment, the above hydrograph with E= -3.7 was determined. Characteristics of the modeled hydrograph are similar to those observed in the Pompeston Creek simulations, as the peaks are not represented as distinctly and the tail end of the modeled hydrograph does not return to baseflow at the rate that the observed data suggests that it should. One explanation for slow rate of the descending limb is that excess precipitation continues to feed the model as overland flow, from cell to cell.

4.2.4 Distributed/Physical Validation

The March 4, 2005 storm event that was used to validate the lumped parameter, HEC-HMS model for the Troy Brook is used here to determine the simulation efficiency of the fully distributed, MIKE SHE model. This event consisted of 0.81 inches of precipitation over 17.3 hours (Figure 39).

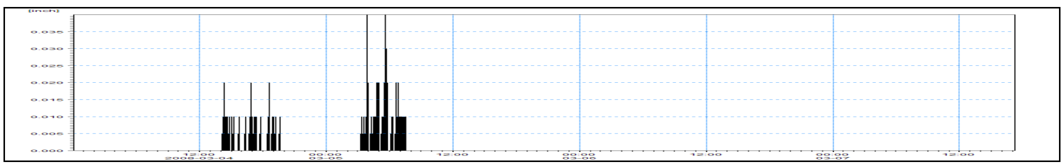

Figure 39: Troy Brook Precipitation March 4, 2008

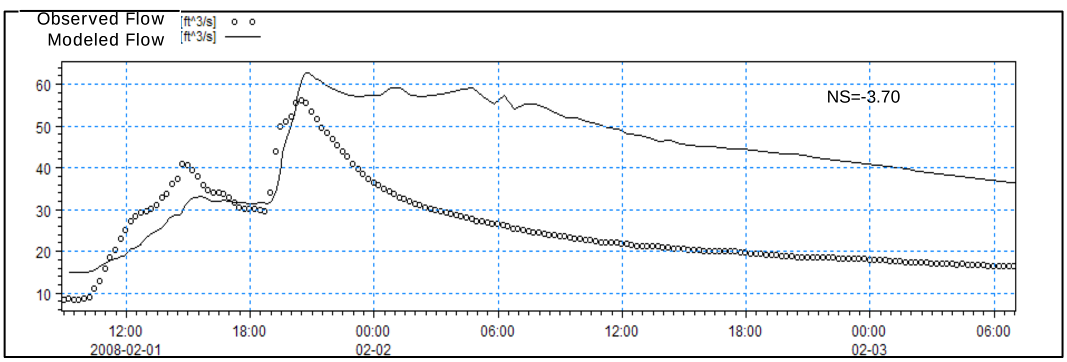

Figure 40: Troy Brook Distributed Model March 4, 2008 Validation

The modeled representation of the observed peaks appears to have better correspondence than those in previous simulations of the distributed model. The tail end of the modeled hydrograph does not return to baseflow conditions similar to the slow rate of return seen in the previous simulations.

4.3 Application and Spatial Representation of Watershed Characteristics for Regional Stormwater Management Planning

The compilation of a Regional Stormwater Management Plan includes the education of watershed stakeholders. The explanation of watershed reaction to precipitation runoff requires the use of maps, flow volumes and mitigation practices that explain the range of observed results. The lumped parameter model can be used to describe the effect of land use or best management practices by altering parameters such as curve number and describing the effect that this change has on watershed output. This is largely theoretical, given the calibration at the subbasin/watershed level and the requirement of a long study period and similar precipitation events to use for comparison purposes.

With the use of distributed, physical based models, it is expected that localized changes, such as disconnection of impervious areas and the creation of bioretention areas could be modeled on a grid basis and have that effect be reflected in the outlet of the watershed. Spatial calibration internal to the watershed is also possible. Physical characteristics can be used for visual assessment and stakeholder education. These spatial databases are available for viewing in GIS format, but computational advances have allowed the fully distributed model to show the hydrologic effects of a precipitation event in a time step pattern over the duration of a simulation. This has the potential value of visually interpreting land use effects on the watershed if characteristics are appropriately quantified.

The visual grid from MIKE-SHE input database can be seen in Figure 41. The model has the capability to show the hydrological effects of a precipitation event as a "movie", viewing depth of overland flow, flow direction and other physical characteristics that can be computed on the grid scale.

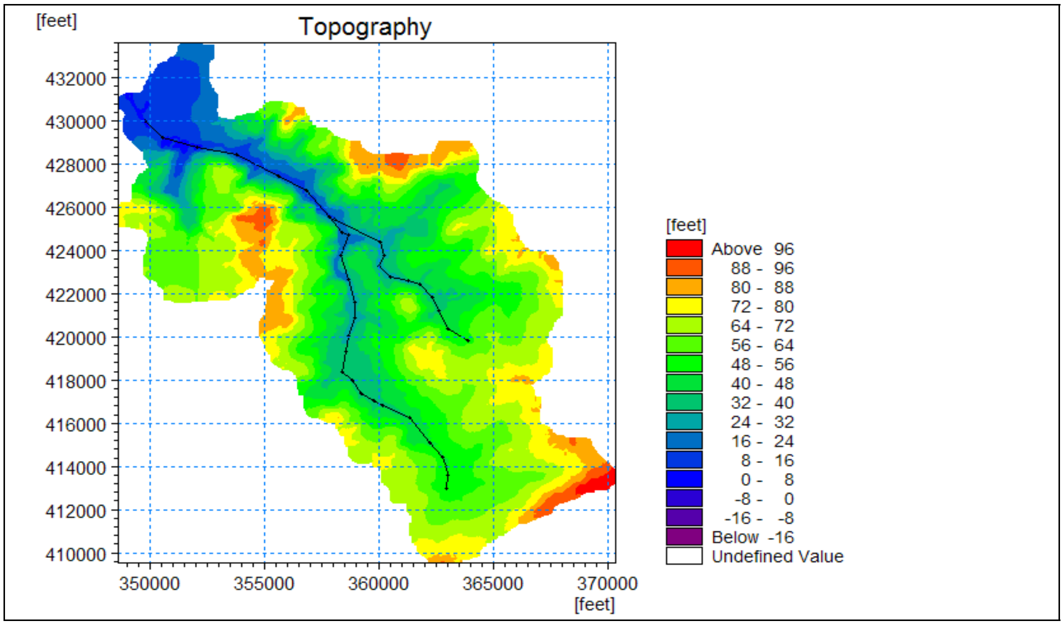

Figure 41: MIKE-SHE Representation of Topography

The lumped parameter model can be used to explain the volume of runoff experienced per delineated subbasin. Planning efforts could consist of altering the curve number to denote management techniques within the subbasin. One example used in both the Pompeston and the Troy Brook Regional Stormwater Management Plans was to increase and decrease the curve numbers to calculate the amount of change in stream volume for a particular design storm event (Table 19). This proved useful to educate stakeholders in the value of increasing infiltration to reduce the runoff and mitigate the effects of the sudden volume and velocity changes on the stream.

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Table 19: Curve Number Alterations for Stakeholder Awareness

				Decrease 10%		Existing Conditions		Increase 10%	
Watershed	Area wt CN	CN + 10%	CN - 10%	Peak Flow (cfs)	Total Vol (Ac-ft)	Peak Flow (cfs)	Total Vol (Ac-ft)	Peak Flow (cfs)	Total Vol (Ac-ft)
R30W30	75	82	67	56.332	30.261	93.023	46.648	135.180	65.477
R70W70	81	89	73	44.578	19.230	69.303	28.301	97.933	39.361
R80W80	85	93	76	93.154	45.832	143.100	68.057	196.020	94.129
R140W140	76	84	69	77.624	44.283	120.590	65.466	177.470	93.874
R280W280	83	91	75	97.710	51.032	146.840	74.138	204.550	103.160
R500W450	85	94	77	94.866	48.626	140.680	70.150	197.550	99.618
				Percent Change				*Percent Change*	
				-39%	-35%			45.32%	40.36%
				-36%	-32%			41.31%	39.08%
				-35%	-33%			36.98%	38.31%
				-36%	-32%			47.17%	43.39%
				-33%	-31%			39.30%	39.15%
				-33%	-31%			40.43%	42.01%

5. Discussion

Hydrologic modeling for use in Regional Stormwater Management Plans requires use of readily available data that will allow for a reasonable simulated reaction of the watershed to storm events. These simulations are necessary to inform watershed stakeholders of their choices to deal with issues related to poor stormwater management. In assessing the differences between using a lumped parameter model and a distributed parameter model, input data were intended to remain as similar as possible. However, given the large difference between empirical parameters and physical parameters, it was necessary to be satisfied with similar input data sources provided for the modeler. In this study, New Jersey GIS layers obtained from the New Jersey Department of Environmental Protection provided the bulk of input information for the models, including topography, land use, soil properties, and hydrography.

