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An Assessment Of The Use Of Green Stormwater Infrastructure For Flood Mitigation At Berry Brook

By

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B.S. Civil Engineering, University of New Hampshire, 2018

THESIS

Submitted to the University of New Hampshire

in Partial Fulfillment of

the Requirements for the Degree of

Master of Science

in

Civil Engineering

May, 2021

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Acknowledgements

This project was funded by the EPA Science to Achieve Results (STAR) project *Taking it to the Streets: Green Infrastructure for Sustainable Philadelphia Communities.*

Thank you to my thesis advisor, Dr. Ballestero for his knowledge, recommendations, helpful criticism, and great patience that have ensured this research reached its conclusion. He taught me to always be thinking about the next question.

Thank you also to my committee members Dr. Houle and Dr. Watts for sharing their expertise and encouraging me to keep pushing through.

I am especially grateful to my friends and family, who have never stopped asking about my progress. Their urging and support kept me moving through the most challenging places.

Table of Contents

List of Tables

List of Figures

List of Acronyms

BMP – Best management practice

CFS – Cubic feet per second

EIC – Effective impervious cover

EPA – Environmental Protection Agency

FDC – Frequency Duration Curve

HSPF – Hydrologic simulation program-Fortran

IC – Impervious cover

ICM – Impervious cover model

ISE – Integral square error

NSE – Nash-Sutcliffe efficiency

GIS – Geographic Information System

GSI – Green stormwater infrastructure

LID – Low impact development

LiDAR – Light detection and ranging

NH – New Hampshire

PCSWMM – Personal computer stormwater management model

Pre – Model of watershed prior to the use of BMPs

Pre_{15}- Model of the watershed prior to the use of BMPs with only 15% IC

Pre_{0} - Model of the watershed prior to the use of BMPs with no impervious cover

$Pre_{Climate}$ – Model of the pre-improvements watershed simulating climate change impacts

Post – Model of the watershed including the BMPs

$Post_{Climate}$ – Model of the post-improvements watershed simulating climate change impacts

RMSE – Root mean square error

SEE – Standard error of the estimate

SRTC – Sensitivity-based radio tuning calibration

SWMM – Stormwater management model

TN – Total nitrogen

TP – Total phosphorous

TSS – Total suspended solids

UNH – University of New Hampshire

UNHSC – University of New Hampshire Stormwater Center

US – United States of America

Zn - Zinc

Abstract

This research examined the effectiveness of GSI and other BMPs to control urban flooding for extreme precipitation events and compared the impacts of increasing impervious cover with the impacts of increasing rainfall intensity caused by climate change. The City of Dover has spent the last decade implementing best management practices in the 185-acre Berry Brook watershed to combat stream pollution and flooding caused by urbanization. Improvements to the watershed included building additional headwater wetland area, daylighting and restoring 1,100 feet of stream, and redirecting stormwater to GSIs, thereby reducing the effective impervious cover from 30% to 10%.

Four PCSWMM models of the Berry Brook watershed were developed for the analysis: a pre-implementation model, a model of the pre-implementation watershed set to 15% IC, a model of the pre-implementation watershed set to 0% IC, and a model of the watershed after BMP implementation. The four models were used to examine the effects of GSI implementation, changing impervious cover, and climate change on urban watershed hydrology for the 2-year, 10-year, 50-year, and 100-year extreme precipitation events.

The effectiveness of GSI and other BMPs to control urban flooding caused by extreme precipitation events was tested by comparing the peak flows, time to peak flows, runoff depth, and total storm flow volume. A long-term rainfall-runoff simulation from 2001 to 2011 was also done for the watershed with and without GSI. It was found that BMP implementation caused an median decrease in extreme peak flow of 7%, an increase in the time to peak flow of 3 minutes, a decrease in the runoff depth of 29%, and a decrease in the total storm flow volume of 30%. GSI impact was more prevalent in short duration extreme precipitation events than in long duration

events. In the 10-year analysis, annual maximum flow decreased 8%. The infiltration of rainfall increased by 17% and the stormwater runoff decreased by 40%. This showed implementing GSI in an urban watershed will reduce flooding caused by extreme precipitation events but not eliminate it. For common storms of about no more than 1.3 inches, it was found that GSI reduced peak flows by a median of 68%.

Increasing IC in the watershed was shown to have a much more dramatic effect than the increase in rainfall caused by climate change. Impact was still more prevalent in short duration extreme precipitation events than in long duration events. The difference between the BMP-managed watershed under future climate change conditions and the traditionally managed watershed under current day conditions was minimal, implying BMP implementation will keep flooding from getting any worse as the climate shifts, but by itself, GSI will not eliminate urban flooding.

Chapter 1: Introduction

1.1 Stormwater in Rivers and Streams

Stormwater is water from rainfall or snowmelt that flows over land or impervious surfaces and does not soak into the ground. The runoff collects pollutants such as chemicals, nutrients, and sediment that can harm bodies of water that the stormwater will eventually enter (US EPA, 2020a). Stormwater is a particular challenge in urbanized areas. The introduction of impervious cover such as paved roads, rooftops, and sidewalks and the shift from a diverse natural ecosystem to agricultural and urban land use drastically shifts the hydrologic condition of a watershed. Urbanized land is expected to continue increasing along with the population, and without proper stormwater management shall result in more runoff and increased pollutant load entering bodies of water (Press, 2012).

One major recipient of stormwater is rivers and streams, which carry it even further through the ecosystem. Urbanization affects water quantity, water quality, channel form, and aquatic biota in the receiving waters (Press, 2012). Across the nation, streams and rivers are showing impairment due to pollutants from stormwater and other sources, with pathogens, sediment, and nutrients being found as top stressors (US EPA, 2017). Surveys and sampling show that 58% of US rivers and streams have excess nutrients, that can lead to decreases in aquatic life (US EPA, 2020b). In New Hampshire, 4,413 miles of stream are impaired, with top pollutants including acidity, low oxygen, metals, degraded aquatic life, salts, algae, flow alterations, invasive species, degraded habitat, and ammonia (US EPA, 2020c). These pollutants are transported by the impaired rivers and streams into lakes and oceans, increasing pollutant issues in those areas.

National, state, and local efforts are all being executed to prevent further impairment and restore currently damaged waters. These efforts include regulations, conservation efforts, and the use of best management practices (BMPs) to address the quantity and quality of runoff. BMPs are site-specific stormwater mitigation strategies including green stormwater infrastructure (GSI) such as bioretention systems and subsurface gravel wetlands, constructed wetlands, and stream restoration (Beach, 2003). While traditional stream management practices involve treating the symptoms of impairment using strategies such as armoring stream banks and channels, BMPs focus on removing the cause of impairment by restoring the watershed hydrology at the catchment scale to its pre-development patterns (Vietz et al., 2015). Stormwater management using BMPs is shown to improve the quality of receiving waterbodies, conserve water resources, protect public health, and help mitigate flooding in developed areas (US EPA, 2020a).

1.2 Impervious Cover

Impervious cover (IC) is any surface in the landscape that cannot effectively infiltrate rainfall. It includes paved roads and driveways, parking lots, rooftops, sidewalks, and heavily compacted soils. Impervious cover is a standard feature of urban development and is projected to almost triple in area by 2030 (Vietz et al., 2015). The presence of IC has been used as an initial gage to the health of a watershed and the associated stream or river (Schueler et al., 2009).

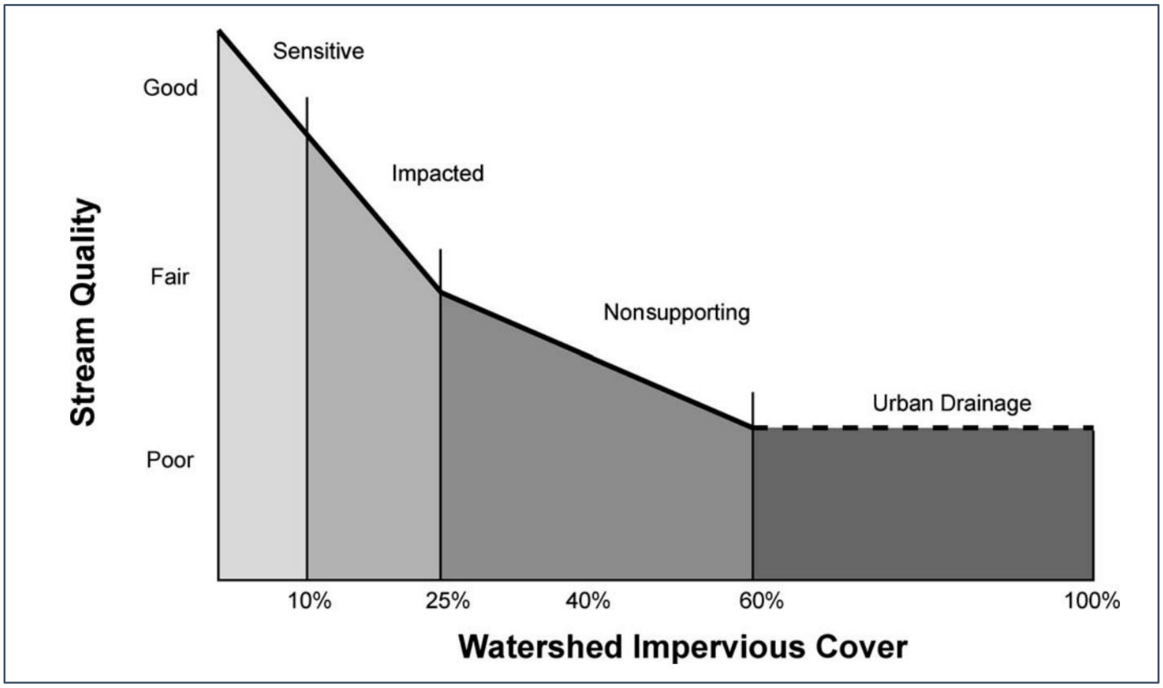

Figure 1: Impervious Cover Model (Schueler et al., 2009)

The impervious cover model (ICM) was developed in 1994 to show the relationship between the impervious area in a watershed and the overall stream quality (Figure 1). According to the ICM, watersheds with less than 10% IC in the watershed area can continue to support a healthy stream, watersheds with 10% IC to 25% IC tend to have impacted streams, watersheds with 25% IC to 60% IC cannot support a healthy stream ecosystem, and watersheds with greater than 60% IC have streams better defined as urban drainage channels with little to no ecosystem value.

The introduction of BMPs to a watershed limits the usefulness of IC as a gage of stream health because the very purpose of BMPs is to remove the impacts caused by IC. Therefore, a new metric is necessary to continue gaging stream health using impervious surface in a catchment. Effective impervious cover (EIC) is the portion of total impervious cover that hydraulically connects to the drainage system (Ebrahimian et al., 2018). It can be considered as the area of total impervious cover in a watershed that is not managed using BMPs. Effective impervious cover can be calculated by multiplying percent IC by a factor determined by the total quantity of water diverted to a BMP (EPA, 2011). It can then be used with the ICM to assess expected stream health.

1.3 Climate Change

Human-caused climate change and it's expected effect on precipitation could cause great effect on streams and rivers. It is expected that within the next 50 years, it will be warmer by more than 1 degree Fahrenheit and total annual precipitation will have increased by 12% to 20% in southern New Hampshire (Wake et al., 2014). In addition to the increased total precipitation, climate change is expected to cause an increase in the frequency and severity of flood-causing precipitation, which will lead to increases in erosion and property damage (Task, 2009).

Incorporating climate change into long-term developmental planning is becoming a necessity. The current New Hampshire guidance for designing climate change resilient systems is to add 15% to the current design extreme precipitation values. This allows decision-makers to account for the increase in storm severity, but it does not account for the expected frequency of storms. An alternative method to increasing storm extremes is to disaggregate daily rainfall from downscaled climate model output into hourly precipitation using mathematical algorithms, then run the expected precipitation on the watershed using a model. This would allow for a multi-year analysis of a watershed using the expected future rainfall, therefore incorporating climate change into the dynamic design of systems. Rainfall disaggregation is difficult to apply in many small watersheds because it requires extensive hourly historic rainfall records to develop an accurate disaggregation methodology. Rainfall disaggregation also assumes that storm behavior at the hourly level will not be affected by climate change (Westra et al., 2012).

1.4 Green Stormwater Infrastructure

Stormwater controls are necessary to prevent the degradation of bodies of water by runoff. Traditional stormwater practices (ponds and swales) are designed to manage runoff flows and flooding to protect property and somewhat reduce pollutant loads. Best Management Practices are designed to accomplish both those tasks and protect stream channels and aquatic habitats. Current practices seek to replicate the pre-development hydrologic patterns of an area using green stormwater infrastructure (GSI) and other BMPs (Press, 2012).

Green stormwater infrastructure (GSI) is designed to capture the runoff from frequent storms and slowly release it. Systems are sized to store the water from more frequent precipitation events, often about the first inch of rain, and bypass the rest into the receiving system. The first inch of rain passes through the full treatment system which is designed to remove pollutants and allow maximum infiltration into the groundwater. Pollutants are removed using physical, biological, and chemical processes. Filtration and plant uptake are two key processes. Installing GSI reduces pollutant loading from stormwater on the receiving body of water (Ballestero et al., 2012).

GSI is also considered useful for localized flood control in urban watersheds. Studies have shown that GSI helps control frequent rainfall events such as a one-inch storm but fails to effectively mitigate extreme storms (Zhu et al., 2017).

1.5 Modeling

Implementing BMPs in an effective way requires good information, planning, decision-making, and practices. The variety of BMPs available causes a need for a method of assessing the impact of each one in a specific watershed. Strategies such as land conservation, reducing impervious cover, and the installation of GSI must be studied in tandem to determine the best protection plan (Peterson et al., 2010). Watershed models are used to simulate hydrology and water quality in runoff, evaluate the impacts of urban development, and investigate the effectiveness of watershed restoration strategies without employing costly field tests (Yadzi et al., 2019).

The EPA developed and supports two commonly used software applications for modeling: the Hydrologic Simulation Program-Fortran (HSPF) and the Stormwater Management Model (SWMM). HSPF looks holistically at a watershed to simulate watershed hydrology and water quality. SWMM simulates conveyance systems of stormwater at a subcatchment or watershed scale. Both models can simulate streamflow, but HSPF performs better in groundwater flow while SWMM predicts peak flow better (Yadzi et al., 2019). Furthermore, HSPF is designed exclusively for modeling at the watershed scale, while SWMM can model GSI as individual systems as well as catchment or watershed scale areas.

1.6 Literature Review of GSI for Urban Stormwater Management

Modeling green stormwater infrastructure and other best management practices is useful in system design and community planning at a catchment and watershed scale. At a catchment scale, modeling allows for a particular GSI system to be tailored to meet flow and pollutant level requirements and to study site-specific infiltration. At a watershed scale, modeling allows wide-spread BMP implementation to be assessed for its usefulness in flood and pollution mitigation.

Watershed and regional flooding are quantified using maximum discharge (cfs) caused in a stream or river due to a storm event. The National Flood Insurance Program assesses flood risk in an area at the 10, 50, 100 and 500-year storms, which have respective annual probabilities of 10, 2, 1, and 0.2 percent respectively (Scholz, 2011). These flood risks dictate flood insurance prices in geographic areas and are used by communities in long-term development planning. Developing land causes changes to the watershed hydrologic response to precipitation, which in turn changes flooding in streams and rivers.

Green stormwater infrastructure, as stated above, is primarily intended to remove pollutants in runoff from impervious surfaces and to detain and infiltrate the first inch of water to reduce peak discharge from the IC. Applying GSI reduces effective impervious cover by hydraulically disconnecting impervious surface from the main drainage system (Scholz, 2011). GSI results with an increase in infiltration of the precipitation (infiltration depth), a decrease in runoff from precipitation (runoff depth), and therefore a decrease in total flow volume in a stream or river caused directly by a storm event (total flow). A study of GSI implementation at the urban catchment scale found that reducing EIC by at least 5% led to peak flow reduction, runoff volume reduction, and increases in the time to peak flow. The GSI systems in the study were designed to accommodate the 10-year storm, which is significantly larger than the usual design size of one inch of rain (Palla and Gnecco, 2015).

Since GSI is typically designed to manage only one inch or runoff, it is not known to be effective at mitigating extreme flooding events such as the 100-year storm at the watershed scale. A study of GSI use at the Lamprey River near Newmarket, New Hampshire showed that at the 100-year event, GSI implementation did not significantly adjust the hydrology for major flooding events (Scholz, 2011). Extreme precipitation events such as the 100-year storm vastly exceed the 1-inch planned for in GSI design and are times at which a stream floods in even a completely undeveloped environment. The performance of the GSI is limited by the rainfall volume and is significantly less effective in even the 10-year storm event (Palla and Gnecco, 2015).

The flood-control capacity of GSI is limited even with full implementation. A study of green roof implementation in four highly urbanized watersheds of the Pacific Northwest showed that even a modelled implementation of 100% for green roofs, or all rooftops acting as green roofs, only reduced mean annual flow by 20-25% (Barnhart et al., 2021). The study did not consider peak flow, but the impact on extreme events would likely have been even smaller.

Rainfall characteristics also impact the effectiveness of GSI to control flooding. A model of a residential area in Guangzhou, China found that changes in rainfall characteristics, such as intensity or duration, cause the effectiveness of GSI to manage flooding to decrease (Zhu and Chen, 2017). This is important when considering the impacts of climate change on a watershed. It is expected that climate change will cause an increase in rainfall intensity, which could in turn negate the usefulness of GSI in stormwater flooding control.

1.7 Berry Brook Watershed Renewal Project

Berry Brook is a 1.2-mile first order stream with a 185-acre drainage area located in Dover, NH that discharges into the Cocheco River (Figure 2). By 2005, the watershed had 55 acres (30%) of IC measured using GIS. The IC is made up primarily of asphalt roads, driveways, parking lots, and rooftops. Prior to the implementation of the Berry Brook Watershed Renewal Project, the IC was unmanaged and discharged all water and pollutants directly into the stream (Ballestero et al., 2016).

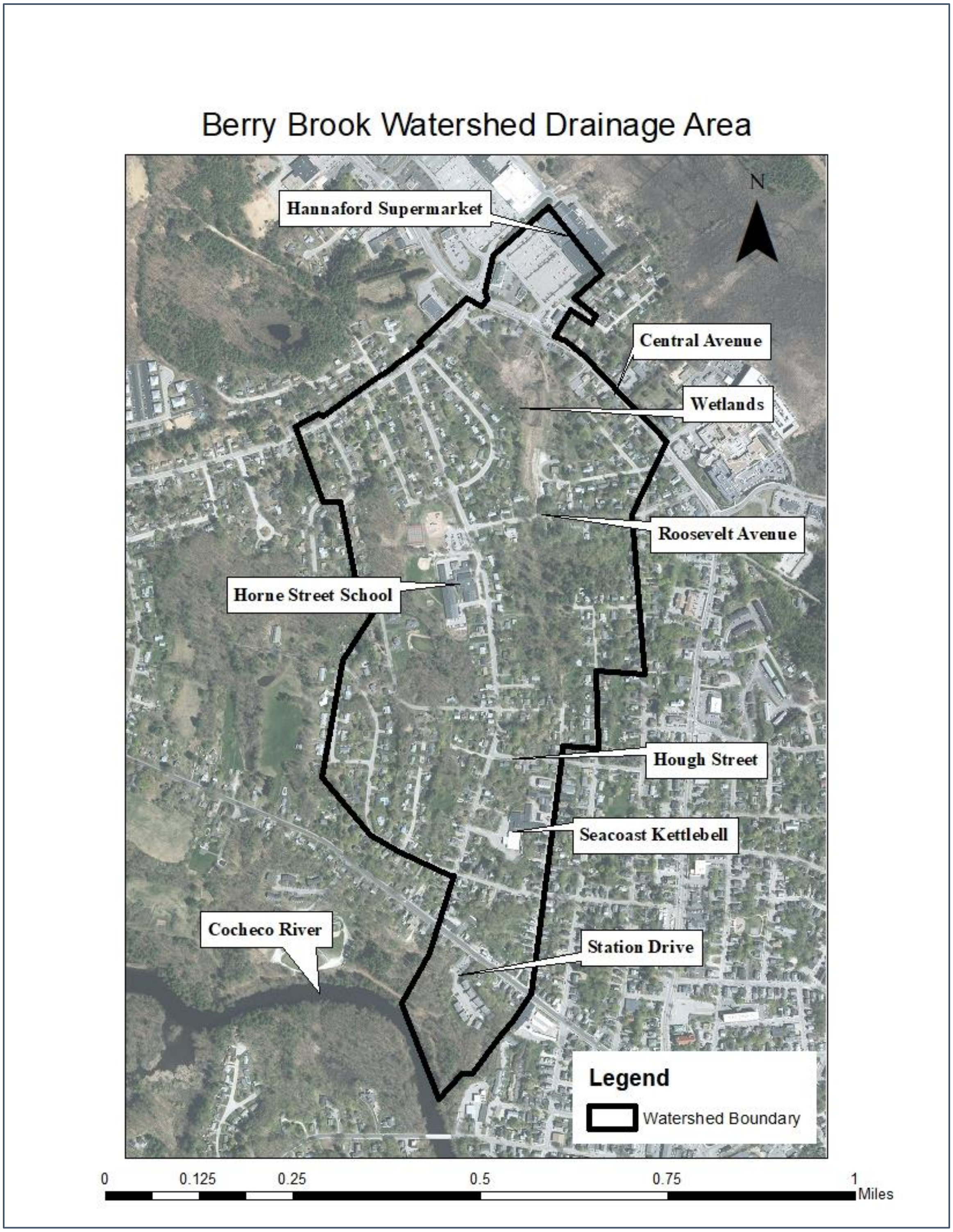

Figure 2: Berry Brook Watershed in Dover, NH (City of Dover and the UNH Stormwater Center, 2017)

In 2006, the state of New Hampshire placed Berry Brook on the EPA 303(d) list of federally impaired waterways due to high levels of pollutants. The stream was declared no longer fit for human contact. This prompted the City of Dover to partner with the University of New Hampshire Stormwater Center (UNHSC) and the Cocheco River Watershed Coalition to develop the Berry Brook Watershed Management Plan to improve Berry Brook water quality by implementing Low Impact Development (LID) best management practices. The goal of the project was to reduce effective impervious cover (EIC) to 10% by disconnecting IC and to lower the pollutant levels and peak discharge within the stream by stormwater filtration and infiltration. Infrastructure installment and stream improvements concluded in 2017 with an EIC of 10.4% (Ballestero et al., 2016). Improvements to the watershed included:

a) installation of GSI (Figure 3, Table 1)

b) one acre of new wetland in the upper watershed

c) a rain barrel program

d) 3 filtering catch basins

e) 1,100 feet of daylighted and restored stream channel

f) 500 additional feet of restored stream channel (Ballestero et al., 2016)

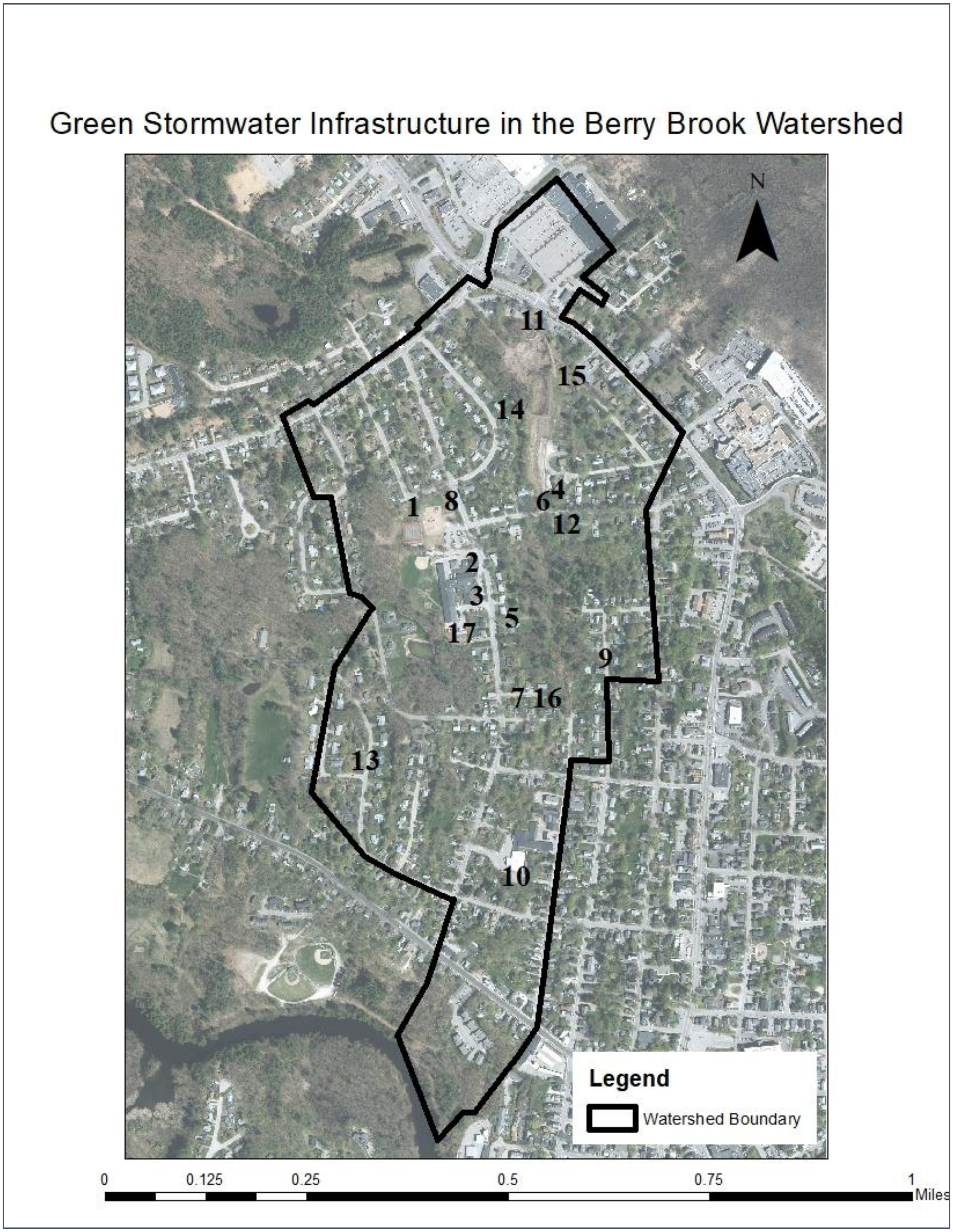

Figure 3: GSI Systems in the Berry Brook Watershed, Dover, NH (City of Dover and the UNH Stormwater Center, 2017)

Table 1: Green Stormwater Infrastructure in Berry Brook Watershed

Map Number	System Type	System Location
1	Bioretention	Glencrest Avenue
2	Bioretention	Horne Street School (1)
3	Bioretention	Horne Street School (2)
4	Bioretention	Lowell Avenue
5	Bioretention	Lower Horne Street
6	Bioretention	Roosevelt Avenue
7	Bioretention	Snow Avenue
8	Bioretention	Upper Horne Street
9	Gravel Filter	Grove Street
10	Gravel Filter	Seacoast Kettlebell
11	Gravel Wetland	Central Avenue
12	Infiltration Basin	Roosevelt Avenue
13	Infiltration Trench	Hillcrest Drive
14	Swale	Crescent Avenue
15	Swale	Page Avenue
16	Swale	Snow Avenue
17	Tree Filter	Horne Street School

The small size of the Berry Brook Watershed allows a full-scale study of the impacts resulting from GSI implementation and stream improvements on an urban watershed. Many large watersheds will not see full-scale BMP implementation in a timeframe that allows for continuous monitoring and a clear demonstration of the stream response. All Berry Brook improvements were completed within one decade of the initial proposal, with monitoring that began six months prior to implementation to the present (Ballestero et al., 2016). This allows for a close analysis of the impacts caused by the change in EIC.

1.8 Prior Studies

Four studies of Berry Brook that relate directly to this research were conducted during the Renewal Project. All these studies were conducted by graduate students at University of New Hampshire: Victor Hlas, Amy Johnson, Daniel Macadam, and Ethan Ely.

Victor Hlas examined the hydrologic and water quality changes caused by the stream restoration efforts and GSI implementation in the first two years of the Renewal Project (2011-2012). Hlas developed a stage-discharge curve of Berry Brook at Station Drive. He also collected water quality samples and water depth data at 15-minute intervals for August to October of 2011. He collected similar data following the construction of 1,100 feet of stream channel and 13 GSI systems. Hlas found that the watershed improvements caused a significant decrease in average, maximum, and minimum measured flows and a 46% decrease in median runoff flows. He also found that concentrations of total suspended solids (TSS), zinc (Zn), and total phosphorous (TP) were reduced by 59%, 50%, and 78% respectively by the improvements. Hlas built three PCSWMM watershed models to examine the long-term response of the watershed improvements. The three models were a pre-improvements model, a post-improvements (GSI included) model, and a model simulating the addition of GSI by considering only EIC. Over a 20-year rainfall runoff simulation, he found a total runoff volume reduction of 18% and total pollutant load reductions of TSS by 28%, TN by 15%, and TP by 7%. He did not find a noticeable difference between pre-improvements peak flows and post-improvement peak flows over the long-term simulation (Hlas, 2013).

Daniel Macadam examined the infiltration capacity of the retrofit bioretention system at the Horne Street School. He monitored the system for 45 storms to determine the real treatment efficacy of the system, which was sized to hold 0.16 inches of rain. He found that 67% of the monitored storms were completely treated by the retrofits. Most of the storms did not exceed 1.27 inches but had more rainfall than the expected capacity of the system. Macadam used a Green-Ampt approach to calculate the true capacity (effective precipitation completely managed) of the system, which he found to be the runoff from 0.52 inches of precipitation (Macadam, 2018).

Ethan Ely researched the infiltration characteristics of the two subsurface gravel filters in the Berry Brook watershed. Ely found that of the two monitored filters, one had a relatively low hydraulic conductivity of less than 0.5 inches per hour and the second had little to no infiltration capacity. He analyzed the two systems with three computer-based models and found that the unsaturated properties of soils appeared to have little effect on the total infiltration volumes because it took very little time to reach the saturated condition. He found that a unit-gradient model was the most accurate for the filters. He determined that the subsurface gravel filters could be more accurately sized if soil infiltration was accounted for in the design process (Ely, 2019).

Amy Johnson monitored Berry Brook for her work in examining the water temperature shift caused in the stream by climate change. Her work began in 2017 and concluded in 2018, therefore studying the Post-improvements watershed behavior. She collected water depth data for Station Drive at 15-minute intervals for September 2017 to May 2018.

1.9 Hypothesis and Objectives

The Berry Brook Watershed Renewal Plan provides an opportunity to closely examine the implementation of GSI on a full-scale urban watershed. The purpose of this research is to 1) determine the effects of green stormwater infrastructure on flooding in urban areas and 2) compare the effect on flooding caused by impervious cover to the effect on flooding expected by climate change.

Project Objectives:

1) Develop a SWMM model of the Berry Brook watershed before the implementation of green stormwater infrastructure (**Pre**).

2) Develop a SWMM model of the Berry Brook watershed including the implemented green stormwater infrastructure (**Post**).

3) Simulate the behavior of Berry Brook from 2001 to 2011 using local rainfall data **for the Pre model and Post model**.

4) Develop a model representing hydrologic response of the watershed prior to human development ($\mathbf{Pre_0}$) by removing all impervious cover from the calibrated Pre model.

5) Develop a model representing hydrologic response of the watershed at 15% impervious cover ($\mathbf{Pre_{15}}$) by reducing impervious cover in the calibrated Pre model uniformly to a total IC of 15%.

6) Simulate the effects of the 2-yr, 10-yr, 50-yr, and 100-yr storms on Berry Brook **for all models**.

7) Simulate the effect of climate change on rainfall intensity by increasing the 2-yr, 10-yr, 50-yr, and 100-yr storms by 15% on the Pre model ($\mathbf{Pre_{Climate}}$) and the Post model ($\mathbf{Post_{Climate}}$).

8) Determine the change in stream peak flow, time to peak flow, runoff depth, and total flow volume during extreme precipitation events caused by the implementation of GSI practice in the **Pre model and Post model**.

9) Determine the change in stream peak flow, time to peak flow, runoff depth, and total flow volume during extreme precipitation events caused by the reduction of impervious cover in the **Pre_{15} model and Pre model** as compared to the values in the **Pre_0 model**.

10) Determine the change in stream peak flow, time to peak flow, runoff depth, and total flow volume during the extreme precipitation events storms caused by the increase in rainfall intensity due to climate change in the **$Pre_{Climate}$** and **$Post_{Climate}$** scenarios as compared to the results in the **Pre_0 model**.

11) Compare the effects of changing impervious cover on the watershed response with the effects of increased rainfall intensity due to climate change.

It is expected that increasing impervious cover will cause a greater increase in flooding in urban areas than the expected increase in rainfall intensity caused by climate change. It is also expected that the use of GSI will reduce flooding in urban areas due to frequent extreme precipitation events such as the 2-year storm by decreasing peak discharge and the total volume of stream discharge (flow) by increasing water travel time and infiltration. Rare extreme precipitation events such as the 100-year storm are not expected to be significantly affected.

Chapter 2: Research Methods

2.1 Software

ArcMap is a GIS proprietary software owned by Esri. The software is designed to analyze GIS datasets such as rasters, aerial photos, and large spatial files. ArcMap is useful for creating map layouts and analyzing LiDAR elevation data. ArcMap represents geographic information as layers on a map.

SWMM is useful to plan, design, and analyze how well GSI improves runoff quality and reduces runoff quantity. It can evaluate GSI performance in individual systems and at a watershed scale. SWMM uses a subcatchment-based approach to calculate runoff generated and sent to various conveyance methods and storage areas (Jayasooriya et al., 2014). SWMM is also a freely available software supported by the EPA, making it ideal for municipalities planning watershed management.

PCSWMM is a proprietary software owned by Computation Hydraulics International (CHI) that is built off the foundation of EPA SWMM. PCSWMM has storage analysis capabilities and Sensitivity-based Radio Tuning Calibration (SRTC) that EPA SWMM does not possess. To use SRTC, the user assigns each parameter in PCSWMM a measure of uncertainty as a percentage of the total value. The SRTC tool will run up to 8 scenarios of that uncertainty with all other parameters held constant: a 100% decrease in the parameter (at the given uncertainty level), a 75% decrease, a 50% decrease, a 25% decrease, and increases in the parameter at the same values. The SRTC tool will take the results from each of these changes and use them to run a sensitivity analysis on each parameter being calibrated. The SRTC tool then calculates the mean normalized sensitivity of each parameter. Once the SRTC tool is activated, the user chooses how much they want to alter each parameter (there is an auto-calibrate function per parameter as well) and can immediately see the expected effect the change will have on the modelled watershed response and the goodness of fit to the calibrated data. When the calibrated model parameters yield output hydrology more like the observed hydrology than the other potential combinations, the user saves the data either as a scenario or by replacing the original parameters. The SRTC tool allows for the easy adjustment of models to fit the observed data. Since PCSWMM can interact perfectly with EPA SWMM files and ArcMap files, it is a powerful tool for building a calibrated model that can then be used on the free EPA SWMM software.

2.2 Model Development

The Berry Brook Watershed was modeled using PCSWMM 2019 software by Computation Hydraulics International. Three pre-improvements models (Figure 5) and one post-improvements model (Figure 6) were built. The Pre model represented the watershed prior to the use of BMPs (about 30% unmanaged impervious cover in the watershed). The Pre_0 model simulated the Berry Brook watershed before human intervention by running the Pre model conditions with no impervious cover. The Pre_{15} model represented the watershed managed using traditional stormwater practices but with only 15% impervious cover, or a less-developed watershed. The Post model represented the watershed at 10% EIC managed using the BMPs installed in the renewal project.

In addition to the four developed models to simulate LID implementation and changes in impervious cover, two additional scenarios were designated to model the impacts of climate change. The $Pre_{Climate}$ scenario denoted the traditionally managed watershed at 30% impervious cover reacting to a rainfall increase of 15%. The $Post_{Climate}$ scenario denoted the watershed at

10% EIC managed using BMPs reacting to the same rainfall increase. These scenarios were used in extreme precipitation event modeling.

Figure 4 shows the model development process. The Pre watershed was developed to simulate the Berry Brook watershed prior to BMP implementation and calibrated using streamflow data collected at that time. The calibrated Pre watershed was then updated to include the new wetland area, GSI implementation, and restored stream channel. The GSI parameters were calibrated using streamflow data collected after construction. The Pre_{15} model was developed by uniformly reducing the impervious cover in each subcatchment of the Pre model such that the total IC in the model was 15%. The model was not recalibrated, and no existing stormwater infrastructure was removed. The Pre_{15} model was used to simulate Berry Brook at a lower level of human development. The Pre_{0} model was developed by setting impervious cover in each subcatchment of the model to 0. Like the Pre_{15} model, the parameters were not recalibrated and no existing stormwater infrastructure was removed. The Pre_{0} model was used to simulate Berry Brook prior to human development. Since there is no data in Berry Brook to assist in calibrating either the Pre_{15} or the Pre_{0} models, the models were not altered beyond removing impervious cover.

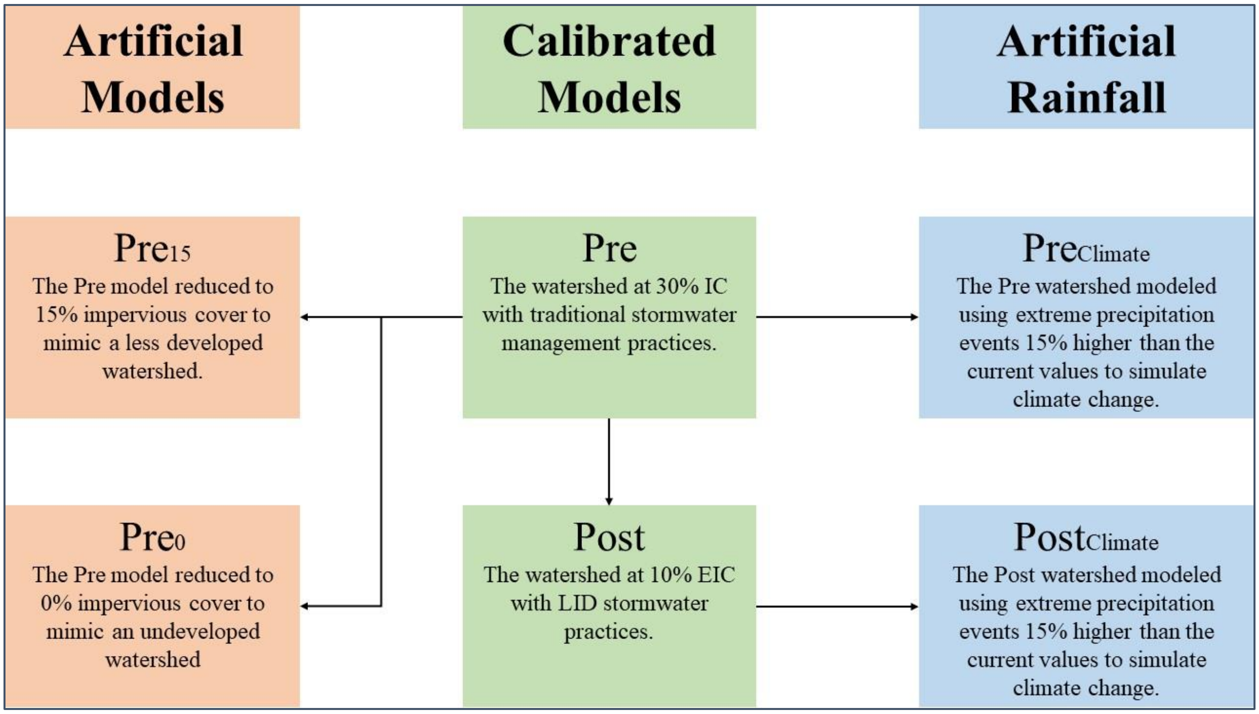

Figure 4: Developed Models for the Berry Brook Watershed

Not recalibrating the Pre_{15} or the Pre_0 models or removing the drainage infrastructure present in the 30% impervious model does impact the results achieved in those models. The models will likely see higher peak flows and faster watershed responses (time to peak flows) than would be seen in the truly undeveloped / less developed watershed.

The topography of the Berry Brook watershed is shown in Figure 5. Topography was generated using a LiDAR DEM of the Dover area conducted in 2015. Lightly shaded areas indicate areas of high elevation and dark shaded areas indicate zones of low elevation. The imprint of Berry Brook is visible running through the watershed as a dark line on the righthand middle of the drainage area. Berry Brook discharges into the Cocheco River.

Figure 5: Berry Brook Watershed Topography. Darkening shades indicate areas of lower elevation. The figure was developed using a 2015 LiDAR survey from NH Granit.

The existing storm sewer drainage for Berry Brook is shown in Figure 6. It is of interest that the black line denoting the watershed boundary shows storm sewer lines that appear to cross into and out of the watershed. At these locations a close examination will show a cut in the storm sewer or a change in pipe slope which led to the boundary being placed in this location. In the case of the watershed boundary being insufficient, however, model results would be underestimated. Since the boundary was kept constant across all models, any existing bias is held constant through the analysis.

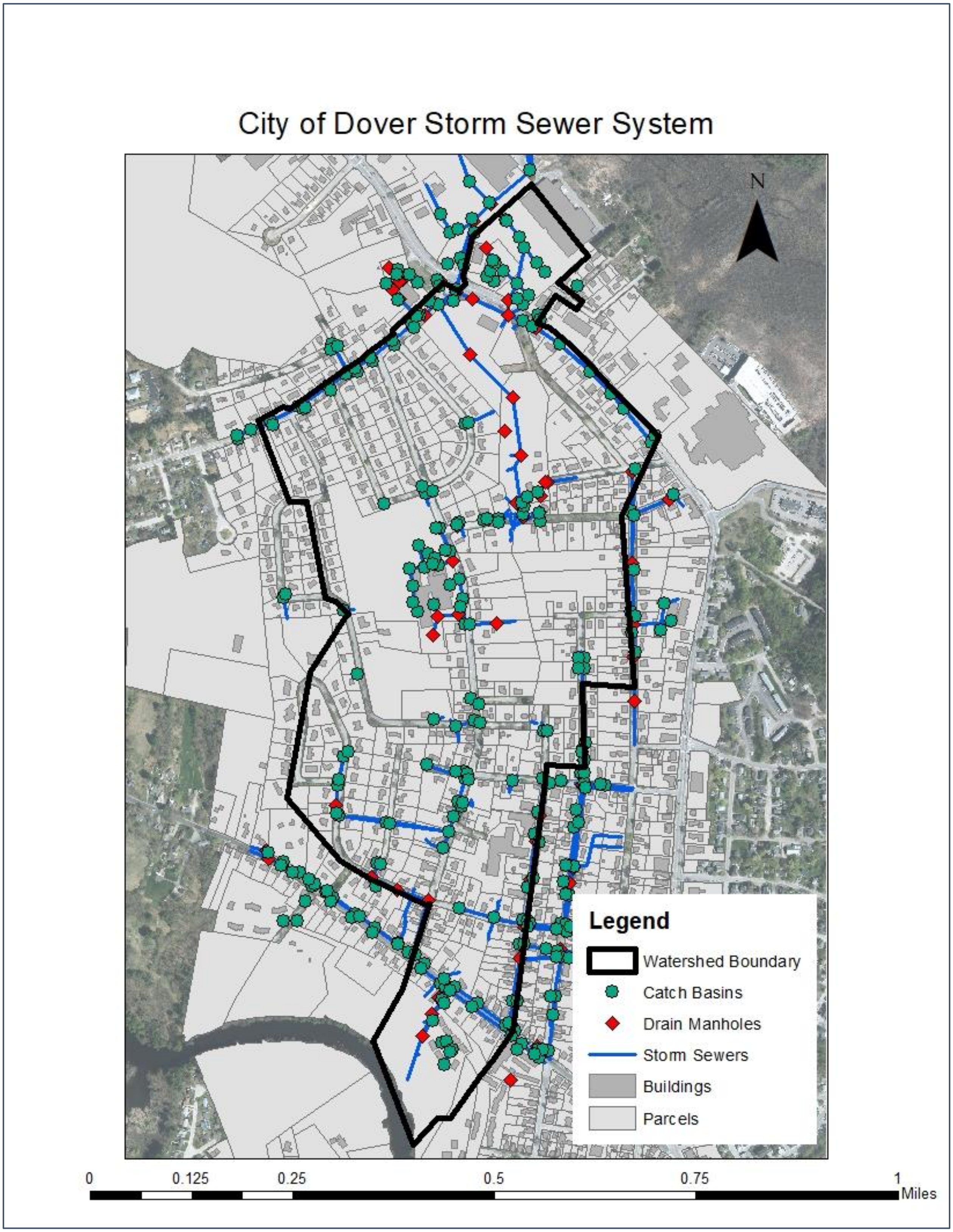

Figure 6: City of Dover Storm Sewers in Berry Brook Watershed. The image was developed using GIS files provided by the City of Dover.