Pompeston Creek HEC-HMS

Using a precipitation data set collected within the drainage area for use specifically with the hydrologic modeling of the Pompeston Creek Watershed, calibration of the November 16, 2005 storm event achieved a Nash-Sutcliffe Efficiency Coefficient of 0.611 **(**Figure 14**).** Four empirical parameters were used to alter the output hydrograph to provide a best fit. The curve number was determined to be a well characterized parameter for this urban area, given that changes to this parameter ranged from 0.1 to 3.8%. The initial abstraction which should be empirically related to the curve number was independently adjusted for fitting purposes. An alteration of this parameter of between 72 and 81% of its original designation was necessary. A possible explanation for this severe adjustment could be the large extent of impervious surfaces in this watershed, creating a large surface area where there would be little abstraction. A lag time adjustment of 11-81% and a peaking coefficient reduction of between 33 and 67% could also be related to the urban impervious components of the watershed.

The Nash-Sutcliffe Efficiency Coefficient of 0.611 does not portend a model that should be greatly depended upon, especially given the fact that a single event is at issue. Visual analysis of the modeled and observed hydrograph suggests three possibilities: that a parameter exists that is not included in the empirical equations, that there exists some error in the measured, observed data, or some combination of the two. Given the empirical nature of the HEC-HMS model and the long use in hydrologic history that exists for the HEC-HMS, the first choice is not expected to explain the entire offset. Error in observed data could exist due to the non-adherence to the calculated rating curve or to the precipitation distribution not being well represented by a single tipping bucket. The sensitivity to precipitation distribution was later assessed by the use of an alternate gauging station and is discussed below.

The altered parameters determined to provide a best fit for the November 16, 2005 storm event were used to validate a storm that occurred on October 24, 2005 (Figure 15**).** The precipitation data collected at the tipping bucket within the drainage area, with a depth of 1.057" over 22.3 hours. This validation effort resulted in a NS = -3.49. The precipitation events totaling 1.03 inches over five days preceding this storm appears to have affected the onset of the modeled storm. The best fit parameters for the calibration effort were determined through the use of a storm event with little antecedent moisture. This level of saturation in the soil appears to reduce lag time, reduce initial abstraction and possibly increase the magnitude of the peaking coefficients, leading to this lower than optimal validation efficiency coefficient and a shift of the onset of the rising limbs of the hydrograph. This aids in explaining the offset of the first two modeled peaks, but does not explain the third modeled peak that greatly exceeds the observed peak. An alteration of input parameters intended to better fit the last peak would alter the entire hydrograph, thereby lowering an already low assessment. A possible explanation would be the accuracy of the measured precipitation distribution. This precipitation distribution shows discrete sections of intensity, with the first and second peaks represented, but the third observed peak falling well below the modeled event.

In determining the sensitivity of the Pompeston Creek HEC-HMS lumped parameter model, a different set of data for the precipitation distribution of the precipitation event was analyzed. Using data obtained by the New Jersey Weather and Climate Network (http://climate.rutgers.edu/njwxnet/index.php) taken from the station located closest to the watershed, results confirmed suggested sensitivity. Using the Mount Holly station precipitation data set for the November 16, 2005 allowed a best fit calibration providing a NS Efficiency Coefficient of 0.96 (Figure 16). Using these calibrated parameters and the October 24, 2005 Mount Holly precipitation data distribution for the October 24, 2005 modeled storm event produced a NS Efficiency Coefficient of -91.0 Figure 17**).** Although the shape of the hydrograph is well represented, the timing of peak onset and the magnitude of the peaks and volume are not well represented. The change in antecedent moisture conditions from 0.3 inches over five days to 1.03 inches over five days appear to have again affected the extent to which the parameters can be applied in distinct conditions, with the modeled output simulating a greater volume coming later

The October 24, 2005 storm used for validation purposes employing both precipitation distributions was larger, longer in duration and proceeded by a higher antecedent moisture condition than that of the calibrated model. The HEC-HMS lumped parameter using the SCS Curve Number runoff method will account for the increased volume and time in the model by the conditions that are created by the last time step calculated. The antecedent moisture condition is included as a part of the determination of the curve number, and therefore is not represented well in storm events that range in the magnitude of that antecedent moisture.

Troy Brook HEC-HMS

In the Troy Brook Watershed HEC-HMS models, the antecedent moisture conditions were similar, with 0.27 inches occurring before the calibration event of February 1, 2008 and 0.23 inches occurring before the March 4, 2008 storm event. Rainfall patterns differed with the calibration storm receiving 1.15” over 11.5 hours and the validation event receiving 0.81” over 17.3 hours. All basin parameters were summarily altered with the best fit curve numbers being 92% of the originally designated curve number, the initial abstraction being 50% of the originally designated number and the lag time being reduced to 10% of the originally designated parameter. The peaking coefficient was reduced to the lowest possible, 0.1.

This best fit analysis of the February 1, 2008 precipitation data allowed for a Nash-Sutcliffe Efficiency Coefficient of -0.3051. Visual analysis showed observed data exceeding volume and peak height after the earlier discrete intensity of the rainfall, and falling below volume and peak height after the second precipitation intensity. This situation occurred in the validation effort used for the March 4, 2008 storm event. Since both storms, having different overall depths and duration, but similar antecedent moisture conditions, possess similar offsets, it can be assumed that a similar parameter characterization, or a missing parameter, may be the cause of the volume and peak offset.

Overall, the Nash-Sutcliffe remains low through a best fitting exercise due to the limited parameters that can be adjusted. Fitting for the first peak would increase the residual of the second peak, and the reverse is also true. The modeling of these events depicts a temporally distributed phenomenon that is not represented by the current empirical calculations. A possible explanation for the earlier onset of volume seen with the first peak would be that connected impervious areas are providing a larger portion of the precipitation volume as runoff with a smaller percentage of overall runoff contributing to the volume in the second peak. The observed data show distinct peaks accounting for discrete intensities of rainfall patterns, but observed peak size does not match model predictions. Antecedent moisture would not be considered a suspect in determining this offset in peak size since the conditions were similar.

Pompeston Creek MIKE-SHE

The fully distributed, physical model, MIKE-SHE, was used to model two storm events in the Pompeston Creek Watershed. These model runs consisted of a calibration and validation model run using only the overland flow component of MIKE-SHE, called Method A by this study. These same storm events were used in best fitting analysis model runs for Method B, which includes a fully distributed impervious percentage grid and a fully distributed soil infiltration component being represented by the 2-layer water balance method. Additionally: a sensitivity analysis of the Mannings M was performed on Method A and a sensitivity analysis on the hydraulic conductivity was performed. A model simulation using Method B, without the impervious area grid, was also performed.

Method A

Input parameters to Method A were somewhat similar to those required for the HEC-HMS model simulations, as in the same GIS data layers were required. Instead of determining a curve number based on soil type and land use, a Mannings M (reciprocal to Mannings n roughness coefficient) needed to be determined. Using tables generated for open channel flow calculations, the soil and land use types were assessed for their capacity to impede overland flow. This was then generated into a spatially distributed grid file used by the model.

Attempts at providing a best fit for the calibration efforts of the November 16, 2005 storm event achieved a Nash-Sutcliffe Efficiency Coefficient of -0.1244. Visual analysis determined that the timing of the rising limb of the modeled peak appeared to occur only slightly later than the observed hydrograph. However, the model was not able to simulate the discrete rainfall patterns, with the first peak continuing to rise well above and far past the observed first peak. Some measure of a second peak can be seen around the time of the onset of the second observed peak, but the magnitude is far less than observed. The model was not able to be adjusted to simulate the return to baseflow condition, with the modeled simulation providing a volume of excess precipitation to the stream after observed data had returned to baseflow.

In the best fit validation effort using the October 24, 2005 precipitation data set, with the same Mannings M roughness coefficients used on the November 16, 2005 data set, a Nash-Sutcliffe Efficiency Coefficient of -11.05 was obtained. Visual analysis of this simulation showed the model had sensitivity to the precipitation distribution, showing peaks in the hydrograph where there were intensities in the precipitation. The magnitude of the peaks show an increase in the percentage of precipitation accounted for in the runoff. Timing of the peaks were offset disproportionately, with the first peak being simulated as coming later, and the second peak being simulated at coming earlier. The size of the third peak is the most disproportional and may be due to cell to cell movement of excess precipitation creating a larger volume available for runoff as the timing of the storm proceeds. Again, the return to baseflow conditions does not occur as quickly as observed data suggests, providing a larger volume of flow later in the simulation.

Since Method A lacks the ability of removing a volume of excess precipitation from the calculations of overland flow, providing information on soil infiltration capabilities was used to assess the models abilities at simulating this physical process. Using the Mannings M determined from the calibration effort in Method A, the best fit for the November 16, 2005 simulation provided a NS= -0.3808. Although a low NS, this efficiency coefficient does not depict the lack of simulation provided by this model. Similar results were garnered from the second storm, with a NS= -10.66. Both model simulations provided a low visual similarity, being unable to pick up on precipitation intensity distribution with no peaks detected in the modeled hydrograph.