Figures 7 and 8 show the developed Pre and Post models for the Berry Brook watershed. Both models were divided into the same 47 subcatchments. Subcatchments were delineated by considering the slope of the watershed (Figure 5) and the existing stormwater infrastructure (Figure 6). Starting at a key junction, subcatchments were traced perpendicular to the surface topographic contours while still following the drainage structures. In the case of watershed areas draining to GSI, the subcatchment area stated in the design plans for the GSI was used. If no construction plans were available, the GSI subcatchment was delineated like any other. GSI system locations were treated as separate watersheds. Excluding the GSI systems, subcatchments varied in size from 0.5 to 25 acres. Junction elevations were calculated as the lowest point in a subcatchment.

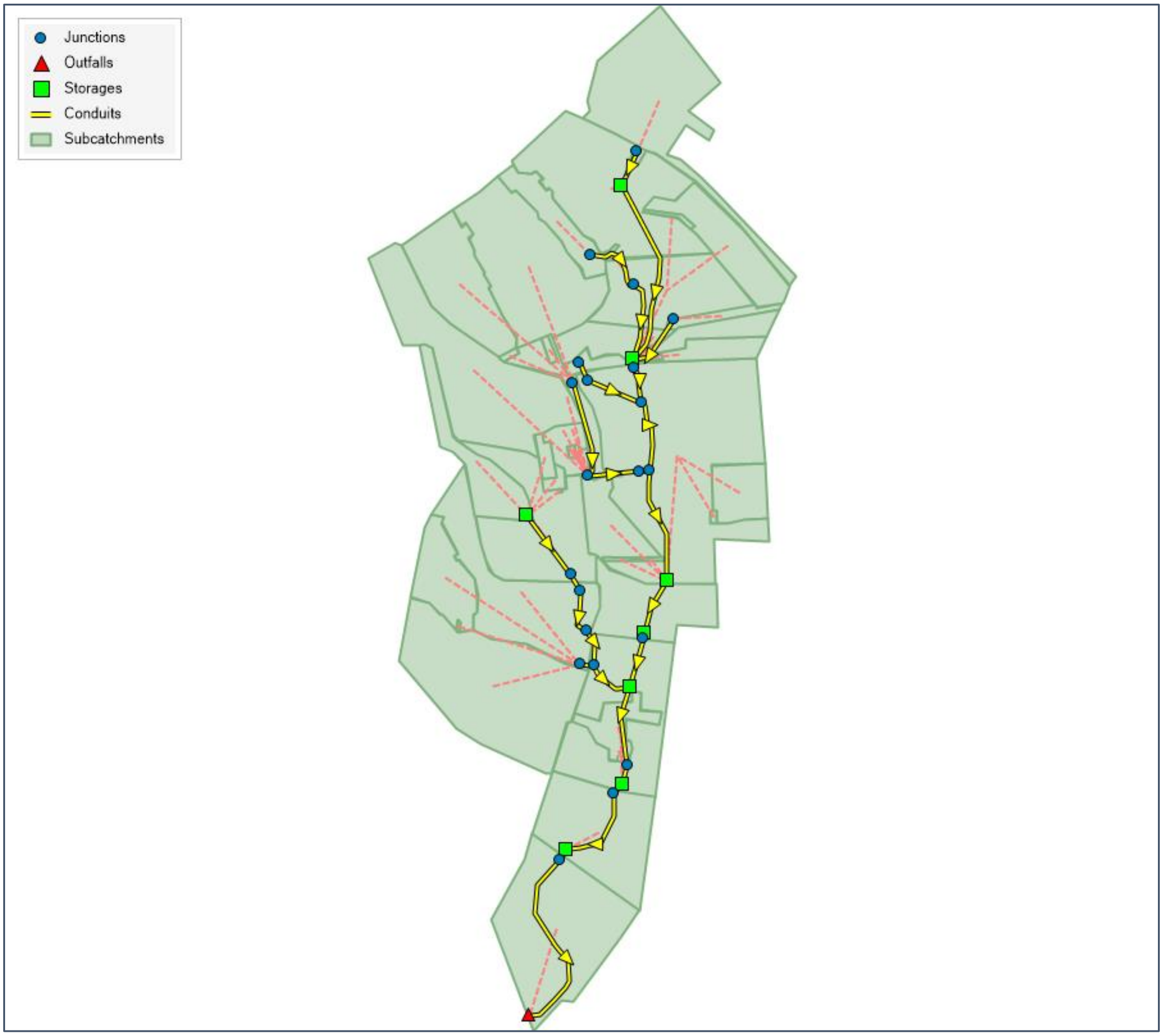

Figure 7: PCSWMM Model of Pre-improvements Watershed. The dark green lines show subcatchment boundaries. The dotted red lines indicate to where subcatchments drained. Arrows indicate the direction of flow.

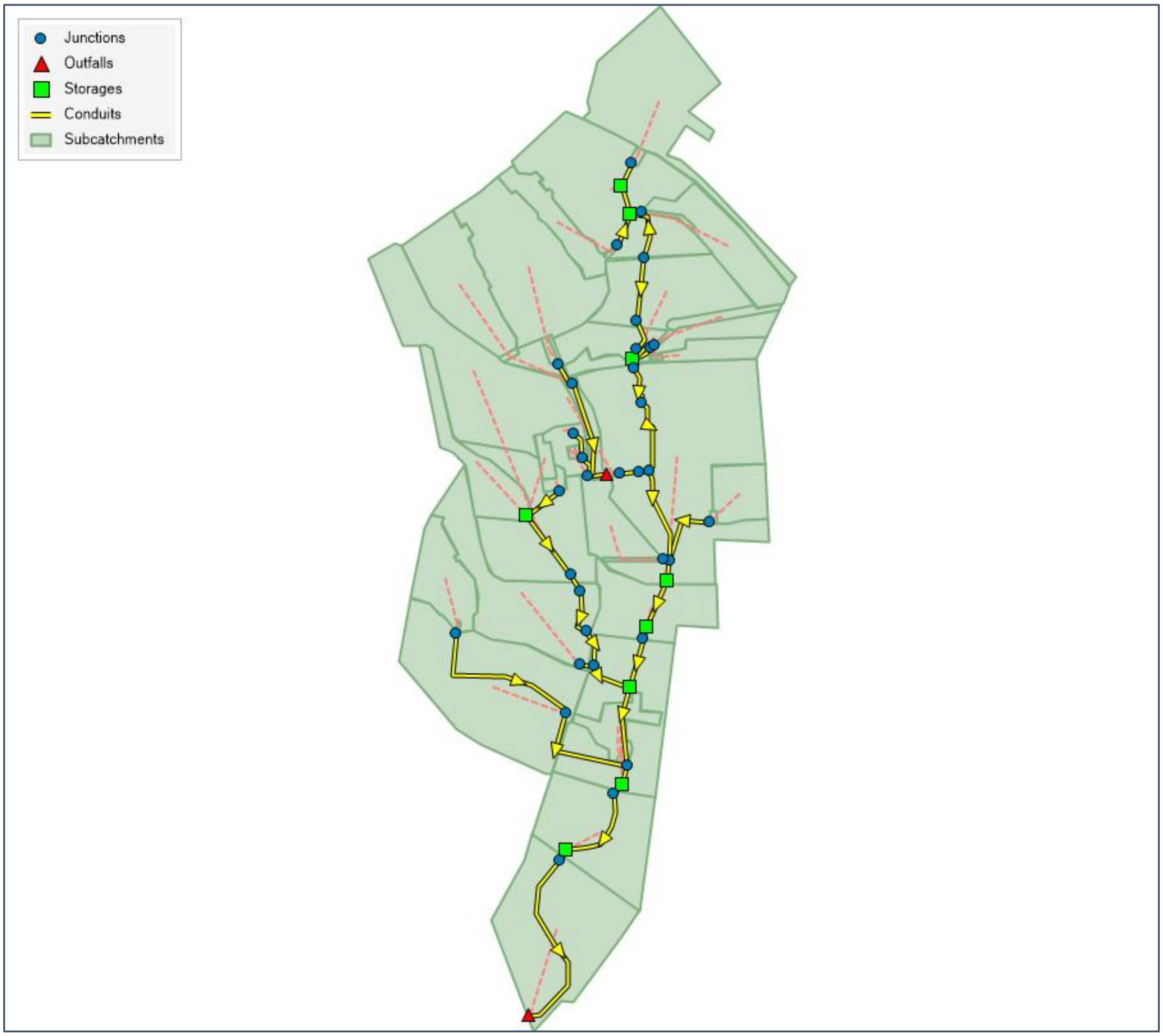

Figure 8: PCSWMM Model of Post-Improvements Watershed. The dark green lines show subcatchment boundaries. The dotted red lines indicate where subcatchments drained to. Arrows indicate the direction of flow.

Subcatchments drained to conduits, outlets, storage areas, GSIs, or other subcatchments. Where a subcatchment drained to was determined by examination of the drainage infrastructure files provided by the City of Dover (Figure 7). In the Pre models, subcatchments denoting a GSI were treated as if they were part of the subcatchment draining into the GSI in the Post model.

Subcatchments with little to no impervious surface and stormwater infrastructure were noted as draining to the local pervious surface before discharging to the outlet. Subcatchments with extensive impervious surface and well-developed stormwater infrastructure were noted as discharging directly to the outlet to simulate the collection system present on the streets. In the post model, areas noted as having extensive rooftop disconnection were also modeled as draining to pervious areas first.

Three water storage locations were noted for the watershed: a homeowner pond, the original upper watershed wetland, and the additional wetland installed for the renewal project. These 3 storage locations were supplemented using the Storage Creator tool in PCSWMM, which created storage polygons based on low places in the elevation data. Storage zones were limited to no less than 3 feet of depth and no less than 1000 ft^2 of potential storage area.

Aquifers to account for the groundwater were developed for each subcatchment Berry Brook passed through. An unfortunate limitation of SWMM and PCSWMM is that groundwater cannot pass from subcatchment to subcatchment, so the only groundwater discharge was directly into the stream from adjected subcatchments. Groundwater infiltration parameters were estimated using Web Soil Survey soil information (Figure 10)

The outfall for Berry Brook was placed at the Cocheco River at Station Drive. In the Post model, a second outfall is shown near the Horne Street School. The second outfall simulates the flow of the drainage pipe from Horne Street entering a bioretention system. The water is free standing in the systems before again being collected at the exit of the bioretention. In the Pre models, this water is transported by pipe all the way to Berry Brook.

Junctions were placed at key stormwater collection points such as GSI locations, ends of roads, outlets into Berry Brook, or areas with potential water storage as determined from the LiDAR elevation data. Some junctions had multiple catchments draining to them. Junctions were positioned in places where catch-basins were located in the City of Dover files.

Conduits were placed between junctions. Some conduits simulated closed pipes transporting water, while others simulated open stream channel. PCSWMM derives conduit slope and inlet/outlet elevations from the accompanying junctions.

Transects were taken from Victor Hlas's model of the Pre and Post-development watershed. Transects were used to depict the geometry of the natural channel. More transects were used in the Post model to show the stream restoration to an A1 – A2 channel.

GSI information was entered into the LID Control Editor in the Post model. GSIs were identified by street and type. Parameters not otherwise specified in construction drawings were left at the default values. Subcatchments were assigned to a GSI by naming it as the outlet of the system. Additional GSI information is provided in Section 2.3.

The model was run as a rainfall/runoff analysis with groundwater and flow routing. It used dynamic wave routing at 5-minute time steps. Infiltration was represented by the Green-Ampt equation. Manning's equation was used for the flow and energy loss relationship. Ponding was permitted in a subcatchment. Daily evaporation was set to the default value of 0.05 inches per day.

2.3 GSI Modeling

LID systems installed at Berry Brook included three filtering catch basins, a rain barrel program, and 17 GSI systems. PCSWMM and SWMM do not at this time have a method to model filtering catch basins. The rain barrel program was modeled as disconnected impervious cover (denoting subcatchments as draining to pervious surfaces prior to draining to the outlet). The 17 GSI systems were modeled using SWMM's LID tool.

SWMM and PCSWMM's LID tool allows the user to enter the characteristics of a GSI system including surface roughness (swales), ponding height, media thickness, storage zone thickness, surrounding soil characteristics, the presence of an underdrain, and pollutant removal characteristics. For Berry Brook, each GSI system was entered as a separate LID. The LID systems were then linked to specific subcatchments. For Berry Brook, each GSI system was modeled as a separate subcatchment, so the LID controls were linked directly to them and marked as taking up the entire subcatchment. Water from subcatchments was then directed to the LID subcatchments, at which point it would enter the LID.

LID ponding, media and storage depth were determined using design plans shown in Appendix D – GSI System Plans. If no system plan was available, then the ponding, media and storage depths were assumed to match an available plan of the same type of system. Ponding height in the systems varied from 3 inches (rain garden) to 24 inches (swale). Media depth varied from 24 inches (bioretention) to 48 inches (tree filter). The crushed stone storage depth varied from 24 inches (bioretention) to 48 inches (subsurface gravel filter).

Media infiltration parameters were initially estimated to match the Type A sand soil parameters listed in Table 3. Seepage rate under the storage layer matched the infiltration rate of the local soils as shown in Figure 10. Underdrains were not included unless specifically shown in the system plans.

While the LID editor tool can simulate pollutant removals, that was not the focus of this research and no data was available to calibrate it.

2.4 Parameter Estimation

Berry Brook Watershed is in Dover, NH. It consists of 185 acres, of which 55 (30%) are classified as impervious cover according to GIS analysis. Berry Brook is a 1.2-mile first order stream with an average slope of 1.5% that discharges into the Cocheco River (Hlas, 2013). Dover's climate it typical of New England with an annual precipitation of 47 inches and typical temperatures of 18 ^{o}F to 81^{o}F.

A minimum of 28 parameters were estimated in the PCSWMM models: 8 subcatchment parameters, 3 infiltration parameters, 5 groundwater parameters, 4 conduit parameters, 1 junction parameter, 6 storage parameters, and 1 outlet parameter (Table 2). The initial values of parameters were estimated from GIS data, literature, prior study, or defaults set in the software. Of the 28 parameters, 11 were calibrated using the observed hydrologic data. The final parameter values are shown in Appendix B – Model Hydrology.

Table 2: Parameters Used in PCSWMM Model

Variable	Variable Description	Initial Value	Calibrated
Subcatchments			
Area	Area of subcatchment	GIS	No
Width	Width of overland flow path	GIS	Yes
Imper	Percent of impervious area	GIS	No
Slope	Average surface slope	LiDAR	No
n Imperv	Manning's n for impervious area	Literature	Yes
n Perv	Manning's n for pervious area	Literature	Yes

Variable	Variable Description	Initial Value	Calibrated
Dstore Imperv	Depth of depression storage on impervious area	Default	Yes
Dstore Perv	Depth of depression storage on pervious area	Default	Yes
Infiltration: Green-Ampt			
Suction head	Soil capillary suction head	Literature	Yes
Conductivity	Soil saturated hydraulic conductivity	Literature	Yes
Initial Deficit	Initial soil moisture deficit	Literature	Yes
Groundwater Formula	$Q_{GW} = A1(H_{GW} - H)^{B1} - A2(H_{SW} - H)^{B2} + A3(H_{GW} H_{SW})$		
Surface Elevation	Elevation of ground surface for the subcatchment	LiDAR	No
GW Flow Coeff.	Value of A1 in the groundwater flow formula	Default	No
GW Flow Expon.	Value of B1 in the groundwater flow formula	Default	No
SW Flow Expon.	Value of A2 in the groundwater flow formula	Default	No
SW Flow Coeff.	Value of B2 in the groundwater flow formula	Default	No
Conduits			
Length	Conduit length	GIS	Yes
Roughness	Manning's roughness coefficient	Literature	Yes
Geom1	First geometric dimension of the conduits cross-sectional shape	Prior Study	No
Cross-Section	Cross-section of irregular shape conduits	Prior Study	No
Junctions			
Invert Elev.	Elevation of junction's invert	LiDAR	No
Storages			
Invert Elev.	Elevation of the bottom of the storage unit	LiDAR	No
Depth	Maximum depth of the storage unit	LiDAR	No
Initial Depth	Initial depth of the storage unit	Default	No
Coefficient	A-value in expression Area = A*Depth^B+C for Depth in ft	Prior Study	No

Variable	Variable Description	Initial Value	Calibrated
Constant	C-value in expression Area = A*Depth^B+C for Depth in ft	Prior Study	No
Baseline	Base line value in direct inflow	Hydrologic Observation	Yes
Outfalls			
Invert Elev.	Elevation of outfall's invert	LiDAR	No

Subcatchment width, which PCSWMM uses to calculate the time of concentration in a subcatchment, was estimated in ArcMap by measuring the distance from the subcatchment outlet to the most geographically distant point in the subcatchment. This is one potential hazard in modelling in SWMM. In reality, the time of concentration in a subcatchment depends on the most hydraulically remote point, which is not always the most geographically distant. This may allow the model to reach peak flow faster than the observed data. For this reason subcatchment width was a parameter calibrated to the observed data after the initial estimation.

Subcatchment area and conduit length were also estimated using ArcMap. Impervious cover in a subcatchment was estimated using the impervious cover data for the City of Dover available from NH Granite (Figure 9). Other values were initially estimated using the defaults present in PCSWMM.

Elevations and surface slopes were estimated using 2011 LiDAR digital elevation data available from NH Granit (Figure 6). The lighter shades in the figure depict higher elevations, and darker shades indicate lower elevations. The LiDAR image clearly shows the slope of the watershed into Berry Brook, and the slope of Berry Brook into the Cocheco river. The LiDAR digital elevation data was used to develop 5-foot contour lines in ArcMap using the Spatial Analyst toolkit, which were then used to delineate subcatchments.

Soil suction head, initial deficit, and conductivity for the Green-Ampt Equation were estimated as a spatially constant value by taking the area-weighted average values of all the soils in each subcatchment (Figure 10) as determined by soil texture class (Tables 3 and 4). The infiltration parameters were then calibrated using the hydrologic observations.

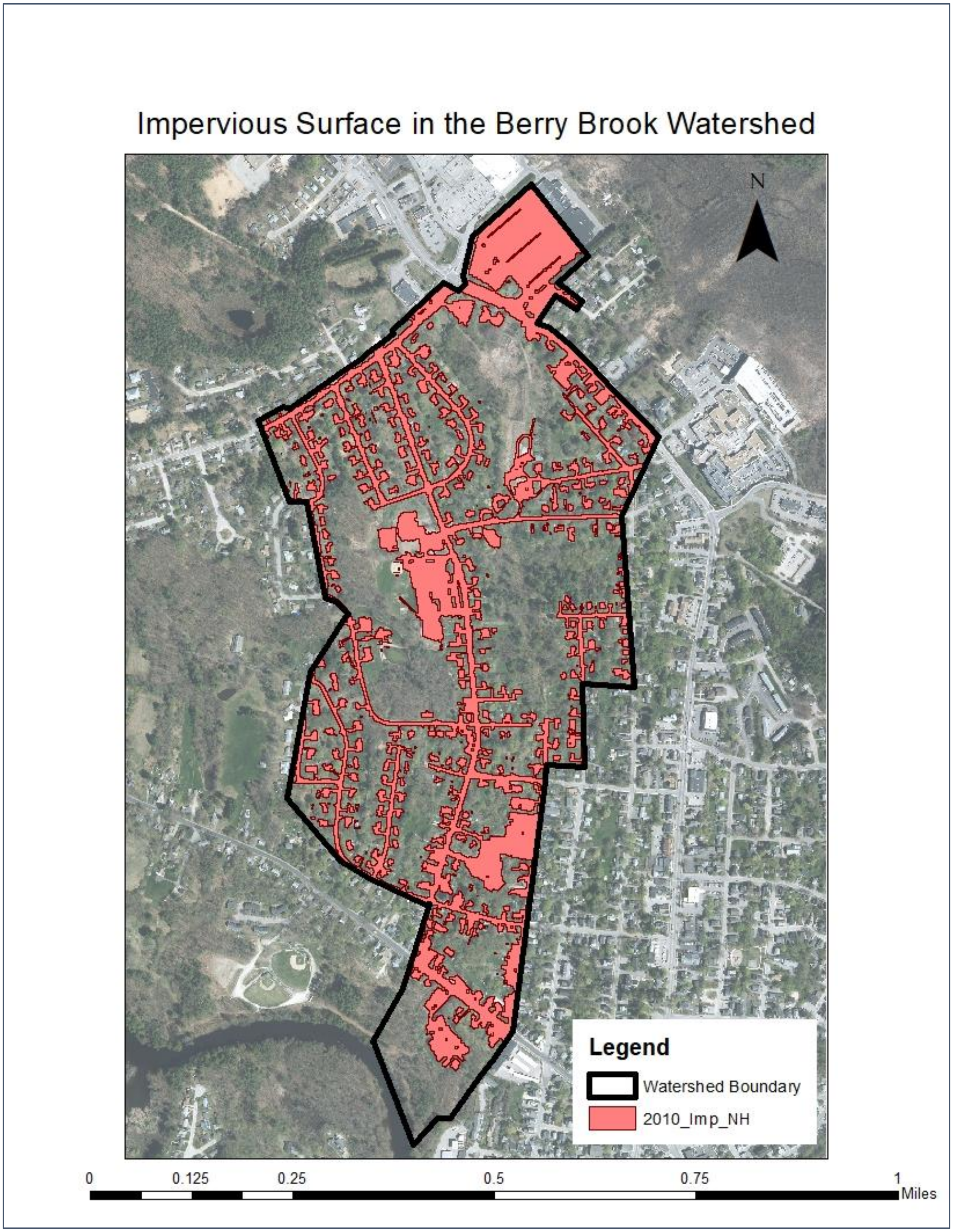

Figure 9: Impervious Surface in the Berry Brook Watershed. Impervious cover information was developed from 2010 survey data from NH Granit.

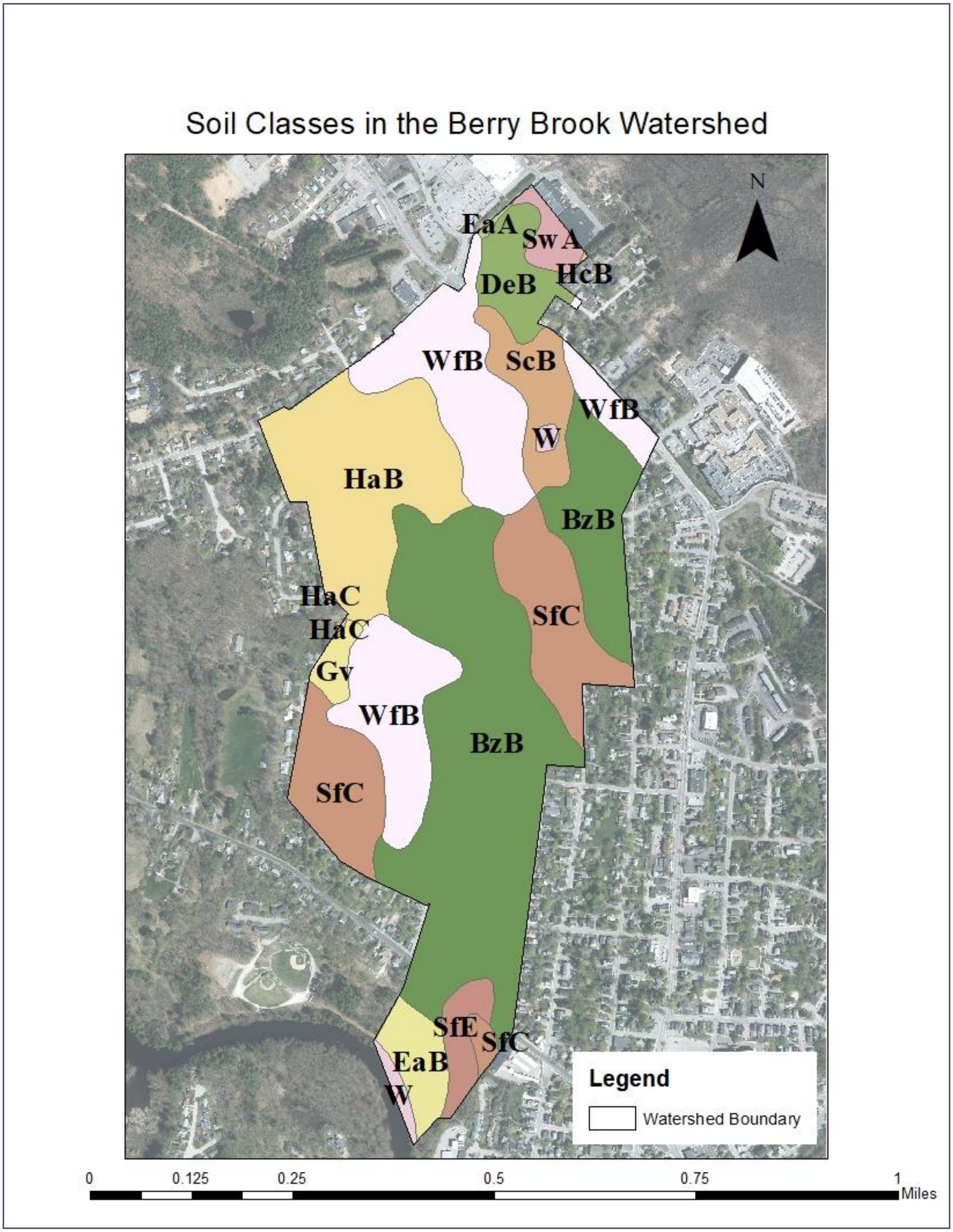

Figure 10: Soil Texture Classes in the Berry Brook Watershed. Soil map developed using Web Soil Survey data for the City of Dover.

Table 3: Soil Texture Classes in the Berry Brook Watershed

Map Name	Soil Type	Soil Texture Class	HSG
BzB	Buxtom silt loam, 3 to 8 percent slopes	Silt Loam	C/D
DeB	Deefield loamy fine sand, 3 to 8 percent slopes	Loamy Sand	A
EaA	Elmwood fine sandy loam, 0 to 3 percent slopes	Sandy Loam	B
EaB	Elmwood fine sandy loam, 3 to 8 percent slopes	Sandy Loam	B
Gv	Gravel and borrow pits	Sand	A
HaB	Hinckley loamy sand, 3 to 8 percent slopes	Loamy Sand	A
HaC	Hinckley loamy sand, 8 to 15 percent slopes	Loamy Sand	A
HcB	Hollis-Charlton fine sandy loams, 3 to 8 percent slopes	Sandy Loam	D
ScB	Scantic silt loam, 3 to 8 percent slopes	Silt Loam	C/D
SfC	Suffield silt loam, 8 to 15 percent slopes	Silt Loam	C
SfE	Suffield silt loam, 15 to 35 percent slopes	Sandy Loam	C
SwA	Swanto fine sandy loam, 0 to 3 percent slopes	Sandy Loam	C/D
W	Water	-	-
WfB	Windsor loamy fine sand, clay subsoil variant, 0 to 8 percent slopes	Loamy Sand	A

Table 4: Soil Characteristics by Soil Texture Class (Rawls et al., 1983)

Soil Texture Class	K	Ψ	φ	FC	WP
Sand	4.74	1.93	0.437	0.062	0.024
Loamy Sand	1.18	2.4	0.437	0.105	0.047
Sandy Loam	0.43	4.33	0.453	0.19	0.085
Loam	0.13	3.5	0.463	0.232	0.116
Silt Loam	0.26	6.69	0.501	0.284	0.135
Sandy Clay Loam	0.06	8.66	0.398	0.244	0.136
Clay Loam	0.04	8.27	0.464	0.31	0.187
Silty Clay Loam	0.04	10.63	0.471	0.342	0.21
Sandy Clay	0.02	9.45	0.43	0.321	0.221
Silty Clay	0.02	11.42	0.479	0.371	0.251
Clay	0.01	12.6	0.475	0.378	0.265

K = saturated hydraulic conductivity, in/hr

Ψ = suction hear, in.

φ = porosity, fraction

FC = field capacity, fraction

WP = wilting point, fraction

Conduit shape, location, and size was determined from the City of Dover documentation (Figure 7) and construction drawings for GSI. Conduit length was estimated using ArcMap. Conduit length was then calibrated at changes of no more than 25% of the length at a time for the stormwater system and no more than 15% at a time for Berry Brook.

2.5 Model Calibration

2.5.1 Calibration Data

Prior work in the Berry Brook Watershed included the collection of continuous depth of flow data and the development of a stage-discharge curve at Station Drive for time periods prior to and after watershed improvements. The data selected for model calibration was 6 storms in the pre-improvements period and 5 storms in the post-improvements period.

The Morse Hall weather gage located on the UNH Campus was used for hourly rainfall and daily temperature data. The Morse Hall rain gage is located 7 miles from the Berry Brook Watershed and hourly rainfall and temperature records exist going back to 1948. Because of the distance to the rainfall gage, some storms appearing in the observed flow did not appear in the modeled flow.

The calibration rainfall came from the UNH Morse Hall weather gage at 60-minute time steps. The stream discharge data for calibration had 15-minute timesteps. The model was set to deliver results at 1-minute time steps to ensure that the model time step was less than the time of concentration in the subcatchments. Unfortunately, having rainfall data at less frequent time steps means the model will dull the peaks from the rainfall. For example, a 1-inch storm that lasted an hour with varying rainfall intensity will be shown as 1-inch split evenly over the hour. This caused a slightly different response in the watershed than the same storm shown at smaller intervals.

The stage-discharge curve used to determine flow during the calibration period had no data points for flows higher than 15 cubic feet per second (cfs). For this reason, the model was calibrated only to storms with peaks smaller than 15 cfs.

All calibrated parameters were within PCSWMM’s range of acceptable values. The model was calibrated until the runoff, groundwater, and flow routing continuity error was less than 1%.

2.5.2 Pre-improvements Model Calibration

The Pre model was calibrated from Victor Hlas's data collected in 2011 at the Station Drive monitoring location. The baseflow was calibrated based over the 3-month monitoring period (Figure 11), and the peak flows were calibrated from 6 storms of varying length and intensity (Table 5). Base flow was treated as a constant value, which made it such that the modeled baseflow sometimes exceeded the observed baseflow and sometimes fell short of the observed baseflow. Key calibration parameters included conduit length, conduit roughness, baseline flow, subcatchment width, and Manning's n for the impervious surfaces. The goodness-of-fit was measured using the Integral Square Error (ISE). The model parameters were adjusted to minimize the ISE and maximize the ISE rating. The calibrated Pre model achieved an ISE rating of Good to Excellent for individual storms and an overall rating of Fair for the overall modelling of maximum flow (Figure 12). The baseflow was calibrated to 0.75 cfs. The calibrated model parameters are shown in Appendix B – Model Hydrology.

Table 5: Summary of Calibration Storms for Pre-improvements Model

Date	Rainfall (in)	Duration (hr)	Maximum Flow (cfs)		Total Flow (ft³)		Runoff Depth (in)		Model Fit	
			Observed	Modeled	Observed	Modeled	Observed	Modeled	ISE	Rating
7/13/2011	0.34	18.75	5.23	8.39	77,330	99,460	0.10	0.13	7.63	Good
7/29/11	0.23	38.33	2.97	3.07	143,400	132,300	0.18	0.17	2.33	Excellent
8/27/11	2.25	44.42	15	14.6	462,700	572,300	0.58	0.72	5.29	Very Good
9/6/2011	1.11	32.08	7.59	11.5	220,200	301,100	0.28	0.38	7.18	Good
9/23/11	0.66	31.58	7.55	8.94	179,700	220,100	0.23	0.28	4.14	Very Good
9/29/2011	0.6	33.08	15	11.4	299,700	210,700	0.38	0.27	7.54	Good

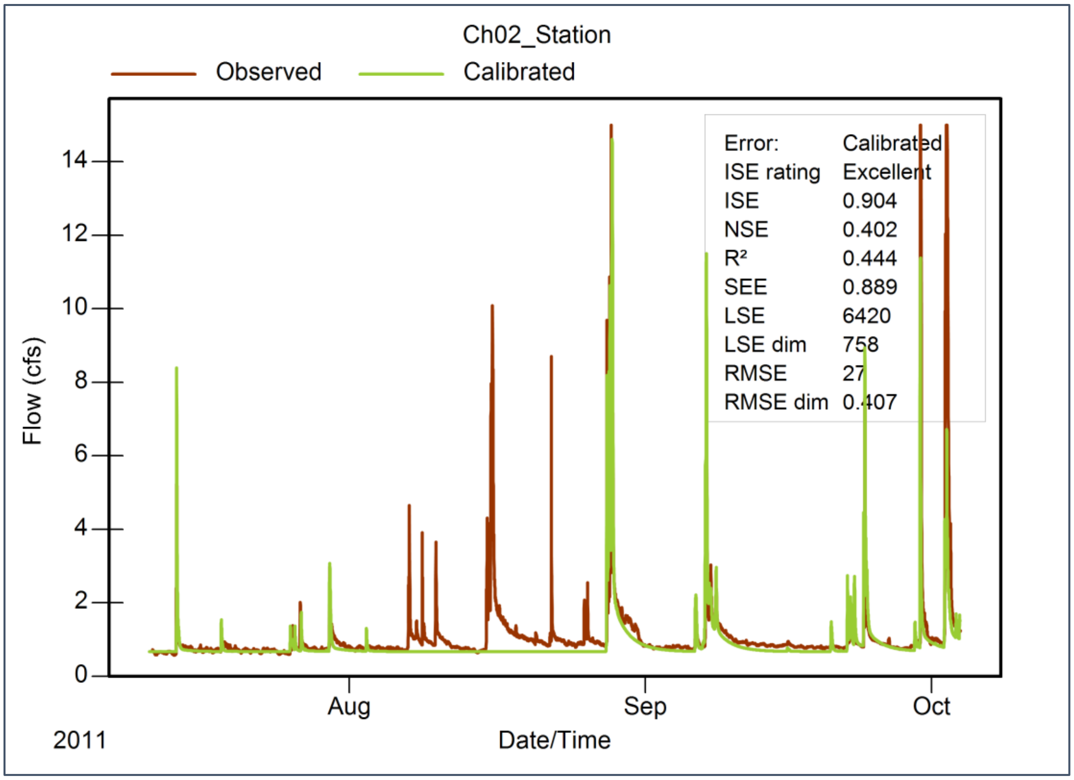

Figure 11: Pre-improvements calibration run for full monitoring period

It should be noted that there are storms that appear on the calibration set that do not appear in the calibrated model. This indicates that there was rainfall in Durham at the gage, but not in the Berry Brook watershed.

The calibrated peak flows for the 6 considered storm events are shown in Figure 12 and 13. The figures show that the model underpredicts the observed flows in some areas and overpredicts in others. Some of this error may be attributed to differences in precipitation between the Berry Brook watershed and the Morse Hall rain gage. Overall, the model is predicting reasonably well with an ISE of 11.9.

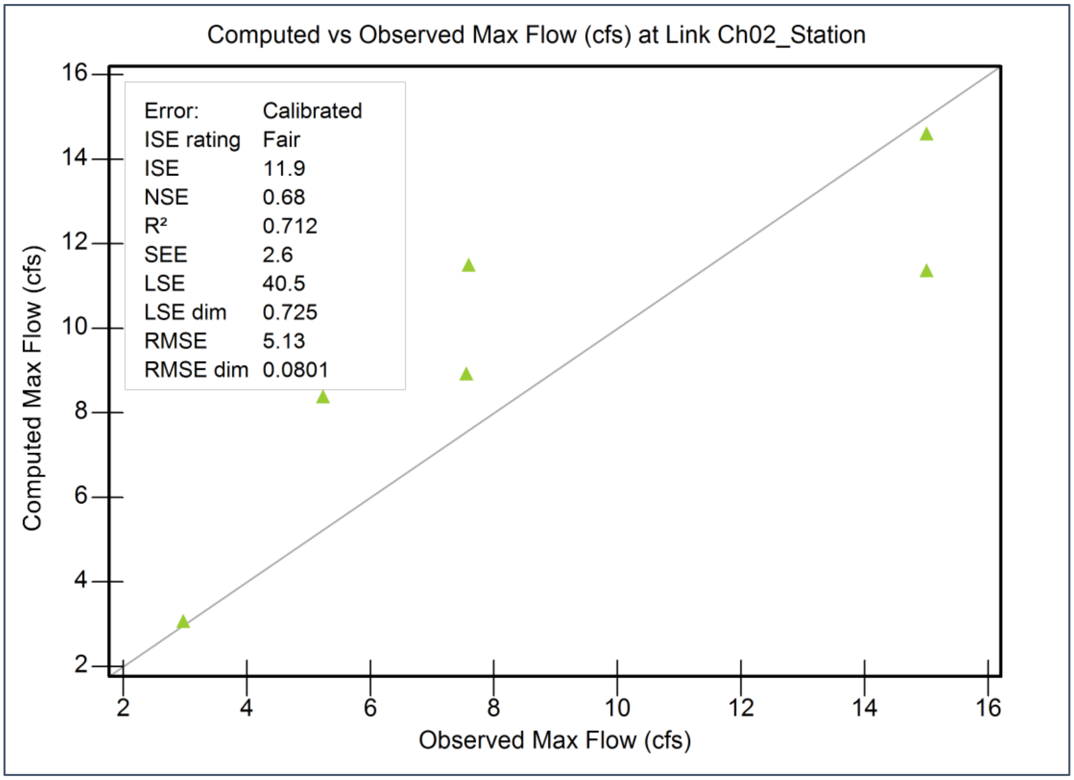

Figure 12: Pre model calibration storms evaluated for peak flow prediction

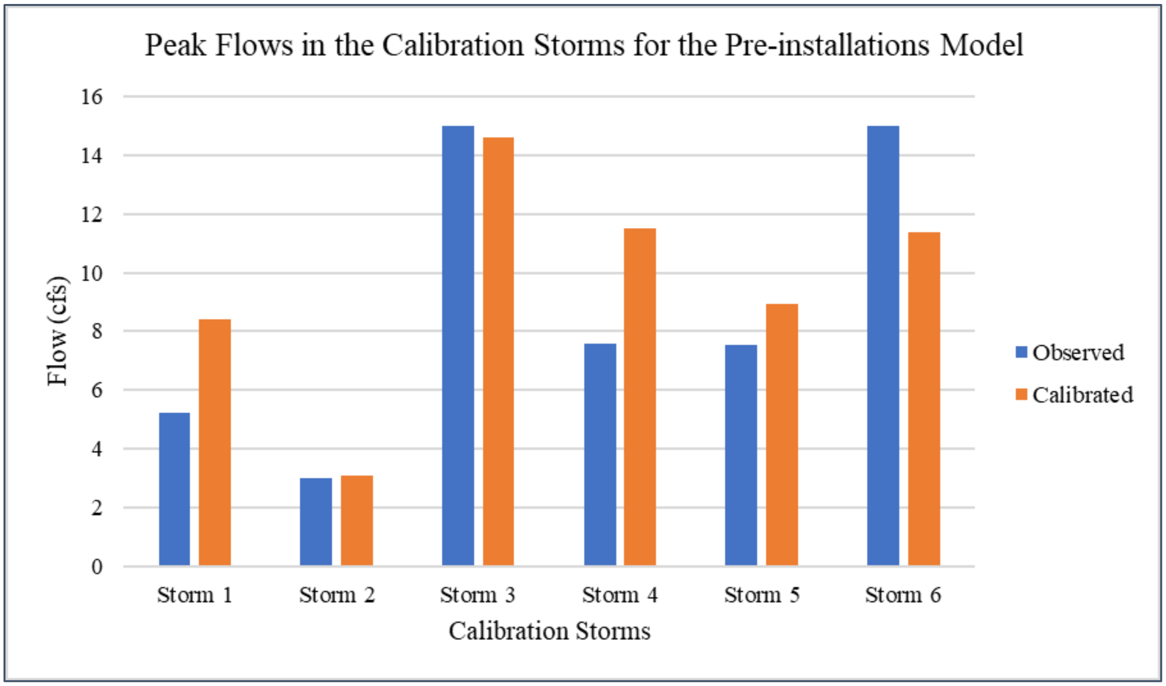

Figure 13: Observed and modeled peak flows in the Pre model calibration storms. Storms are numbered in chronological order.

The calibrated total flows (cubic feet) for the 6 considered storm events are shown in Figure 14. The figure shows that the model again underpredicts the observed total flows in some areas and overpredicts in others.

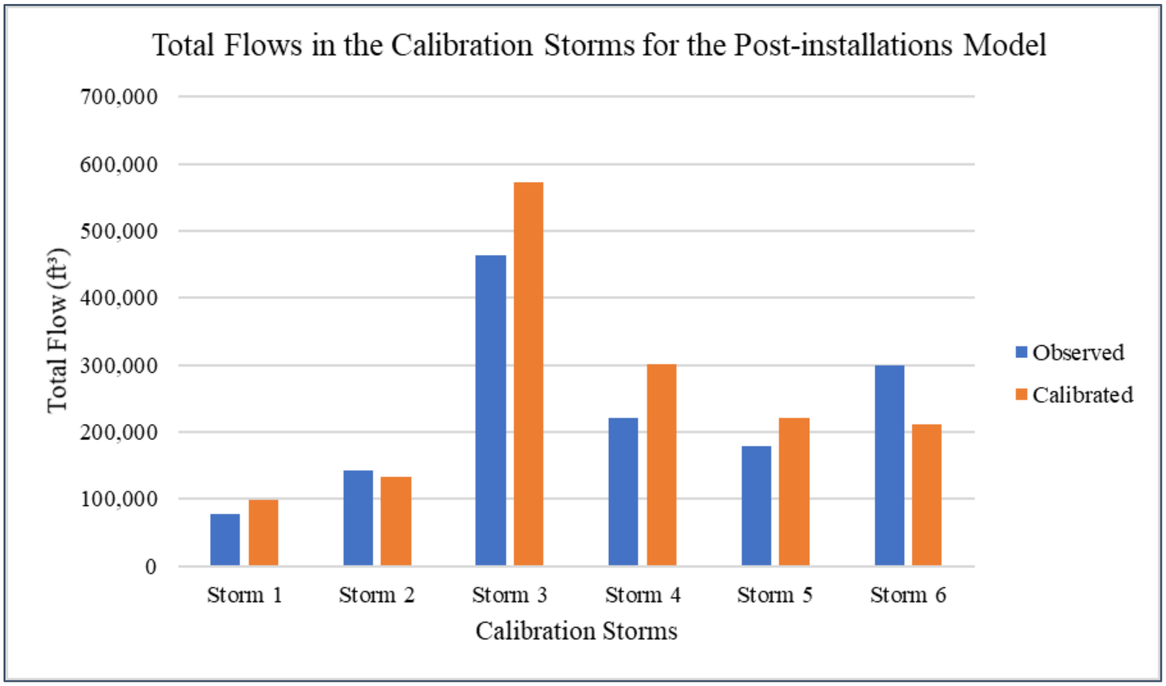

Figure 14: Observed and modeled total flow in the Pre model calibration storms. Storms are numbered in chronological order.