Method A was subjected to a sensitivity analysis of one empirical parameter, Manning M. Visual analysis of the four scenarios used in the sensitivity analysis showed that the model was sensitive to changes in the Mannings M. Increasing the values by 10% created a steeper rising and falling limb, as a change in the peaking coefficient would have in the HEC-HMS model. A 20% increase allowed for a higher, wider peak, indicating excess precipitation reaching the stream more quickly. Reducing the Mannings M had the effect of slimming the peak at 10% down and reducing peak magnitude and volume more noticeably at 20% down.

Method B

Method B built on Method A and included a 2-layer water balance to simulate water movement into the unsaturated zone and a grid depicting the spatial location of impervious area with related drainage. The inclusion of soil infiltration parameters and impervious surfaces was expected to be able to represent the physical characteristics of the watershed to a greater degree. The ability to include the effects of the impervious cover on the magnitude and timing of stormwater runoff was expected to be especially useful in regional stormwater management planning.

The first issue regarding the routing of excess runoff from the impervious area dictated that all excess would be routed directly to the stream, as a direct connect through a storm sewer would do. This did not allow for additional modeling scenarios depicting connected versus disconnected impervious areas, a critical management tool in stormwater management.

The second factor confounded the purpose of using similar databases for the comparison of lumped parameter and distributed parameter. However, saturated zone parameters were assigned default parameters that would not interact with saturated zone processes during a single storm event.

The original hydraulic conductivity parameters were assigned according to published accepted values (Table 8). These values were discovered to be much higher than the calibration of the full watershed model suggests they should be. However, once the hydraulic conductivity parameters were reduced, it could be seen that the distributed model could represent the physical characteristics of runoff processes of the watershed, including the impervious surfaces. It is simply a matter of programming that the option of modeling connected and disconnected impervious surfaces is not available at this time.

The addition of the impervious layer resulted in a simulation hydrograph that showed good relationship to the observed hydrograph. This layer allowed the connected impervious layer to provide excess precipitation to be added to the stream flow more directly, thereby following the temporal distribution of the precipitation intensity. The modeled reaction observed through this simulation is considered to better quantify the important characteristics of the rainfall-runoff process in an urban watershed.

However, the resultant hydrograph shows an early start to the rising limb of the hydrograph which cannot be easily calibrated with an empirical parameter. Two considerations are potentially contributing to this artifact. First, the input impervious layer taken from the land use/land cover GIS database details all impervious cover and does not provide information on that impervious area which is disconnected or directly connected impervious area. Second, the MIKE-SHE model only allows the use of this impervious cover layer in connection with a drain file, routing all excess precipitation directly to the stream. This represents all impervious cover as directly connected impervious cover, which overestimates the volume that gets to the stream at a particular time.

Values for hydraulic conductivities were assigned to the spatial distribution of soil types according to literature values (Rawls, et al, 1982; Cosby, et al., 1984 and Rijtema, 1969) The calibration of the model dictated the reduction of the hydraulic conductivity up to two orders of magniturde (Figure 29). The sensitivity analysis altering the hydraulic conductivity parameter shows that a bulk attempt at refining this parameter does not aid in determining the optimal estimation. This parameter is expected to have various ranges in the varying spatial distribution the watershed covers. A more thorough investigation of the spatial distribution of the hydraulic conductivity of urban soils is necessary.

Once the Pompeston Creek Watershed attained a reasonable calibration for the storm events, the removal of the impervious layer from the model calculation was able to show the influence that this physical characteristic had on the runoff processes. It can be seen that there is no rapid influence of the precipitation event on the stream as would be expected to occur in an urban watershed. Excess precipitation is routed to the stream over a period of time, and the stream does not experience the “flashy” nature that the introduction of directly connected impervious surfaces brings to a watershed. However, the model suggests a large volume of water entering the stream over a longer period of time. This could suggest that the saturated zone should play a greater role, even in event based modeling.

Troy Brook MIKE-SHE

Method A was the sole model used for simulation purposes in the Troy Brook Watershed. The calibration effort performed with the February 1, 2008 precipitation data produced a NS= -3.703. Visual analysis of the model results show that the model can detect the rise and fall of the first section of intensity in rainfall, and also follows the observed rise with the second section of precipitation. After precipitation ends, the model still has excess precipitation from overland flow that it continues to provide to the stream flow, reducing the capacity of the model to return to observed baseflow conditions, and negatively affecting the NS coefficient. A similar situation is seen in the validation effort using the March 4, 2008 storm event, with modeled results and observed flow being represented, but not the falling limb of the second peak that would bring modeled flow closer to the baseflow conditions of the observed data.

The ability to simulate the effect of the precipitation distribution in an urban watershed is performed without the inclusion of soil infiltration parameters or impervious areas. The Mannings M was the optimal parameter to use in calibration efforts, providing a reasonable simulation of the effects of the rainfall event. However, without incorporating the removal process of infiltration, the water balance will not properly allocate the precipitation, leaving a large amount of water to travel as overland flow. This is expected to be one reason that the modeled return to baseflow occurs at a much slower rate than observations suggest.

Intercomparison

Data input is a critical component to any watershed model. Good quality spatially distributed descriptive digital files are becoming more readily available as state, county and local entities collect the data for public use. These GIS files are creating a large body of information that can be used to determine the factors that influence watershed health. GIS began with open source software with Geographic Resources Analysis Support System (GRASS), but has since required private support to manage the programs as technology improves and needs become apparent. ArcMAP supported by ESRI is the current standard in GIS applications. Models that are compatible with the ESRI framework create a fluid transition from spatial database to hydrologic project. The HEC-HMS software has incorporated pre-processing software for input data called the HEC-GeoHMS, to evaluate the GIS data layers for input metrics to the hydrologic model. MIKE-SHE is able to incorporate the GIS layers as the original shapefiles and transform the shapefiles into the .dfs2 grid format that the model uses to calculate on a grid basis. However, the GIS layers used for calculations have to be put in as point files, not as polygon or raster files. This creates the need to produce the layers in a separate GIS project. Projection management in the MIKE-SHE model requires diligence as the model was created based on European standards.

An identified limitation within the lumped parameter model is the deficiencies that exist in the weighted averaging of subbasin characteristics of soil and land use. This error may be attributed to the unknown quantity of connected and disconnected impervious area. In the lumped parameter model this will be most notably reflected in the designation of the curve number. Although the curve number is a parameter that can be calibrated, initial assignment of a curve number based on soil and land use properties serve in the overall assessment of the watershed and are rarely calibrated at a subbasin level. If subbasins are not individually calibrated, but calibrated after several subbasins converge, then the disproportionate properties of the improperly designated subbasin is not readily apparent and therefore cannot be managed as such.

Similar internal error is inherent with the distributed model. Although the model is simulated with calculations at the grid level, the calibration is performed at one site, essentially lumping all internal parameters. It is the proper initial characterization of the spatially distributed watershed properties that contributes to the usefulness of the fully distributed model. Although the spatial distribution of connected and disconnected impervious areas are not readily available at this time, this could become part of the data acquired as a regional plan forms. However, in order to use this information in a management scenario, the modeling of connected versus disconnected impervious area would be necessary. The MIKE-SHE model does not allow for that at this time, as it treats all impervious surfaces as directly connected.

Antecedent Moisture Sensitivity

The calibration of the lumped parameter model will produce a set of fitting parameters that are based on the magnitude of the antecedent moisture condition, but is not explicitly represented in the event model. Therefore, when this set of parameters is used to simulate a different storm event, the onset of the storm and the volume of runoff will be capable of simulating the observations even if antecedent conditions are not similar.

In the HEC-HMS model, antecedent moisture conditions are represented within the initial abstraction and the curve number. Given that the initial abstraction is the depth of water on the ground that needs to be met before runoff can occur, a greater level of precipitation in the preceding days would provide a best fit parameter that would be lower, allowing the timing of the runoff to begin earlier. The curve numbers are generated according to tables that represent volume runoff according to the median antecedent conditions for the region (USDA, 1986). Both of these situations create best fitted parameters that are only applicable to an event with similar conditions.

Evaluation of both precipitation data sets for the Pompeston Creek calibration and validation lumped parameter model simulations, the validation produced a simulated hydrograph whose rising limb rose earlier than the observed data, showing the sensitivity of the model to the antecedent moisture conditions. Since the calibration run produced a set of best fitting parameters based on a low level of precipitation in the days preceding the event, when the ground was actually saturated with moisture, runoff began earlier. Visual inspection of these hydrographs suggests a greater sensitivity to the initial abstraction parameter, which would affect timing of the onset of the hydrograph compared with the curve number, which would affect volume to a greater extent.

Since the MIKE-SHE model was run with a “hot start” precipitation file that is similar for both models, it would be assumed that a similar situation exists for the parameters determined to be best fitted. This result is not clearly visible in the Pompeston Creek calibration and validation simulations for Method A, however a small difference in the timing of the first peak may appear to be rising earlier, but the following peaks do not follow in this manner. The physical model presents a large variety of physical factors that may make this one characteristic difficult to evaluate separately.

In the HEC-HMS model, the most sensitive parameter affecting model output was determined to be the curve number. With the initial designation of curve numbers requiring minimal alteration, this can be considered a parameter that is properly quantified, or found by calibration techniques. The curve numbers that were originally assigned according to published data sources were well quantified, as only a 0.1 to 3.8% change was necessary in the Pompeston Creek model and a 8% change was necessary to calibrate the Troy Brook model. In the fully distributed model using Method A, the overland flow was affected by changes in Manning M roughness coefficients. These parameters are also able to be determined through calibration. Although the lumping of the upstream drainage area will allow for the calibration, it will produce roughness coefficients that are changed as a lump. These parameters need to be properly designated at a grid level with land use and soil data to be reliable distributed parameters. Using roughness coefficients in the Strickler flow velocity equation to quantify the effects of land use across a watershed has not been well established and would require many internal calibration points to ensure adequate assignment of parameters in a distributed manner.

Precipitation runoff and transformation performance based on empirical calculations has been well established in the HEC-HMS model. Limitations of the lumped parameter model include the lack of spatial identity within the model, the use of several empirical parameters and the error that is introduced with area-weight averaging of land use and soil characteristics. These limitations were sought to be rectified in the MIKE-SHE model with no loss of usefulness in the performance of runoff and transformation. Reasonable simulation results with the MIKE-SHE model have suggested that this physical model could be used for stormwater management support using somewhat similar input databases.

Overall, the input parameters were generally better characterized for the lumped parameter model than for the distributed parameter model (Table 20). The lowest alteration of assigned parameter was for the curve number in the lumped parameter model. The two empirical parameters used for calibration in the distributed model were generally not found to be within a range that would allow confidence in a theoretical model.

Table 20 : Model Input Comparison

Lumped	Parameter	Percent Change	Sensitivity Rank	Level of Initial Parameterization
	Curve Number	0.1 to 8%	1	good
	Initial Abstraction	50 to 81%	2	fair
	Peaking Coefficient	33 to 67%	3	fair
	Precipitation	D	–	fair
	Antecedent Moisture	*	–	fair
Distributed				
	Manning M	2.4 to 85%	2	poor
	Hydraulic Conductivity	10 to 97%	1	poor
	Precipitation	D	–	fair
	Antecedent Moisture	*	–	fair

Regional Stormwater Management Planning

Regional Stormwater Management can use models at various stages of the planning process. Education of stakeholders is one element of a plan that allows the plan to merge into implementation. In un-gauged watersheds, this education may occur before data is collected for calibration purposes. The curve number is an easily understandable empirical quantification of the characteristic of runoff that has been used to teach environmental groups about the varying hydrology of watersheds (Goodrow and Obropta, 2005). Given that the curve number is lumped and lacks spatial distribution, the data output is difficult to visualize on a time series basis.

Spatial databases are used for input to both models. The HEC-HMS produces a volume and a velocity over time, but does not characterize the processes occurring in the watershed during the event in a visual manner. The MIKE-SHE model has the ability to produce a series of spatial maps displaying the simulation of the hydrology over time, showing overland flow depth, direction of water movement, soil moisture or a variety of other results. These displays can be formatted to a movie type file and projected for stakeholders. These distributed map-like simulations of the watershed hydrology would be expected to contribute to the detection of spatially distributed stormwater issues, if data sets and model sensitivity are reliable.

6. Conclusions and Recommendations

There are nine goals of stormwater management planning laid out in N.J.A.C. 7:8-2.2. Included among these goals is the maintenance of groundwater recharge, maintenance of the integrity of stream channels for biological functions as well as for drainage purposes, and the minimization of pollutants in stormwater runoff. To address these goals, the model that is used to represent the hydrological processes in the watershed should be able to capture the effects of a "typical" rain event. These typical rain events have been considered to be events under 1.25 inches of precipitation depth. Essential elements of the model should capture the precipitation effect and the creation of runoff over time. The properly quantified excess runoff over time will allow for management decisions to be made regarding the mitigation of effects on groundwater recharge, stream bank integrity and water quality. Improperly managed runoff can create lower groundwater recharge, the erosion of stream banks and the reduction of water quality since the runoff may carry diffuse source pollution.

Two distinctly different models have been implemented for the Regional Stormwater Management Planning process for two urban watersheds in New Jersey. The lumped parameter model, HEC-HMS, uses empirical parameters to replicate past storms and predict potential stream flow for design storms. The distributed parameter model MIKE-SHE used the physical parameters gathered from readily available digital data sets in an attempt to replicate runoff and stream reaction. The event based model simulations produced for this evaluation had several findings:

- Sensitivity analysis provided in this study has highlighted the data elements that are essential to represent hydrologic processes occurring in the urban watershed. The correct characterization of the Manning's M roughness coefficients in the distributed model and the curve numbers in the lumped parameter model were determined to affect the simulations of the event based runoff generation. The curve number was initially well characterized due to its thorough representation in the literature. The Mannings M values that were determined after a best fit analysis varied greatly from the initial characterization, and this is not well defined in the literature.
- The heightened sensitivity of the Manning's M parameter may enforce the notion that overland flow dominates event based hydrographs and should be better quantified for this use. However, this may be due to the effect of impervious surfaces on the roughness coefficient, and may be represented better by the proper representation of the impervious areas.
- The hydraulic conductivity parameterization necessary to simulate the 2-layer water balance in the urban unsaturated zone was determined to not be well quantified with literature values. A sharp decrease in the values expected to represent the soils was necessary. This is likely due to the urban nature of the watershed.
- The true characteristics of the soil hydraulic properties need to be well developed in available spatial digital format. Although quantifying the runoff was easily represented within the curve number of the empirical

model, the physical soil characteristics and connection distribution regarding urban areas are not well defined. The spatial distribution of soils available from the Natural Resource Conservation Service does contain several hydraulic properties, such as hydrologic group (empirical parameter used in the designation of curve number), soil types (loam, sand, gravel, etc.) and soil names. These properties are not specific enough for application into a physical hydrologic model and extrapolation must be made to relate these properties to values reported in the literature. The estimation of soil hydraulic properties in an urban area could require additional data collection. Richard Grabowski, NJDEP, during the National Cooperative Soil Survey (NCSS) Work Planning Conference, has suggested that pedotransfer functions used by the regional soils laboratory could be used to generate additional soil water retention and hydraulic conductivity data for each layer of each applicable soil-map unit in New Jersey and made available through the Soil Data Mart web sites. The nature of these soils in an urban setting should also be considered. These functions may serve to better quantify the hydraulic properties of the land phase of the hydrologic cycle.

- The proper representation of the hydrologic properties of connected and disconnected impervious areas requires the compilation of a methodology that would serve to guide the GIS analysis of aerial photography together with the collection of on-site data. Current impervious quantification by aerial analysis alone may be misleading as to the hydrologic effects.

Although the current modeling effort using the MIKE-SHE model does not allow for the disconnection of impervious areas, the future of using a distributed model for stormwater management dictates the need for the proper representation of drainage from impervious areas. Using the impervious layer with the related drainage network, the excess runoff is directly routed to the stream and would not have a chance for infiltration as disconnected impervious surfaces would. Although this may be acceptable given larger time steps, evaluation of storm events and the use in stormwater management, this is a shortcoming that needs to be remedied.

- Accurate data sets of the temporal and spatial distribution of the precipitation events are essential to proper calibration and may not be easily determined through current in-the-field measurements.
- Distributed models require a more extensive network of observed data within the watershed that can be used for calibration. These internal points would generally be expected to be un-gauged and posses no long term data. The implementation of urban research watersheds with multiple interior gauging stations could better characterize sensitive input parameters for broader use in the distributed hydrological modeling of urban watersheds.
- A unified effort for increasing the use and efficiency of the distributed parameter model will be necessary to ensure professional review and proper coding of calculations as well as of input data. The HEC-HMS

model has the benefit of being a supported, open source model. The MIKE-SHE model exists under the authority of DHI, a consulting firm, making use of the model for widespread use an expensive endeavor.

As computing abilities increase, the fully distributed hydrologic model will be the best tool to integrate natural resource decision making with regards to water quantity, water quality and groundwater recharge. The compilation of input data will aid in the creation of reliable models. These models need to be undertaken in a methodical, open source environment in order to deliver successful management of our water resources.