2.5.3 Post-Improvements Model Calibration

The Post model was calibrated using individual storms from Amy Johnson's data collected in 2017 and 2018. The added GSI systems, additional wetland area, and altered stream channel were the only parameters altered in the Post model calibration. All other parameters (subcatchment width, infiltration, conduit roughness, etc.) were kept the same as in the Pre model. This was done because the actual hydrology of the watershed was not altered between Pre and Post except for already mentioned changes.

The addition of the LID controls, new wetland, and restored stream channel did not yield results similar to the observed flow. This was likely due to two factors. First, SWMM does not model side wall infiltration out of LID systems – only vertical infiltration through the bottom. This causes SWMM to underpredict the amount of infiltrated water. Solutions to this are to increase the infiltration rate in the LID control by 30 to 50 percent (Macadam, 2018) or to add an artificial underdrain to the LID control to force extra drainage (Alegria Silveira, 2020). Second, the model was underestimating the amount of water disconnected from the direct drainage system by the rain barrel program, efforts toward disconnection, or a lack of drainage infrastructure in an area marked as draining directly to an outlet. This could be corrected for by adjusting the subcatchments with rain barrels or limited drainage infrastructure to pervious routing, or water flow to pervious areas before it reached the outlet.

Three calibration scenarios were evaluated for the Post model. First, adding the LID controls only. Second, adding the LID controls and the pervious routing to subcatchments with large amounts of disconnected area. Third, adding LID controls with the infiltration rate increased by 50% and the additional pervious routing. The goodness-of-fit for each scenario was measured using the Integral Square Error (ISE). The model parameters were adjusted to minimize the ISE and maximize the ISE rating. It was found that the third scenario, LID controls with increased infiltration and pervious subcatchments best fit the observed data.

The best model fit (LID, Increase Infiltration, Pervious Routing) is shown with the observed stream data in Table 6. The calibrated Post model achieved an ISE rating of Fair to Very Good for individual storms and an overall rating of Fair for the overall modelling of maximum flow (Figure 15). The calibrated model parameters are shown in Appendix B – Model Hydrology.

Table 6: Summary of Calibration Storms for Post-improvements Model

Date	Rainfall (in)	Duration (hr)	Maximum Flow (cfs)		Total Flow (ft³)		Runoff Depth (in)		Model Fit	
			Observed	Modeled	Observed	Modeled	Observed	Modeled	ISE	Rating
9/3/2017	0.4	4.33	8	5	55,670	46,480	0.07	0.06	9.01	Good
9/6/2017	0.87	25.92	15	13	202,000	200,600	0.25	0.25	5.23	Very Good
9/15/2017	0.71	7.75	9	10	67,100	70,420	0.08	0.09	20.2	Fair
2/4/2018	0.52	20.17	3.4	2.5	36,180	45,900	0.05	0.06	7.15	Good
4/16/2018	0.66	10.67	10	11	80,130	164,600	0.10	0.21	11.8	Fair

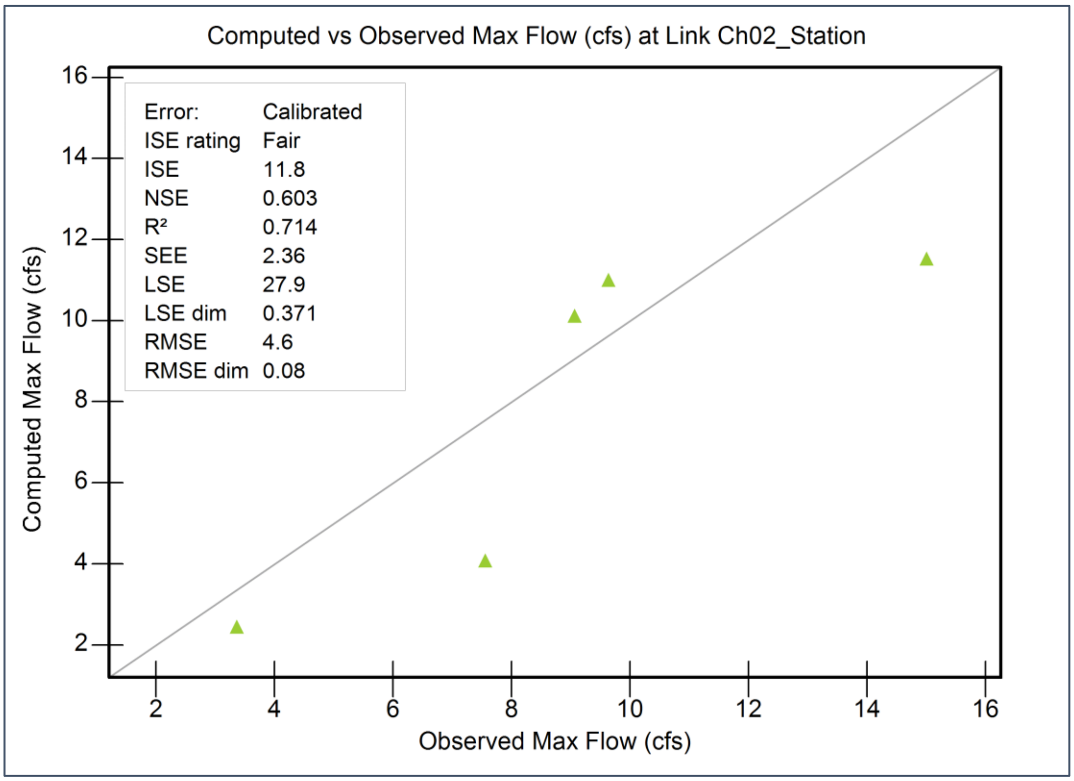

Figure 15: Post model calibration storms evaluated for peak flow prediction

The calibrated peak flows (Figure 16) and total flows (Figure 17) for the 5 considered storm events show the model had acceptable success. The model is predicting fairly well the observed values from Berry Brook with one exception: total flow in calibration storm 5. This could be due to variation in the rainfall between Berry Brook and the rain gage. In the whole, the model predicted reasonably well with an ISE rating of 11.8.

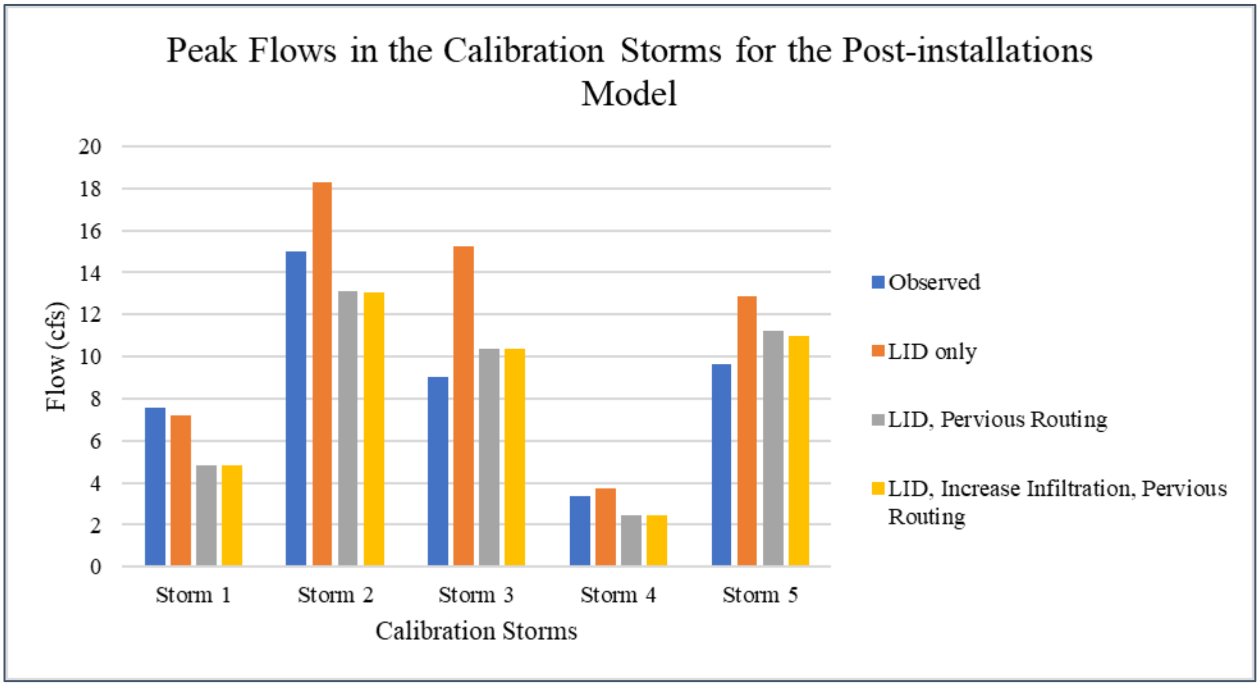

Figure 16: Observed and modeled peak flow in the Post model calibration storms. Storms are numbered in chronological order.

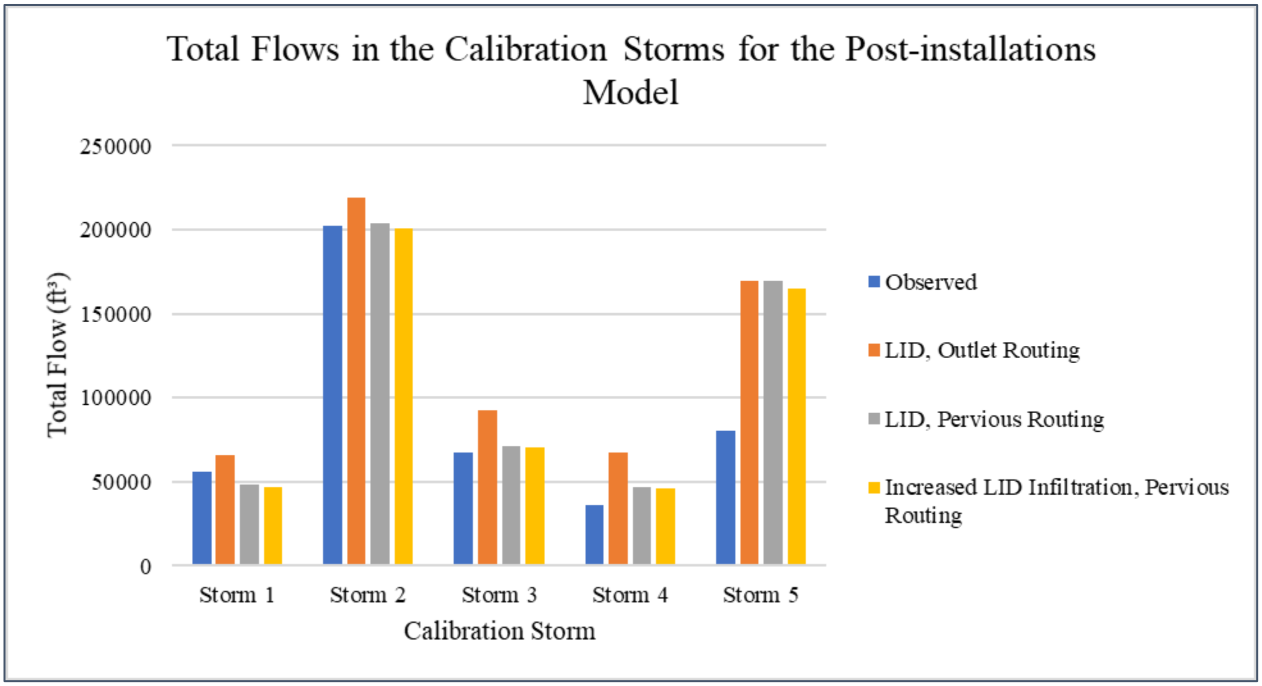

Figure 17: Observed and modeled total flow in the Post model calibration storms. Storms are numbered in chronological order.

2.6 Model Runs

2.6.1 Rainfall Data

The effectiveness of GSI at controlling floods during extreme rainfall events and the impact of increasing or decreasing IC on flooding were evaluated using Atlas 14 extreme precipitation estimates for the 2-yr, 10-yr, 50-yr, and 100-yr events (Table 7). The models were evaluated for a short storm (1 hour) and a long storm (24 hours) to study the efficacy of GSI to control short-term flooding and long-term flooding. In the 1-hour storms, precipitation varied from 0.98 inches to 2.28 inches. In the 24-hour storms, precipitation from 3.23 inches to 8.27 inches, a more than 300% increase from the 1-hour storm.

Table 7: NOAA Atlas 14 Precipitation Data for Berry Brook Watershed

Storm Duration	2-yr	10-yr	50-yr	100-yr
1 hr	0.98	1.49	2.04	2.28
24 hr	3.23	5.18	7.29	8.27

The effects of climate change were simulated using the New Hampshire guidance of increasing the extreme precipitation estimates by 15% (Table 8). In the 1-hour storms, precipitation varied from 1.13 inches to 2.63 inches. In the 24-hour storms, precipitation varied from 3.71 inches to 9.51 inches. It should be noted that adjusting the extreme precipitation by 15% is in effect shifting the extreme precipitation estimates to left (Figure 18). What is currently a 50-year storm is becoming a 28-year storm, and what is going to be a 5-year storm is right now a 22-year storm. While this method grasps the increase in rainfall intensity, it does not include any other changes in the hydrologic cycle that may result from climate change.

Table 8: Extreme Precipitation Data Adjusted for Climate Change

Storm Duration	2-yr	10-yr	50-yr	100-yr
1 hr	1.13	1.71	2.34	2.63
24 hr	3.71	5.95	8.38	9.51

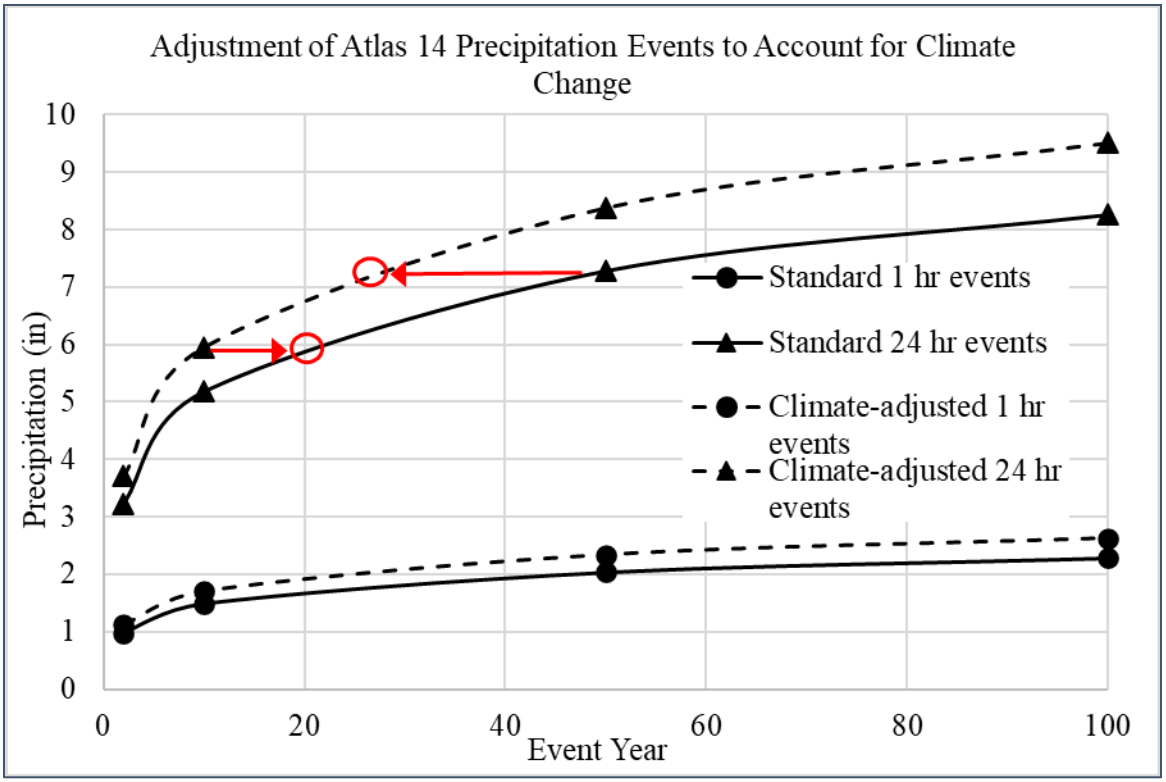

Figure 18: Effect of adjusting Atlas 14 precipitation events to account for climate change

2.6.2 Extreme Precipitation Event Modeling

The extreme precipitation events were modeled using artificial storms to turn the total rainfall into a distributed storm. The events were broken into the smallest intervals available to better determine the peak flows for each storm.

The 1-hour storms were modeled at 5-minute rainfall intensity intervals using the Huff Quartile II rainfall distribution (Figure 19). This distribution was chosen for its close resemblance to the SCS Type II distribution recommended by the Natural Resource Conservation Service for use in New Hampshire.

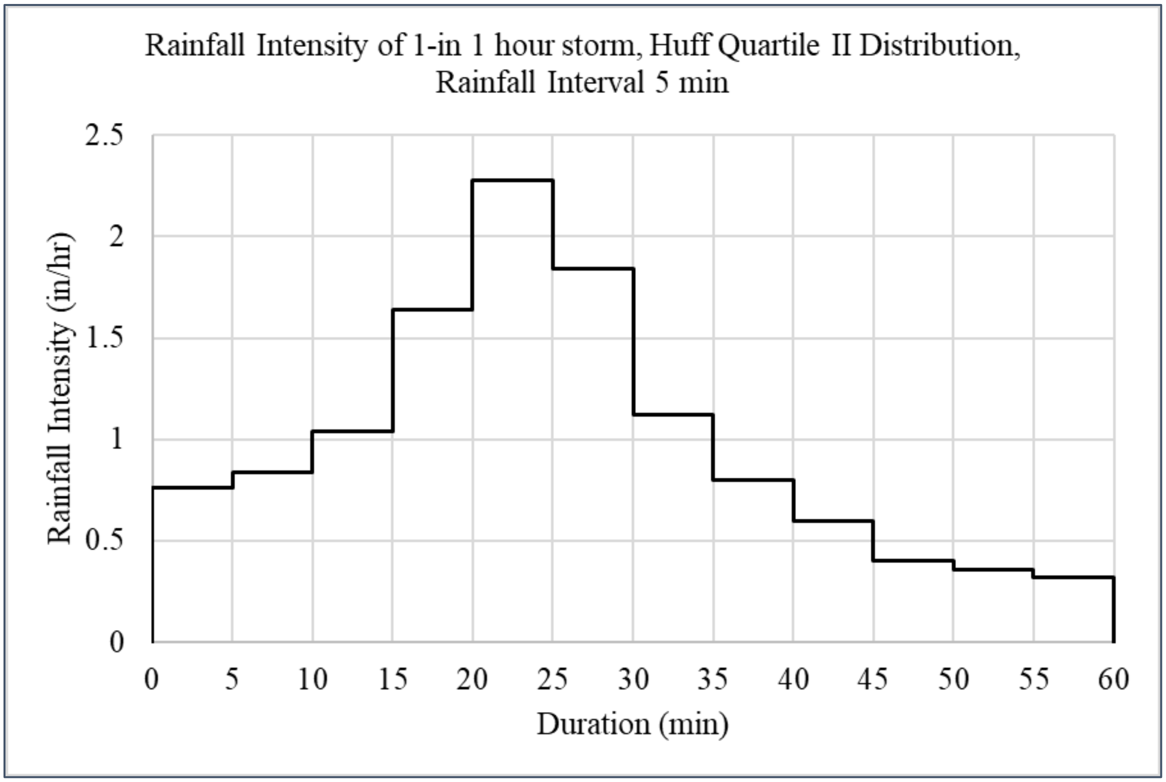

Figure 19: Rainfall intervals for the 1-inch 1 hour storm

The 24-hour storms were modeled at 6-minute intervals using the SCS Type II rainfall distribution (Figure 20). The SCS Type II distribution is recommended for use in seacoast New Hampshire. The very small intervals allow for the simulation of a constantly changing storm.

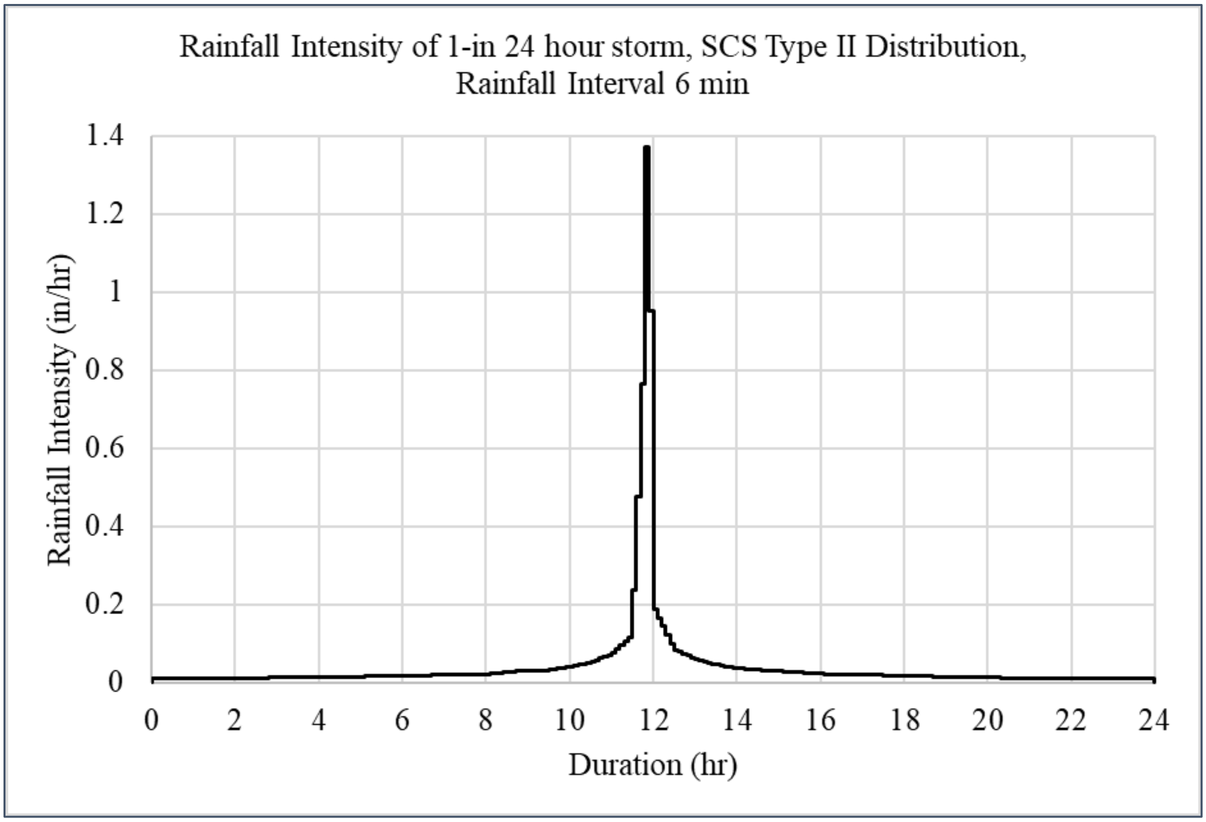

Figure 20: Rainfall intervals for the 1-inch 24 hour storm

<u>2.6.3 Long-Term Modeling</u>

The Pre and Post models were run using the UNH 10-year hourly rainfall record from 10/1/1999 to 10/1/2010, or for water years 2000 to 2010. Figure 21 shows the daily rainfall for the long-term analysis. The full dataset consisted of hourly rainfall, which allows a finer rainfall-runoff response. The largest storm modeled was about 5.33 inches of rain in April of 2007.

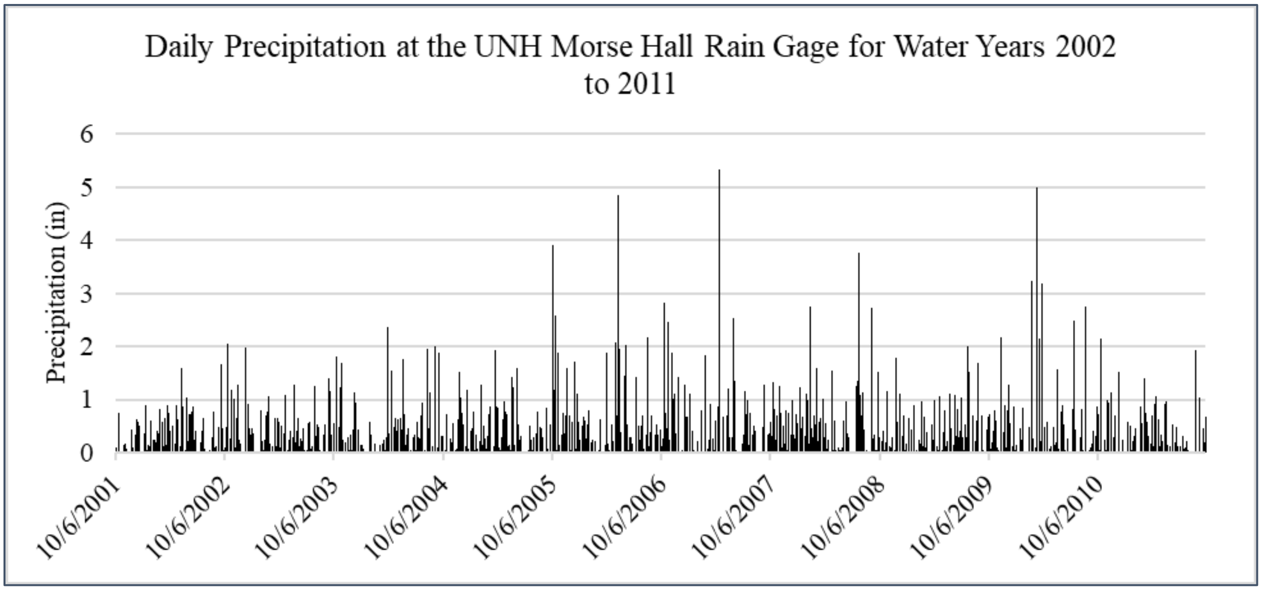

Figure 21: Rainfall for the long-term analysis. The full dataset consisted of hourly data.

2.7 Watershed Response Analysis

2.7.1 Time of Concentration

Time of concentration is not a variable directly calculated by PCSWMM. For this reason, the time of concentration for each model was estimated using the NRCS relationship between lag and the time of concentration.

$$Time\ of\ Concentration = \frac{Lag\ Time}{0.6}$$

where

$$Lag\ Time = Time\ to\ Peak\ Flow - \frac{Period\ of\ Runoff\ Generating\ Rain}{2}$$

The time of concentration was estimated by simulating a 10-minute storm of runoff-generating constant intensity in the watershed. The simulation was run at a reporting time step of 1 minute with a calculation time step of 30 seconds. The time of concentration was calculated from the time to peak and storm duration (Table 9). Time of concentration was checked to ensure the models were reflecting an increased time of concentration caused by a lower hydraulic efficiency resulting from the addition of GSI or the reduction in IC.

Table 9: Time of Concentration for Each Model

Model	Pre	Pre15	Pre0	Post
Duration of Excess Rainfall (min)	10	10	10	10
Time to Peak (min)	21	30	36	26
Lag (min)	16	25	31	21
Time of Concentration (min)	27	42	52	35

The modeled time of concentration was 27 minutes for the Pre model, 42 minutes for the Pre_{15} model, 52 minutes for the Pre_0 model, and 35 minutes for the Post model. These results show that a decrease in impervious cover or BMP implementation will decrease the hydraulic efficiency of the collection system as it is currently modeled. It also shows that adding 30% impervious cover to a watershed cuts the time of concentration in the watershed by about 50%.

2.7.2 BMP Implementation

The impact of BMPs, particularly GSI, that reduced the EIC to 10% in Berry Brook on urban flooding was quantified by running rainfall-response analysis on the Pre model and Post model for Atlas 14 extreme precipitation events shown in Table 8. The peak flows, time to peak flow, total flow volume, and runoff depth for each storm were recorded. The magnitude of change in each parameter and the percent change in peak flow, total flow, and runoff depth for each storm from the Pre model to the Post model was calculated. The median percent change was then calculated per storm event and for all model events.

To remove any bias caused by the decrease in baseflow in the model between the Pre and Post scenarios, baseflow for the simulation was calculated by running each model without rainfall for the duration of each simulation. The calculated baseflow peak discharge and total flow volume were then subtracted from each calculated storm value before analysis.

Percent change was calculated as:

$$\%\,Change = 100 * \frac{Peak\ Flow\ (X) - Peak\ Flow\ (Y)}{Peak\ Flow\ (X)}$$

The long-term effectiveness of BMPs to reduce urban flooding was also assessed. The rainfall-runoff relationship was simulated from October 01, 2001 to October 1, 2011 for the Pre model and the Post model. No snowmelt was included. For water years 2002 to 2011, the minimum, average, and maximum annual flows were calculated. The percent change in the annual maximum flow values per water year from Pre to Post was computed. The total infiltration and runoff depth in Berry Brook over the 10-year period was also computed. Finally, a frequency duration curve (FDC) was developed from the average daily flow data for both models.

<u>2.7.3 Impervious Cover Analysis</u>

The impact of impervious cover on urban flooding was quantified by running rainfall-response analysis on the Pre model, Pre_{15} model, and the Pre_0 model for Atlas 14 extreme precipitation events shown in Table 7. The peak flows, time to peak flow, total flow volume, and runoff depth for each storm were recorded. The magnitude of change and percent change in values of the Pre and Pre_{15} models for each storm were calculated with respect to the Pre_0 , or simulated undeveloped watershed. Baseflow was removed and percent change was calculated as shown in section 2.6.2.

2.7.4 Climate Change Analysis

The impact of climate change on urban flooding was quantified by running rainfall-response analysis on the Pre and Post models for the climate-adjusted extreme precipitation events shown in Table 8. The model responses from the Pre watershed using the rainfall for climate change were denoted as $Pre_{Climate}$ while responses from the Post watershed were denoted as $Post_{Climate}$. The peak flows, time to peak flow, total flow volume, and runoff depth for each storm were recorded. The percent change in recorded values for each storm moving from the Pre_0 (undeveloped) model with the current rainfall to the $Pre_{Climate}$ model with the projected rainfall were calculated. The same was calculated for the the $Post_{Climate}$ model data. The mean percent change, median percent change, and standard deviation of percent change were then calculated per storm event and for all model events for both scenarios. Baseflow was removed and percent change was calculated as shown in section 2.6.2.

Chapter 3: Results and Discussion

3.1 BMP Implementation Compared to Traditional Stormwater Management

The Pre and Post model rainfall-runoff responses were examined to determine the usefulness of best management practices, in particular GSI, for flood control in developed areas. It should be noted that while the majority of the BMPs installed in the Berry Brook watershed were GSI systems, 1,100 feet of stream channel was daylighted and restored to a Rosgen C channel, additional wetland was constructed, and another 500 feet of stream channel was daylighted and restored to a Rosgen A1 – A2 geometry. These additional improvements also impacted the monitored and modeled rainfall-runoff response.

3.1.1 Extreme Precipitation Events

The extreme precipitation events shown in Table 7 were run for the Pre model and the Post model at a reporting time step of 1 minute with a wet-weather calculation time step of 30 seconds. To ensure uniformity in the results, each rainfall-runoff response simulation was run for 96 hours from the beginning of the rainfall event. The peak flows, time to peak flow, total flow volume, and runoff depth for each storm were recorded. To ensure that only the storm discharge was directly compared from Pre to Post, the calibrated baseflow and total flow volume from baseflow over the 36-hour period were subtracted from the total peak discharge and total flow volume for each simulation for all calculations.

The 2-year 1-hour extreme precipitation event from Atlas 14 was 0.98 inches. GSI systems are typically fully designed for the 1-inch storm, so this event is a good example of how the watershed behaves under expected conditions (Figure 22). The Pre response had a peak flow of 23 cfs, a time to peak flow of 48 minutes, a total flow of 179,810 cubic feet, and a total runoff depth of 0.28 inches. The Post model had a peak flow of 16 cfs, a time to peak flow of 49 minutes, a total flow of 99,720 cubic feet, and a total runoff depth of 0.14 inches. The reduction in peak flow and longer time to peak are expected results of GSI implementation and the overall watershed improvements. However, typically a Post-improvements hydrograph would show approximately the same total flow dispersed over a longer period of time. While some water would infiltrate through the GSI system, most of it would still be accounted for as storm runoff and baseflow. In SWMM and PCSWMM, however, water that infiltrates into the ground is removed from future flow calculations and effectively disappears from the hydrograph. The increased infiltration caused by GSI installation accounts for the water displaced in the Post model at a 1-inch storm. Also, infiltrating water will not show up in baseflow immediately after an event but will rather percolate through the watershed over time. A short-term simulation as modeled here will miss most of the impacts of the extreme precipitation event on baseflow.

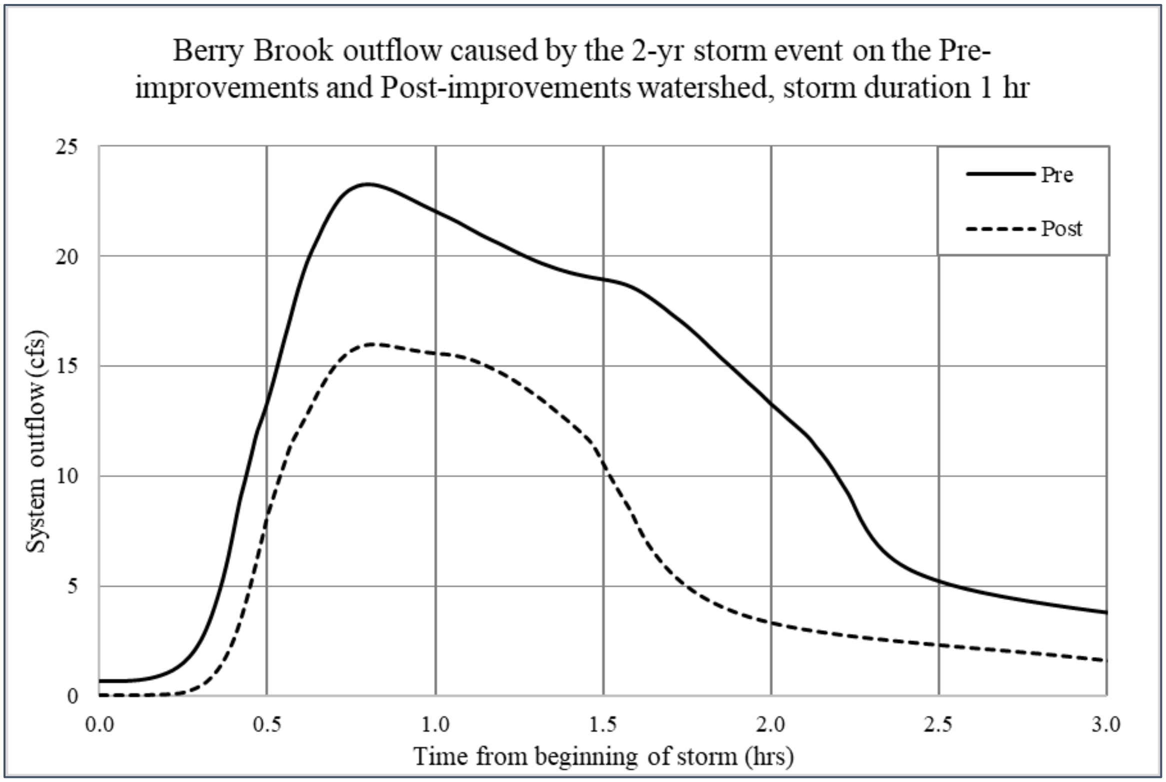

Figure 22: Outflow in the Pre and Post models caused by the 2-yr 1-hr extreme precipitation event

The introduction of BMPs to the watershed noticeably decreased the peak flows, increased the time to peak flow, decreased the runoff depth, and decreased the total flow volume. Decrease in the peak flow varied from 5% to 29% (Table 10). The time to peak flow increased by 1 to 8 minutes at the watershed scale (Table 10). Decrease in the runoff depth varied from 19% to 49% (Table 11). Decrease in the total flow varied from 25% to 45% (Table 11).

Table 10: Watershed Response to BMP implementation: Peak Flow and Time to Peak

Event	Duration	Rain (in)	Peak Flow (cfs) Pre	Post	Reduction	% Reduction	Time to Peak (min) Pre	Post	Increase
2-yr storms	1 hr	0.98	23	16	7	29	48	49	1.0
	24 hr	3.23	34	31	3	10	723	727	4.0
10-yr storms	1 hr	1.49	28	25	3	11	40	48	8.0
	24 hr	5.18	44	42	2	5	722	724	2.0
50-yr storms	1 hr	2.04	35	32	3	8	36	42	6.0
	24 hr	7.29	55	52	3	5	721	723	2.0
100-yr storms	1 hr	2.28	37	34	2	6	35	41	6.0
	24 hr	8.27	61	57	4	6	721	723	2.0

Table 11: Watershed Response to BMP implementation: Runoff Depth and Flow Volume

Event	Duration	Rain (in)	Runoff Depth (in) Pre	Post	Reduction	% Reduction	Total Flow (ft^3) Pre	Post	Reduction	% Reduction
2-yr storms	1 hr	0.98	0.28	0.14	0.14	49	179,810	99,720	80,090	45
	24 hr	3.23	1.07	0.73	0.34	31	591,010	383,220	207,790	35
10-yr storms	1 hr	1.49	0.44	0.27	0.17	38	243,610	158,120	85,490	35
	24 hr	5.18	2.19	1.67	0.51	23	919,710	644,120	275,590	30
50-yr storms	1 hr	2.04	0.62	0.43	0.19	31	294,410	205,220	89,190	30
	24 hr	7.29	3.72	2.98	0.74	20	1,267,710	925,220	342,490	27
100-yr storms	1 hr	2.28	0.72	0.51	0.20	28	313,810	225,320	88,490	28
	24 hr	8.27	4.46	3.63	0.83	19	1,397,710	1,043,720	353,990	25

For all variables, the impact was more prevalent in extreme precipitation events lasting 1 hour than in events lasting 24 hours (Figures 23 and 24). For the peak flow, runoff depth, and total flow, this difference in impact between the 1-hour storms and the 24-hour storms was likely due to two factors. First, GSI systems are statically designed to infiltrate rain and to drain over a 24-hour period. A short storm would closely mimic static design conditions, showing the full effect of LID implementation. Second, 1-hour extreme precipitation events have significantly less rainfall than their 24-hour counterparts. The sheer volume of water in the 24-hour storms can overwhelm the GSI systems and bypass directly to Berry Brook. What decrease is present is due to the combination of improvements in Berry Brook, which include increased wetland area and stream channel improvements. This also explains why the impact on peak flow decreases as the precipitation event becomes more extreme (more rainfall). As the events become more extreme and the precipitation on the watershed increases, the GSI becomes less useful for decreasing peak flow because an increasing percentage of the storm runoff simply bypasses the GSI storage. At that point, the chief reducers to the peak runoff are the additional wetland area and the stream channel improvements, which are shown to have less effect on peak flow than the GSI systems, but still demonstrate an improvement compared to the Pre system.

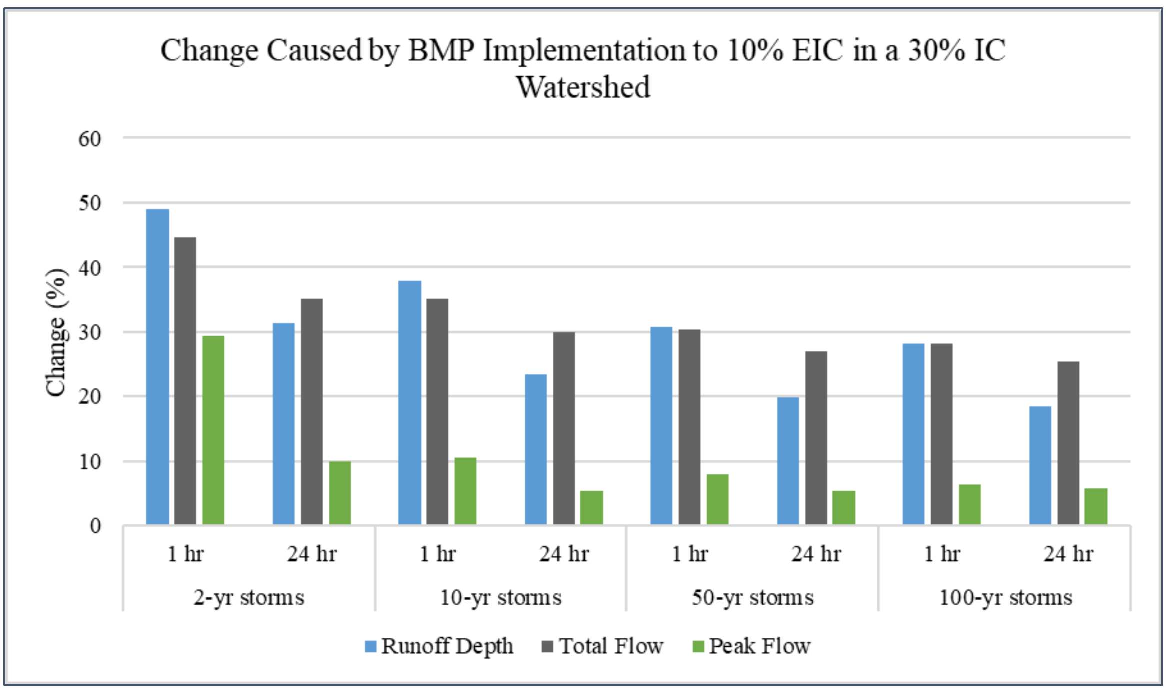

Figure 23: Percent Change in Runoff Depth, Total Flow, and Peak Flow Caused by BMP Implementation to 10% EIC in a 30% IC Watershed

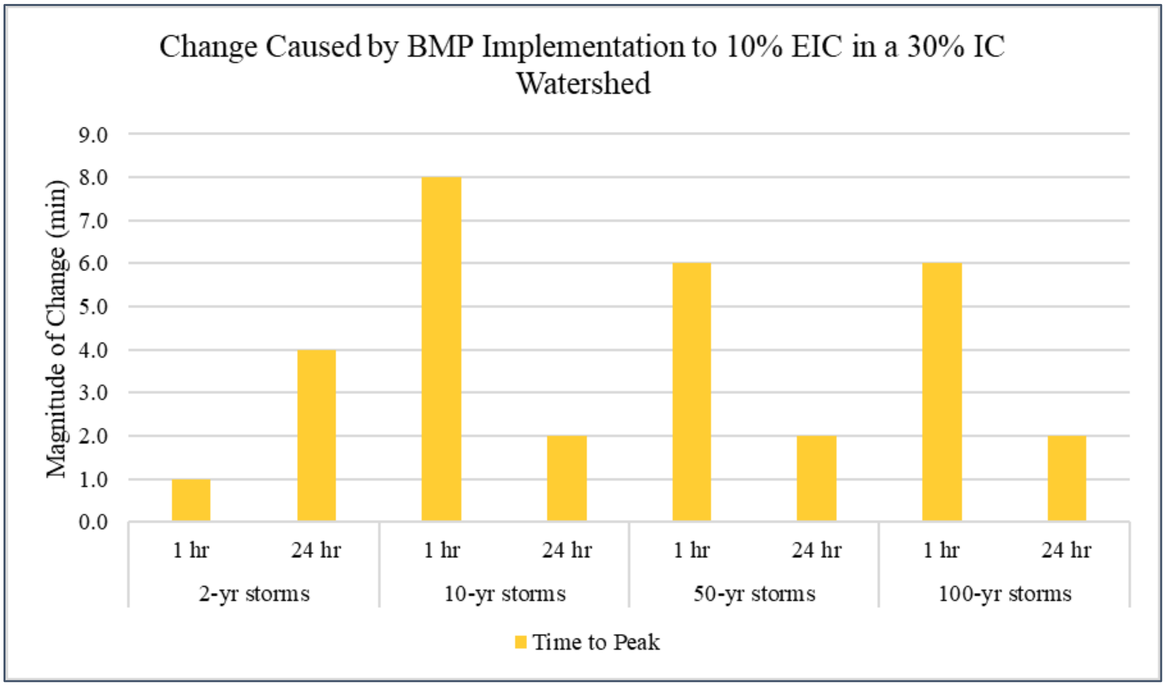

Figure 24: Change in Time to Peak Flow Caused by BMP Implementation to 10% EIC in a 30% IC Watershed

For the time to peak flow, the difference in impact between the 1-hour storms and the 24-hour storms was likely due to how the time of concentration is calculated in the dynamic wave equation, which is used by the SWMM model. Time of concentration is dependent on rainfall intensity, which varies in the extreme precipitation events based on event and duration, but is overall higher for the 1-hour events than for the 24-hour events even though the 24-hour events end up with more rain. What is important to note is that the time to peak increased for all storms, which demonstrates that the installation of BMPs successfully increased the travel time for the storm runoff to reach Berry Brook.