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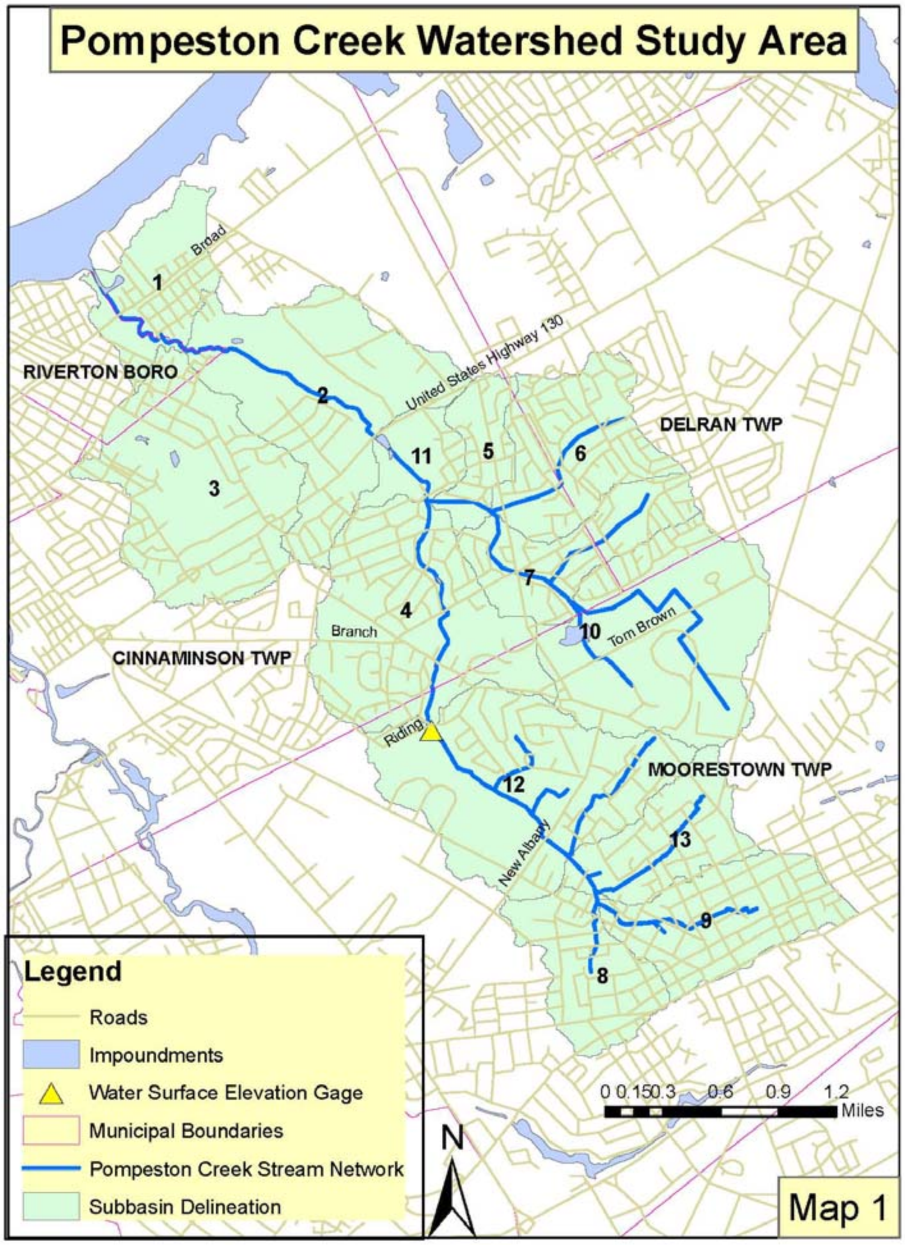
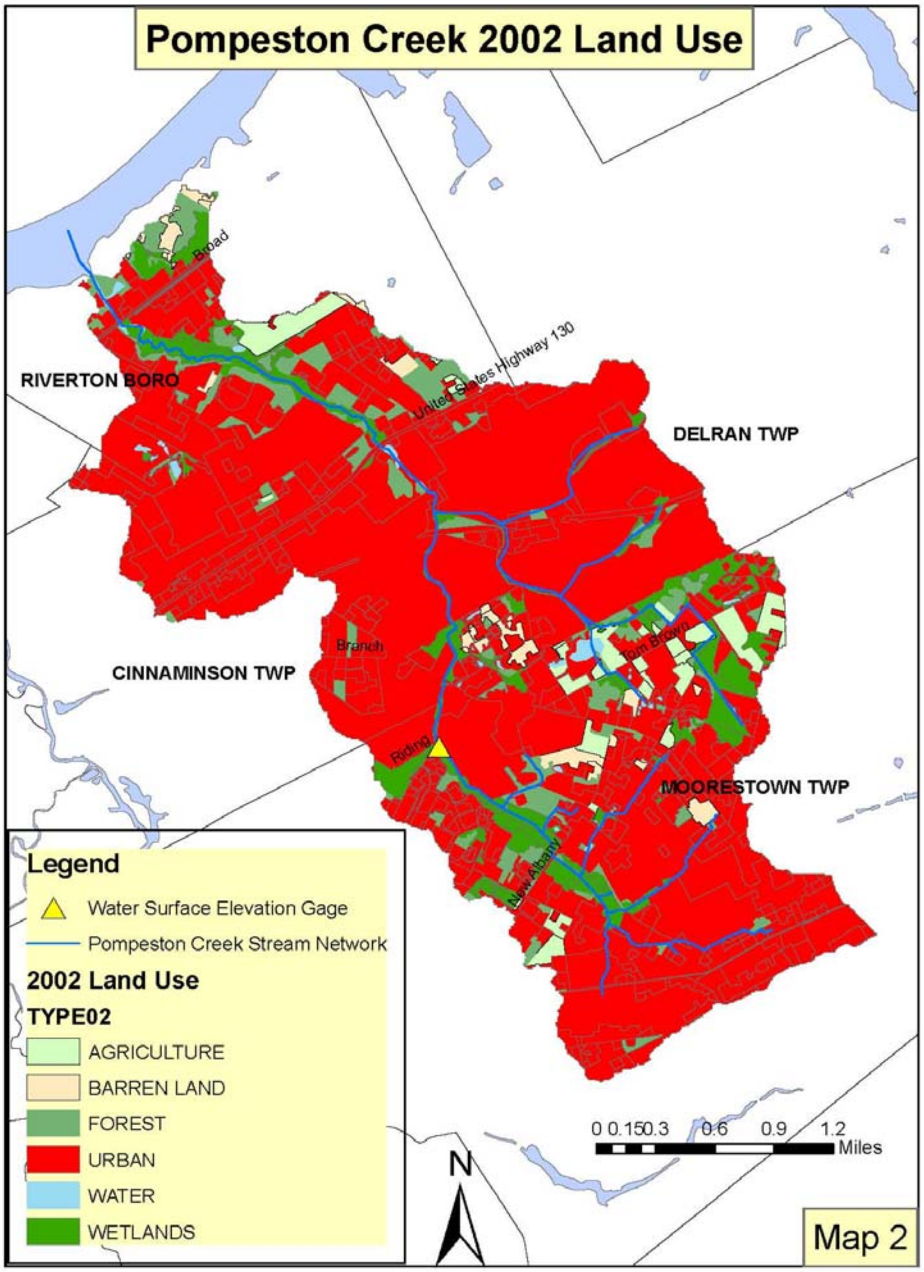
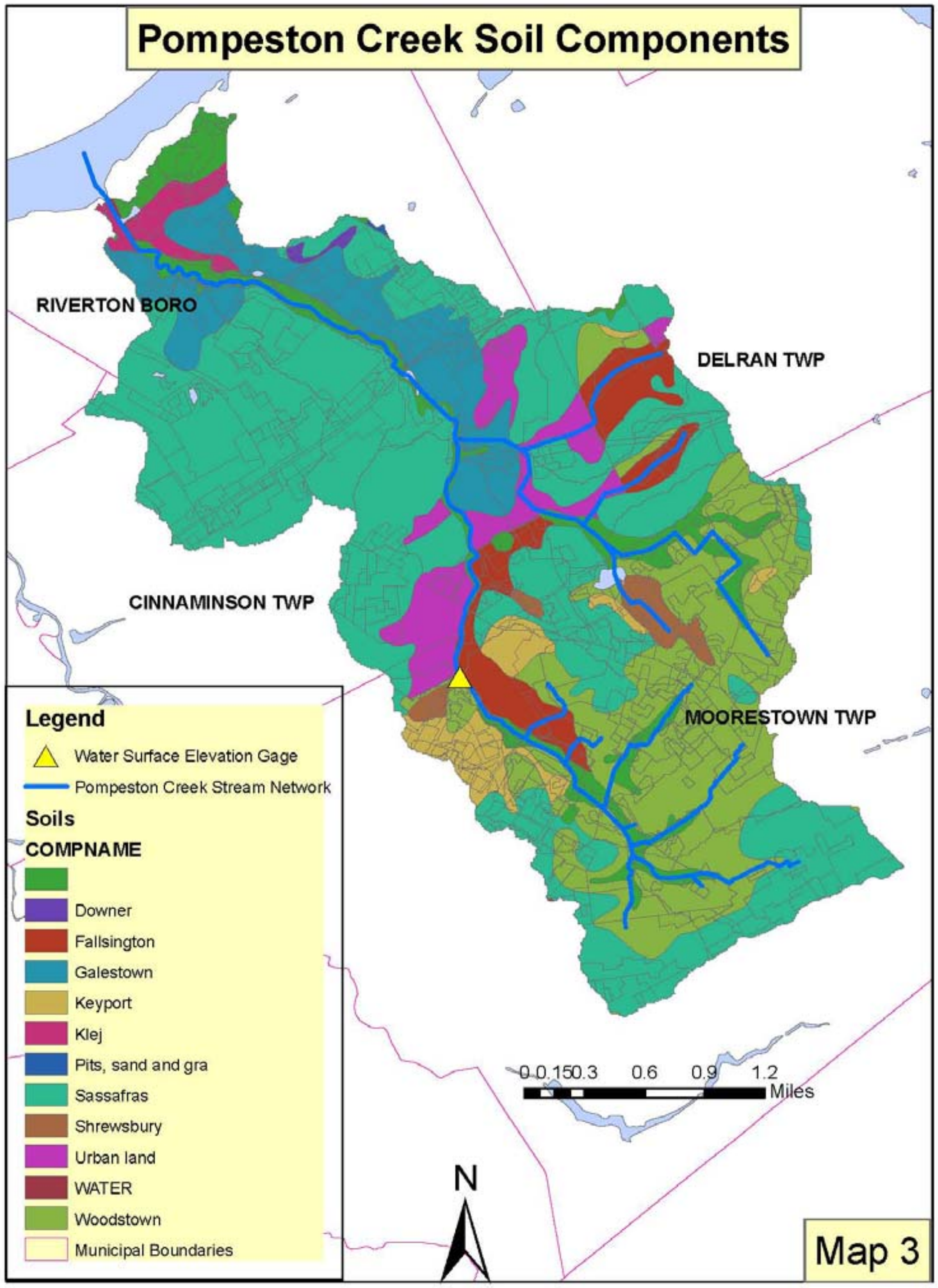
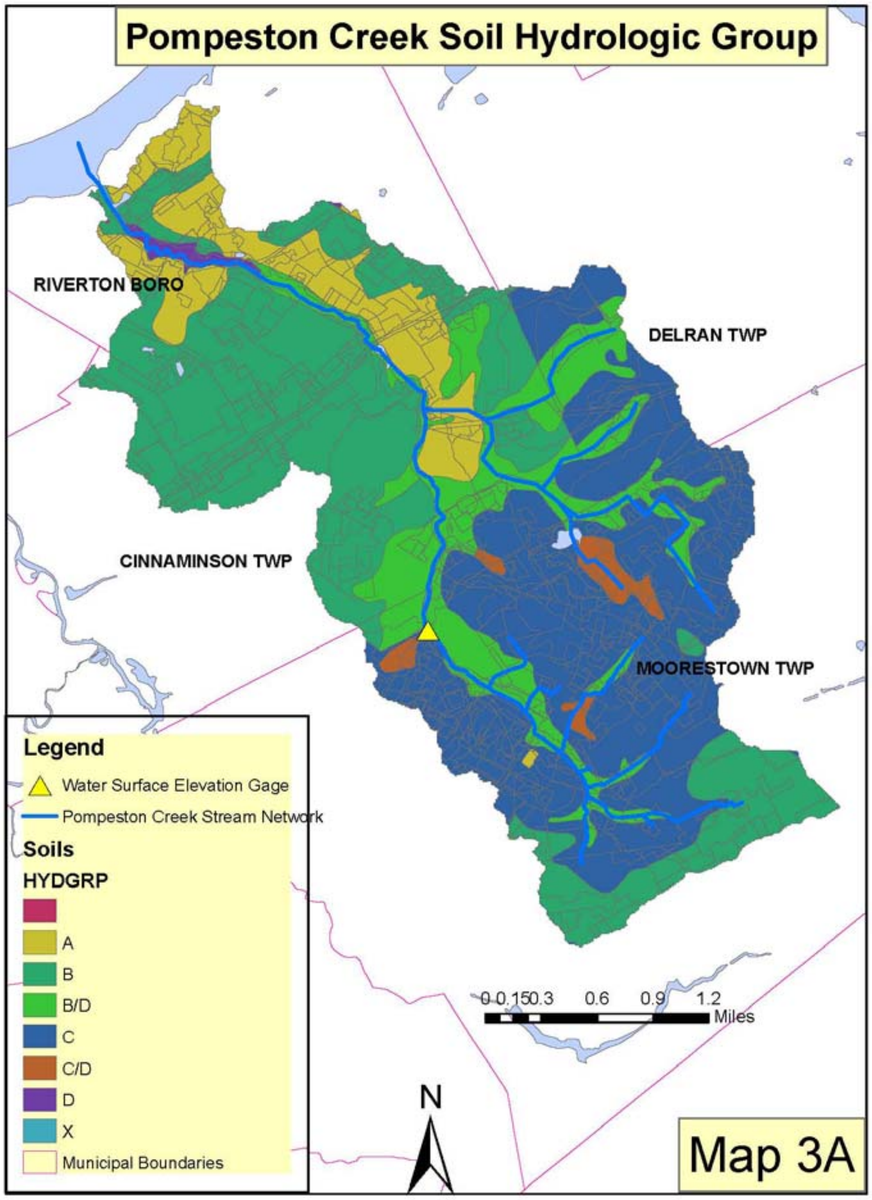
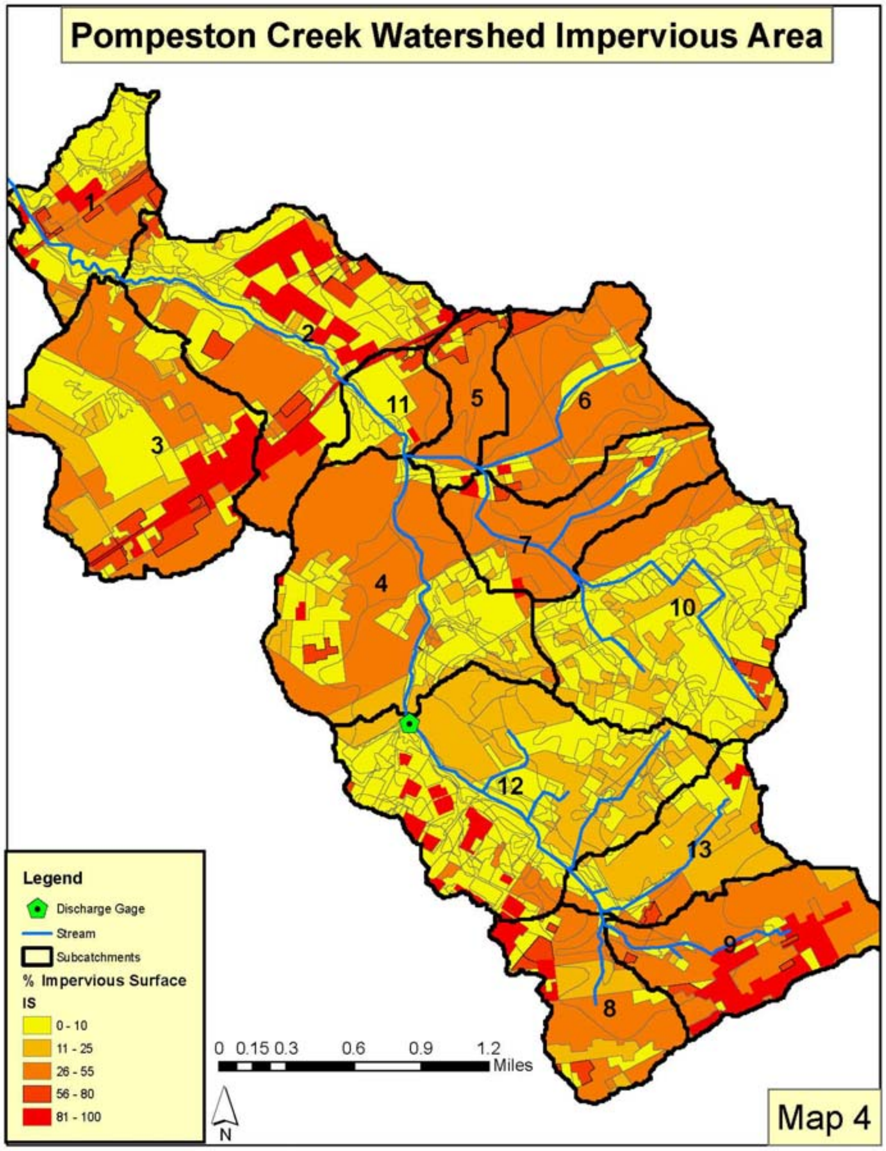
Appendix A: Maps