It should be noted that over the long term, the percent change in the runoff depth from Pre to Post and the percent change in the flow volume from Pre to Post should be almost identical. In theory, what runs off should be the same as what flows in the stream. Once again, the discrepancy between the impact on runoff depth and the impact on flow volume demonstrates the challenge SWMM faces with infiltrated water. Since infiltration does not reenter the system as baseflow or groundwater flow, this is essentially lost water in the flow volume. Also, what infiltration is accounted for in directly connected aquifers will not be immediately visible in the stream but will slowly appear over several days. Since the analysis was only for 36 hours, this water will not be seen in the analysis. Runoff depth, on the other hand, is calculated by SWMM as the quantity of precipitation not infiltrated, evaporated, or stored. For this reason, it is the more accurate determination of BMP performance in reducing the overall volume of water caused by these extreme precipitation events.

3.1.2 Long-Term Simulations

Table 12: Minimum, Mean, and Maximum Annual Flows (cfs) for Water Years 2002-2011

Water Year	Pre			Post		
	Minimum	Average	Maximum	Minimum	Average	Maximum
2002	0.67	0.94	22	0.03	0.18	16
2003	0.67	1.03	23	0.03	0.26	18
2004	0.67	1.09	24	0.03	0.30	23
2005	0.67	1.06	26	0.03	0.27	24
2006	0.67	1.38	23	0.03	0.51	21
2007	0.67	1.18	25	0.03	0.37	24
2008	0.67	1.25	26	0.03	0.41	25
2009	0.67	1.05	23	0.03	0.27	20
2010	0.67	1.15	23	0.03	0.35	22
2011	0.67	0.97	18	0.03	0.21	11

The Pre and Post watersheds were simulated from October 01, 2001 to October 1, 2011 at 60-minute reporting time steps and 30-second wet weather calculation time steps. The minimum, average, and maximum daily flows for water years 2002 to 2011 are shown in Table 12. Unlike in the models of extreme precipitation events, the modeled baseflow was not subtracted from any values. This allowed consideration of how the model behaved in dry periods. The minimum and mean flows are governed primarily by the calibrated baseflow, which was 0.67 cfs for the Pre model and 0.03 cfs for the Post model. This indicates the baseflow in the watershed, or groundwater flow, is the most powerful value in the model for total modeled flow volume in Berry Brook. Again, both the Pre and Post models were dictated as having about 0.75 cfs flowing from the wetland area as baseflow. However, the Post model infiltrates most of that flow and thus effectively removes it from the data. The storms had some effect on total volume, but days with rain were outnumbered by days without rain, which leaves only the baseflow to supply water to the stream. The maximum flow, however, was controlled by the storm events over the 10-year simulation. Maximum annual flow ranged from 18 cfs to 26 cfs in the Pre model and from 11 cfs to 25 cfs in the Post model. This was as expected and demonstrated again that BMP implementation successfully combats flooding to at least a small extent.

The percent change in flow from the Pre model to the Post model in the 10-year simulation indicated that while the change in baseflow controlled the change in minimum and average annual flows, there was a discernable change in the maximum annual flows caused by the watershed improvements (Table 13, Figure 25). The decrease in annual peak flow caused by BMP implementation ranged from 5% to 38% and had a median decrease of 8% in peak flow (median rainfall depth of 2.05 inches). This information means the BMPs are decreasing flooding in Berry Brook by 8% for the typical large annual storm. This estimate is about one third of the 29% decrease in peak flow expected in the 2-year 1-hour storm event, which was the example of a very common event. In other words, even in storms twice the size of the 1 inch most GSI is designed for, the model is demonstrating an improvement in watershed flood hydrology. The BMP implementation is working.

Table 13: Percent Change in Maximum Annual Flows Caused by BMP Implementation

Water Year	24-hour Rainfall (in)	Maximum Flow (cfs)		Impact of BMPs	
		Pre	Post	Decrease (cfs)	Decrease (%)
2002	1.67	22	16	6	27
2003	1.16	23	18	6	24
2004	1.95	24	23	1	5
2005	1.58	26	24	2	8
2006	2.57	23	21	2	8
2007	5.33	25	24	1	5
2008	3.77	26	25	1	5
2009	1.52	23	20	3	13
2010	2.49	23	22	1	6
2011	2.14	18	11	7	38

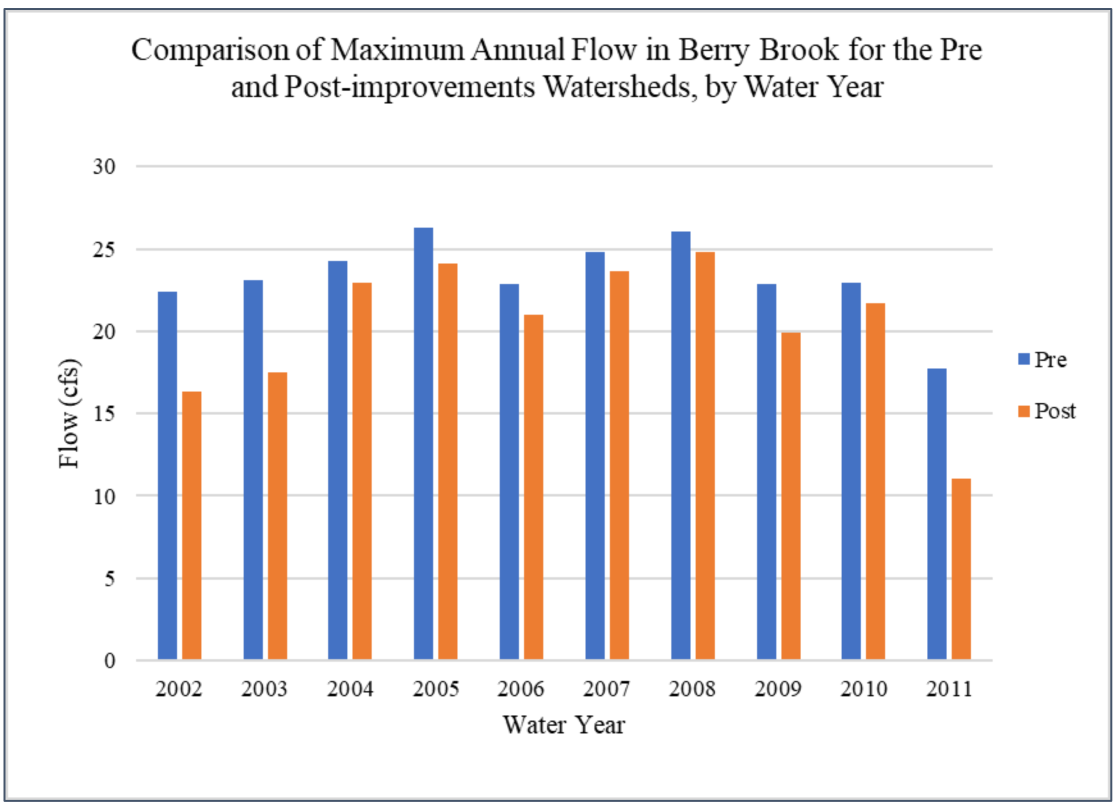

Figure 25: Maximum Annual Flow in Berry Brook in the Pre and Post Models, by Water Year

The use of BMPs increased the infiltration and decreased surface runoff in Berry Brook by 17% and 40% respectively from October 2001 to October 2011 (Table 14). The total rainfall on the watershed was 487 inches. In the Pre model, 309 inches of rain infiltrated into the groundwater and 161 inches of rain ran off. BMP implementation allowed infiltration to increase by 53 inches and surface runoff to decrease by 65 inches. GSI infiltration from the LID controls shows infiltration from the systems as 25 inches. This demonstrates again that SWMM's LID controls underpredict the infiltration capacity of GSI. These numbers show once again that BMPs and the installation of GSI are successful in decreasing surface runoff and increasing infiltration in a watershed. SWMM dictates that the surface runoff decrease is specifically caused by the increase in infiltration. Interestingly, total evaporation also decreased. This result was unexpected because typically the introduction of GSI to a watershed leads to increased ponding areas and therefore increased evaporation, not decreased. This was likely due to how evaporation was modeled. Evaporation was treated as a constant value for both the Pre model and the Post model. In the Post model, however, water that may have ponded in shallow places or flooded out of the conveyance system in the Pre model instead was taken to GSI systems with high infiltration capabilities. The decrease in evaporation is likely due to that water being infiltrated instead.

Table 14: Infiltration and Surface Runoff in the 10-year Simulation

	Pre	Post	Change	% Change	Type
Years	10	10	-	-	-
Total Precipitation (in)	487	487	-	-	-
Evaporation (in)	17	11	6	33	Decrease
Infiltration (in)	309	362	53	17	Increase
GSI Infiltration (in)	0	25	25	-	Increase
Runoff (in)	161	96	65	40	Decrease

The volume of infiltrated water provides the opportunity to get a more accurate estimate of modelled baseflow. As previously stated, PCSWMM and SWMM effectively remove infiltrated water from streamflow calculations. However, by taking the depth of infiltrated water and multiplying it by the total watershed area, we can get an estimate of the actual volume of baseflow attributed to infiltration. Dividing this number over the 10-year period allows an estimation of baseflow, which would therefore be 0.70 cfs for the Pre model and 0.82 cfs for the Post model. This shows a 0.12 cfs increase in baseflow due to GSI implementation. These are significantly different numbers than what is shown by PCSWMM. Again, this is because SWMM is showing this water as infiltrating, at which point SWMM no longer considers it in the stream. For the Pre model this number is very similar. This value varies very little from the calibrated baseflow in the Pre model, which was about 0.67 cfs. For the Post model this is a significantly higher value than the 0.03 cfs reported as groundwater flow for the model. Groundwater flow after BMP implementation should actually be higher than prior to implementation, which is what is seen in the baseflow calculated from infiltration. This result is more comparable to the expected impact of GSI installations and accounts for the missing volume of water from storms.

The hourly streamflow data modeled over the 10-year period was processed to produce daily average streamflow. The daily averages were then used to develop a flow duration curve (FDC) for the Pre and Post-improvements watersheds (Figure 26). The FDC visually demonstrates the modeled difference in baseflow accounted for above and the change in high flows caused by BMP implementation. For the Pre-improvements watershed, 50% of the average daily flow can be considered controlled by the baseflow, 0.67 cfs. This implied that the remaining 50% of average flow was impacted by precipitation events. In other words, stormwater was flowing in the stream 50% of the time. This is sensible in terms of the number of days of precipitation in New Hampshire, which is about 1 in 3 days. For the Post-improvements watershed, which effectively acted as if it had a baseflow of 0.03 cfs, 80% of the time the streamflow exceeded baseflow. This indicates that the BMP installations, while infiltrating most of the baseflow, still left enough storm runoff or infiltration from it to be detected for 80% of the monitoring time. This implies that in reality the Pre model should show higher flows this frequently as well, but the impact is disguised by the greater baseflow present in the model. This is sensible because in truth baseflow is not a constant value. It is constantly decreasing and increasing depending on the depth of groundwater, which in turn depends on precipitation.

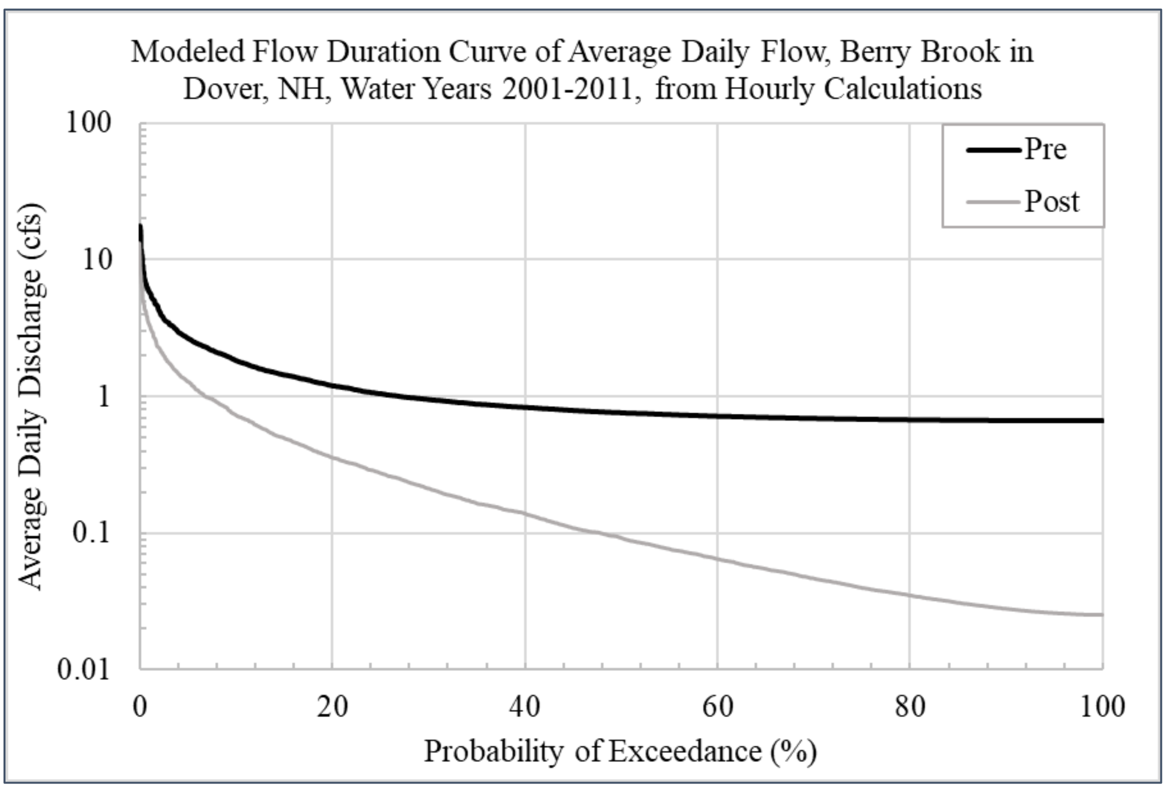

Figure 26: Full Flow Duration Curve for Berry Brook Pre and Post Models

The wet-weather behavior of the modeled flow duration curve of average daily flow is shown in Figure 27. This includes the top 5% average daily flows from the 10-year analysis. The discharge in the Post model is approximately 2 to 10 cfs lower than the discharge in the Pre model, but is in all cases significantly greater than the baseflow of the model. This again demonstrates that GSI implantation is successfully reducing flow from extreme precipitation events, but does not eliminate it.

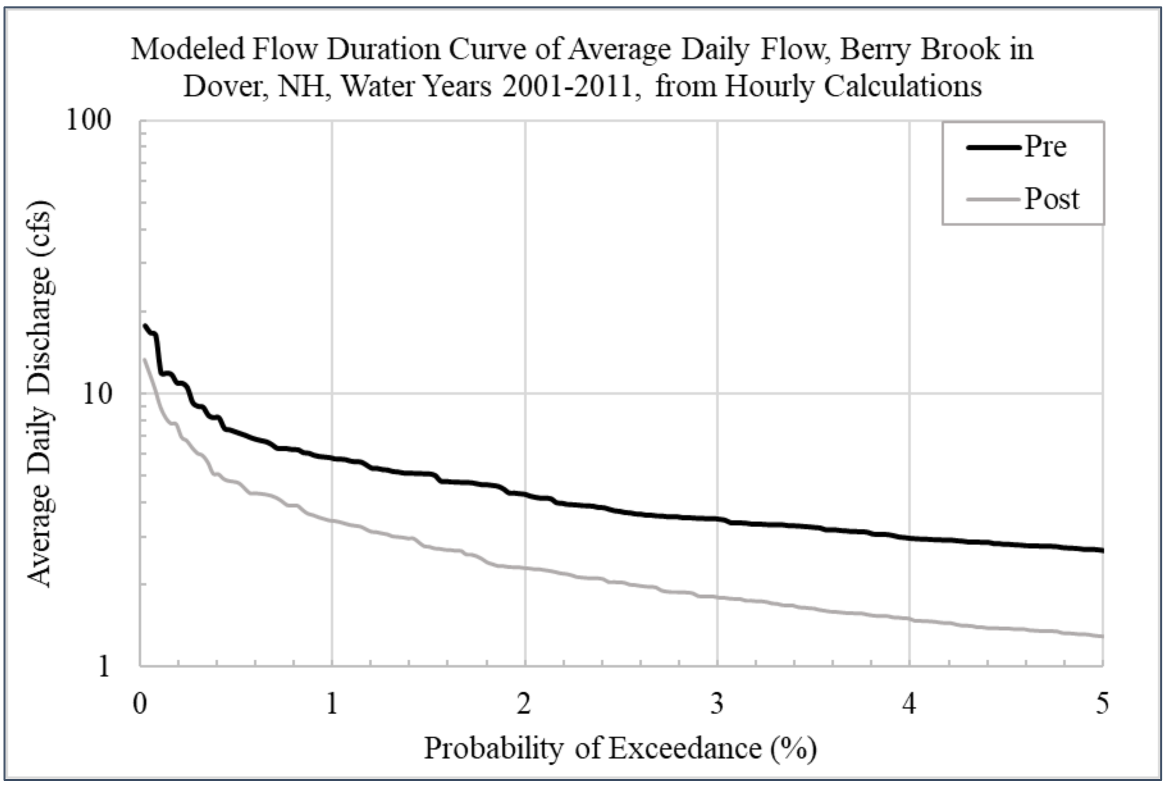

Figure 27: Flow Duration Curve for Berry Brook Pre and Post Models for Wet-Weather Flows Only

The peak flow response of the Pre and Post models, for every storm in the 10-year period, is shown in Figure 28. This figure shows that on every occasion, the modeled storm response in the Post watershed was less than the modeled storm response in the Pre watershed. The decrease in peak flow was most noticeable up to about 20 cfs in the Pre model (up to about 1.3 inches of precipitation). In this range, GSI installation caused a median percent decrease of 68% of peak flow. It should be noted that in the case of the 20 cfs modeled Pre response, this still showed a 15 cfs response in the Post model. The flooding was not eliminated, only reduced. This is because the purpose of GSI is to remove pollutants from runoff, not eliminate flooding. Flooding is reduced by GSI as a side effect of storing water for pollutant removal, but it is not the primary purpose of GSI and should not be used as the sole flood prevention measure in an urbanized area. This is further demonstrated in the storms exceeding about 20 cfs. At this point, the Post watershed was producing modelled flows only slightly smaller than those modelled in the Pre watershed. This indicates that the rainfall necessary to generate 20 cfs in the stream is approximately the amount of rainfall at which GSI is no longer effective at reducing flooding, because at that point the systems are overwhelmed. This was modeled to be about 1.3 inches of rain.

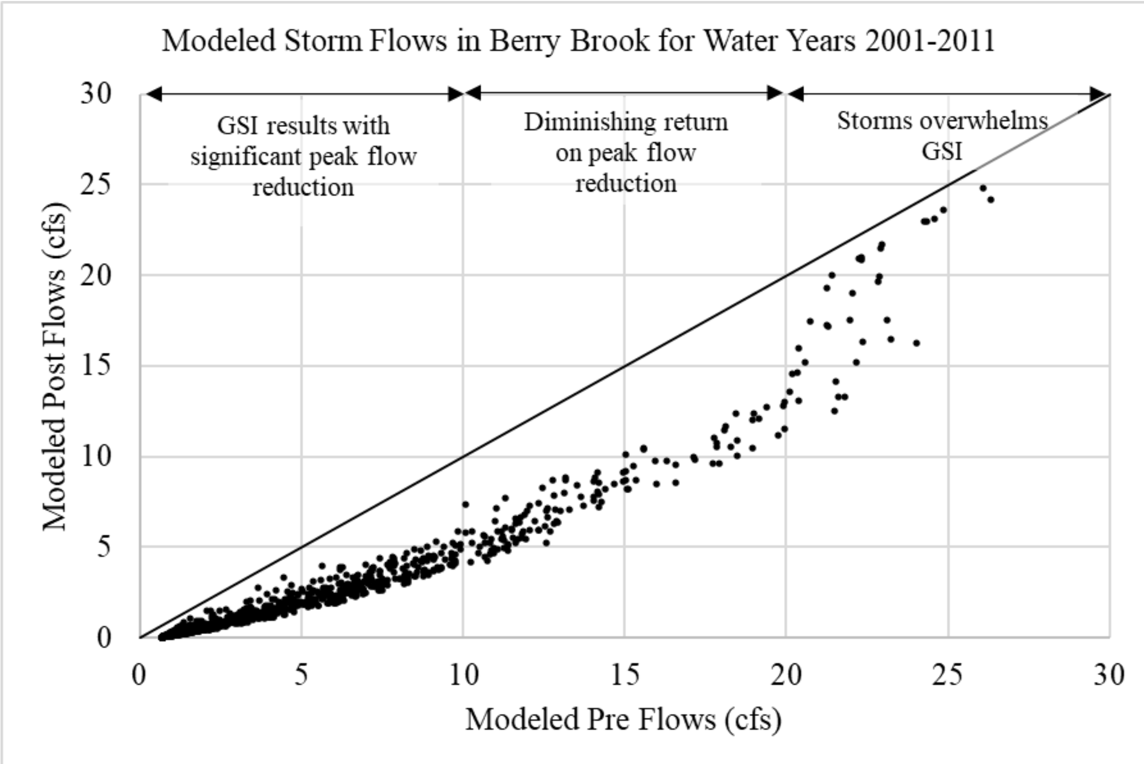

Figure 28: Modeled Storm Flows for Pre and Post in Berry Brook for Water Years 2001-2011

Figure 28 graphically shows the diminishing impacts of GSI on peak flow reduction as storms become more extreme. The smallest flows (up to about 10 cfs in the Pre model) show a significant percent reduction in peak flow caused by GSI implementation. Flows from about 10 cfs to about 20 cfs in the Pre model still show the positive impacts of GSI on reducing flooding, but the percent impact is diminishing. Finally, storms above 20 cfs in the Pre model show almost no reduction due to GSI implementation, which means that the storm is overwhelming the GSI systems.

It should be noted that the minimum Pre and Post flows show a significant reduction as well, in which the Pre flows are approximately 0.7 cfs and the Post flows are approximately

0.035 cfs. The drastic change in flow here is caused by how SWMM handles infiltration and not by the storm event that caused a local peak flow.

3.2 Impacts of Impervious Cover Compared to the Impacts of Climate Change in Extreme Precipitation Events

The purpose of these runs was to compare the impacts of impervious cover to the impacts of the expected increase in rainfall intensity due to climate change for extreme precipitation events. The rainfall values shown in Table 7 were run for the Pre model and the Pre_{15} model, the Pre_{0} model, and the Post model at a reporting time step of 1 minute with a wet-weather calculation time step of 30 seconds. The climate change-adjusted extreme precipitation events shown in Table 8 were run in the Pre model and the Post model to yield the $Pre_{Climate}$ and $Post_{Climate}$ scenarios. To ensure uniformity in the results, each rainfall-runoff response simulation was run for 36 hours from the beginning of the rainfall event. The peak flow, time to peak flow, total flow volume, and runoff depth for each storm were recorded. To ensure that only the storm discharge was directly compared, the calibrated baseflow and total flow volume from baseflow over the 36-hour period were subtracted from the total peak discharge and total flow volume for each simulation for all calculations (Table 15). The magnitude of change from the Pre_{0} (pre-development) watershed response was calculated for all other models (Table 16). The percent change of the peak flow, runoff depth, and total flow were then calculated (Table 17). The magnitude of change in time to peak and the percent change in peak flow, runoff depth, and total flow were then summarized using the median change from Pre_{0} for all 8 modeled extreme precipitation events (Tables 18 and 19). The median percent impact on peak flow, runoff depth, and total flow were graphically compared for each scenario (Figure 29). The median impact on time to peak was also graphically compared for each scenario (Figure 30).

Table 15: Watershed Responses: Modeled Extreme Precipitation Responses

Peak Flow (cfs)									
				Modeled Values					
Event	Duration	Base Rain (in)	Climate Rain (in)	Pre_0	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	0.33	16	23	16	24	19
	24 hr	3.23	3.71	11	20	34	31	37	34
10-yr storms	1 hr	1.49	1.71	1.0	18	28	25	31	28
	24 hr	5.18	5.95	23	24	44	42	48	46
50-yr storms	1 hr	2.04	2.34	5.5	18	35	32	37	35
	24 hr	7.29	8.38	29	29	55	52	62	58
100-yr storms	1 hr	2.28	2.63	9	19	37	34	40	37
	24 hr	8.27	9.51	32	32	61	57	65	62
Time to Peak (min)									
				Modeled Values					
Event	Duration	Rain (in)	Climate Rain (in)	Pre_0	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	518	61	48	49	45.0	62
	24 hr	3.23	3.71	762	742	723	727	722	726
10-yr storms	1 hr	1.49	1.71	61	47	40	48	38.0	45
	24 hr	5.18	5.95	754	744	722	724	721	723
50-yr storms	1 hr	2.04	2.34	63	48	36	42	35.0	40
	24 hr	7.29	8.38	742	738	721	723	721	723
100-yr storms	1 hr	2.28	2.63	65	51	35	41	34	39
	24 hr	8.27	9.51	739	736	721	723	722	724
Total Flow (ft^3)									
				Modeled Values					
Event	Duration	Rain (in)	Climate Rain (in)	Pre_0	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	28,410	109,610	179,810	99,720	200,710	119,420
	24 hr	3.23	3.71	185,010	404,210	591,010	383,220	667,110	445,220
10-yr storms	1 hr	1.49	1.71	61,110	163,310	243,610	158,120	266,910	177,620
	24 hr	5.18	5.95	536,310	733,010	919,710	644,120	1,058,710	750,220
50-yr storms	1 hr	2.04	2.34	104,910	213,910	294,410	205,220	318,510	230,320
	24 hr	7.29	8.38	896,910	1,100,710	1,267,710	925,220	1,410,710	1,056,720
100-yr storms	1 hr	2.28	2.63	129,110	236,810	313,810	225,320	341,710	254,020
	24 hr	8.27	9.51	1,017,710	1,231,710	1,397,710	1,043,720	1,541,710	1,185,720
Runoff Depth (in)									
				Modeled Values					
Event	Duration	Rain (in)	Climate Rain (in)	Pre_0	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	0.00	0.14	0.28	0.14	0.33	0.18
	24 hr	3.23	3.71	0.17	0.6	1.1	0.7	1.3	0.9
10-yr storms	1 hr	1.49	1.71	0.01	0.22	0.44	0.27	0.51	0.33
	24 hr	5.18	5.95	0.86	1.5	2.2	1.7	2.7	2.1
50-yr storms	1 hr	2.04	2.34	0.03	0.32	0.62	0.43	0.74	0.54
	24 hr	7.29	8.38	2.01	2.9	3.7	3.0	4.5	3.7
100-yr storms	1 hr	2.28	2.63	0.05	0.37	0.72	0.51	0.86	0.65
	24 hr	8.27	9.51	2.59	3.5	4.5	3.6	5.4	4.5

Table 16: Watershed Responses: Model Difference from Pre_0

Peak Flow (cfs)								
		Base Rain	Climate	Modeled Value Minus Pre_0				
Event	Duration	(in)	Rain (in)	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	15	22	16	24	19
	24 hr	3.23	3.71	8.5	23	20	26	23
10-yr storms	1 hr	1.49	1.71	17	27	24	30	27
	24 hr	5.18	5.95	0.28	21	18	25	22
50-yr storms	1 hr	2.04	2.34	13	29	26	32	29
	24 hr	7.29	8.38	0.22	26	23	32	29
100-yr storms	1 hr	2.28	2.63	10.2	28	26	31	29
	24 hr	8.27	9.51	0.21	29	25	33	30
Time to Peak (min)								
		Base Rain	Climate	Modeled Value Minus Pre_0				
Event	Duration	(in)	Rain (in)	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	-457	-470	-469	-473	-456
	24 hr	3.23	3.71	-20	-39	-35	-40	-36
10-yr storms	1 hr	1.49	1.71	-14	-21	-13	-23	-16
	24 hr	5.18	5.95	-10	-32	-30	-33	-31
50-yr storms	1 hr	2.04	2.34	-15	-27	-21	-28	-23
	24 hr	7.29	8.38	-4	-21	-19	-21	-19
100-yr storms	1 hr	2.28	2.63	-14	-30	-24	-31	-26
	24 hr	8.27	9.51	-3	-18	-16	-17	-15
Total Flow (ft3)								
		Base Rain	Climate	Modeled Value Minus Pre_0				
Event	Duration	(in)	Rain (in)	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	81,200	151,400	71,310	172,300	91,010
	24 hr	3.23	3.71	219,200	406,000	198,210	482,100	260,210
10-yr storms	1 hr	1.49	1.71	102,200	182,500	97,010	205,800	116,510
	24 hr	5.18	5.95	196,700	383,400	107,810	522,400	213,910
50-yr storms	1 hr	2.04	2.34	109,000	189,500	100,310	213,600	125,410
	24 hr	7.29	8.38	203,800	370,800	28,310	513,800	159,810
100-yr storms	1 hr	2.28	2.63	107,700	184,700	96,210	212,600	124,910
	24 hr	8.27	9.51	214,000	380,000	26,010	524,000	168,010
Runoff Depth (in)								
		Base Rain	Climate	Modeled Value Minus Pre_0				
Event	Duration	(in)	Rain (in)	Pre_{15}	Pre	Post	$Pre_{Climate}$	$Post_{Climate}$
2-yr storms	1 hr	0.98	1.13	0.14	0.28	0.14	0.33	0.18
	24 hr	3.23	3.71	0.44	0.90	0.56	1.1	0.75
10-yr storms	1 hr	1.49	1.71	0.21	0.43	0.27	0.50	0.33
	24 hr	5.18	5.95	0.66	1.3	0.82	1.9	1.3
50-yr storms	1 hr	2.04	2.34	0.29	0.59	0.40	0.71	0.51
	24 hr	7.29	8.38	0.87	1.7	1.0	2.5	1.7
100-yr storms	1 hr	2.28	2.63	0.32	0.67	0.46	0.81	0.60
	24 hr	8.27	9.51	0.95	1.9	1.0	2.8	1.9

Table 17: Watershed Responses: Percent Change from Pre$_0$

Peak Flow (%)								
		Base Rain	Climate	Percent Change From Pre$_0$				
Event	Duration	(in)	Rain (in)	Pre$_{15}$	Pre	Post	Pre$_{Climate}$	Post$_{Climate}$
2-yr storms	1 hr	0.98	1.13	0	0	0	0	0
	24 hr	3.23	3.71	0	0	0	0	0
10-yr storms	1 hr	1.49	1.71	0	0	0	0	0
	24 hr	5.18	5.95	0.0	0.0	0.0	0.0	0
50-yr storms	1 hr	2.04	2.34	0	0	0	0	0
	24 hr	7.29	8.38	0.00	0	0	0	0
100-yr storms	1 hr	2.28	2.63	0	0	0	0	0
	24 hr	8.27	9.51	0.00	0	0	0	0
Total Flow (%)								
	Duration	(in)	Rain (in)	: Change From Pre$_0$				
Event				Pre$_{15}$	Pre	Post	Pre$_{Climate}$	Post$_{Climate}$
2-yr storms	1 hr	0.98	1.13	0	0	0	0	0
	24 hr	3.23	3.71	0	0	0	0	0
10-yr storms	1 hr	1.49	1.71	0	0	0	0	0
	24 hr	5.18	5.95	0	0	0	0	0
50-yr storms	1 hr	2.04	2.34	0	0	0	0	0
	24 hr	7.29	8.38	0	0	0	0	0
100-yr storms	1 hr	2.28	2.63	0	0	0	0	0
	24 hr	8.27	9.51	0	0	0	0	0
Runoff Depth (%)								
		Base Rain	Climate	Percent Change From Pre$_0$				
Event	Duration	(in)	Rain (in)	Pre$_{15}$	Pre	Post	Pre$_{Climate}$	Post$_{Climate}$
2-yr storms	1 hr	0.98	1.13	-	-	-	-	-
	24 hr	3.23	3.71	0	0	0	0	0
10-yr storms	1 hr	1.49	1.71	0	0	0	0	0
	24 hr	5.18	5.95	0	0	0	0	0
50-yr storms	1 hr	2.04	2.34	0	0	0	0	0
	24 hr	7.29	8.38	0	0	0	0	0
100-yr storms	1 hr	2.28	2.63	0	0	0	0	0
	24 hr	8.27	9.51	0	0	0	0	0

Tables 15, 16, and 17 show that in every model scenario, the impact on extreme event peak flow, time to peak flow, runoff depth, and total flow was more prevalent in more common extreme precipitation events than in the rare ones such as the 100-year storm just as previously seen in Figures 23 and 24. This demonstrates that common storms such as the 2-year event are the storms that LID implementation can impact. Extreme events such as the 100-year event cause extreme flooding even in a completely undeveloped watershed.

Table 18: Median Change in Peak Flow, Time to Peak, Total Flow, and Runoff Depth from the Pre_0 Model for Extreme Precipitation Events

	N	Median Magnitude of Change				
		Pre_{15}	Pre_{30}	Post	$Pre_{Climate}$	$Post_{Climate}$
Peak Flow (cfs)	8	9.4	27	24	30	28
Time to Peak (min)	8	-14	-29	-23	-30	-25
Total Storm Flow (cf)	8	152,850	280,150	96,610	347,850	142,610
Runoff Depth (in)	8	0.38	0.78	0.51	0.97	0.67

Table 19: Median Percent Change in Runoff Depth, Total Flow, and Peak Flow from the Pre_0 Model for Extreme Precipitation Events

	N	Pre15	Pre30	Post	PreClimate	PostClimate
Peak Flow	8	97	263	234	292	267
Total Storm Flow	8	94	162	85	184	108
Runoff Depth	7	255	525	329	656	440

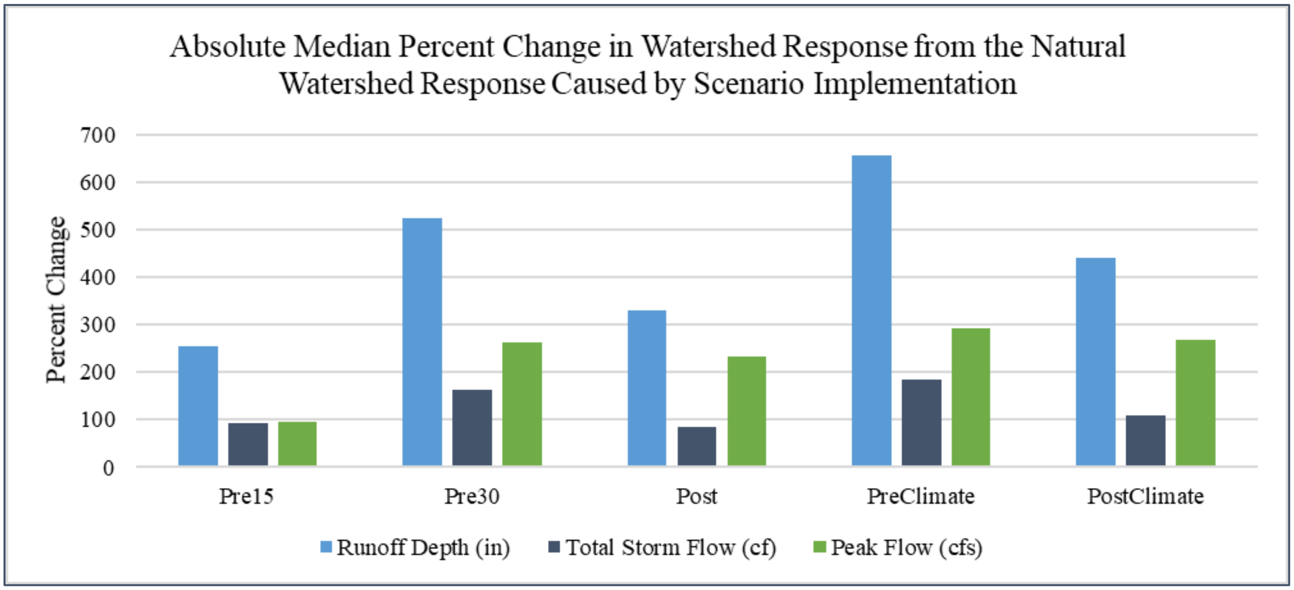

Figure 29: Absolute Value of Median Percent Change in Model Runoff Depth, Total Flow, and Peak Flow from the Pre$_0$ Response

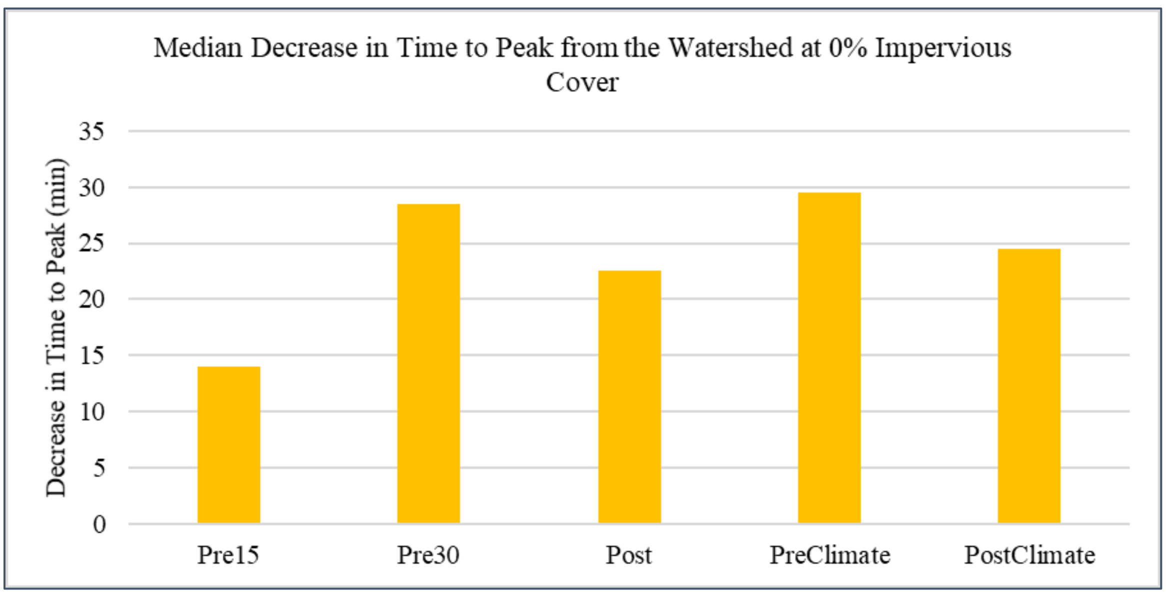

Figure 30: Median Change in Time to Peak Flow from the Pre$_0$ Response

Increasing percent impervious cover to 15% from 0% in a traditionally managed watershed leads to a median increase in peak flow of 97%, a median decrease in time to peak of

14 minutes, a median increase in total flow of 94%, and a median increase in runoff depth of 255%. These changes are indicating the dramatic change in watershed response caused by human development. When impervious cover is increased to 30%, the watershed has a median response: peak flow increase of 263%, time to peak decrease of 29 minutes, total flow increase of 162%, and runoff depth increase of 525%. This serves to say than human development drastically impacts a watershed's hydrology. In the Post model, with an EIC of 10%, the watershed has a median response: peak flow increase of 234%, time to peak decrease of 23 minutes, total flow increase of 85%, and runoff depth increase of 329% when compared to the Pre_0 model. These results show that even with LID implementation, it is virtually impossible for a developed watershed to behave like an undeveloped watershed during extreme precipitation events. This is because flooding is not the design criteria for GSI, but rather a small consequential benefit. GSI is not meant to prevent extreme floods, and it does not.

Interestingly, even though the GSI systems results with an EIC of 10% in the watershed, the model of 15% IC is actually less impacted when compared to the watershed at 0% IC. The Post watershed varied from the impacts of the Pre_{15} watershed by: 137% more increase in peak flow, 9 minutes less decrease in time to peak flow, 9% less increase in total flow, and 74% more increase in runoff depth. This is because GSI systems are designed to store and infiltration no more than 1 inch of rain which extreme precipitation events far exceed. A watershed at 15% impervious cover has the potential to be continuously infiltrating water on all the pervious surface. A watershed managed by GSI, on the other hand, generates the same amount of runoff as the traditionally managed watershed, but stores it in each GSI system to infiltrate. When the system is overwhelmed, the hydrology returns to the traditionally managed behavior: everything runs off the impervious cover directly into the conveyance system. This demonstrates that while

BMPs work well to remove pollutants from water, limiting impervious cover is still a more effective means of flood mitigation.

Increasing rainfall intensity by 15% in the Pre (30% IC) watershed leads to a median increase in peak flow of 292%, a median decrease in time to peak of 30 minutes, a median increase in total flow of 184%, and a median increase in runoff depth of 656%. These exceed the comparison of 30% IC to 0% IC by 29% more increase in peak flow, 1 minute less time to peak, 22% more increase in total flow, and 132% more increase in runoff depth. These values are significantly smaller than the impact adding the impervious cover had on the watershed, demonstrating that impervious cover has a much more important influence on urban flooding than climate change in a traditionally management stormwater system.

Increasing rainfall intensity by 15% in the Post (10% EIC) watershed leads to a median increase in peak flow of 267%, a median decrease in time to peak of 25 minutes, a median increase in total flow of 108%, and a median increase in runoff depth of 440%. These exceed the comparison of the Post model to 0% IC by 33% more increase in peak flow, 2 minutes less time to peak, 23% more increase in total flow, and 111% more increase in runoff depth. These vary from the comparison of the 30% IC model (Pre) to 0% IC by 4% more increase in peak flow, 4 minutes more time to peak, 54% less increase in total flow, and 85% less increase in runoff depth. The comparison of the Post model to the Post model under increased rainfall showed, to no surprise, that climate change once again has less impact than impervious cover. Comparing the traditionally managed watershed at 30% impervious cover to the same watershed at 10% EIC through the use of BMPs under climate change, however, shows that sufficient BMP implementation will allow an urban watershed to continue to operate under similar flooding conditions under climate change that it currently faces without BMPs. This is because the very purpose of GSI implementation is to treat and infiltrate the first inch of rain, and the maximum amount of additional rainfall due to climate change is less than one inch. Therefore, the remaining rainfall is not very different from the rainfall in Table 7.

It should be noted that in truth, the percent change in the runoff depth and the percent change in the flow volume should be almost identical. In theory, what runs off should be the same as what flows in the stream. The discrepancy between the impact on runoff depth and the impact on flow volume demonstrates the challenge SWMM faces with infiltrated water. Since infiltration does not reenter the system as baseflow or groundwater flow, this is essentially lost water in the flow volume. Runoff depth, on the other hand, is calculated by SWMM as the quantity of precipitation not infiltrated, evaporated, or stored. For this reason, it is the more accurate determination of BMP performance in reducing the overall volume of water caused by precipitation events.