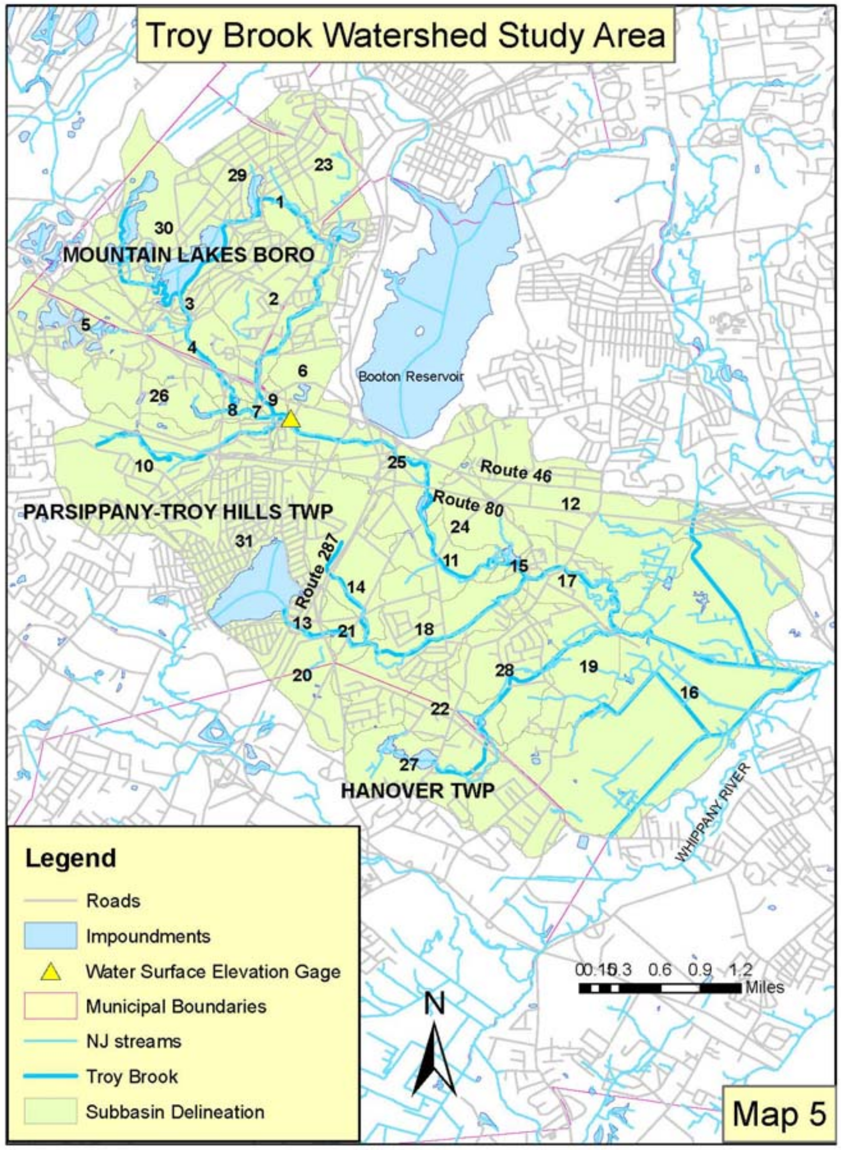

Pompeston Creek Watershed Study Area
Broad
1
2
3
4
5
6
7
8
9
10
11
12
13
RIVERTON BORO
United States Highway 130
DELRAN TWP
Branch
Tom Brown
CINNAMINSON TWP
Riding
MOORESTOWN TWP
New Albany
Legend
Roads
Impoundments
Water Surface Elevation Gage
Municipal Boundaries
Pompeston Creek Stream Network
Subbasin Delineation
0 0.150.3 0.6 0.9 1.2
Miles
N
Map 1

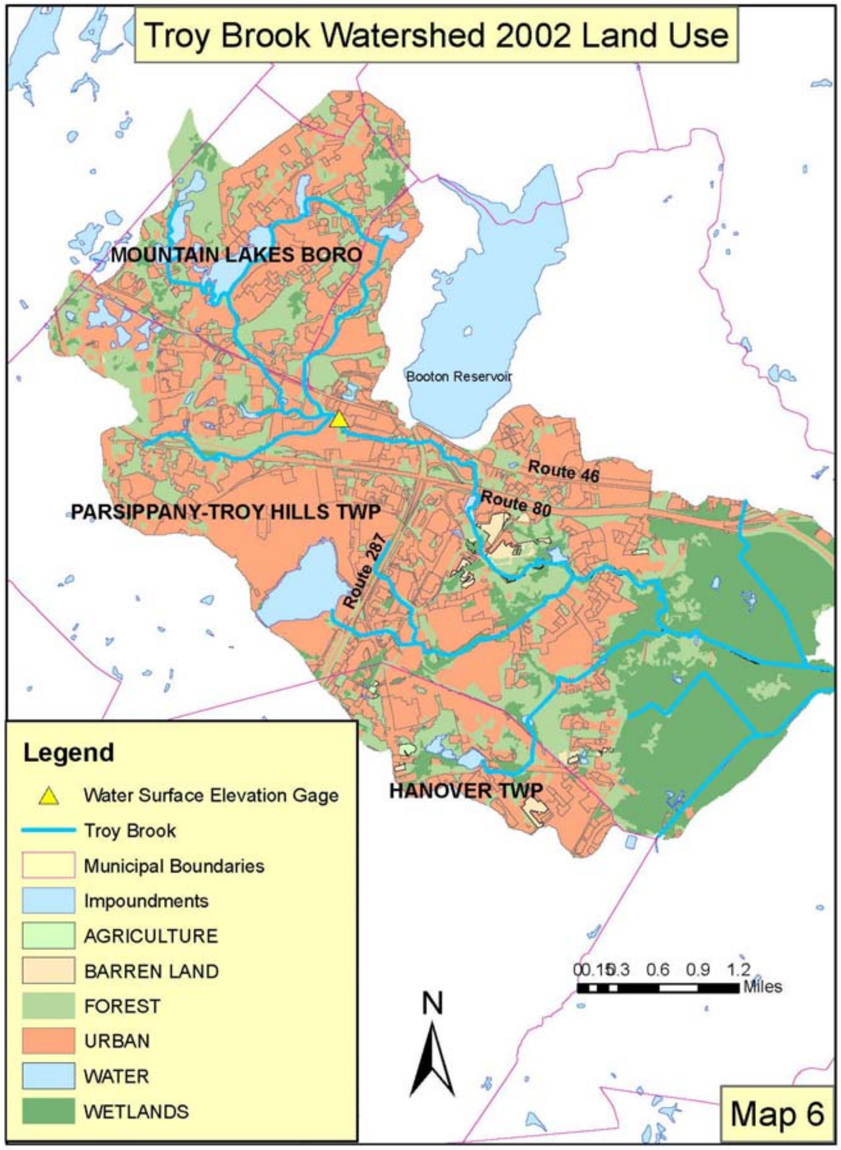

Pompeston Creek 2002 Land Use
Broad
United States Highway 130
RIVERTON BORO
DELRAN TWP
Branch
CINNAMINSON TWP
Tom Brown
Riding
MOORESTOWN TWP
New Albany
Legend
Water Surface Elevation Gage
Pompeston Creek Stream Network
2002 Land Use
TYPE02
AGRICULTURE
BARREN LAND
FOREST
URBAN
WATER
WETLANDS
0 0.150.3 0.6 0.9 1.2
Miles
N
Map 2