Figures 29 and 30 visually demonstrate that the impact of climate change on a watershed is significantly less important to the hydrologic response than the impact of impervious cover and that the impacts of climate change can be mitigated in the system through the use of BMPs. The Pre_{15} watershed is significantly less impacted that the Pre watershed and somewhat less impacted than the Post watershed, which has a physical impervious cover of 30% and an effective impervious cover of 10%. This shows that while BMP implementation will reduce flooding in a developed watershed, it will not remove the impacts of impervious cover. Figure 28 also shows that climate change will not have comparatively more drastic impact on traditionally managed watersheds than it will have on BMP managed watersheds. The relative impact is about the same.

Chapter 4: Conclusion

4.1 Summary and Conclusions

The purpose of this research was to determine the effectiveness of GSI and other BMPs to control urban flooding at the watershed scale for extreme precipitation events and to compare the impacts of increasing impervious cover with the impacts of increasing rainfall caused by climate change. Berry Brook watershed, a 185-acre developed watershed located in Dover, NH, was modeled using the proprietary stormwater management software PCSWMM developed by Computations Hydraulics International. The City of Dover has spent the last decade implementing best management practices to combat stream pollution and flooding in the Berry Brook watershed. Improvements to the watershed included building additional headwater wetland area, daylighting and restoring sections of the stream, and redirecting stormwater to GSIs such as bioretention and subsurface gravel wetland systems.

Four PCSWMM models of the Berry Brook watershed were developed for the analysis: a pre-implementation model (Pre), a model of the pre-implementation watershed set to 15% IC (Pre_{15}), a model of the pre-implementation watershed set to 0% IC (Pre_0), and a model of the watershed after BMP implementation (Post). The four models were used to examine the effects of GSI implementation, changing impervious cover, and climate change on urban watershed hydrology.

The effectiveness of GSI and other BMPs to control urban flooding caused by extreme precipitation events was tested by comparing the peak flows, time to peak flow, runoff depth, and total volume of storm flow in the Pre watershed simulations of the 2-year, 10-year 50-year, and 100-year precipitation events to those in the Post watershed. A long-term rainfall-runoff simulation from 2001 to 2011 was also done for both models. The minimum, mean, and maximum annual flows were determined for water years 2002 to 2011 and the total infiltration and surface runoff in the watershed over the 10-year period were determined. A FDC was constructed from the average daily flow for the Pre model and the Post model. The minimum and mean flows in the long-term simulation were largely controlled by the baseflow in Berry Brook. The maximum annual flow in Berry Brook, the total infiltration in the watershed, and the total surface runoff in the watershed over the 10-year period were compared from the Pre model to the Post model.

The implementation of GSI, additional wetland area, and restored stream channel resulted with a median decrease in extreme event peak flow of 7%, an increase in the time to peak flow of 3 minutes, a decrease in the runoff depth of 29%, and a decrease in the total storm flow volume of 30%. GSI impact was more prominent in short duration extreme precipitation events than in long duration events. For the peak flow, this was likely because a short storm would more closely mimic GSI static design conditions, showing the full effect of LID implementation. Also, 1-hour extreme precipitation events have significantly less rainfall than their 24-hour counterparts. The sheer volume of water in the 24-hour storms could overwhelm the GSI systems and bypass directly to the stream.

In the 10-year analysis, annual maximum flow had a median decrease of 8% between the Pre and Post models. The infiltration of rainfall increased by 17% and the stormwater runoff decreased by 40%. The 8% median decrease in annual maximum flow over the 10-year analysis corresponded well to the median decrease in peak flow for the modelled extreme precipitation events since the annual maxima are extreme events. All peak flows caused by precipitation over the 10-year analysis were compared from Pre to Post. It was found that while GSI installation always caused a reduction in peak flow due to precipitation, the impact was most noticeable up to about 20 cfs of flow in the Pre model. When peak flow exceeded this value, GSI became much less effective at reducing flooding in the watershed. GSI implementation resulted with a 68% decrease in peak discharge for all peak flows in the 10-year analysis less than 20 cfs in the Pre model, or about 1.3 inches of precipitation. Above this peak flow the GSI systems were overwhelmed and ineffective at reducing peak flow. It should be noted that flooding was not eliminated, but rather reduced.

The FDCs of the Pre and Post simulations showed a decrease in average daily flow in Berry Brook caused by GSI implementation, but that flood flows would still occur. This showed that GSI and other BMPs can be used to help mitigate common flooding in urban watersheds but should not be used as the only form of flood control, especially for extreme precipitation events. GSI may reduce the hydrologic watershed response to extreme precipitation, but flooding will still occur under conditions that would cause floods in undeveloped watersheds. A mix of GSI and other flood control practices should be used in urban watersheds in order to improve runoff water quality and reduce flood severity.

It was expected that increasing impervious cover would cause a greater increase in flooding in urban areas than the expected increase in rainfall caused by climate change. This was tested by first quantifying the impact of impervious cover on the peak flow, time to peak flow, runoff depth, and total flow volume and second quantifying the impact of higher intensity rainfall caused by climate change on the same parameters in a developed watershed with and without GSI implementation.

The impact of impervious cover on the watershed was tested using the Pre, Pre_{15}, and Pre_0 models. The Pre_0 and Pre_{15} models were compared to simulate the effect of adding 15% IC to a previously undeveloped watershed. The Pre_0 and Pre models were compared to examine the effect of adding 30% IC to a previously undeveloped watershed, or the effects of developing a watershed. The change in total storm flow, runoff depth, peak flow, and time to peak flow due to the 2-year, 10-year, 50-year, and 100-year extreme precipitation events was calculated for each comparison.

Increasing IC in the watershed was shown to have a much more dramatic effect than the increase in rainfall caused by climate change. The initial introduction of even 15% impervious cover to an undeveloped watershed let to median increase in peak flow of 97%, a median decrease in time to peak of 14 minutes, a median increase in total flow of 94%, and a median increase in runoff depth of 255%. For comparison, increasing rainfall by 15% in the Pre (30% IC) watershed increased peak flow 29%, 1 minute less time to peak, total flow 22%, and runoff depth 132% more than that of simply increasing impervious cover from 0% to 30%. In a BMP managed watershed, increasing rainfall by 15% increase peak flow 33%, 2 minutes less time to peak, total flow 23%, and runoff depth 111% more than simply adding at a BMP-managed watershed to an undeveloped watershed. Impact was still more prevalent in short duration extreme precipitation events than in long duration events. The difference between the GSI-managed watershed under future climate change conditions and the traditionally managed watershed under current day conditions was minimal, implying BMP implementation will keep flooding from getting any worse as the climate shifts.

The impacts of IC were much greater than the impacts of the expected increase in rainfall due to climate change. This showed that managing impervious cover in a watershed has a greater impact on urban flooding than the expected changes in precipitation caused by climate change. This showed that using GSI and other BMPs to reduce EIC to 10%, the maximum IC for a healthy stream according to the ICM, will not only reduce flooding from extreme precipitation events and increase infiltration from precipitation but also reduce the impacts of climate change-altered rainfall on the watershed.

In summary, implementing GSI and other BMPs in an urban watershed will reduce flooding caused by the more common, smaller extreme precipitation events (less than 1.3 inches), but not eliminate it for extreme events. Other stormwater control measures are still necessary to prevent property damage and health hazards caused by urban flooding particularly during rare events such as the 100-year storm. While climate change will cause an increase in urban flooding, that increase is best addressed by reducing effective impervious cover through GSI and reduction in impervious cover.

4.2 Future Projects at Berry Brook

The findings of this project can be used by future projects in Berry Brook to continue monitoring the changes caused by GSI implementation. Further work into pollutant analysis in the system is necessary to see the complete watershed response.

The PCSWMM software proved extremely useful for the calibration of the two watershed models. However, the software is limited in its ability to deal with groundwater discharge. Further exploration into software to account for groundwater infiltration from GSI resulting in stream baseflow would be helpful for grasping the complete impact of GSI implementation.

4.3 Limitations

This study looked at the Berry Brook Watershed at the full scale. As a result, many small-scale details, such as the exact length of conduits and the number of junctions, were not included to keep the model from having too many parameters to calibrate. These small details may impact the overall watershed response in ways not completely represented by the calibrated model.

This study was unable to model the implemented rain barrel program and installation of 3 filtering catch basins in the Berry Brook watershed. While the model was calibrated excluding the catch basins, this affects the accuracy of the modeled rainfall-runoff responses.

One challenge always present in research is the accuracy of data. The stage-discharge curve used to calculate the observed flow at Station Drive was limited to observations exceeding 15 cfs. For this reason, the model was calibrated with storms of 15 cfs or lower. Most of the results from the storm events modeled calculated flows high above 15 cfs, which limits the certainty of the model.

The rainfall and temperature data used in the model for calibration and long-term analysis were collected 7 miles away from the Berry Brook watershed. Rainfall depths, intensity, and temperature can vary greatly over large spatial distances. This limited calibration efforts to storms observed both at Berry Brook and at the weather station and caused the assumption that the amount of rainfall recorded at the station was equal to the amount of rain falling at Berry Brook.

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Appendix A – Model Calibration

This section provides supplementary information to *2.5 Model Calibration.* It contains the monitoring period rainfall used in the calibration of the Pre-improvements model and Post-improvements model. The full datasets for the rainfall contained hourly rainfall counts. Shown below are the total daily rainfalls at the UNH Morse Hall gage. Total daily rainfalls were computed by summing the hourly rainfall for each day. Days with no rain are not shown on the figures.

Also shown are the SRTC parameter sensitivity values from PCSWMM. These values show the most sensitive parameters for each model for each calibration event.

Supplementary to Section 2.5.1

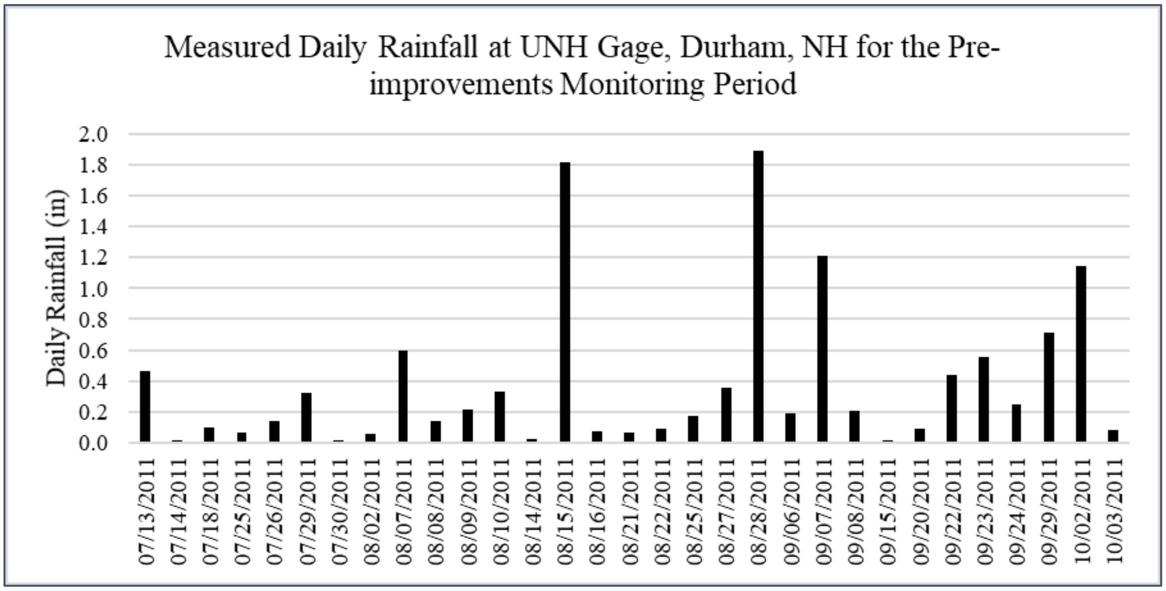

Figure 31: Rainfall for calibration of the Pre-improvements model. The full dataset consisted of hourly data.

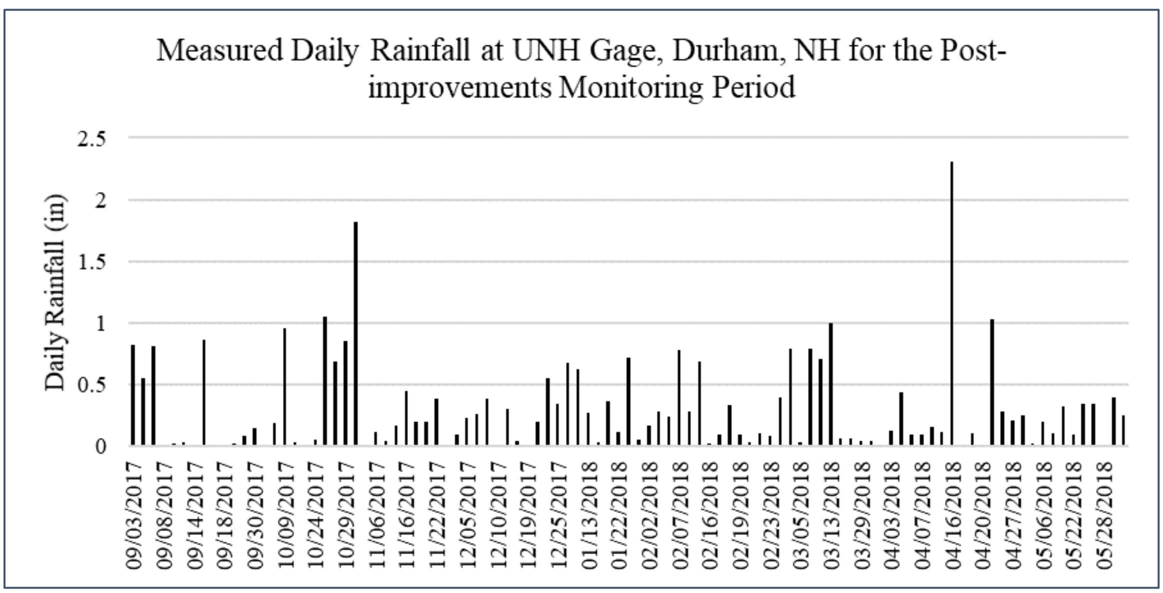

Figure 32: Rainfall for calibration of the post-improvements model. The full dataset consisted of hourly data.

Supplementary to Section 2.5.2

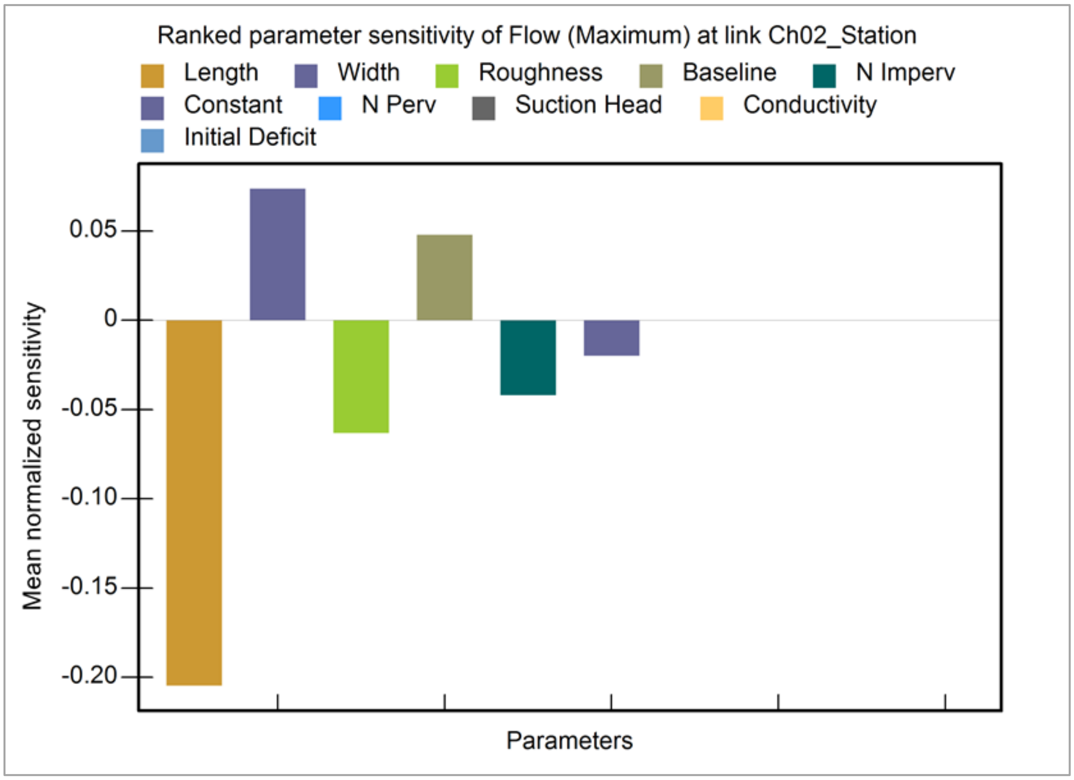

Figure 33: Ranked parameter sensitivity for calibration of the full Pre monitoring period

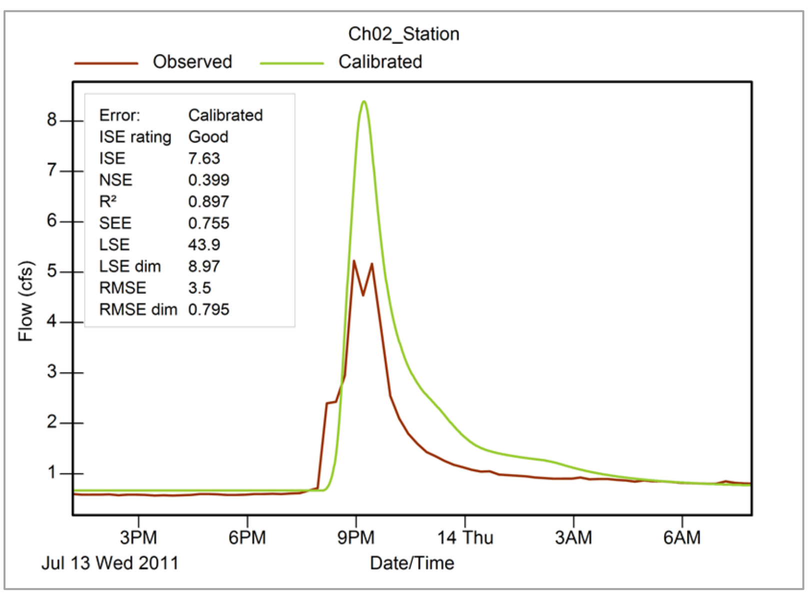

Figure 34: Pre model calibration storm 7/13/2011

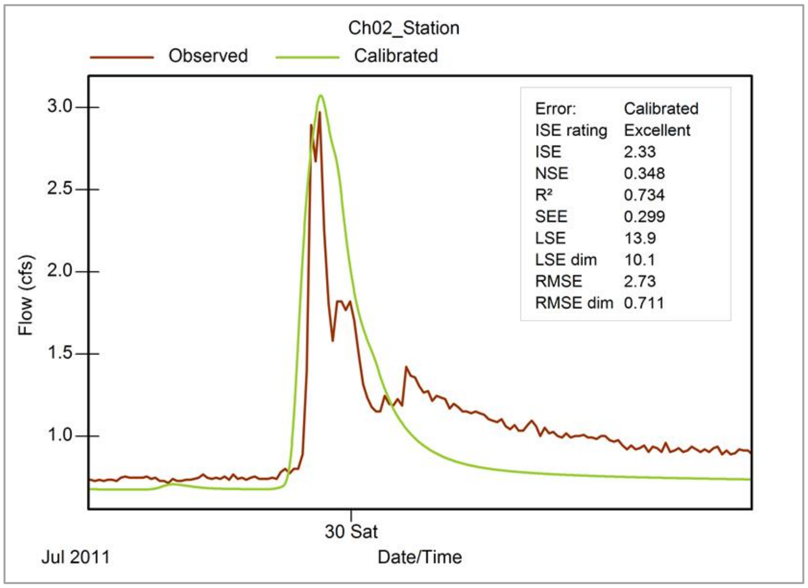

Figure 35: Pre model calibration storm 7/29/2011

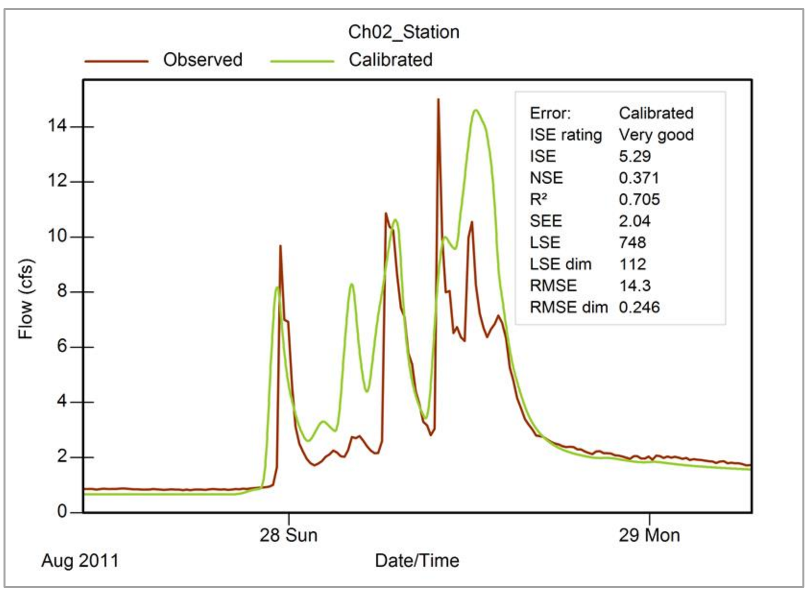

Figure 36: Pre model calibration storm 8/27/2011

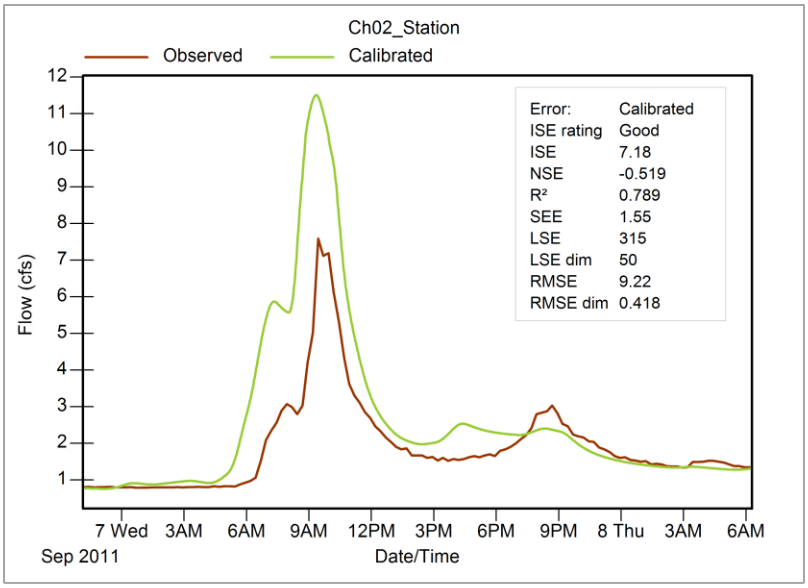

Figure 37: Pre model calibration storm 9/6/2011

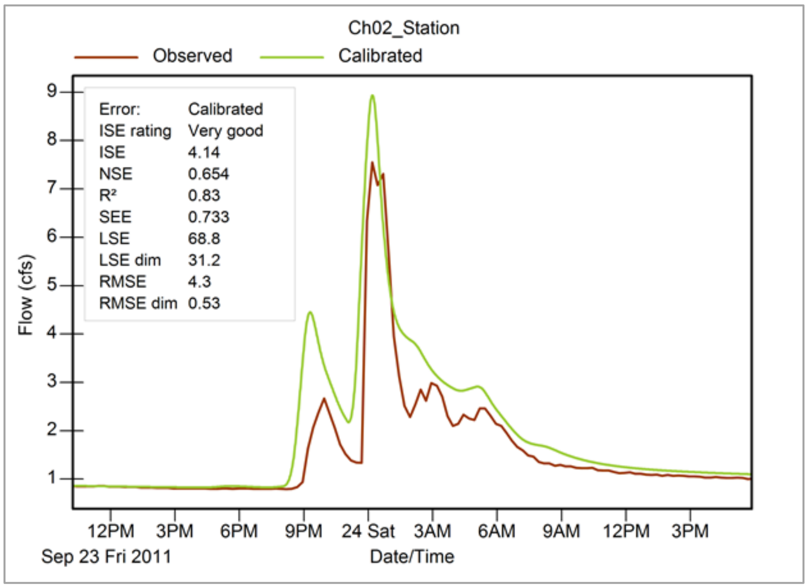

Figure 38: Pre model calibration storm 9/23/2011

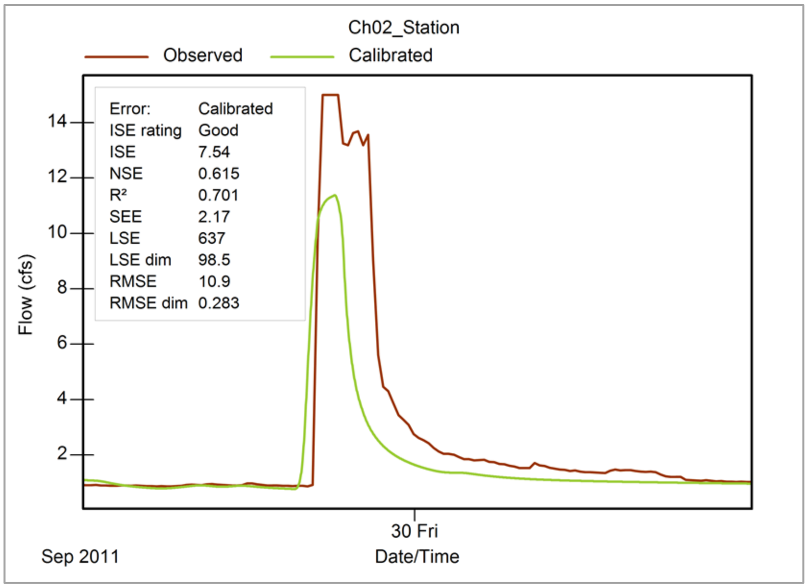

Figure 39: Pre model calibration storm 9/29/2011

Supplementary to Section 2.5.3

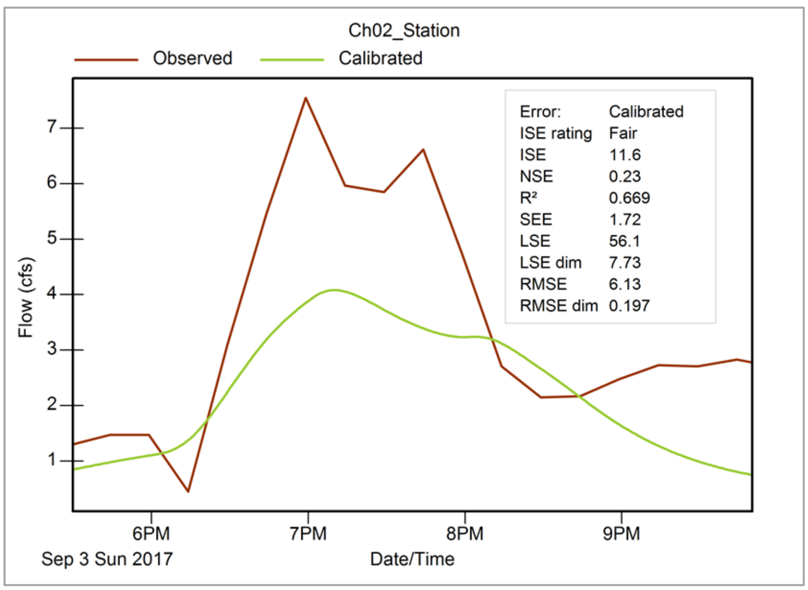

Figure 40: Post model calibration storm 9/3/2017

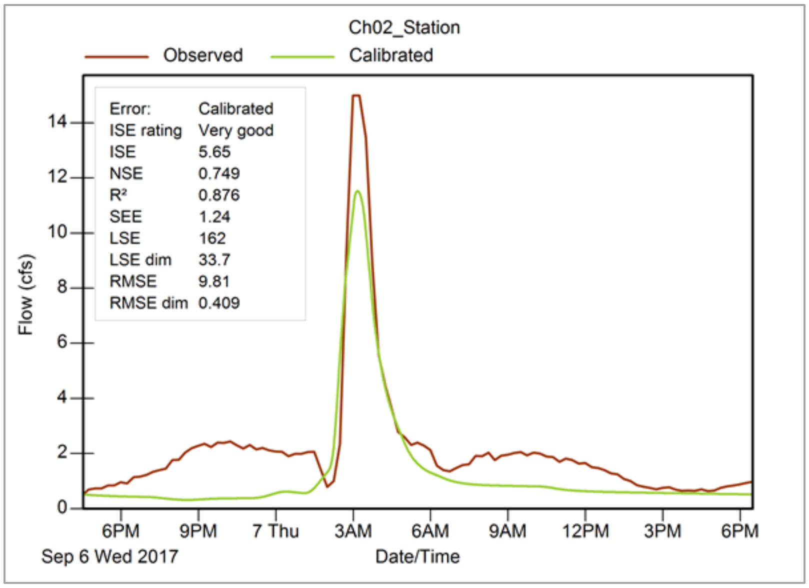

Figure 41: Post model calibration storm 9/6/2017

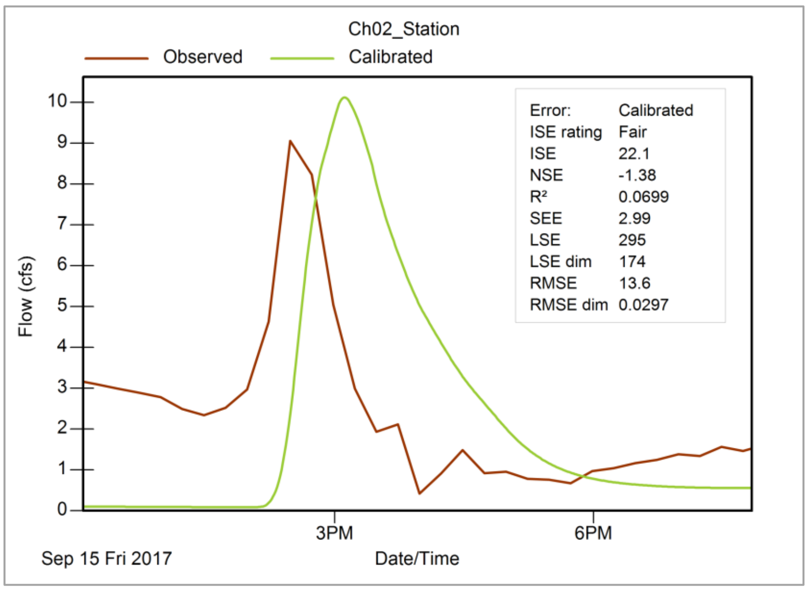

Figure 42: Post model calibration storm 9/15/2017

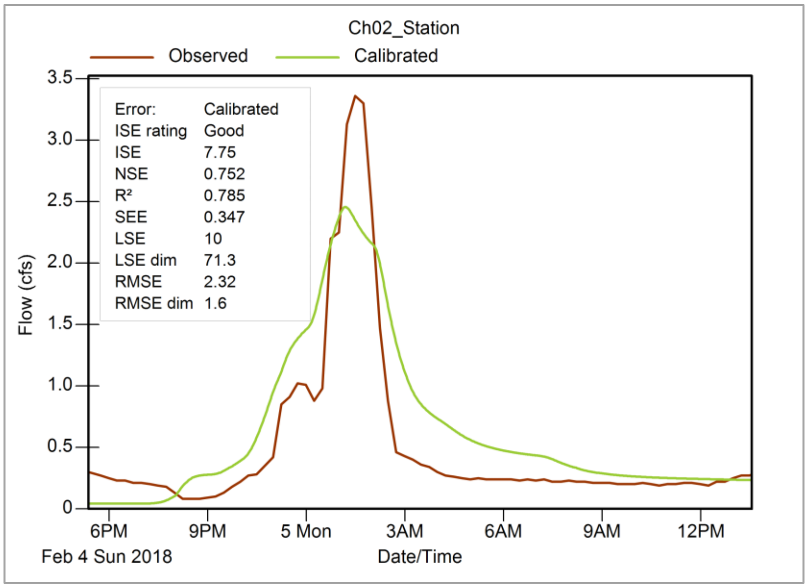

Figure 43: Post model calibration storm 2/4/2018

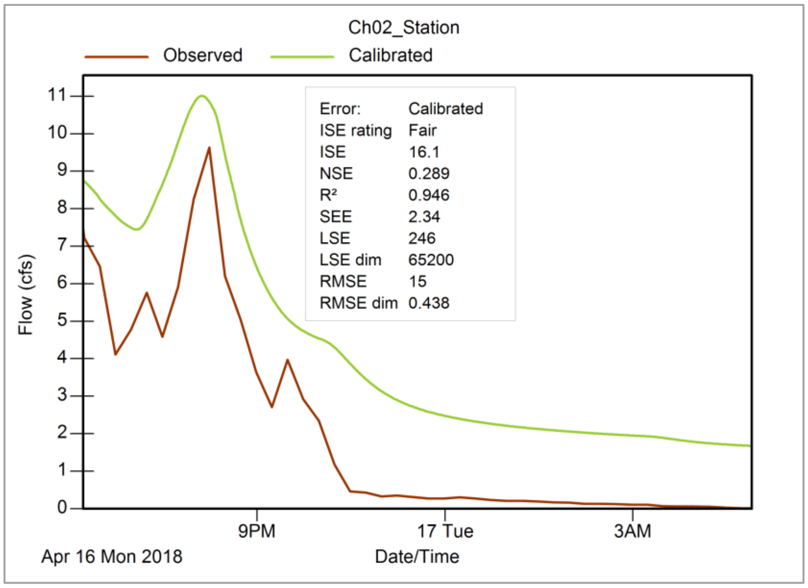

Figure 44: Post model calibration storm 4/16/2018

Appendix B – Model Hydrology

This section provides supplementary information to *2.4 Parameter Estimation* and *2.5 Model Calibration.* It contains an example of the groundwater parameters used in the model, set at the default values for PCSWMM. The parameters were not moved from the default values. It also shows the final calibrated model parameters for the Pre model and the Post model. It should be noted that no parameters were altered from the Pre values for the Pre15 and Pre0 models. Only actively used parameters are listed below.

This section also contains an example of the GSI system parameters input to the Post model.

Example of Groundwater Aquifer Parameters

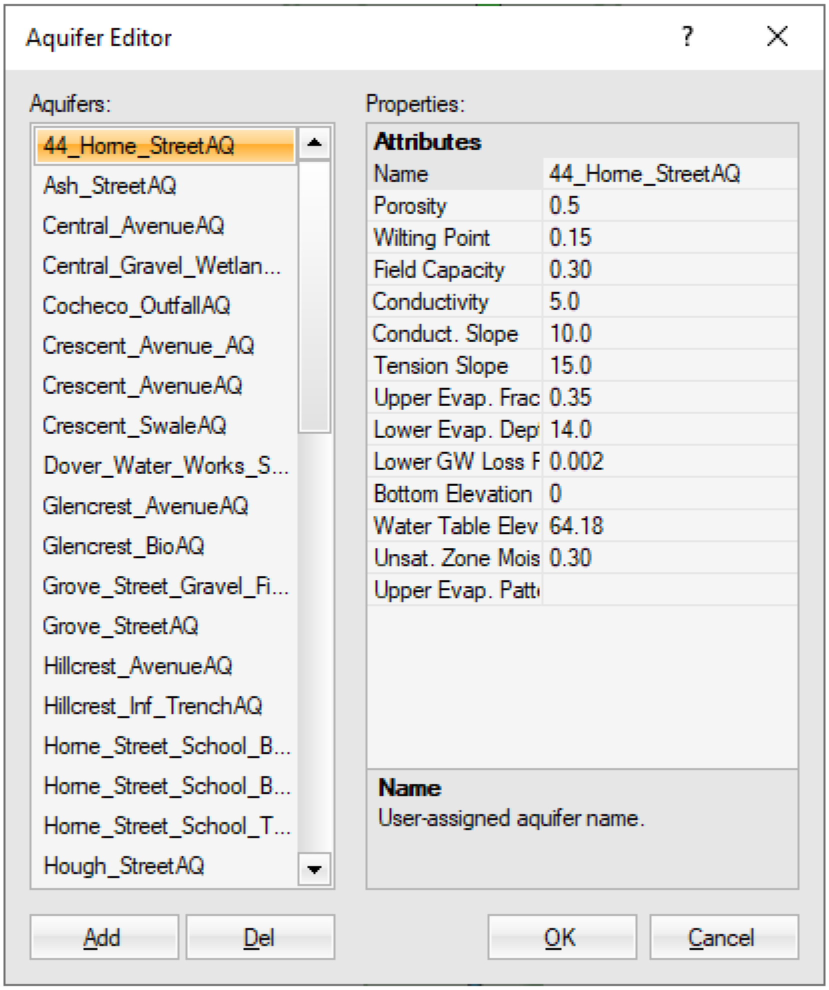

Figure 45: Example of Aquifer Parameter Editor in PCSWMM

Groundwater parameters in a subcatchment were set to match the soil characteristics of the subcatchment. Subcatchment soil parameters are listed below.

Example of GSI System Parameters

Seepage rates in storage areas were assumed to match the infiltration rates of the surrounding subcatchment.

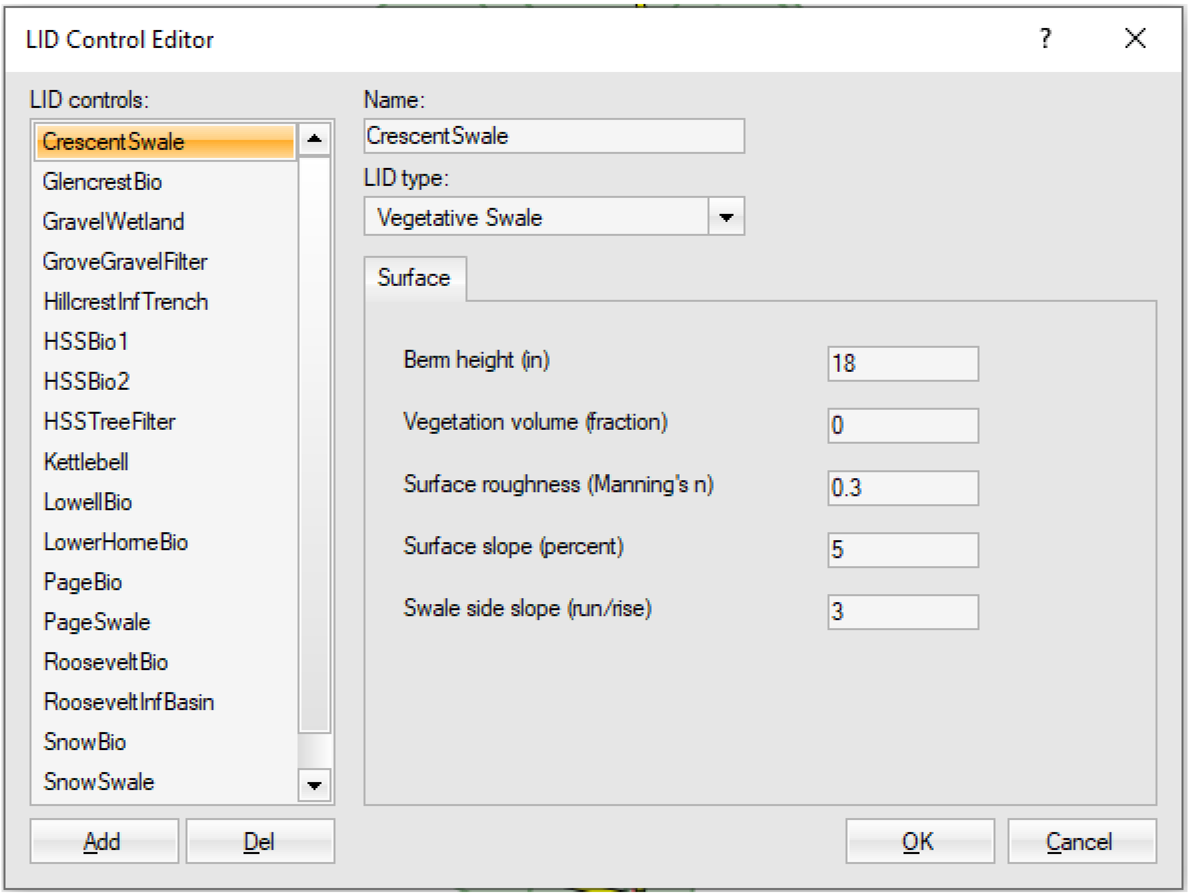

Figure 46: Example of GSI Control Editor in PCSWMM

Table 20: LID Control Soil Media Infiltration Parameters

	K	Ψ	φ	FC	WP
Media	4.74	1.93	0.44	0.06	0.02
Media at increase Infiltration	7.11	2.90	0.66	0.09	0.04

Soil Parameters in Each Subcatchment

Table 21: Soil Parameters by Subcatchment for Aquifers, LID Controls, and Subcatchments

Subcatchment	Porosity	WP	FC	Conductivity (in/hr)	Suction Head (in)	Initial Deficit (frac.)
44_Horne_Street	0.46	0.08	0.17	2.44	4.01	0.53
Ash_Street	0.50	0.14	0.28	0.48	6.69	0.51
Central_Avenue	0.44	0.06	0.13	1.78	2.99	0.52
Central_Gravel_Wetland	0.46	0.08	0.16	1.63	3.79	0.52
Cocheco_Outfall	0.44	0.10	0.22	0.57	5.11	0.46
Crescent_Avenue	0.44	0.05	0.11	2.18	2.40	0.53
Crescent_Swale	0.44	0.05	0.11	2.18	2.40	0.53
Dover_Water_Works_Site	0.44	0.09	0.19	1.13	4.52	0.48
Glencrest_Avenue	0.44	0.05	0.11	2.18	2.40	0.53
Glencrest_Bio	0.46	0.07	0.16	1.67	3.70	0.52
Grove_Street	0.50	0.14	0.28	0.48	6.69	0.51
Grove_Street_Gravel_Filter	0.50	0.14	0.28	0.48	6.69	0.51
Hillcrest_Avenue	0.48	0.10	0.22	2.16	5.27	0.52
Hillcrest_Inf_Trench	0.50	0.14	0.28	0.48	6.69	0.51
Horne_Street_School_Bio_1	0.50	0.14	0.28	0.48	6.69	0.51
Horne_Street_School_Bio_2	0.50	0.14	0.28	0.48	6.69	0.51
Horne_Street_School_Tree_Filter	0.50	0.13	0.28	0.48	6.69	0.51
Hough_Street	0.50	0.14	0.28	0.48	6.69	0.51
HSS Property	0.50	0.14	0.28	0.48	6.69	0.51
HSS_Bio1	0.50	0.14	0.28	0.48	6.69	0.51
HSS_Bio2	0.50	0.14	0.28	0.48	6.69	0.51
HSS_Tree_Filter	0.50	0.14	0.28	0.48	6.69	0.51
HSS_Wet_Pond	0.50	0.14	0.28	0.48	6.69	0.51
Hull_Avenue	0.49	0.12	0.26	0.74	6.03	0.51
Kettlebell_Gravel_Filter	0.50	0.14	0.28	0.48	6.69	0.51
Lowell_Avenue	0.50	0.13	0.28	0.52	6.58	0.51
Lowell_Bio	0.47	0.10	0.21	1.22	4.81	0.52
Lower_Horne_Bio	0.50	0.14	0.28	0.48	6.69	0.51
Lower_Horne_Street	0.49	0.12	0.26	0.76	6.00	0.51
Maple_Street	0.50	0.14	0.28	0.48	6.69	0.51
Page_Avenue	0.47	0.09	0.18	1.44	4.28	0.52
Page_Swale	0.50	0.14	0.28	0.48	6.69	0.51
Redden_Ext_HSS_North	0.45	0.07	0.15	1.74	3.53	0.52
Redden_Street	0.46	0.08	0.17	1.61	3.85	0.52
Redden_Wet_Pond	0.44	0.05	0.10	2.41	2.38	0.53
Roosevelt_Bio	0.46	0.08	0.17	1.54	4.05	0.52
Roosevelt_Inf_Basin	0.50	0.14	0.28	0.48	6.69	0.51
Roosevelt_Lower	0.50	0.13	0.28	0.50	6.64	0.51
Roosevelt_Upper	0.47	0.09	0.19	1.41	4.37	0.52
Seacoast_Kettlebell	0.50	0.14	0.28	0.48	6.69	0.51
Sixth_Street	0.50	0.14	0.28	0.48	6.69	0.51
Snow_Avenue	0.50	0.13	0.28	0.48	6.67	0.51
Snow_Bio	0.50	0.14	0.28	0.48	6.69	0.51
Snow_Swale	0.50	0.14	0.28	0.48	6.69	0.51
Upper_Horne_Bio	0.44	0.05	0.11	2.18	2.40	0.53
Upper_Horne_Street	0.44	0.05	0.11	2.18	2.40	0.53
Wetland_Weir_Wall	0.46	0.08	0.17	1.61	3.87	0.52

Calibrated Parameters for the Pre-improvements Model

All non-zero parameters are included.

Table 22: Junctions in the Pre Model

Name	X-Coordinate	Y-Coordinate	Inflows	Treatment	Invert Elev. (ft)	Rim Elev. (ft)
BB03_Sixth	1193644.598	257349.757	NO	NO	44	44
BB05_Hough	1193975.742	257755.873	NO	NO	45.93	45.93
BB07_Kettlebell	1194056.92	257925.848	NO	NO	52.49	52.49
BB09_Ash	1194156.493	258702.789	NO	NO	59.05	59.05
BB13	1194195.44	259732.469	NO	NO	75.46	75.46
BB14	1194144.322	260151.159	NO	NO	82.02	82.02
BB15_Roosevelt	1194096.537	260366.235	NO	NO	91.86	91.86
J02_01_Redden_Horne	1193853.251	258539.4	NO	NO	63.14	63.14
J02_02_LowerHorne	1193768.404	258546.306	NO	NO	64.18	72.18
J03_01_Ash	1193804.908	258749.545	NO	NO	68.9	68.9
J03_02_Redden	1193771.364	258995.207	NO	NO	70	78
J03_03_Redden	1193712.168	259094.853	NO	NO	71	79
J06_01_HSS	1194127.251	259730.247	NO	NO	95.14	95.14
J06_04_HSS	1193818.32	259702.418	NO	NO	104	112
J07_01_Red_Glen_UpperHorne	1193723.968	260270.208	NO	NO	113	121
J08_01_Roosevelt	1193811.849	260287.224	NO	NO	106.83	114.83
J08_02_Roosevelt	1193761.349	260396.107	NO	NO	113.39	121.39
J09_01_Lowell	1194343.265	260666.048	NO	NO	116.43	124.43
J10_02_Crescent	1194096.825	260873.129	NO	NO	122.03	130.03
J10_03_Crescent	1193827.926	261058.85	NO	NO	129.8	137.8
J12_01_Central	1194117.572	261688.833	NO	NO	138.09	138.09

Table 23: Outfalls in the Pre Model

Name	X-Coordinate	Y-Coordinate	Inflows	Treatment	Invert Elev. (ft)	Rim Elev. (ft)	Tide Gate	Type
O_Cocheco	1193456.258	256394.825	NO	NO	36.09	0	NO	FREE

Table 24: Storages in the Pre Model

Name	X-Coordinate	Y-Coordinate	Inflows	Treatment	Invert Elev. (ft)	Rim Elev. (ft)
Horne_Wet_Pond	1193439.551	259459.377	NO	NO	99.71	101.71
Existing_Wetland	1194023.343	261483.353	YES	NO	133.51	134.51
SP3	1194091.302	260415.981	NO	NO	102	115
SP5	1194301.23	259055.662	NO	NO	65.75	69.75
SP7	1194072.57	258403.504	NO	NO	54	58
SP11	1193685.432	257412.692	NO	NO	45	49
SP10	1194026.638	257806.392	NO	NO	49	56
SP6	1194164.433	258738.149	NO	NO	61	68
Name	**Depth (ft)**	**Storage Curve**	**Coefficient**	**Constant (ft^2)**	**Curve Name**	**Baseline (cfs)**
Horne_Wet_Pond	2	FUNCTIONAL	1230	0	*	0
Existing_Wetland	1	FUNCTIONAL	1230	36230	*	0.75
SP3	13	TABULAR	1000	0	SP3	0
SP5	4	TABULAR	1000	0	SP5	0
SP7	4	TABULAR	1000	0	SP7	0
SP11	4	TABULAR	1000	0	SP11	0
SP10	7	TABULAR	1000	0	SP10	0
SP6	7	TABULAR	1000	0	SP6	0

Table 25: Conduits in the Pre Model Part 1

Name	Inlet Node	Outlet Node
C02_01_Red_Horne	J02_01_Redden_Horne	SP7
C02_02_Red_Horne	J02_02_LowerHorne	J02_01_Redden_Horne
C03_01_Ash	J03_01_Ash	J02_01_Redden_Horne
C03_02_Redden	J03_02_Redden	J03_01_Ash
C03_03_ReddenCulvert	J03_03_Redden	J03_02_Redden
C03_04_WetPond	Horne_Wet_Pond	J03_03_Redden
C06_01_LowerHorne	J06_01_HSS	BB13
C06_02_LowerHorneBio	J06_04_HSS	J06_01_HSS
C07_01_LowerHorne	J07_01_Red_Glen_UpperHorne	J06_04_HSS
C08_01_Roosevelt	J08_01_Roosevelt	BB14
C08_02_Roosevelt	J08_02_Roosevelt	J08_01_Roosevelt
C09_01_Lowell	J09_01_Lowell	SP3
C10_01_Crescent	J10_02_Crescent	SP3
C10_02_Crescent	J10_03_Crescent	J10_02_Crescent
C12_01_Central	J12_01_Central	Existing_Wetland
Ch04_SixthCulvert	SP11	BB03_Sixth
Ch05_Sixth	BB05_Hough	SP11
Ch06_HoughCulvert	SP10	BB05_Hough
Ch07_Hough	BB07_Kettlebell	SP10
Ch08_Kettlebell	SP7	BB07_Kettlebell
Ch09_Ash	BB09_Ash	SP7
Ch11_Maple_Ash	SP5	SP6
Ch14_Roosevelt_Snow	BB14	BB13
Ch15_Roosevelt	BB15_Roosevelt	BB14
Ch16_RooseveltCulvert	SP3	BB15_Roosevelt
Ch21_Headwaters	Existing_Wetland	SP3
Ch13_Snow	BB13	sp5
Ch10_AshCulvert	SP6	BB09_Ash
Ch02_Station	BB03_Sixth	O_Cocheco

Table 26: Conduits in the Pre Model Part 2

Name	Length (ft)	Roughness	Flap Gate	Cross-Section	Geom1 (ft)
C02_01_Red_Horne	522.346	0.016	NO	IRREGULAR	0
C02_02_Red_Horne	176.892	0.016	NO	CIRCULAR	1
C03_01_Ash	474.483	0.016	NO	IRREGULAR	0
C03_02_Redden	584.782	0.016	NO	CIRCULAR	1
C03_03_ReddenCulvert	241.401	0.016	NO	CIRCULAR	1
C03_04_WetPond	946.884	0.016	NO	CIRCULAR	1
C06_01_LowerHorne	141.511	0.016	NO	IRREGULAR	0
C06_02_LowerHorneBio	645.132	0.016	NO	CIRCULAR	1
C07_01_LowerHorne	1236.153	0.016	NO	CIRCULAR	1
C08_01_Roosevelt	747.102	0.016	NO	IRREGULAR	0
C08_02_Roosevelt	249.726	0.016	NO	CIRCULAR	1
C09_01_Lowell	769.995	0.016	NO	CIRCULAR	1
C10_01_Crescent	1042.617	0.016	NO	CIRCULAR	1
C10_02_Crescent	838.668	0.016	NO	TRAPEZOIDAL	1
C12_01_Central	470.322	0.016	NO	CIRCULAR	2
Ch04_SixthCulvert	72.12	0.017	NO	CIRCULAR	5
Ch05_Sixth	478.62	0.017	NO	IRREGULAR	0
Ch06_HoughCulvert	67.437	0.017	NO	CIRCULAR	3
Ch07_Hough	110.523	0.017	NO	IRREGULAR	0
Ch08_Kettlebell	428.979	0.017	NO	IRREGULAR	0
Ch09_Ash	328.758	0.017	NO	IRREGULAR	0
Ch11_Maple_Ash	291.293	0.017	NO	CIRCULAR	3
Ch14_Roosevelt_Snow	425.232	0.017	NO	IRREGULAR	0
Ch15_Roosevelt	215.426	0.017	NO	IRREGULAR	0
Ch16_RooseveltCulvert	46.833	0.017	NO	FILLED_CIRCULAR	4
Ch21_Headwaters	1122.089	0.017	NO	CIRCULAR	1
Ch13_Snow	657.518	0.017	NO	IRREGULAR	0
Ch10_AshCulvert	68.375	0.017	NO	IRREGULAR	0
Ch02_Station	1113.657	0.017	NO	IRREGULAR	0

Table 27: Conduits in the Pre Model Part 3

Name	Geom2 (ft)	Geom3	Geom4	Barrels
C02_01_Red_Horne	0	0	0	1
C02_02_Red_Horne	0	0	0	1
C03_01_Ash	0	0	0	1
C03_02_Redden	0	0	0	1
C03_03_ReddenCulvert	0	0	0	1
C03_04_WetPond	0	0	0	1
C06_01_LowerHorne	0	0	0	1
C06_02_LowerHorneBio	0	0	0	1
C07_01_LowerHorne	0	0	0	1
C08_01_Roosevelt	0	0	0	1
C08_02_Roosevelt	0	0	0	1
C09_01_Lowell	0	0	0	1
C10_01_Crescent	0	0	0	1
C10_02_Crescent	2	2	2	1
C12_01_Central	0	0	0	1
Ch04_SixthCulvert	0	0	0	1
Ch05_Sixth	0	0	0	1
Ch06_HoughCulvert	0	0	0	1
Ch07_Hough	0	0	0	1
Ch08_Kettlebell	0	0	0	1
Ch09_Ash	0	0	0	1
Ch11_Maple_Ash	0	0	0	1
Ch14_Roosevelt_Snow	0	0	0	1
Ch15_Roosevelt	0	0	0	1
Ch16_RooseveltCulvert	0.5	0	0	1
Ch21_Headwaters	0	0	0	1
Ch13_Snow	0	0	0	1
Ch10_AshCulvert	0	0	0	1
Ch02_Station	0	0	0	1

Table 28: Conduits in the Pre Model Part 4

Name	Transect	Control Rules	Slope (ft/ft)
C02_01_Red_Horne	Maple_X-Section	NO	0.0175
C02_02_Red_Horne		NO	0.00588
C03_01_Ash	Maple_X-Section	NO	0.01214
C03_02_Redden		NO	0.00188
C03_03_ReddenCulvert		NO	0.00414
C03_04_WetPond		NO	0.03033
C06_01_LowerHorne	Maple_X-Section	NO	0.14044
C06_02_LowerHorneBio		NO	0.01373
C07_01_LowerHorne		NO	0.00728
C08_01_Roosevelt	Maple_X-Section	NO	0.03323
C08_02_Roosevelt		NO	0.02628
C09_01_Lowell		NO	0.01874
C10_01_Crescent		NO	0.01921
C10_02_Crescent		NO	0.00927
C12_01_Central		NO	0.00974
Ch04_SixthCulvert		NO	0.01387
Ch05_Sixth	Hough_X-Section	NO	0.00194
Ch06_HoughCulvert		NO	0.04557
Ch07_Hough	Maple_X-Section	NO	0.03159
Ch08_Kettlebell	Maple_X-Section	NO	0.00352
Ch09_Ash	Maple_X-Section	NO	0.01536
Ch11_Maple_Ash		NO	0.01631
Ch14_Roosevelt_Snow	Maple_X-Section	NO	0.01543
Ch15_Roosevelt	Maple_X-Section	NO	0.04572
Ch16_RooseveltCulvert		NO	0.22177
Ch21_Headwaters		NO	0.02809
Ch13_Snow	Maple_X-Section	NO	0.01477
Ch10_AshCulvert	Maple_X-Section	NO	0.02853
Ch02_Station	Station_X-Section	NO	0.0071

Table 29: Subcatchments in the Pre Model Part 1

Name	X-Coordinate	Y-Coordinate	Tag	Outlet	Area (ac)	Width (ft)	Slope (%)
44_Horne_Street	1193399.984	258988.832	Lower	J02_02_LowerHorne	9.771	25.77	10.5
Ash_Street	1194204.119	258898.618	Lower	SP6	5.838	37.794	8.7
Central_Avenue	1194253.554	262006.058	Upper	J12_01_Central	11.539	46.221	3.3
Central_Gravel_Wetland	1194117.129	261663.626	Upper	J12_01_Central	0.14	4.991	0.5
Cocheco_Outfall	1193624.728	256926.99	Outfall	O_Cocheco	13.046	31.007	10.2
Crescent_Avenue	1193624.186	261266.021	Upper	J10_03_Crescent	2.936	14.234	6.1
Crescent_Swale	1193961.414	261078.189	Upper	J10_02_Crescent	0.062	2.208	0.5
Dover_Water_Works_Site	1194302.722	260836.902	Upper	SP3	7.333	44.665	8.2
Glencrest_Avenue	1193023.682	260878.371	Lower	J07_01_Red_Glen_UpperHorne	6.803	26.667	6.2
Glencrest_Bio	1193332.366	260441.78	Lower	J07_01_Red_Glen_UpperHorne	0.098	9.901	0.5
Grove_Street	1194746.271	259600.556	Lower	Maple_Street	2.538	21.024	8.7
Grove_Street_Gravel_Filter	1194586.896	259448.469	Lower	Maple_Street	0.06	6.053	0.5
Hillcrest_Avenue	1192935.929	259075.605	Lower	J02_02_LowerHorne	3.881	18.978	6.8
Hillcrest_Inf_Trench	1193021.313	258778.54	Lower	J02_02_LowerHorne	0.006	0.328	0.5
Horne_Street_School_Bio_1	1193663.943	259979.37	Lower	J06_04_HSS	0.145	5.156	0.5
Horne_Street_School_Bio_2	1193719.567	259849.3	Lower	J06_04_HSS	0.072	6.38	0.5
Horne_Street_School_Tree_Filter	1193617.073	259674.9	Lower	Horne_Wet_Pond	0.331	7.363	6.3
Hough_Street	1194015.909	258240.741	Lower	SP10	9.745	39.268	8.1
HSS_Bio1	1193719.669	259991.939	Lower	J06_04_HSS	0.015	0.983	0.5
HSS_Bio2	1193752.526	259855.084	Lower	J06_04_HSS	0.015	1.881	0.5
HSS_Property	1193699.088	259873.858	Lower	J06_04_HSS	1.232	10.963	3.7
HSS_Tree_Filter	1193647.445	259613.664	Lower	Horne_Wet_Pond	0.003	1.144	0.5
HSS_Wet_Pond	1193554.472	259815.668	Lower	Horne_Wet_Pond	0.495	6.38	0.5
Hull_Avenue	1193233.846	258408.46	Lower	J02_02_LowerHorne	15.03	45.813	8.3
Kettlebell_Gravel_Filter	1193999.871	258020.513	Lower	BB07_Kettlebell	0.042	2.454	0.5
Lowell_Avenue	1194634.27	260684.018	Upper	J09_01_Lowell	0.787	4.008	7.2
Lowell_Bio	1194289.776	260559.055	Upper	SP3	0.062	1.801	0.5
Lower_Horne_Bio	1193977.532	259711.251	Lower	J06_01_HSS	0.026	1.064	0.5
Lower_Horne_Street	1193684.104	260185.191	Lower	J06_04_HSS	2.34	8.834	5
Maple_Street	1194360.433	259824.32	Lower	SP5	24.651	62.745	12.8
Page_Avenue	1194673.999	261118.447	Upper	Dover_Water_Works_Site	5.01	23.068	5.8
Page_Swale	1194331.716	261289.974	Upper	Dover_Water_Works_Site	0.179	2.126	4.2
Redden_Ext_HSS_North	1193110.085	260355.413	Lower	J06_04_HSS	13.102	28.306	5.6
Redden_Street	1193503.891	259391.713	Lower	J03_03_Redden	8.76	33.54	8.8
Redden_Wet_Pond	1193128.113	259794.514	Lower	Horne_Wet_Pond	3.914	10.963	7.3
Roosevelt_Bio	1194208.818	260476.136	Upper	SP3	0.028	1.961	0.5
Roosevelt_Inf_Basin	1194234.743	260427.841	Upper	SP3	0.045	2.29	0.5
Roosevelt_Lower	1194374.675	260449.831	Upper	SP3	2.514	11.454	6.7
Roosevelt_Upper	1194219.281	260553.087	Upper	SP3	4.615	19.143	8.5
Seacoast_Kettlebell	1193996.468	258170.245	Lower	BB07_Kettlebell	2.067	18.899	5.8
Sixth_Street	1193882.699	257518.651	Lower	SP11	8.603	48.672	6.3
Snow_Avenue	1193953.205	259404.612	Lower	SP5	3.098	20.86	6.2
Snow_Bio	1194014.108	259191.406	Lower	SP5	0.085	1.474	0.5
Snow_Swale	1194201.262	259191.52	Lower	SP5	0.042	0.983	5
Upper_Horne_Bio	1193579.608	260474.953	Lower	J07_01_Red_Glen_UpperHorne	0.167	3.603	0.5
Upper_Horne_Street	1193449.03	260986.996	Lower	J07_01_Red_Glen_UpperHorne	11.394	39.019	5.4
Wetland_Weir_Wall	1193950.58	261460.087	Upper	Existing_Wetland	13.087	44.421	6.6

Table 30: Subcatchments in the Pre Model Part 2

Name	Imperv. (%)	N Imperv	N Perv	Dstore Imperv (in)	Dstore Perv (in)	Zero Imperv (%)
44_Horne_Street	28	0.015	0.2	0.05	0.05	100
Ash_Street	38	0.015	0.2	0.05	0.05	100
Central_Avenue	88	0.015	0.2	0.05	0.05	100
Central_Gravel_Wetland	0	0.015	0.2	0.05	0.05	100
Cocheco_Outfall	22	0.015	0.2	0.05	0.05	100
Crescent_Avenue	49	0.015	0.2	0.05	0.05	100
Crescent_Swale	0	0.015	0.2	0.05	0.05	100
Dover_Water_Works_Site	18	0.015	0.2	0.05	0.05	100
Glencrest_Avenue	37	0.015	0.2	0.05	0.05	100
Glencrest_Bio	0	0.015	0.2	0.05	0.05	100
Grove_Street	33	0.015	0.2	0.05	0.05	100
Grove_Street_Gravel_Filter	100	0.015	0.2	0.05	0.05	100
Hillcrest_Avenue	32	0.015	0.2	0.05	0.05	100
Hillcrest_Inf_Trench	0	0.015	0.2	0.05	0.05	100
Horne_Street_School_Bio_1	100	0.015	0.2	0.05	0.05	100
Horne_Street_School_Bio_2	100	0.015	0.2	0.05	0.05	100
Horne_Street_School_Tree_Filter	100	0.015	0.2	0.05	0.05	100
Hough_Street	44	0.015	0.2	0.05	0.05	100
HSS_Bio1	0	0.015	0.2	0.05	0.05	100
HSS_Bio2	0	0.015	0.2	0.05	0.05	100
HSS_Property	76	0.015	0.2	0.05	0.05	100
HSS_Tree_Filter	100	0.015	0.2	0.05	0.05	100
HSS_Wet_Pond	100	0.015	0.2	0.05	0.05	100
Hull_Avenue	30	0.015	0.2	0.05	0.05	100
Kettlebell_Gravel_Filter	100	0.015	0.2	0.05	0.05	100
Lowell_Avenue	66	0.015	0.2	0.05	0.05	100
Lowell_Bio	0	0.015	0.2	0.05	0.05	100
Lower_Horne_Bio	0	0.015	0.2	0.05	0.05	100
Lower_Horne_Street	50	0.015	0.2	0.05	0.05	100
Maple_Street	15	0.015	0.2	0.05	0.05	100
Page_Avenue	40	0.015	0.2	0.05	0.05	100
Page_Swale	0	0.015	0.2	0.05	0.05	100
Redden_Ext_HSS_North	29	0.015	0.2	0.05	0.05	100
Redden_Street	10	0.015	0.2	0.05	0.05	100
Redden_Wet_Pond	37	0.015	0.2	0.05	0.05	100
Roosevelt_Bio	0	0.015	0.2	0.05	0.05	100
Roosevelt_Inf_Basin	0	0.015	0.2	0.05	0.05	100
Roosevelt_Lower	41	0.015	0.2	0.05	0.05	100
Roosevelt_Upper	29	0.015	0.2	0.05	0.05	100
Seacoast_Kettlebell	95	0.015	0.2	0.05	0.05	100
Sixth_Street	46	0.015	0.2	0.05	0.05	100
Snow_Avenue	40	0.015	0.2	0.05	0.05	100
Snow_Bio	0	0.015	0.2	0.05	0.05	100
Snow_Swale	0	0.015	0.2	0.05	0.05	100
Upper_Horne_Bio	0	0.015	0.2	0.05	0.05	100
Upper_Horne_Street	33	0.015	0.2	0.05	0.05	100
Wetland_Weir_Wall	19	0.015	0.2	0.05	0.05	100

Table 31: Subcatchments in the Pre Model Part 3

Name	Subarea Routing	Percent Routed (%)	LID Control	Groundwater	Aquifer Name
44_Horne_Street	OUTLET	100	0	NO	
Ash_Street	OUTLET	100	0	YES	Ash_StreetAQ
Central_Avenue	OUTLET	100	0	NO	
Central_Gravel_Wetland	OUTLET	100	0	NO	
Cocheco_Outfall	OUTLET	100	0	YES	Cocheco_OutfallAQ
Crescent_Avenue	OUTLET	100	0	NO	
Crescent_Swale	OUTLET	100	0	NO	
Dover_Water_Works_Site	OUTLET	100	0	YES	Dover_Water_Works_SiteAQ
Glencrest_Avenue	PERVIOUS	100	0	NO	
Glencrest_Bio	PERVIOUS	100	0	NO	
Grove_Street	PERVIOUS	100	0	NO	
Grove_Street_Gravel_Filter	OUTLET	100	0	NO	
Hillcrest_Avenue	OUTLET	100	0	NO	
Hillcrest_Inf_Trench	OUTLET	100	0	NO	
Horne_Street_School_Bio_1	OUTLET	100	0	NO	
Horne_Street_School_Bio_2	OUTLET	100	0	NO	
Horne_Street_School_Tree_Filter	OUTLET	100	0	NO	
Hough_Street	OUTLET	100	0	YES	Hough_StreetAQ
HSS_Bio1	OUTLET	100	0	NO	
HSS_Bio2	OUTLET	100	0	NO	
HSS_Property	OUTLET	100	0	NO	
HSS_Tree_Filter	OUTLET	100	0	NO	
HSS_Wet_Pond	OUTLET	100	0	NO	
Hull_Avenue	OUTLET	100	0	NO	
Kettlebell_Gravel_Filter	OUTLET	100	0	NO	Kettlebell_Gravel_FilterAQ
Lowell_Avenue	OUTLET	100	0	NO	
Lowell_Bio	OUTLET	100	0	NO	
Lower_Horne_Bio	OUTLET	100	0	NO	
Lower_Horne_Street	OUTLET	100	0	NO	
Maple_Street	OUTLET	100	0	YES	Maple_StreetAQ
Page_Avenue	PERVIOUS	100	0	NO	
Page_Swale	OUTLET	100	0	NO	
Redden_Ext_HSS_North	OUTLET	100	0	NO	
Redden_Street	OUTLET	100	0	NO	
Redden_Wet_Pond	OUTLET	100	0	NO	
Roosevelt_Bio	OUTLET	100	0	NO	
Roosevelt_Inf_Basin	OUTLET	100	0	NO	
Roosevelt_Lower	OUTLET	100	0	YES	Roosevelt_LowerAQ
Roosevelt_Upper	OUTLET	100	0	YES	Roosevelt_UpperAQ
Seacoast_Kettlebell	OUTLET	100	0	NO	
Sixth_Street	OUTLET	100	0	YES	Sixth_StreetAQ
Snow_Avenue	OUTLET	100	0	NO	
Snow_Bio	OUTLET	100	0	NO	
Snow_Swale	OUTLET	100	0	NO	
Upper_Horne_Bio	OUTLET	100	0	NO	
Upper_Horne_Street	OUTLET	100	0	NO	
Wetland_Weir_Wall	PERVIOUS	100	0	YES	Wetland_Weir_WallAQ

Table 32: Subcatchments in the Pre Model Part 4

Name	Receiving Node	Surface Elevation (ft)	A1 Coefficient	B1 Exponent	A2 Coefficient	B2 Exponent
44_Horne_Street		0	0	0	0	0
Ash_Street	SP6	61	0.1	1	0.1	1
Central_Avenue		0	0	0	0	0
Central_Gravel_Wetland		0	0	0	0	0
Cocheco_Outfall	O_Cocheco	36.09	0.1	1	0.1	1
Crescent_Avenue		0	0	0	0	0
Crescent_Swale		0	0	0	0	0
Dover_Water_Works_Site	SP3	102	0.1	1	0.1	1
Glencrest_Avenue		0	0	0	0	0
Glencrest_Bio		0	0	0	0	0
Grove_Street		0	0	0	0	0
Grove_Street_Gravel_Filter		0	0	0	0	0
Hillcrest_Avenue		0	0	0	0	0
Hillcrest_Inf_Trench		0	0	0	0	0
Horne_Street_School_Bio_1		0	0	0	0	0
Horne_Street_School_Bio_2		0	0	0	0	0
Horne_Street_School_Tree_Filter		0	0	0	0	0
Hough_Street	SP10	56	0.1	1	0.1	1
HSS_Bio1		0	0	0	0	0
HSS_Bio2		0	0	0	0	0
HSS_Property		0	0	0	0	0
HSS_Tree_Filter		0	0	0	0	0
HSS_Wet_Pond		0	0	0	0	0
Hull_Avenue		0	0	0	0	0
Kettlebell_Gravel_Filter	BB07_Kettlebell	52.49	0.1	1	0.1	1
Lowell_Avenue		0	0	0	0	0
Lowell_Bio		0	0	0	0	0
Lower_Horne_Bio		0	0	0	0	0
Lower_Horne_Street		0	0	0	0	0
Maple_Street	SP5	65.75	0.1	1	0.1	1
Page_Avenue		0	0	0	0	0
Page_Swale		0	0	0	0	0
Redden_Ext_HSS_North		0	0	0	0	0
Redden_Street		0	0	0	0	0
Redden_Wet_Pond		0	0	0	0	0
Roosevelt_Bio		0	0	0	0	0
Roosevelt_Inf_Basin		0	0	0	0	0
Roosevelt_Lower	SP3	102	0.1	1	0.1	1
Roosevelt_Upper	SP3	102	0.1	1	0.1	1
Seacoast_Kettlebell		0	0	0	0	0
Sixth_Street	SP11	49	0.1	1	0.1	1
Snow_Avenue		0	0	0	0	0
Snow_Bio		0	0	0	0	0
Snow_Swale		0	0	0	0	0
Upper_Horne_Bio		0	0	0	0	0
Upper_Horne_Street		0	0	0	0	0
Wetland_Weir_Wall	Existing_Wetland	134.51	0.1	1	0.1	1

Calibrated Parameters for the Post-improvements Model

Table 33: Junctions in the Post Model

X-Coordinate	Y-Coordinate	Inflows	Treatment	Invert Elev. (ft)	Rim Elev. (ft)	Depth (ft)
1193644.598	257349.757	NO	NO	44	49	5
1193975.742	257755.873	NO	NO	45.93	45.93	0
1194056.92	257925.848	NO	NO	52.49	52.49	0
1194156.493	258702.789	NO	NO	59.05	59.05	0
1194317.701	259181.754	NO	NO	66	66	0
1194195.44	259732.469	NO	NO	75.46	75.46	0
1194144.322	260151.159	NO	NO	82.02	82.02	0
1194096.537	260366.235	NO	NO	91.86	91.86	0
1194114.51	260480.323	NO	NO	104.99	104.99	0
1194116.704	260653.565	NO	NO	121.39	121.39	0
1194159.362	261036.728	NO	NO	131.23	131.23	0
1193681.732	258247.679	NO	NO	60.9	68.9	8
1193009.905	258739.379	NO	NO	110.11	118.11	8
1193853.251	258539.4	NO	NO	63.14	63.14	0
1193768.404	258546.306	NO	NO	64.18	72.18	8
1193804.908	258749.545	NO	NO	68.9	68.9	0
1193771.364	258995.207	NO	NO	70	78	8
1193712.168	259094.853	NO	NO	71	79	8
1193641.507	259609.304	NO	NO	103.55	111.55	8
1194279.16	259194.741	NO	NO	67.46	75.46	8
1194562.571	259417.237	NO	NO	90.43	98.43	8
1194127.251	259730.247	NO	NO	95.41	95.41	0
1194015.955	259717.223	NO	NO	100.61	104.61	4
1193818.32	259702.418	NO	NO	104	112	8
1193782.381	259813.808	NO	NO	106.83	114.83	8
1193731.263	259961.89	NO	NO	110.11	118.11	8
1193723.968	260270.208	NO	NO	113	121	8
1193633.461	260387.914	NO	NO	113.39	121.39	8
1194204.513	260491.722	NO	NO	106.83	114.83	8
1194225.702	260507.887	NO	NO	110.11	118.11	8
1193998.218	261118.095	NO	NO	132.51	134.51	2
1194145.047	261320.065	NO	NO	131.07	133.07	2
1194084.434	261617.756	NO	NO	137.08	141.08	4

Table 34: Outfalls in the Post Model

Name	X-Coordinate	Y-Coordinate	Inflows	Treatment	
O_Cocheco	1193456.258	256394.825	NO	NO	
O_06_03_LowerHorneBio	1193930.763	259714.898	NO	NO	
Name	**Invert Elev. (ft)**	**Rim Elev. (ft)**	**Tide Gate**	**Route To**	**Type**
O_Cocheco	36.09	0	NO		FREE
O_06_03_LowerHorneBio	103.79	0	NO	Lower_Horn	FREE

Table 35: Storages in the Post Model

Name	X-Coordinate	Y-Coordinate	Inflows	Treatment	Invert Elev. (ft)	Rim Elev. (ft)	Depth (ft)
Horne_Wet_Pond	1193439.551	259459.377	NO	NO	99.71	101.71	2
Existing_Wetland	1194023.343	261483.353	NO	NO	133.51	134.51	1
New_Wetland	1194076.158	261308.855	YES	NO	128.83	131.33	2.5
SP1	1194091.302	260415.981	NO	NO	93	106	13
SP2	1194301.23	259055.662	NO	NO	65.75	69.75	4
SP3	1194174.228	258773.372	NO	NO	59.3	66.3	7
SP4	1194072.57	258403.504	NO	NO	56	60	4
SP6	1194026.638	257806.392	NO	NO	49	56	7
SP7	1193685.432	257412.692	NO	NO	45	49	4
Name	**Initial Depth (ft)**	**Storage Curve**	**Coefficient**	**Constant (ft²**	**Curve Name**	**Baseline (cfs)**	
Horne_Wet_Pond	0.5	FUNCTIONAL	1230	0	*	0	
Existing_Wetland	0.5	FUNCTIONAL	1230	36230	*	0	
New_Wetland	0.5	FUNCTIONAL	1230	43560	*	0.75	
SP1	0.5	TABULAR	1000	0	SP1	0	
SP2	0.5	TABULAR	1000	0	SP2	0	
SP3	0.5	TABULAR	1000	0	SP3	0	
SP4	0.5	TABULAR	1000	0	SP4	0	
SP6	0.5	TABULAR	1000	0	SP6	0	
SP7	0.5	TABULAR	1000	0	SP7	0	

Table 36: Conduits in the Post Model Part 1

Name	Inlet Node	Outlet Node
C01_01_Hull_Red	J01_01_Hull_Redden	BB07_Kettlebell
C01_02_Hull	J01_02_Hillcrest	J01_01_Hull_Redden
C02_01_Red_Horne	J02_01_Redden_Horne	SP4
C02_02_Red_Horne	J02_02_LowerHorne	J02_01_Redden_Horne
C03_01_Ash	J03_01_Ash	J02_01_Redden_Horne
C03_02_Redden	J03_02_Redden	J03_01_Ash
C03_03_Redden	J03_03_Redden	J03_02_Redden
C03_04_WetPond	Horne_Wet_Pond	J03_03_Redden
C03_05_HSSTreeFilter	J03_04_HSSTreeFilter	Horne_Wet_Pond
C04_01_Snow	J04_01_Snow	BB12_Snow
C05_01_Grove	J05_01_Grove	BB12_Snow
C06_01_HSS_LowerHorne	J06_01_HSS	BB13
C06_02_LowerHorneBio	J06_02_LowerHorneBio	J06_01_HSS
C06_03_LowerHorneBio	J06_04_HSS	O_06_03_LowerHorneBio
C06_04_HSSBio2	J06_05_HSSBio2	J06_04_HSS
C06_05_HSSBio1	J06_06_HSSBio1	J06_05_HSSBio2
C07_01_LowerHorne	J07_01_Red_Glen_UpperHorne	J06_04_HSS
C07_02_UpperHorne	J07_02_UpperHorne	J07_01_Red_Glen_UpperHorne
C08_01_RooseveltBio	J08_01_RooseveltBio	SP1
C09_01_Lowell	J09_01_Lowell	SP1
C10_01_Crescent	J10_01_Crescent	New_Wetland
C11_01_Page	J11_01_Page	New_Wetland
C12_01_Central	J12_01_Central	Existing_Wetland
Ch04_SixthCulvert	SP7	BB03_Sixth
Ch05_Sixth	BB05_Hough	SP7
Ch06_HoughCulvert	SP6	BB05_Hough
Ch07_Hough	BB07_Kettlebell	SP6
Ch08_Kettlebell	SP4	BB07_Kettlebell
Ch09_Ash_Kettlebell	BB09_Ash	SP4
Ch10_AshCulvert	SP3	BB09_Ash
Ch11_Maple_Ash	SP2	SP3
Ch13_Snow	BB13	BB12_Snow
Ch14_Roosevelt_Snow	BB14	BB13
Ch15_Roosevelt	BB15_Roosevelt	BB14
Ch16_RooseveltCulvert	SP1	BB15_Roosevelt
Ch17_A2_Channel	BB17_A1-A2_Channel	SP1
Ch18_A1_Channel	BB18_C-A_Channel	BB17_A1-A2_Channel
Ch19_C_Channel	BB19_Weir-C_Channel	BB18_C-A_Channel
Ch20_Wetland	BB19_Weir-C_Channel	New_Wetland
Ch21_Wetland	Existing_Wetland	New_Wetland
Ch12_Snow_Maple	BB12_Snow	SP2
Ch02_Station	BB03_Sixth	O_Cocheco

Table 37: Conduits in the Post Model Part 2

Name	Length (ft)	Roughness	Flap Gate	Cross-Section
C01_01_Hull_Red	695.187	0.017	NO	CIRCULAR
C01_02_Hull	1021.996	0.017	NO	CIRCULAR
C02_01_Red_Horne	250.193	0.017	NO	IRREGULAR
C02_02_Red_Horne	85.128	0.017	NO	CIRCULAR
C03_01_Ash	226.953	0.017	NO	IRREGULAR
C03_02_Redden	280.552	0.017	NO	CIRCULAR
C03_03_Redden	115.903	0.017	NO	CIRCULAR
C03_04_WetPond	455.239	0.017	NO	CIRCULAR
C03_05_HSSTreeFilter	251.524	0.017	NO	CIRCULAR
C04_01_Snow	40.671	0.017	NO	TRAPEZOIDAL
C05_01_Grove	444.871	0.017	NO	TRAPEZOIDAL
C06_01_HSS_LowerHorne	68.225	0.017	NO	IRREGULAR
C06_02_LowerHorneBio	112.049	0.017	NO	CIRCULAR
C06_03_LowerHorneBio	112.747	0.017	NO	CIRCULAR
C06_04_HSSBio2	126.121	0.017	NO	CIRCULAR
C06_05_HSSBio1	162.796	0.017	NO	CIRCULAR
C07_01_LowerHorne	594.062	0.017	NO	CIRCULAR
C07_02_UpperHorne	158.779	0.017	NO	CIRCULAR
C08_01_RooseveltBio	136.211	0.017	NO	CIRCULAR
C09_01_Lowell	173.144	0.017	NO	CIRCULAR
C10_01_Crescent	206.068	0.017	NO	TRAPEZOIDAL
C11_01_Page	69.795	0.017	NO	TRAPEZOIDAL
C12_01_Central	147.692	0.017	NO	CIRCULAR
Ch04_SixthCulvert	77.071	0.017	NO	CIRCULAR
Ch05_Sixth	510.621	0.017	NO	IRREGULAR
Ch06_HoughCulvert	71.979	0.017	NO	CIRCULAR
Ch07_Hough	117.64	0.017	NO	IRREGULAR
Ch08_Kettlebell	453.794	0.017	NO	IRREGULAR
Ch09_Ash_Kettlebell	350.958	0.017	NO	IRREGULAR
Ch10_AshCulvert	72.777	0.017	NO	IRREGULAR
Ch11_Maple_Ash	311.449	0.017	NO	CIRCULAR
Ch13_Snow	574.667	0.017	NO	IRREGULAR
Ch14_Roosevelt_Snow	454.033	0.017	NO	IRREGULAR
Ch15_Roosevelt	229.75	0.017	NO	IRREGULAR
Ch16_RooseveltCulvert	50.021	0.017	NO	FILLED_CIRCULAR
Ch17_A2_Channel	68.431	0.017	NO	IRREGULAR
Ch18_A1_Channel	195.498	0.017	NO	IRREGULAR
Ch19_C_Channel	497.319	0.017	NO	IRREGULAR
Ch20_Wetland	368.327	0.017	NO	TRAPEZOIDAL
Ch21_Wetland	182.256	0.017	NO	TRAPEZOIDAL
Ch12_Snow_Maple	129.577	0.017	NO	IRREGULAR
Ch02_Station	1189.181	0.017	NO	IRREGULAR

Table 38: Conduits in the Post Model Part 3

Name	Geom1 (ft)	Geom2 (ft)	Geom3	Geom4	Barrels	Transect
C01_01_Hull_Red	1	0	0	0	1	
C01_02_Hull	1.25	0	0	0	1	
C02_01_Red_Horne	0	0	0	0	1	Maple_X-Section
C02_02_Red_Horne	1	0	0	0	1	
C03_01_Ash	0	0	0	0	1	Maple_X-Section
C03_02_Redden	1	0	0	0	1	
C03_03_Redden	1	0	0	0	1	
C03_04_WetPond	1	0	0	0	1	
C03_05_HSSTreeFilter	2	0	0	0	1	
C04_01_Snow	3	12	2	2	1	
C05_01_Grove	3	12	2	2	1	
C06_01_HSS_LowerHorne	0	0	0	0	1	Maple_X-Section
C06_02_LowerHorneBio	1	0	0	0	1	
C06_03_LowerHorneBio	1	0	0	0	1	
C06_04_HSSBio2	1	0	0	0	1	
C06_05_HSSBio1	1	0	0	0	1	
C07_01_LowerHorne	1	0	0	0	1	
C07_02_UpperHorne	1	0	0	0	1	
C08_01_RooseveltBio	1	0	0	0	1	
C09_01_Lowell	1	0	0	0	1	
C10_01_Crescent	2	3	3	3	1	
C11_01_Page	2	3	3	3	1	
C12_01_Central	3	0	0	0	1	
Ch04_SixthCulvert	5	0	0	0	1	
Ch05_Sixth	0	0	0	0	1	Hough_X-Section
Ch06_HoughCulvert	3	0	0	0	2	
Ch07_Hough	0	0	0	0	1	Maple_X-Section
Ch08_Kettlebell	0	0	0	0	1	Maple_X-Section
Ch09_Ash_Kettlebell	0	0	0	0	1	Maple_X-Section
Ch10_AshCulvert	0	0	0	0	1	Maple_X-Section
Ch11_Maple_Ash	3	0	0	0	1	
Ch13_Snow	0	0	0	0	1	Maple_X-Section
Ch14_Roosevelt_Snow	0	0	0	0	1	Maple_X-Section
Ch15_Roosevelt	0	0	0	0	1	Maple_X-Section
Ch16_RooseveltCulvert	4	0.5	0	0	1	
Ch17_A2_Channel	0	0	0	0	1	BB-A1_Channel
Ch18_A1_Channel	0	0	0	0	1	BB-A1_Channel
Ch19_C_Channel	0	0	0	0	1	BB-C_Channel
Ch20_Wetland	3	100	5	5	1	
Ch21_Wetland	1	100	5	5	1	
Ch12_Snow_Maple	0	0	0	0	1	Maple_X-Section
Ch02_Station	0	0	0	0	1	Station_X-Section

Table 39: Subcatchments in the Post Model Part 1

Name	X-Coordinate	Y-Coordinate	Outlet	Area (ac)	Width (ft)
44_Horne_Street	1193399.984	258988.832	J02_02_LowerHorne	9.771	25.77
Ash_Street	1194204.119	258898.618	SP3	5.838	37.794
Central_Avenue	1194253.554	262006.058	Central_Gravel_Wetland	11.539	46.221
Central_Gravel_Wetland	1194117.129	261663.626	J12_01_Central	0.14	4.991
Cocheco_Outfall	1193624.728	256926.99	O_Cocheco	13.046	31.007
Crescent_Avenue	1193624.186	261266.021	Crescent_Swale	2.936	14.234
Crescent_Swale	1193961.414	261078.189	J10_01_Crescent	0.062	2.208
Dover_Water_Works_Site	1194302.722	260836.902	SP1	7.333	44.665
Glencrest_Avenue	1193023.682	260878.371	Glencrest_Bio	6.803	26.667
Glencrest_Bio	1193332.366	260441.78	J07_01_Red_Glen_UpperHorne	0.098	9.901
Grove_Street	1194746.271	259600.556	Grove_Street_Gravel_Filter	2.538	21.024
Grove_Street_Gravel_Filter	1194586.896	259448.469	J05_01_Grove	0.06	6.053
Hillcrest_Avenue	1192935.929	259075.605	Hillcrest_Inf_Trench	3.881	18.978
Hillcrest_Inf_Trench	1193021.313	258778.54	J01_02_Hillcrest	0.006	0.328
Horne_Street_School_Bio_1	1193663.943	259979.37	HSS_Bio1	0.145	5.156
Horne_Street_School_Bio_2	1193719.567	259849.3	HSS_Bio2	0.072	6.38
Horne_Street_School_Tree_Filter	1193617.073	259674.9	HSS_Tree_Filter	0.331	7.363
Hough_Street	1194015.909	258240.741	SP6	9.745	39.268
HSS_Bio1	1193719.669	259991.939	J06_06_HSSBio1	0.015	0.983
HSS_Bio2	1193752.526	259855.084	J06_05_HSSBio2	0.015	1.881
HSS_Property	1193699.088	259873.858	J06_04_HSS	1.232	10.963
HSS_Tree_Filter	1193647.445	259613.664	Horne_Wet_Pond	0.003	1.144
HSS_Wet_Pond	1193554.472	259815.668	Horne_Wet_Pond	0.495	6.38
Hull_Avenue	1193233.846	258408.46	J01_01_Hull_Redden	15.03	45.813
Kettlebell_Gravel_Filter	1193999.871	258020.513	BB07_Kettlebell	0.042	2.454
Lowell_Avenue	1194634.27	260684.018	Lowell_Bio	0.787	4.008
Lowell_Bio	1194289.776	260559.055	SP1	0.062	1.801
Lower_Horne_Bio	1193977.532	259711.251	J06_02_LowerHorneBio	0.026	1.064
Lower_Horne_Street	1193684.104	260185.191	Lower_Horne_Bio	2.34	8.834
Maple_Street	1194360.433	259824.32	SP2	24.651	62.745
Page_Avenue	1194673.999	261118.447	Page_Swale	5.01	23.068
Page_Swale	1194331.716	261289.974	J11_01_Page	0.179	2.126
Redden_Ext_HSS_North	1193110.085	260355.413	Redden_Street	13.102	28.306
Redden_Street	1193503.891	259391.713	J03_03_Redden	8.76	33.54
Redden_Wet_Pond	1193128.113	259794.514	Horne_Wet_Pond	3.914	10.963
Roosevelt_Bio	1194208.818	260476.136	SP1	0.028	1.961
Roosevelt_Inf_Basin	1194234.743	260427.841	Roosevelt_Bio	0.045	2.29
Roosevelt_Lower	1194374.675	260449.831	Roosevelt_Inf_Basin	2.514	11.454
Roosevelt_Upper	1194219.281	260553.087	J08_01_RooseveltBio	4.615	19.143
Seacoast_Kettlebell	1193996.468	258170.245	Kettlebell_Gravel_Filter	2.067	18.899
Sixth_Street	1193882.699	257518.651	SP7	8.603	48.672
Snow_Avenue	1193953.205	259404.612	Snow_Bio	3.098	20.86
Snow_Bio	1194014.108	259191.406	Snow_Swale	0.085	1.474
Snow_Swale	1194201.262	259191.52	J04_01_Snow	0.042	0.983
Upper_Horne_Bio	1193579.608	260474.953	J07_02_UpperHorne	0.167	3.603
Upper_Horne_Street	1193449.03	260986.996	Upper_Horne_Bio	11.394	39.019
Wetland_Weir_Wall	1193950.58	261460.087	Existing_Wetland	13.087	44.421