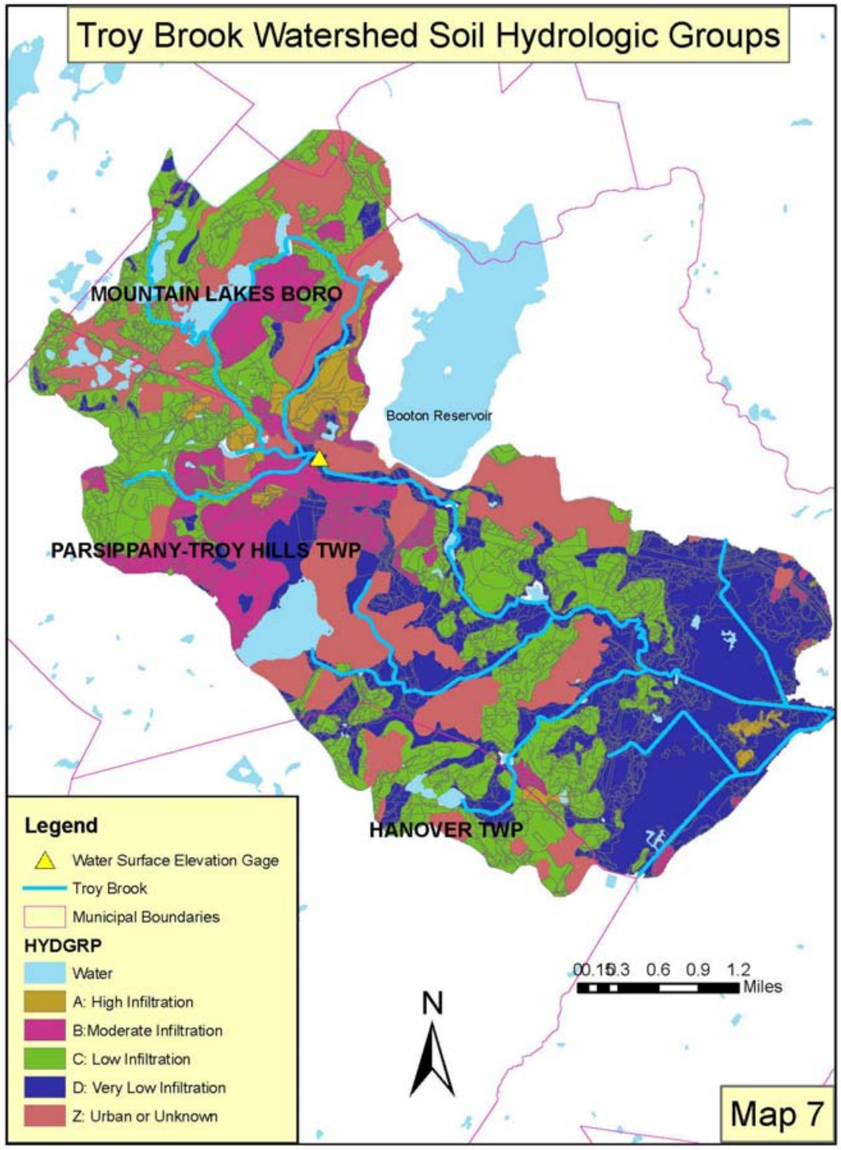

Pompeston Creek Soil Components
RIVERTON BORO
DELRAN TWP
CINNAMINSON TWP
MOORESTOWN TWP
Legend
Water Surface Elevation Gage
Pompeston Creek Stream Network
Soils
COMPNAME
Downer
Fallsington
Galestown
Keyport
Klej
Pits, sand and gra
Sassafras
Shrewsbury
Urban land
WATER
Woodstown
Municipal Boundaries
0 0.150.3 0.6 0.9 1.2
Miles
N
Map 3

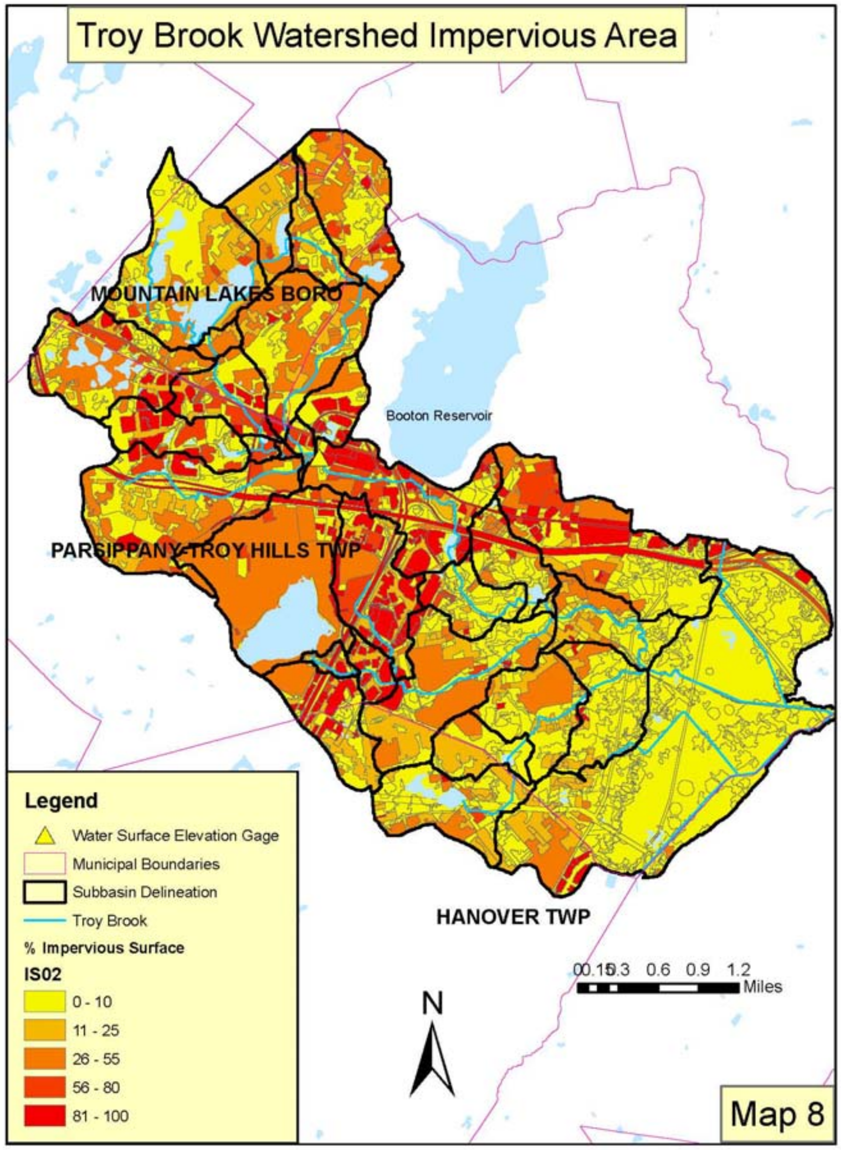

Pompeston Creek Soil Hydrologic Group
RIVERTON BORO
DELRAN TWP
CINNAMINSON TWP
MOORESTOWN TWP
Legend
Water Surface Elevation Gage
Pompeston Creek Stream Network
Soils
HYDGRP
A
B
B/D
C
C/D
D
X
Municipal Boundaries
0 0.150.3 0.6 0.9 1.2
Miles
N
Map 3A


Pompeston Creek Watershed Impervious Area
1
2
3
4
5
6
7
8
9
10
11
12
13
Legend
Discharge Gage
Stream
Subcatchments
% Impervious Surface
IS
0 - 10
11 - 25
26 - 55
56 - 80
81 - 100
0 0.15 0.3 0.6 0.9 1.2
Miles
N
Map 4


Troy Brook Watershed Study Area
MOUNTAIN LAKES BORO
PARSIPPANY-TROY HILLS TWP
HANOVER TWP
Booton Reservoir
Route 46
Route 80
Route 287
WHIPPANY RIVER
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
Legend
Roads
Impoundments
Water Surface Elevation Gage
Municipal Boundaries
NJ streams
Troy Brook
Subbasin Delineation
0 0.15 0.3 0.6 0.9 1.2
Miles
N
Map 5


Troy Brook Watershed 2002 Land Use
MOUNTAIN LAKES BORO
Booton Reservoir
Route 46
Route 80
PARSIPPANY-TROY HILLS TWP
Route 287
HANOVER TWP
Legend
Water Surface Elevation Gage
Troy Brook
Municipal Boundaries
Impoundments
AGRICULTURE
BARREN LAND
FOREST
URBAN
WATER
WETLANDS
0 0.15 0.3 0.6 0.9 1.2
Miles
N
Map 6


Troy Brook Watershed Soil Hydrologic Groups
MOUNTAIN LAKES BORO
Booton Reservoir
PARSIPPANY-TROY HILLS TWP
HANOVER TWP
Legend
Water Surface Elevation Gage
Troy Brook
Municipal Boundaries
HYDGRP
Water
A: High Infiltration
B:Moderate Infiltration
C: Low Infiltration
D: Very Low Infiltration
Z: Urban or Unknown
0 0.15 0.3 0.6 0.9 1.2
Miles
N
Map 7


Troy Brook Watershed Impervious Area
MOUNTAIN LAKES BORO
Booton Reservoir
PARSIPPANY-TROY HILLS TWP
HANOVER TWP
Legend
Water Surface Elevation Gage
Municipal Boundaries
Subbasin Delineation
Troy Brook
% Impervious Surface
IS02
0 - 10
11 - 25
26 - 55
56 - 80
81 - 100
0 0.15 0.3 0.6 0.9 1.2
Miles
N
Map 8

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