Table 40: Subcatchments in the Post Model Part 2

Name	Slope (%)	Imperv. (%)	N Imperv	N Perv	Dstore Imperv (in)	Dstore Perv (in)
44_Horne_Street	10.5	28	0.015	0.2	0.05	0.05
Ash_Street	8.7	38	0.015	0.2	0.05	0.05
Central_Avenue	3.3	88	0.015	0.2	0.05	0.05
Central_Gravel_Wetland	0.5	0	0.015	0.2	0.05	0.05
Cocheco_Outfall	10.2	22	0.015	0.2	0.05	0.05
Crescent_Avenue	6.1	49	0.015	0.2	0.05	0.05
Crescent_Swale	0.5	0	0.015	0.2	0.05	0.05
Dover_Water_Works_Site	8.2	18	0.015	0.2	0.05	0.05
Glencrest_Avenue	6.2	37	0.015	0.2	0.05	0.05
Glencrest_Bio	0.5	0	0.015	0.2	0.05	0.05
Grove_Street	8.7	33	0.015	0.2	0.05	0.05
Grove_Street_Gravel_Filter	0.5	100	0.015	0.2	0.05	0.05
Hillcrest_Avenue	6.8	32	0.015	0.2	0.05	0.05
Hillcrest_Inf_Trench	0.5	0	0.015	0.2	0.05	0.05
Horne_Street_School_Bio_1	0.5	100	0.015	0.2	0.05	0.05
Horne_Street_School_Bio_2	0.5	100	0.015	0.2	0.05	0.05
Iorne_Street_School_Tree_Filte	6.3	100	0.015	0.2	0.05	0.05
Hough_Street	8.1	44	0.015	0.2	0.05	0.05
HSS_Bio1	0.5	0	0.015	0.2	0.05	0.05
HSS_Bio2	0.5	0	0.015	0.2	0.05	0.05
HSS_Property	3.7	76	0.015	0.2	0.05	0.05
HSS_Tree_Filter	0.5	100	0.015	0.2	0.05	0.05
HSS_Wet_Pond	0.5	100	0.015	0.2	0.05	0.05
Hull_Avenue	8.3	30	0.015	0.2	0.05	0.05
Kettlebell_Gravel_Filter	0.5	100	0.015	0.2	0.05	0.05
Lowell_Avenue	7.2	66	0.015	0.2	0.05	0.05
Lowell_Bio	0.5	0	0.015	0.2	0.05	0.05
Lower_Horne_Bio	0.5	0	0.015	0.2	0.05	0.05
Lower_Horne_Street	5	50	0.015	0.2	0.05	0.05
Maple_Street	12.8	15	0.015	0.2	0.05	0.05
Page_Avenue	5.8	40	0.015	0.2	0.05	0.05
Page_Swale	4.2	0	0.015	0.2	0.05	0.05
Redden_Ext_HSS_North	5.6	29	0.015	0.2	0.05	0.05
Redden_Street	8.8	10	0.015	0.2	0.05	0.05
Redden_Wet_Pond	7.3	37	0.015	0.2	0.05	0.05
Roosevelt_Bio	0.5	0	0.015	0.2	0.05	0.05
Roosevelt_Inf_Basin	0.5	0	0.015	0.2	0.05	0.05
Roosevelt_Lower	6.7	41	0.015	0.2	0.05	0.05
Roosevelt_Upper	8.5	29	0.015	0.2	0.05	0.05
Seacoast_Kettlebell	5.8	95	0.015	0.2	0.05	0.05
Sixth_Street	6.3	46	0.015	0.2	0.05	0.05
Snow_Avenue	6.2	40	0.015	0.2	0.05	0.05
Snow_Bio	0.5	0	0.015	0.2	0.05	0.05
Snow_Swale	5	0	0.015	0.2	0.05	0.05
Upper_Horne_Bio	0.5	0	0.015	0.2	0.05	0.05
Upper_Horne_Street	5.4	33	0.015	0.2	0.05	0.05
Wetland_Weir_Wall	6.6	19	0.015	0.2	0.05	0.05

Table 41: Subcatchments in the Post Model Part 3

Name	Zero Imperv (%)	Subarea Routing	Percent Routed (%)	LID Controls	LID Names
44_Horne_Street	100	PERVIOUS	100	0	
Ash_Street	100	OUTLET	100	0	
Central_Avenue	100	OUTLET	100	0	
Central_Gravel_Wetland	100	PERVIOUS	100	1	GravelWetland
Cocheco_Outfall	100	OUTLET	100	0	
Crescent_Avenue	100	OUTLET	100	0	
Crescent_Swale	100	PERVIOUS	100	1	CrescentSwale
Dover_Water_Works_Site	100	PERVIOUS	100	0	
Glencrest_Avenue	100	OUTLET	100	0	
Glencrest_Bio	100	PERVIOUS	100	1	GlencrestBio
Grove_Street	100	OUTLET	100	0	
Grove_Street_Gravel_Filter	100	PERVIOUS	100	1	GroveGravelFilter
Hillcrest_Avenue	100	OUTLET	100	0	
Hillcrest_Inf_Trench	100	PERVIOUS	100	1	HillcrestInfTrench
Horne_Street_School_Bio_1	100	OUTLET	100	0	
Horne_Street_School_Bio_2	100	OUTLET	100	0	
Iorne_Street_School_Tree_Filte	100	OUTLET	100	0	
Hough_Street	100	OUTLET	100	0	
HSS_Bio1	100	PERVIOUS	100	1	HSSBio1
HSS_Bio2	100	PERVIOUS	100	1	HSSBio2
HSS_Property	100	OUTLET	100	0	
HSS_Tree_Filter	100	PERVIOUS	100	1	HSSTreeFilter
HSS_Wet_Pond	100	OUTLET	100	0	
Hull_Avenue	100	OUTLET	100	0	
Kettlebell_Gravel_Filter	100	PERVIOUS	100	1	Kettlebell
Lowell_Avenue	100	OUTLET	100	0	
Lowell_Bio	100	PERVIOUS	100	1	LowellBio
Lower_Horne_Bio	100	PERVIOUS	100	1	LowerHorneBio
Lower_Horne_Street	100	OUTLET	100	0	
Maple_Street	100	PERVIOUS	100	0	
Page_Avenue	100	PERVIOUS	100	0	
Page_Swale	100	PERVIOUS	100	1	PageSwale
Redden_Ext_HSS_North	100	PERVIOUS	100	0	
Redden_Street	100	PERVIOUS	100	0	
Redden_Wet_Pond	100	PERVIOUS	100	0	
Roosevelt_Bio	100	PERVIOUS	100	1	RooseveltBio
Roosevelt_Inf_Basin	100	PERVIOUS	100	1	RooseveltInfBasin
Roosevelt_Lower	100	OUTLET	100	0	
Roosevelt_Upper	100	OUTLET	100	0	
Seacoast_Kettlebell	100	OUTLET	100	0	
Sixth_Street	100	OUTLET	100	0	
Snow_Avenue	100	OUTLET	100	0	
Snow_Bio	100	PERVIOUS	100	1	SnowBio
Snow_Swale	100	PERVIOUS	100	1	SnowSwale
Upper_Horne_Bio	100	PERVIOUS	100	1	UpperHorneBio
Upper_Horne_Street	100	OUTLET	100	0	
Wetland_Weir_Wall	100	PERVIOUS	100	0	

Table 42: Subcatchments in the Post Model Part 4

Name	Groundwater	Aquifer Name	Receiving Node	Surface Elevation (ft)
44_Horne_Street	NO			0
Ash_Street	YES	Ash_StreetAQ	BB09_Ash	59.05
Central_Avenue	NO			0
Central_Gravel_Wetland	NO			0
Cocheco_Outfall	YES	Cocheco_OutfallAQ	O_Cocheco	36.09
Crescent_Avenue	NO			0
Crescent_Swale	NO			0
Dover_Water_Works_Site	YES	Dover_Water_Works_SiteAQ	SP1	106
Glencrest_Avenue	NO			0
Glencrest_Bio	NO			0
Grove_Street	NO			0
Grove_Street_Gravel_Filter	NO			0
Hillcrest_Avenue	NO			0
Hillcrest_Inf_Trench	NO			0
Horne_Street_School_Bio_1	NO			0
Horne_Street_School_Bio_2	NO			0
Horne_Street_School_Tree_Filter	NO			0
Hough_Street	YES	Hough_StreetAQ	SP6	56
HSS_Bio1	NO			0
HSS_Bio2	NO			0
HSS_Property	NO			0
HSS_Tree_Filter	NO			0
HSS_Wet_Pond	NO			0
Hull_Avenue	NO			0
Kettlebell_Gravel_Filter	NO			0
Lowell_Avenue	NO			0
Lowell_Bio	NO			0
Lower_Horne_Bio	NO			0
Lower_Horne_Street	NO			0
Maple_Street	YES	Maple_StreetAQ	SP2	65.75
Page_Avenue	NO			0
Page_Swale	NO			0
Redden_Ext_HSS_North	NO			0
Redden_Street	NO			0
Redden_Wet_Pond	NO			0
Roosevelt_Bio	NO			0
Roosevelt_Inf_Basin	NO			0
Roosevelt_Lower	YES	Roosevelt_LowerAQ	SP1	106
Roosevelt_Upper	YES	Roosevelt_UpperAQ	J08_01_RooseveltBio	114.83
Seacoast_Kettlebell	NO			0
Sixth_Street	YES	Sixth_StreetAQ	SP7	49
Snow_Avenue	NO			0
Snow_Bio	NO			0
Snow_Swale	NO			0
Upper_Horne_Bio	NO			0
Upper_Horne_Street	NO			0
Wetland_Weir_Wall	YES	Wetland_Weir_WallAQ	Existing_Wetland	134.51

Table 43: Subcatchments in the Post Model Part 5

Name	A1 Coefficient	B1 Exponent	A2 Coefficient	B2 Exponent
44_Horne_Street	0	0	0	0
Ash_Street	0.1	1	0.1	1
Central_Avenue	0	0	0	0
Central_Gravel_Wetland	0	0	0	0
Cocheco_Outfall	0.1	1	0.1	1
Crescent_Avenue	0	0	0	0
Crescent_Swale	0	0	0	0
Dover_Water_Works_Site	0.1	1	0.1	1
Glencrest_Avenue	0	0	0	0
Glencrest_Bio	0	0	0	0
Grove_Street	0	0	0	0
Grove_Street_Gravel_Filter	0	0	0	0
Hillcrest_Avenue	0	0	0	0
Hillcrest_Inf_Trench	0	0	0	0
Horne_Street_School_Bio_1	0	0	0	0
Horne_Street_School_Bio_2	0	0	0	0
Horne_Street_School_Tree_Filter	0	0	0	0
Hough_Street	0.1	1	0.1	1
HSS_Bio1	0	0	0	0
HSS_Bio2	0	0	0	0
HSS_Property	0	0	0	0
HSS_Tree_Filter	0	0	0	0
HSS_Wet_Pond	0	0	0	0
Hull_Avenue	0	0	0	0
Kettlebell_Gravel_Filter	0	0	0.1	1
Lowell_Avenue	0	0	0	0
Lowell_Bio	0	0	0	0
Lower_Horne_Bio	0	0	0	0
Lower_Horne_Street	0	0	0	0
Maple_Street	0.1	1	0.1	1
Page_Avenue	0	0	0	0
Page_Swale	0	0	0	0
Redden_Ext_HSS_North	0	0	0	0
Redden_Street	0	0	0	0
Redden_Wet_Pond	0	0	0	0
Roosevelt_Bio	0	0	0	0
Roosevelt_Inf_Basin	0	0	0	0
Roosevelt_Lower	0.1	1	0.1	1
Roosevelt_Upper	0.1	1	0.1	1
Seacoast_Kettlebell	0	0	0	0
Sixth_Street	0.1	1	0.1	1
Snow_Avenue	0	0	0	0
Snow_Bio	0	0	0	0
Snow_Swale	0	0	0	0
Upper_Horne_Bio	0	0	0	0
Upper_Horne_Street	0	0	0	0
Wetland_Weir_Wall	0.1	1	0.1	1

Appendix C – Model Output

This information is intended to supplement Chapter 3. It contains additional information about the rainfall-runoff response simulations such as different graphical representations of the extreme precipitation events and a summary the Pre and Post baseflow over a 36-hour period.

Table 44: Baseflow Over a 36-hour Period for the Pre and Post Models

	Pre	Post
Maximum Flow (cfs)	0.66	0.03
Minimum Flow (cfs)	0.66	0.03
Mean Flow (cfs)	0.66	0.03
Duration (hr)	36	36
Total Flow (ft^3)	85,290	3,280

Supplementary to Section 3.1.1

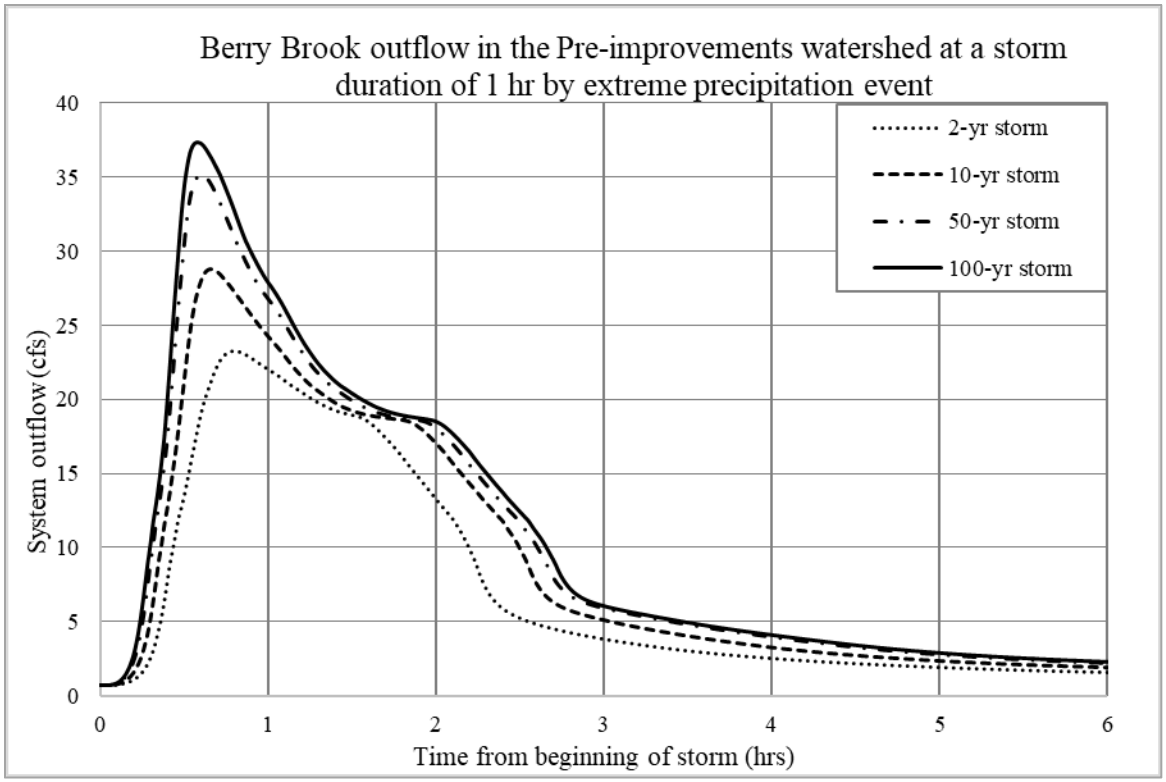

Figure 47: Outflow in the Pre model for the 1-hr extreme precipitation events

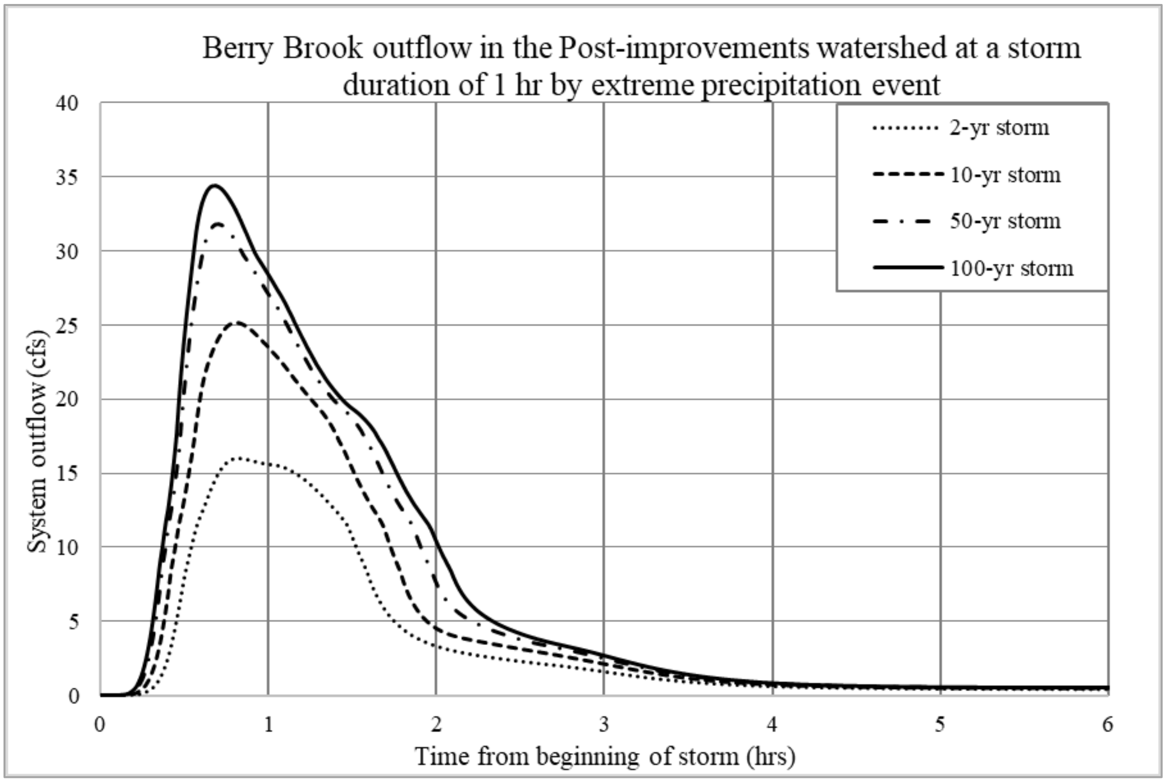

Figure 48: Outflow in the Post model for the 1-hr extreme precipitation events

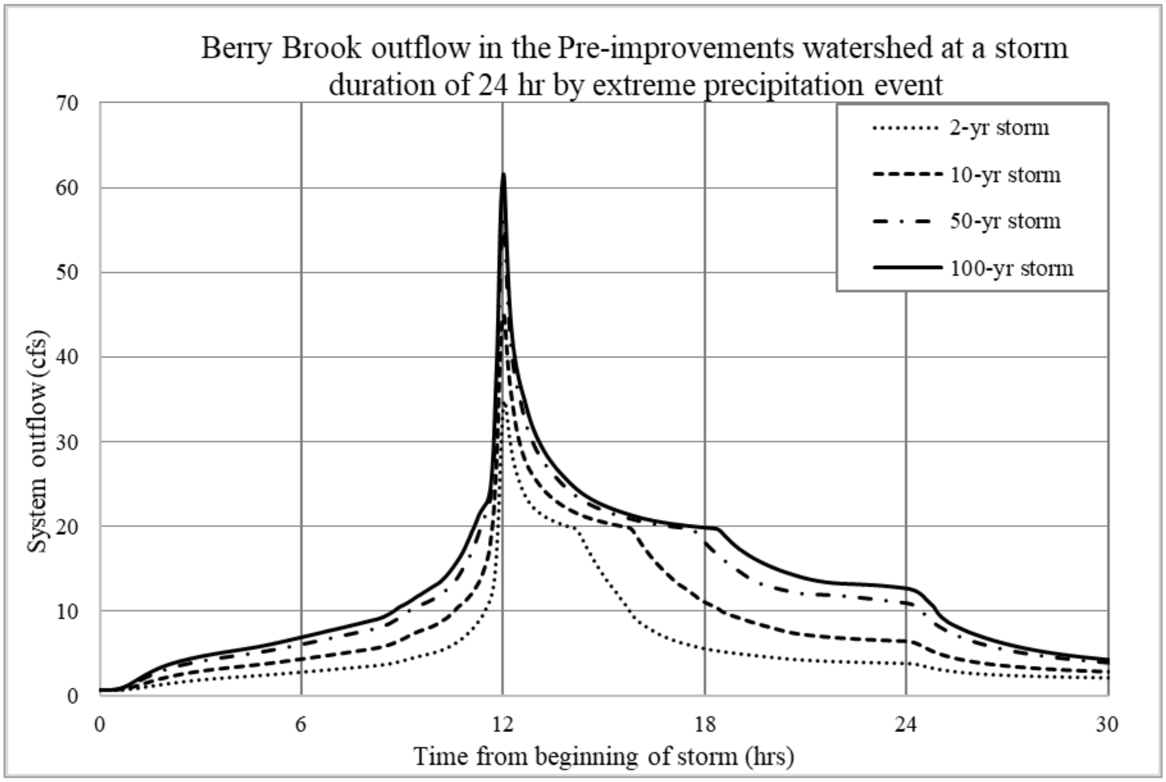

Figure 49: Outflow in the Pre model for the 24-hr extreme precipitation events

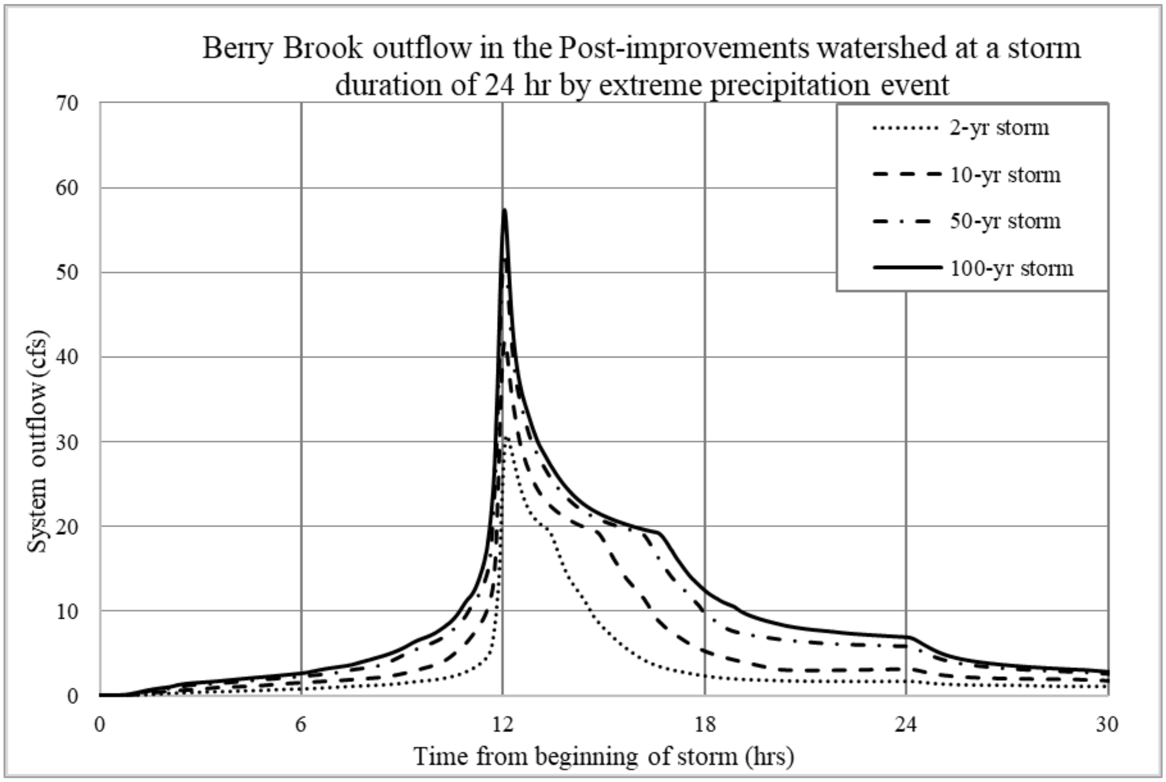

Figure 50: Outflow in the Post model for the 24-hr extreme precipitation events

Supplementary to Section 3.2

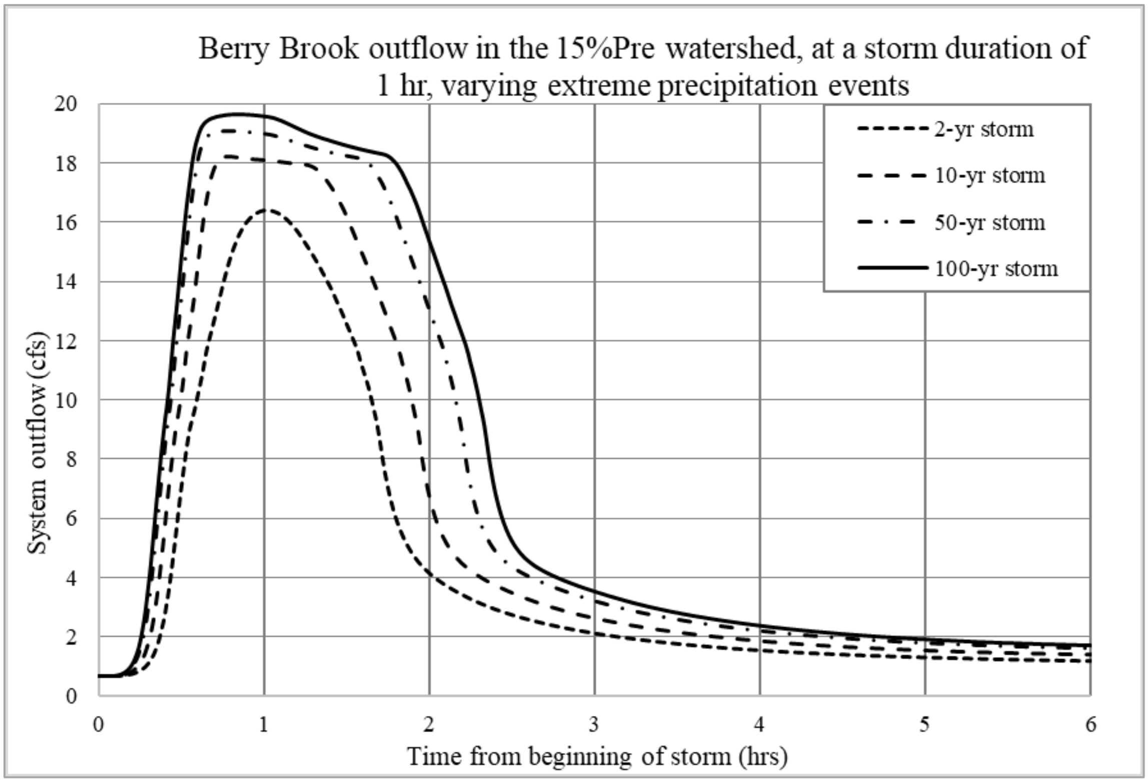

Figure 51: Outflow in the Pre_{15} model for the 1-hr extreme precipitation events

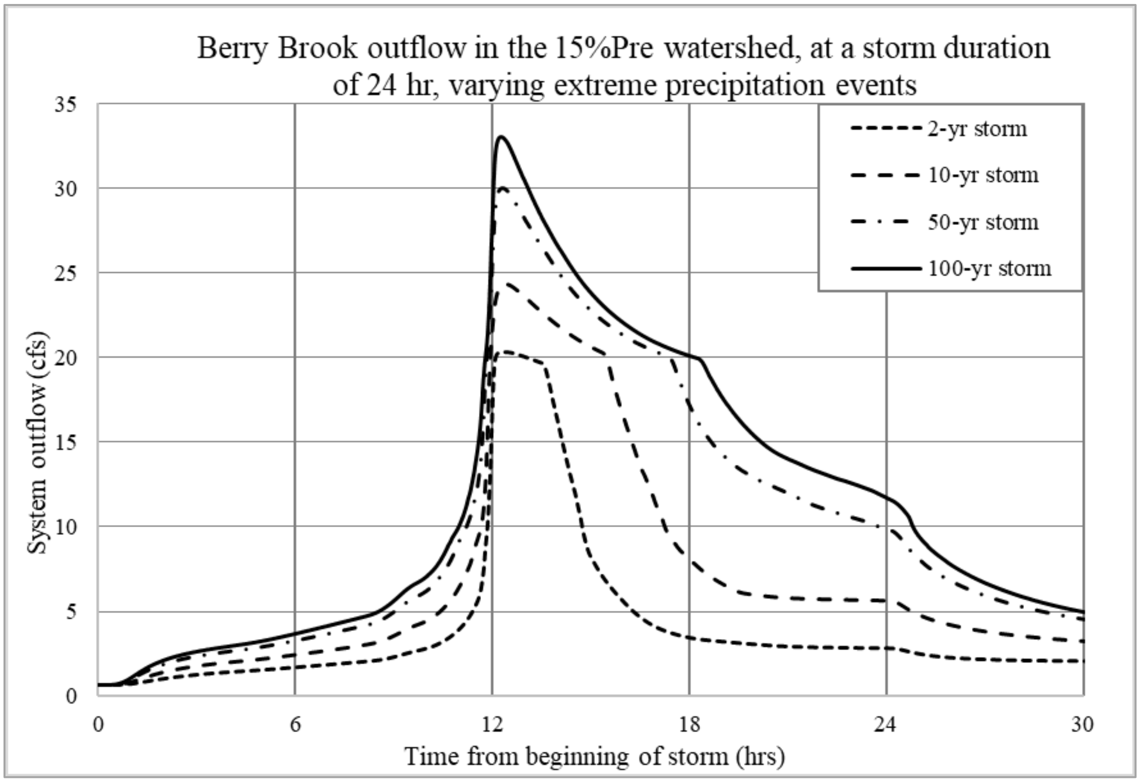

Figure 52: Outflow in the Pre_{15} model for the 24-hr extreme precipitation events

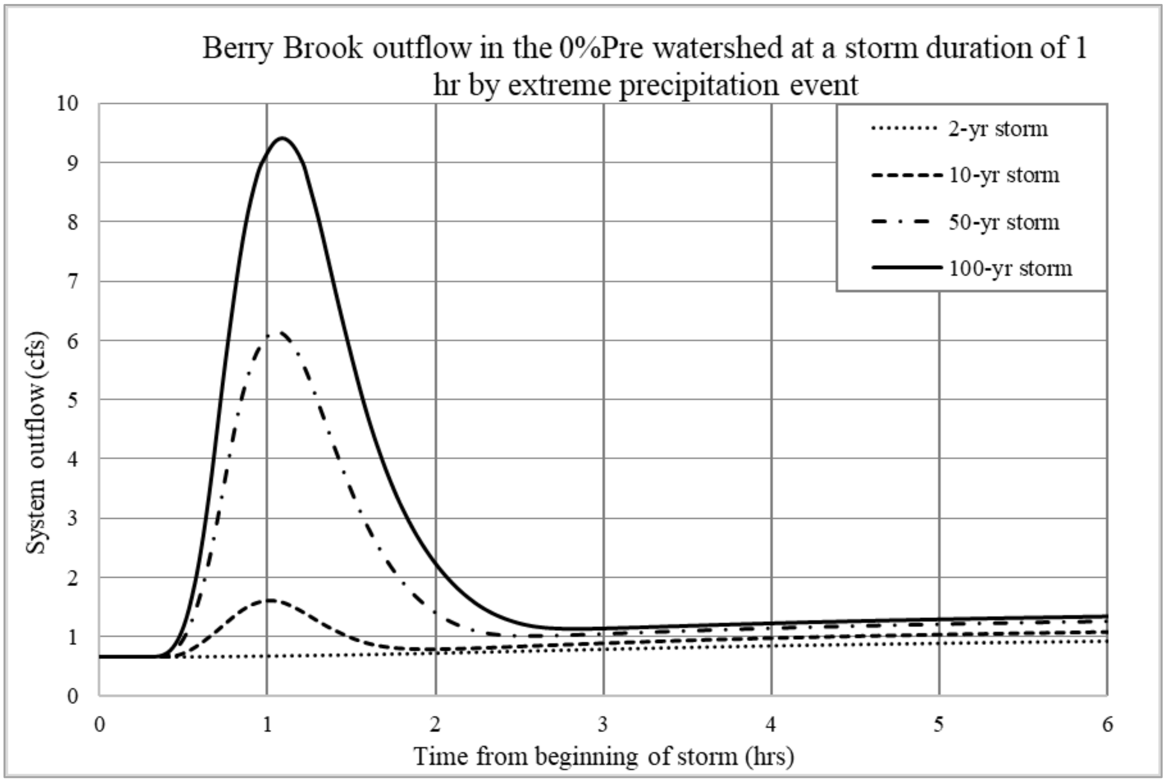

Figure 53: Outflow in the Pre_0 model for the 1-hr extreme precipitation events

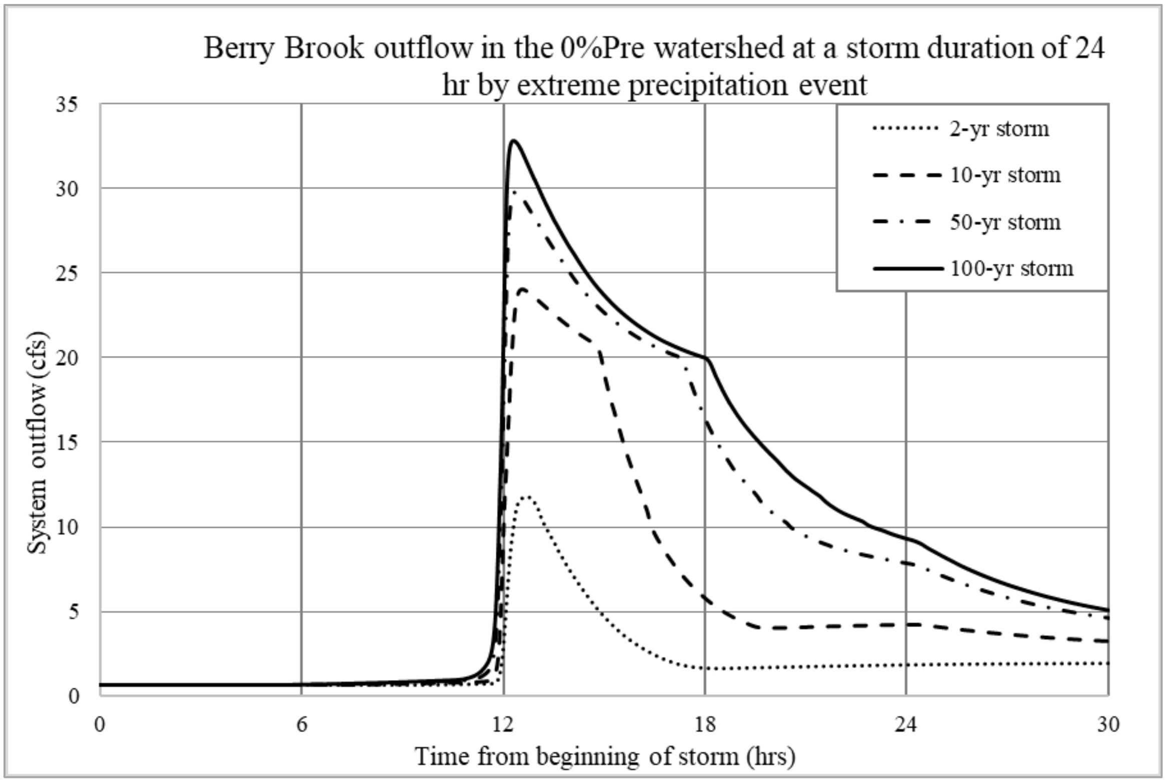

Figure 54: Outflow in the Pre_0 model for the 24-hr extreme precipitation events

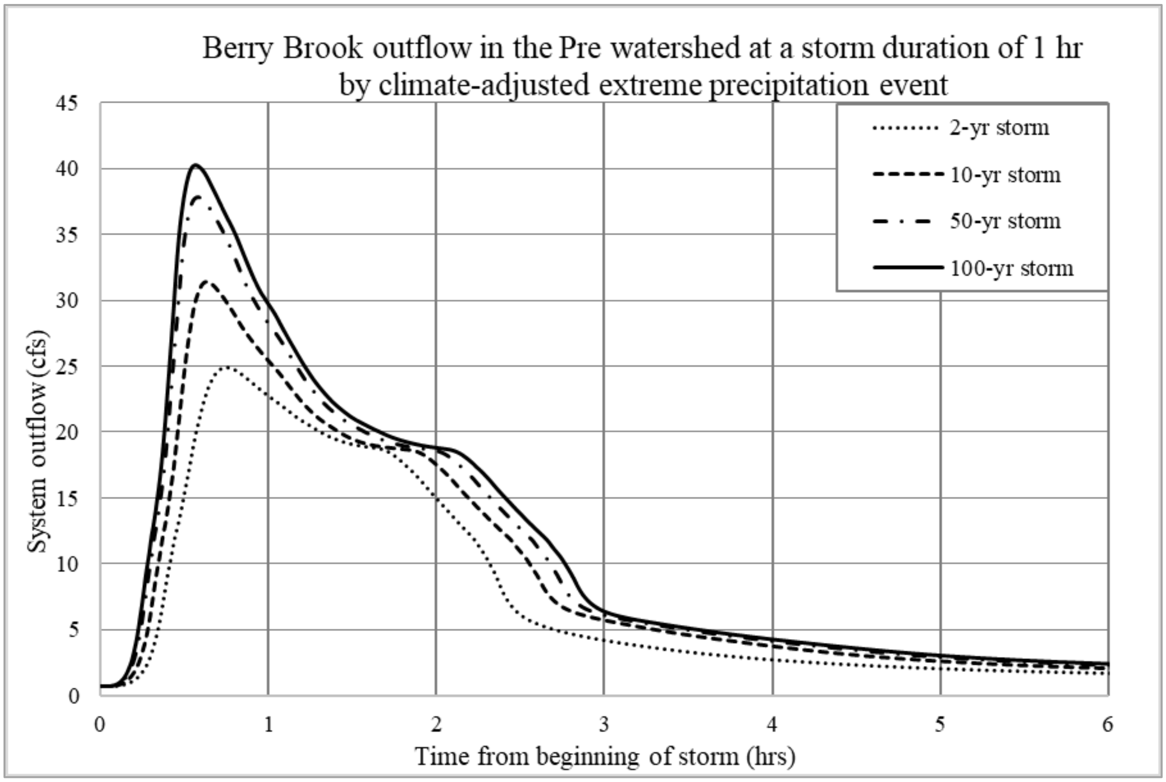

Figure 55: Outflow in the $Pre_{Climate}$ model for the 1-hr extreme precipitation events

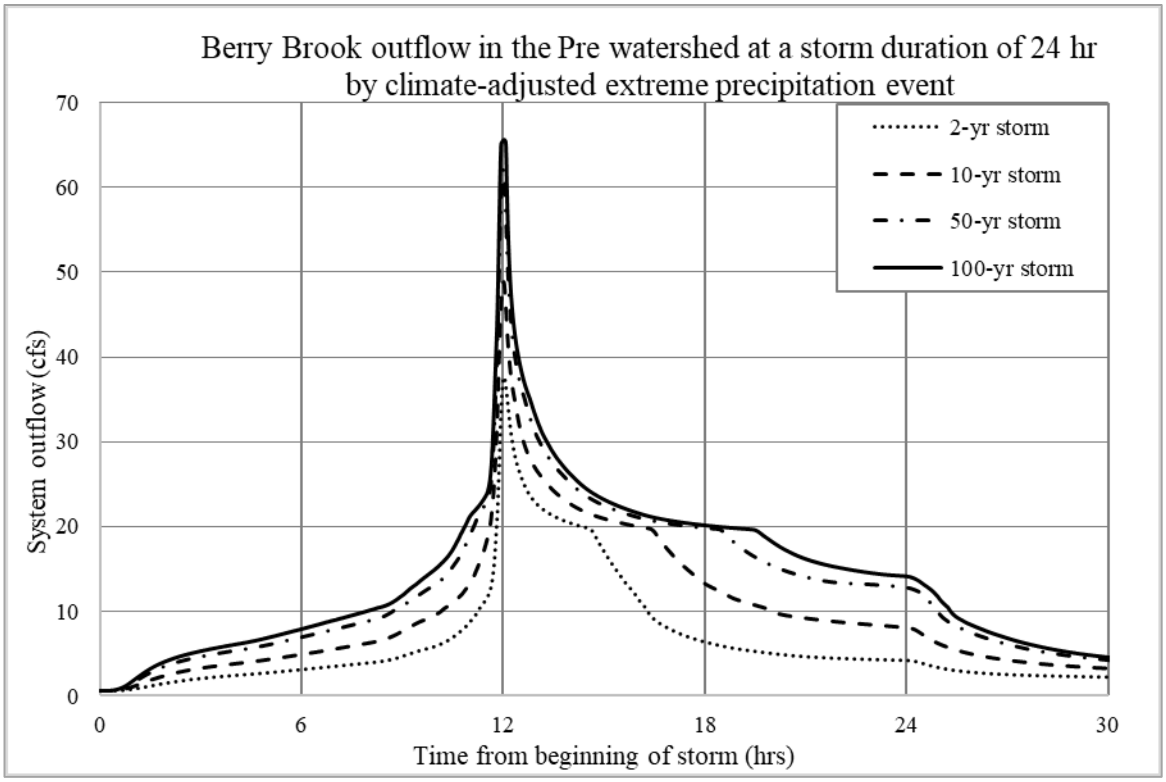

Figure 56: Outflow in the Pre$_{Climate}$ model for the 24-hr extreme precipitation events

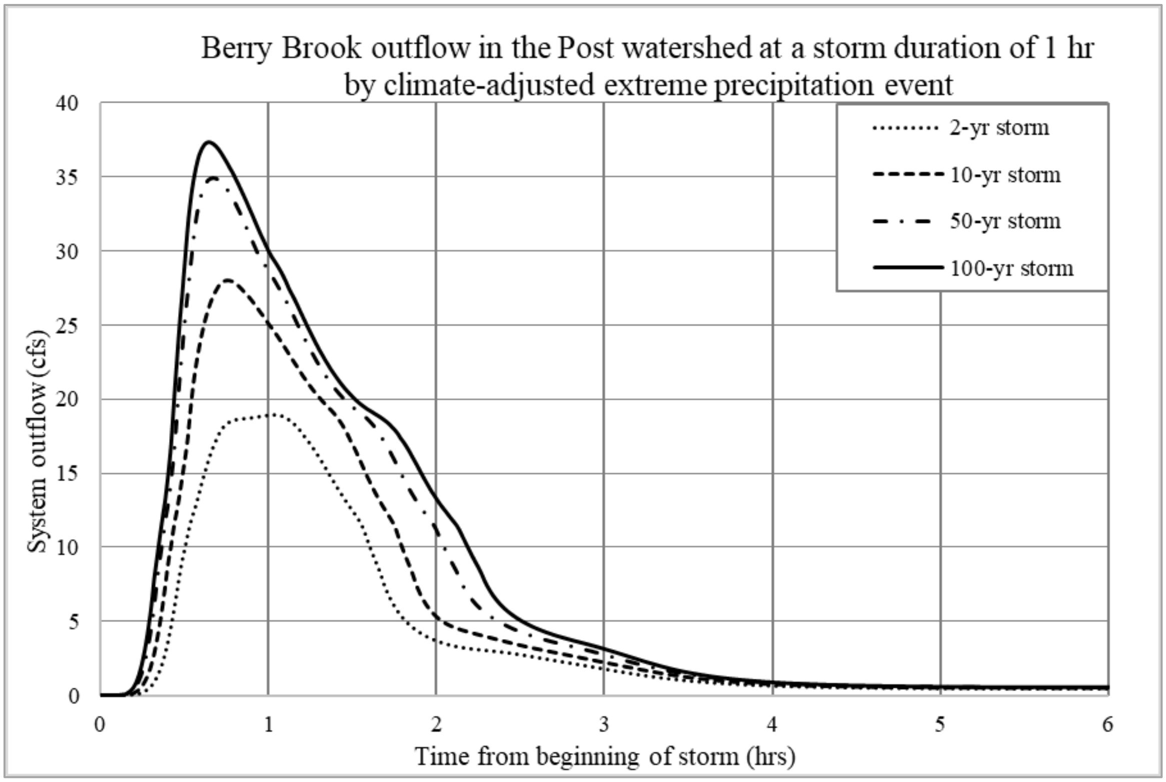

Figure 57: Outflow in the $Post_{Climate}$ model for the 1-hr extreme precipitation events

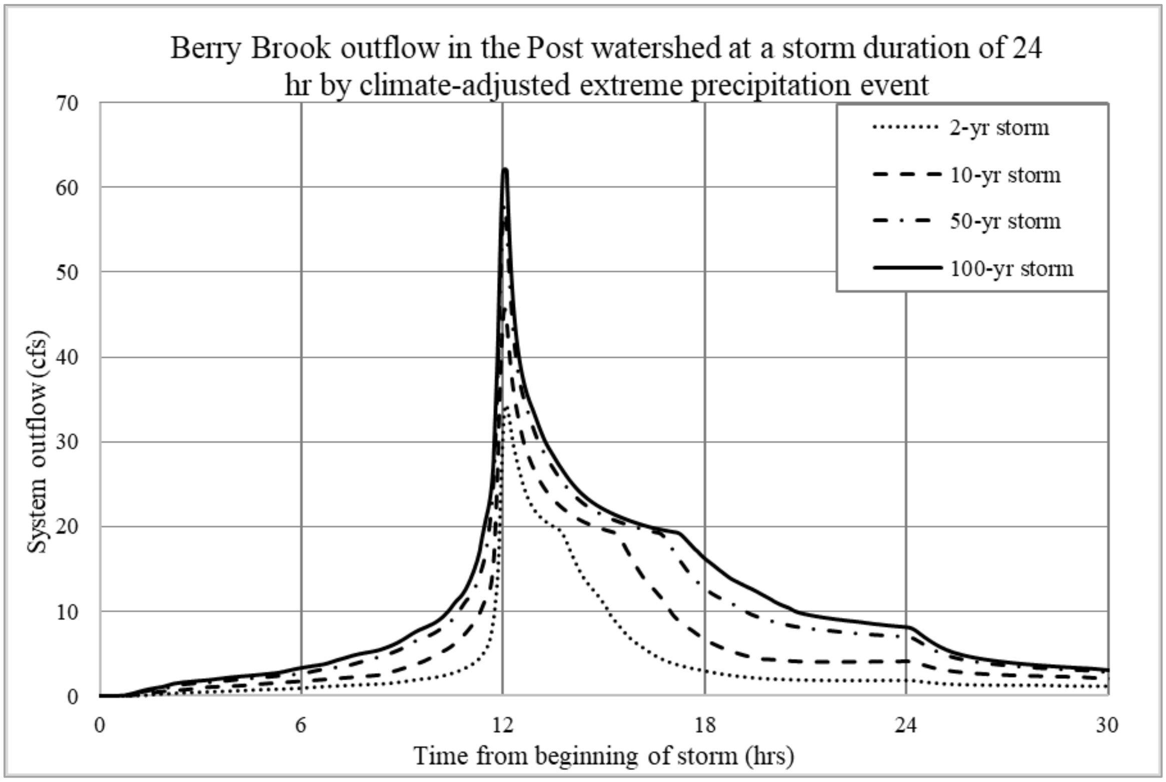

Figure 58: Outflow in the $Post_{Climate}$ model for the 24-hr extreme precipitation events

Appendix D – GSI System Plans

This section is intended to supplement Section 2.2 providing further GSI system details. The available construction drawings for the GSI systems installed in the Berry Brook watershed are listed by project. Information such as watershed area, proposed system design and size, and media depths are shown. If information could not be found, assumptions were based off the available information from other sites.

Central Avenue Gravel Wetland

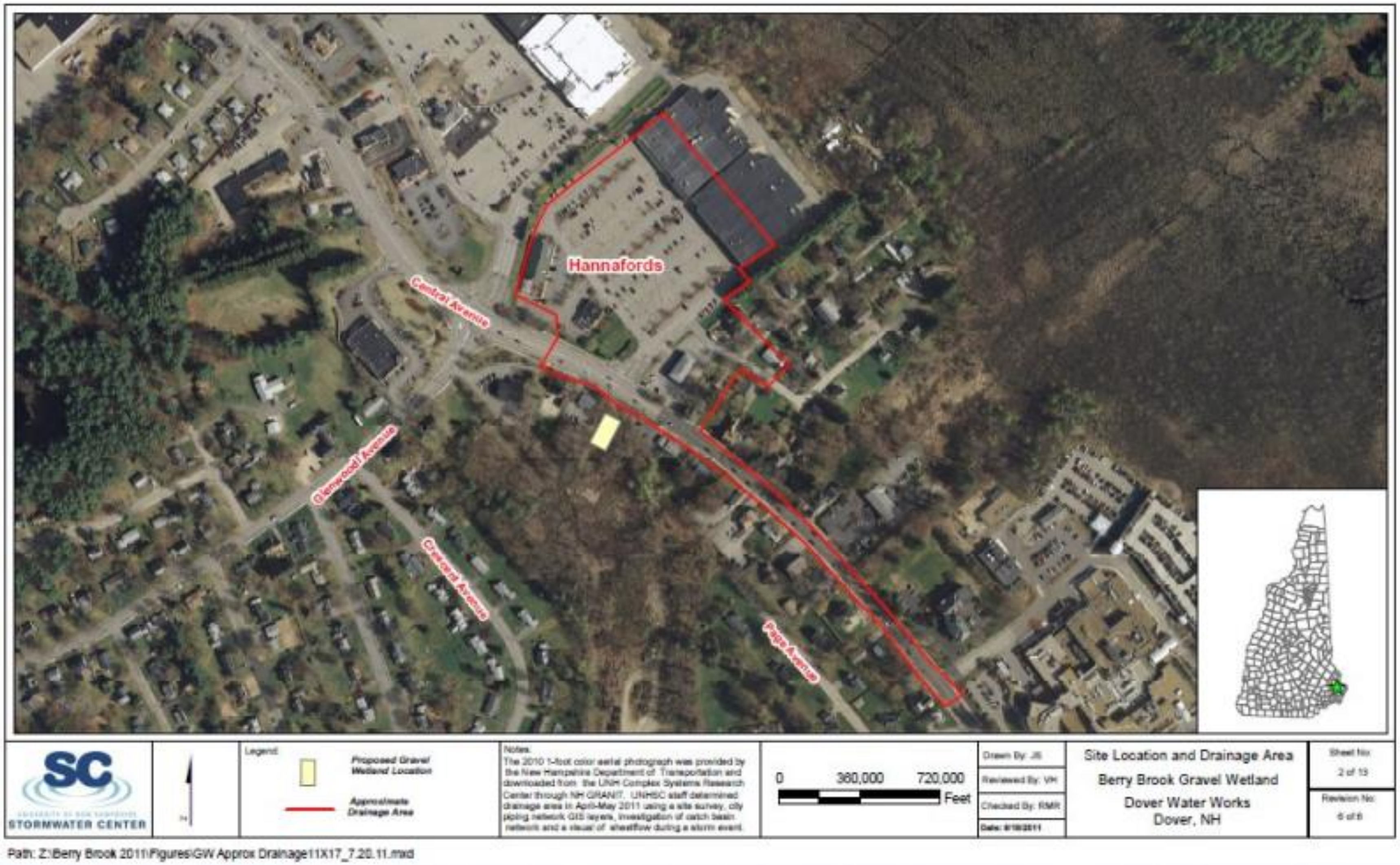

Figure 59: Central Avenue Gravel Wetland site location and drainage area

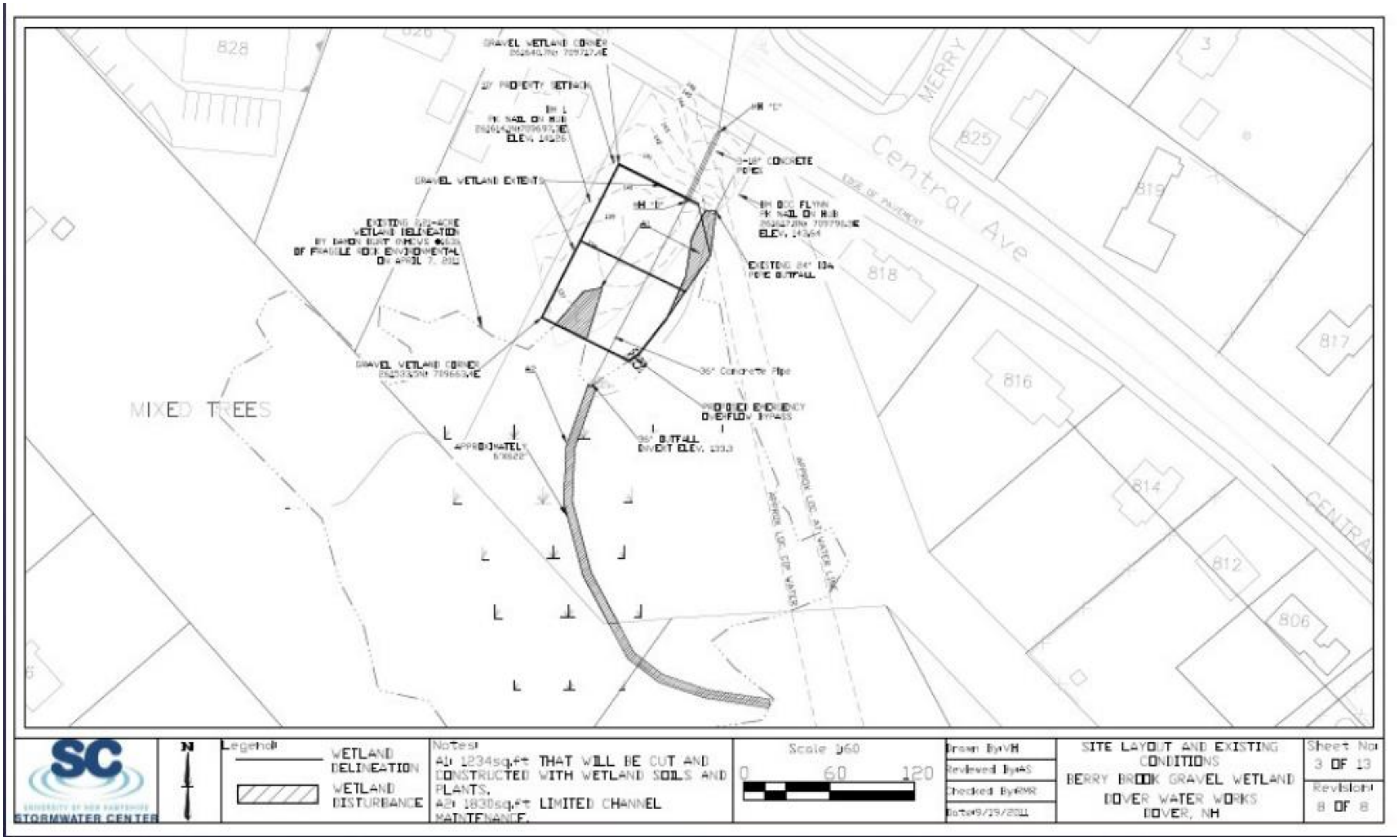

Figure 60: Central Avenue Gravel Wetland site layout and existing conditions

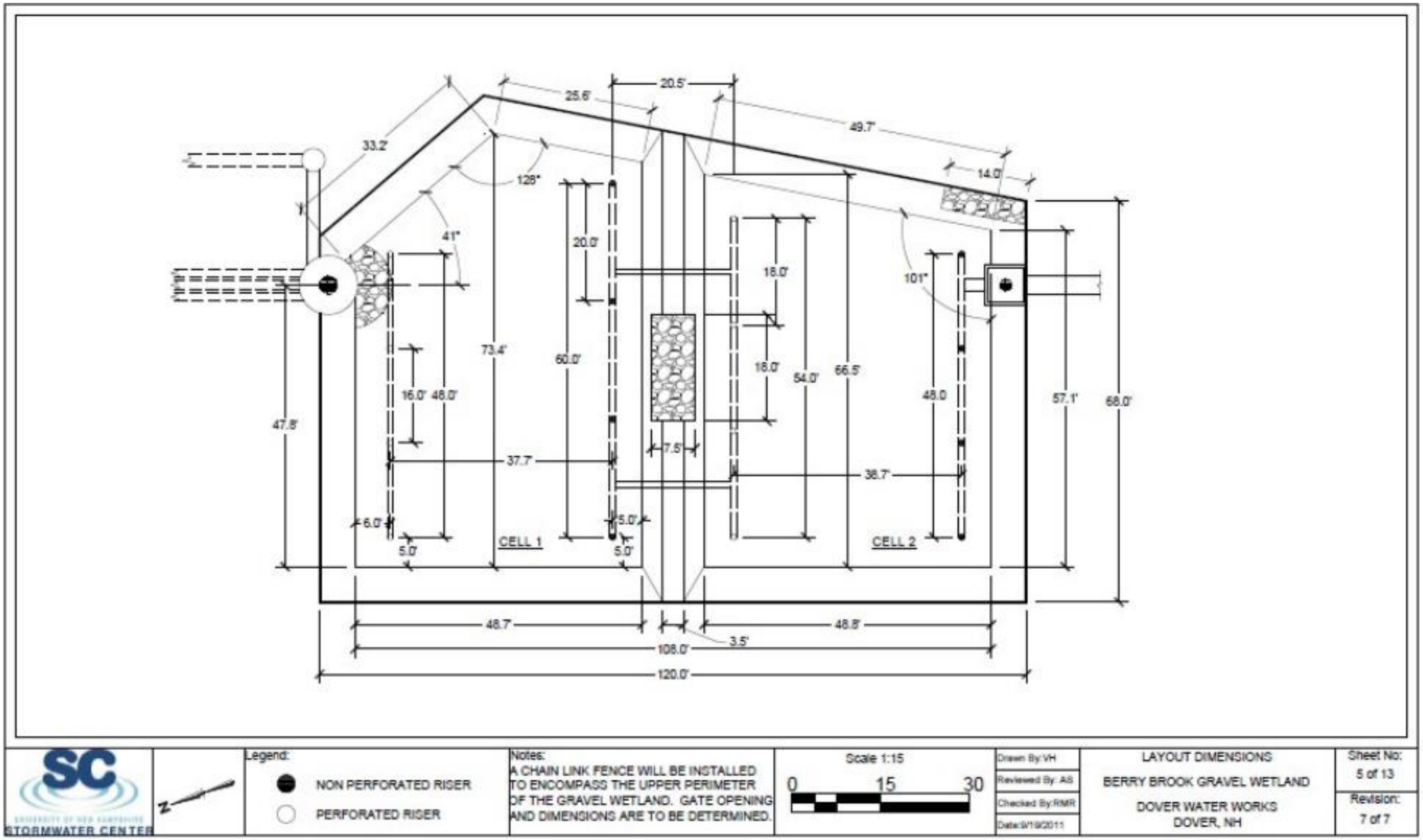

Figure 61: Central Avenue Gravel Wetland layout dimensions

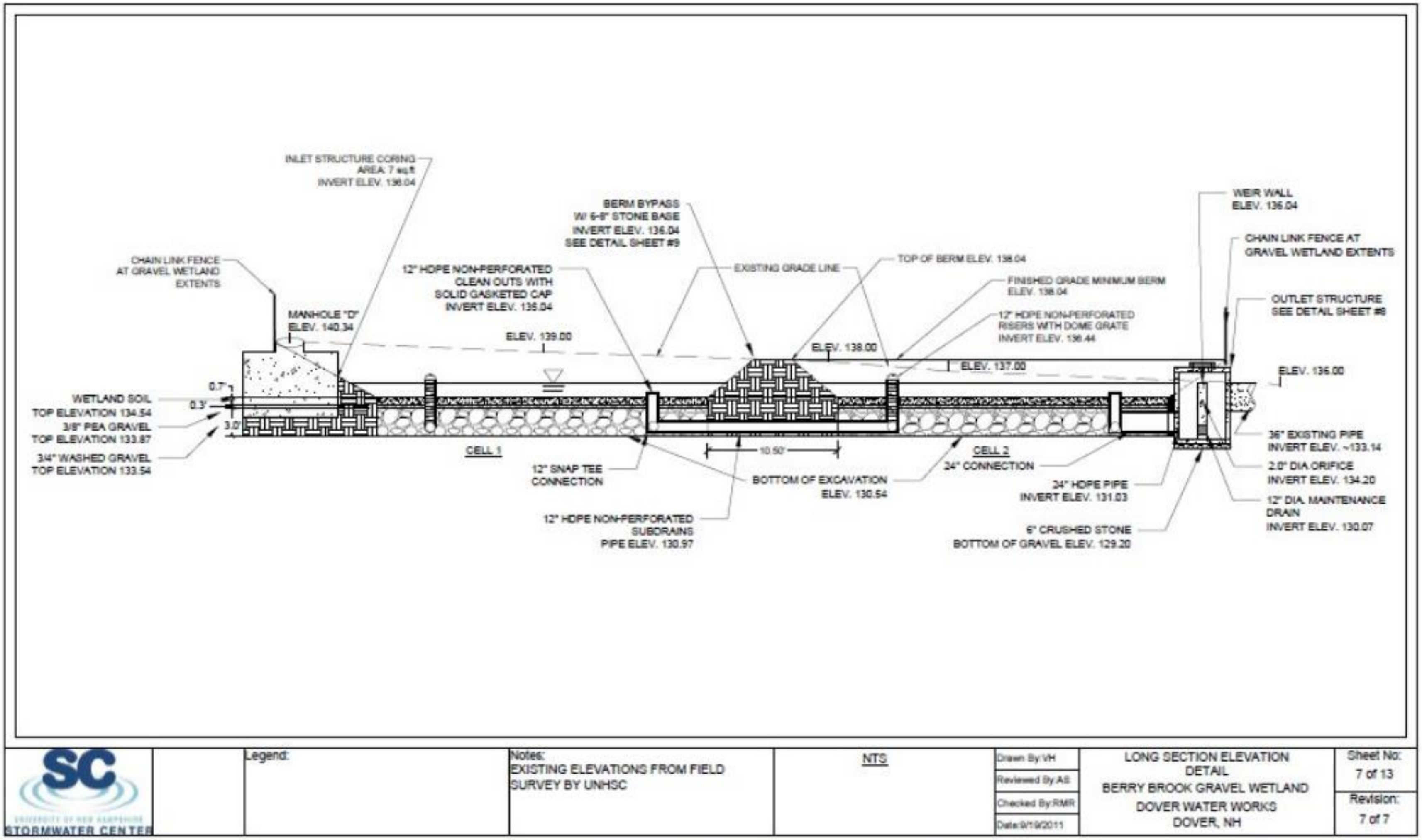

Figure 62: Central Avenue Gravel Wetland long section elevation

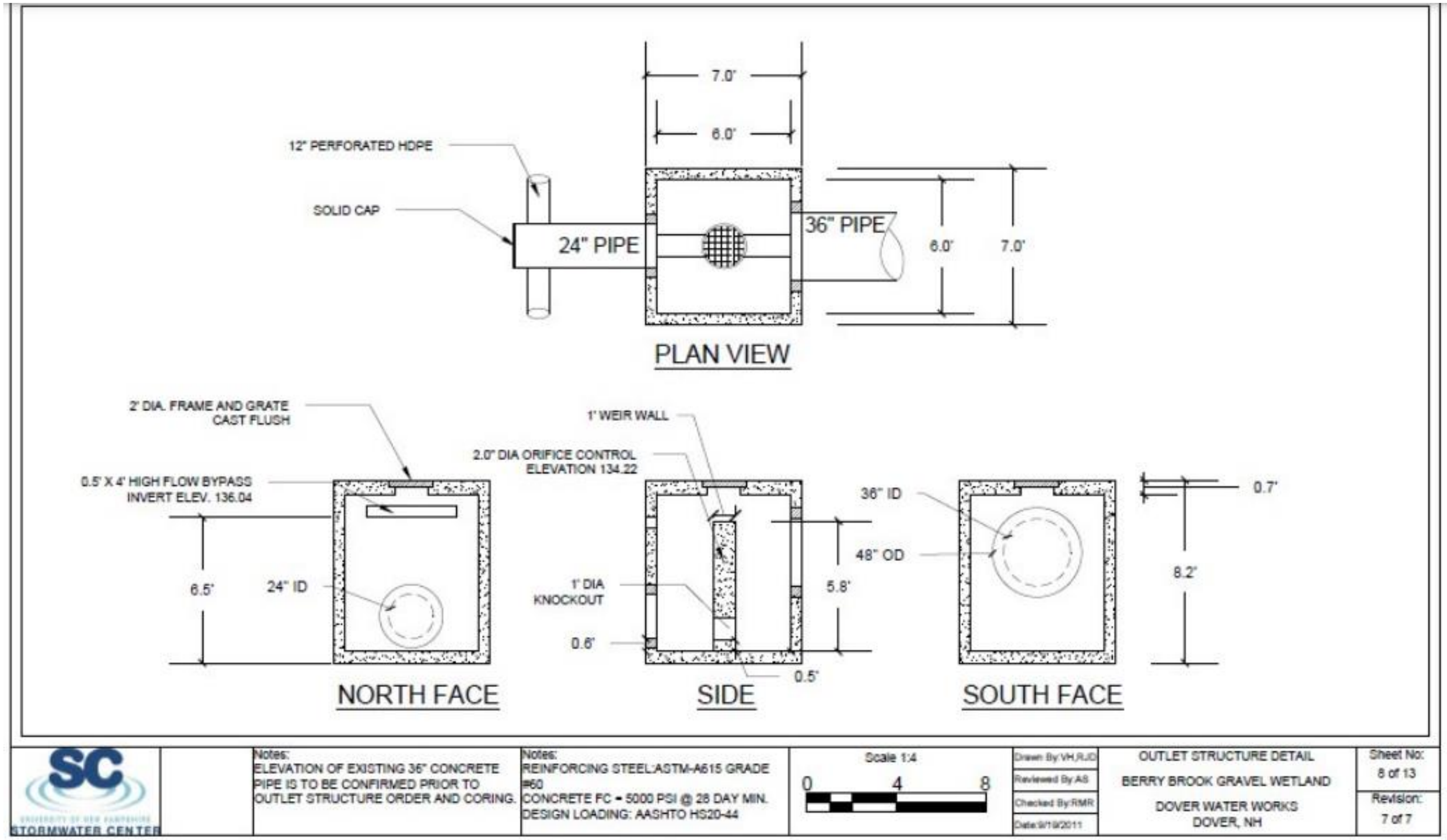

Figure 63: Central Avenue Gravel Wetland outlet structure

Glencrest Avenue Bioretention

Figure 64: Glencrest Avenue Bioretention drainage area

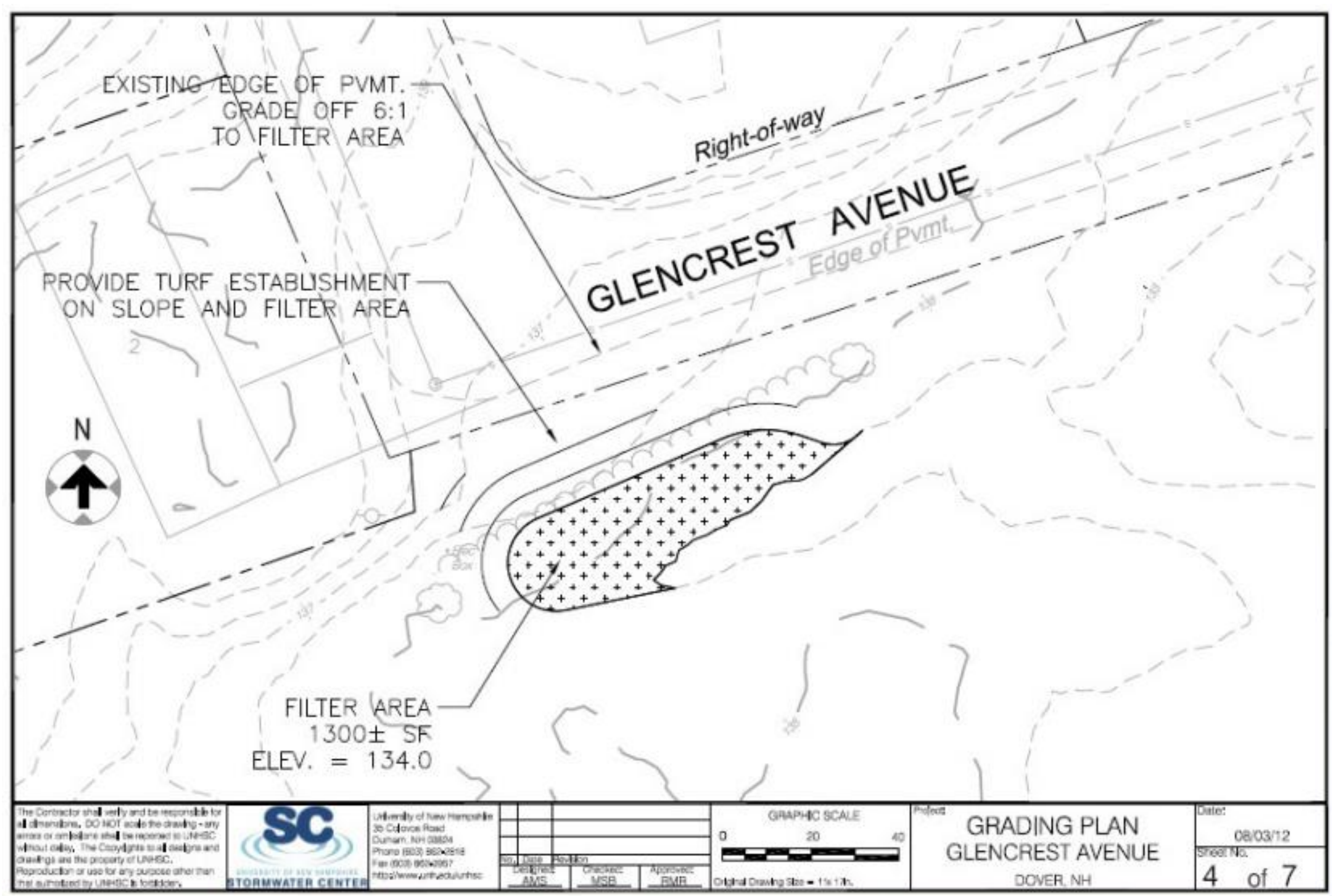

Figure 65: Glencrest Avenue Bioretention grading plan

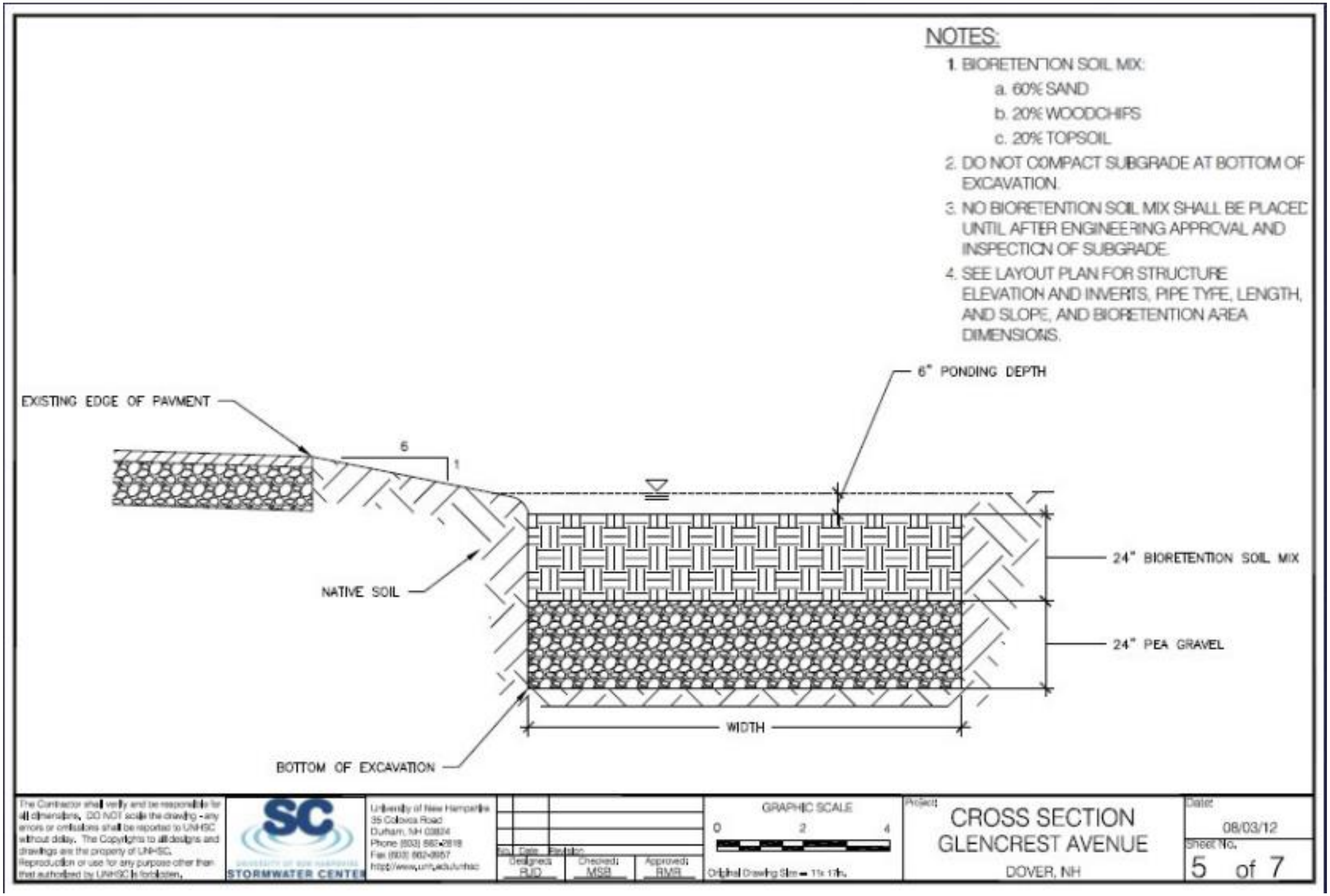

Figure 66: Glencrest Avenue Bioretention cross section

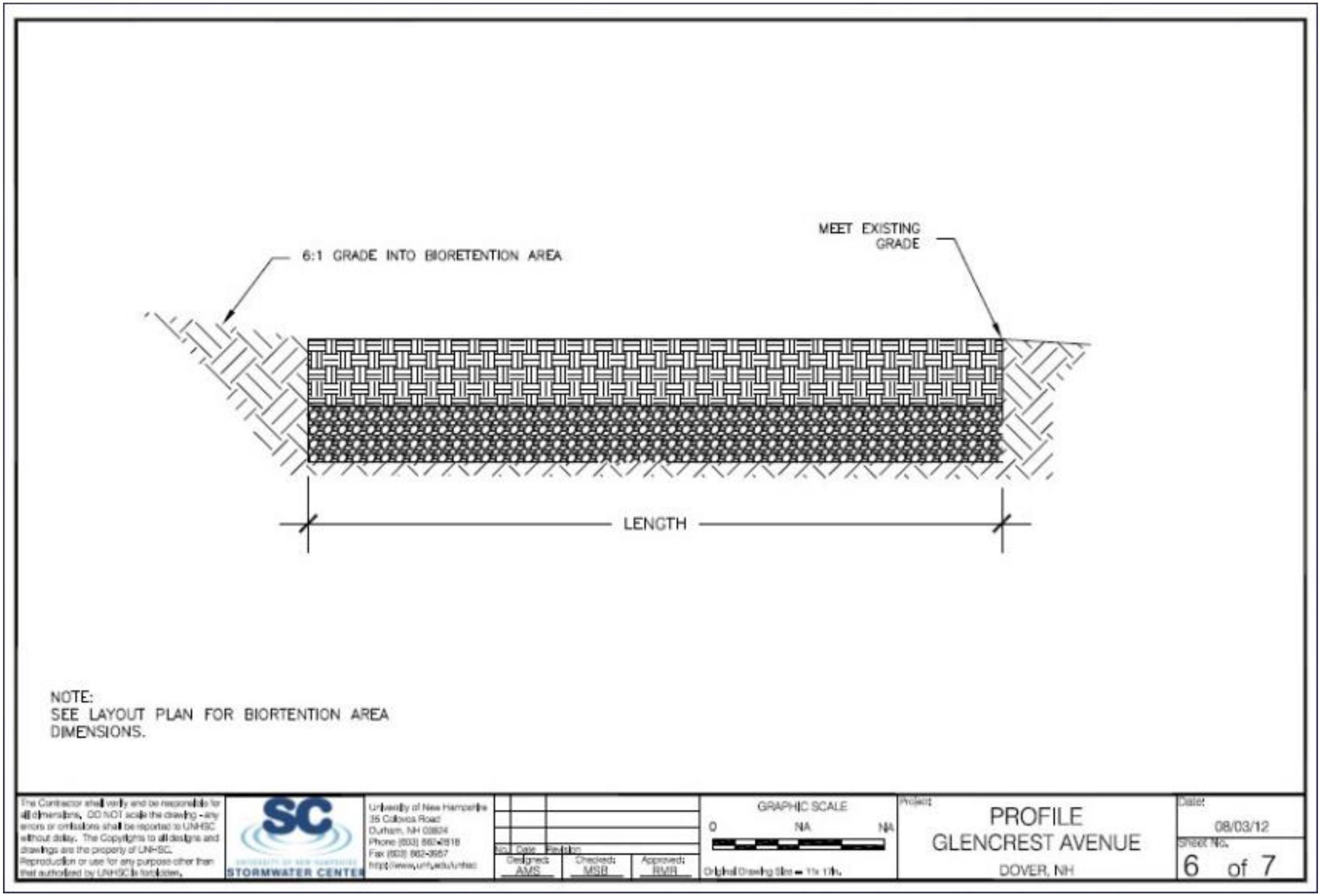

Figure 67: Glencrest Avenue Bioretention profile

Grove Street Gravel Filter

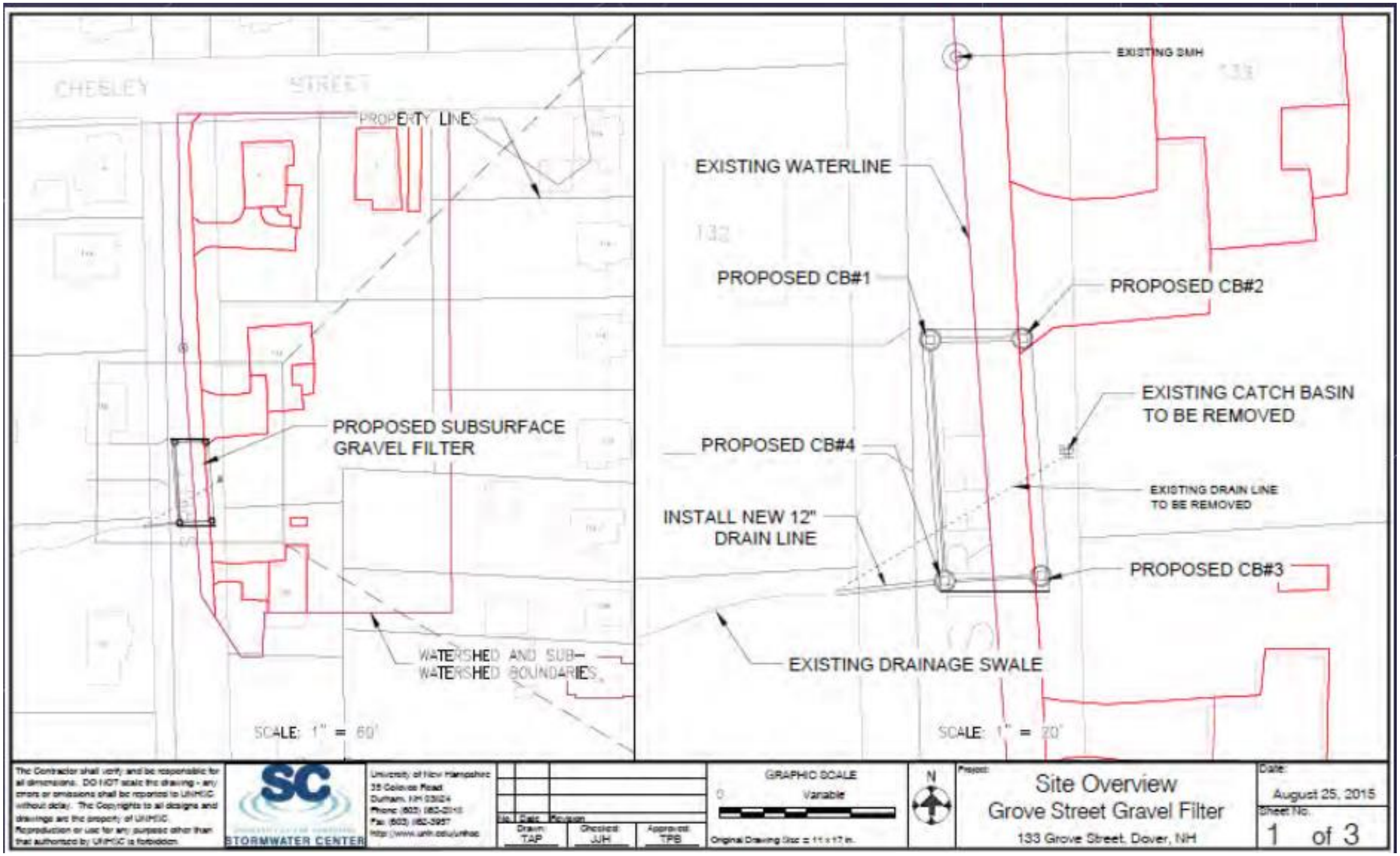

Figure 68: Grove Street Gravel Filter site overview

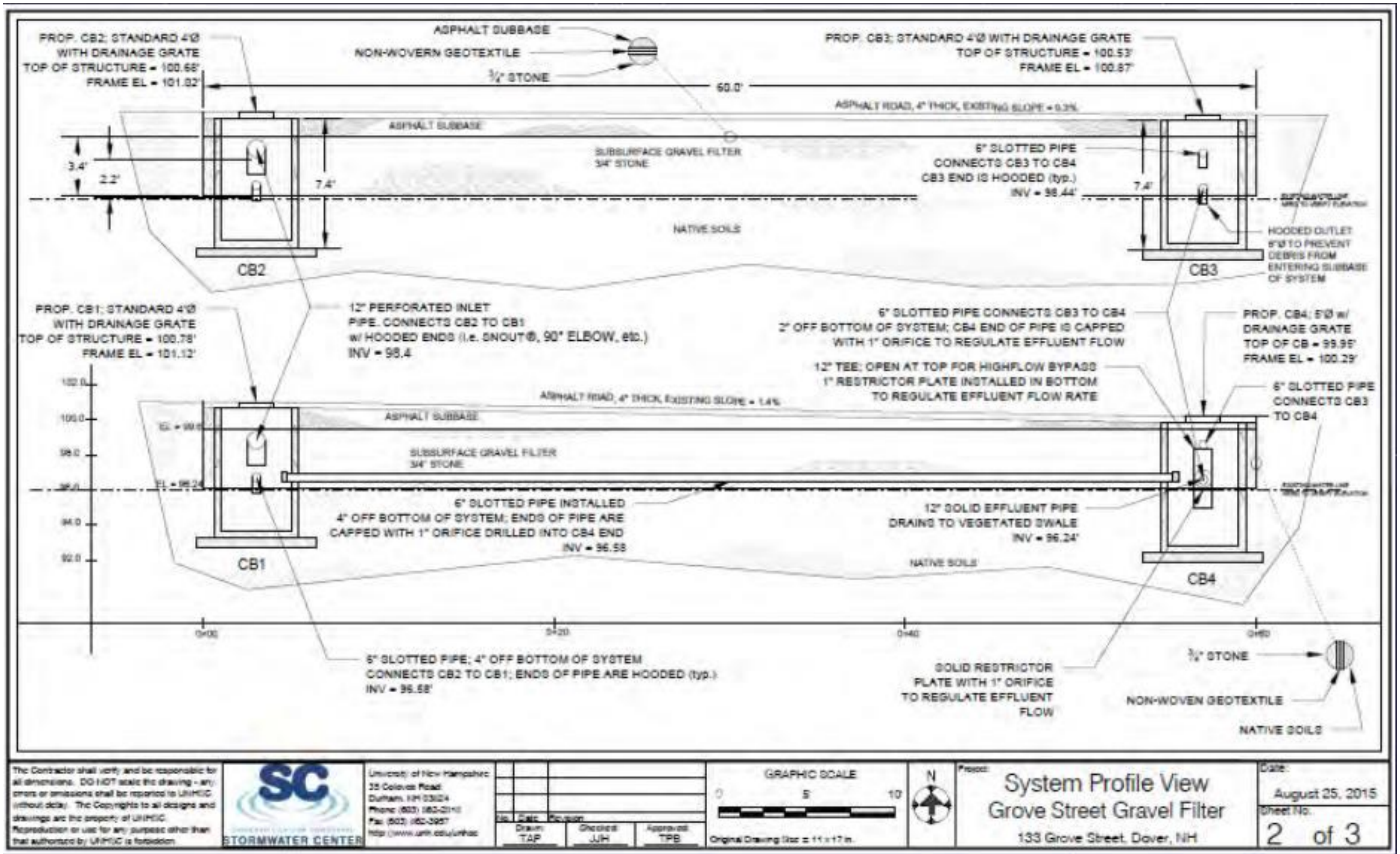

Figure 69: Grove Street Gravel Filter system profile view

Hillcrest Infiltration Trench

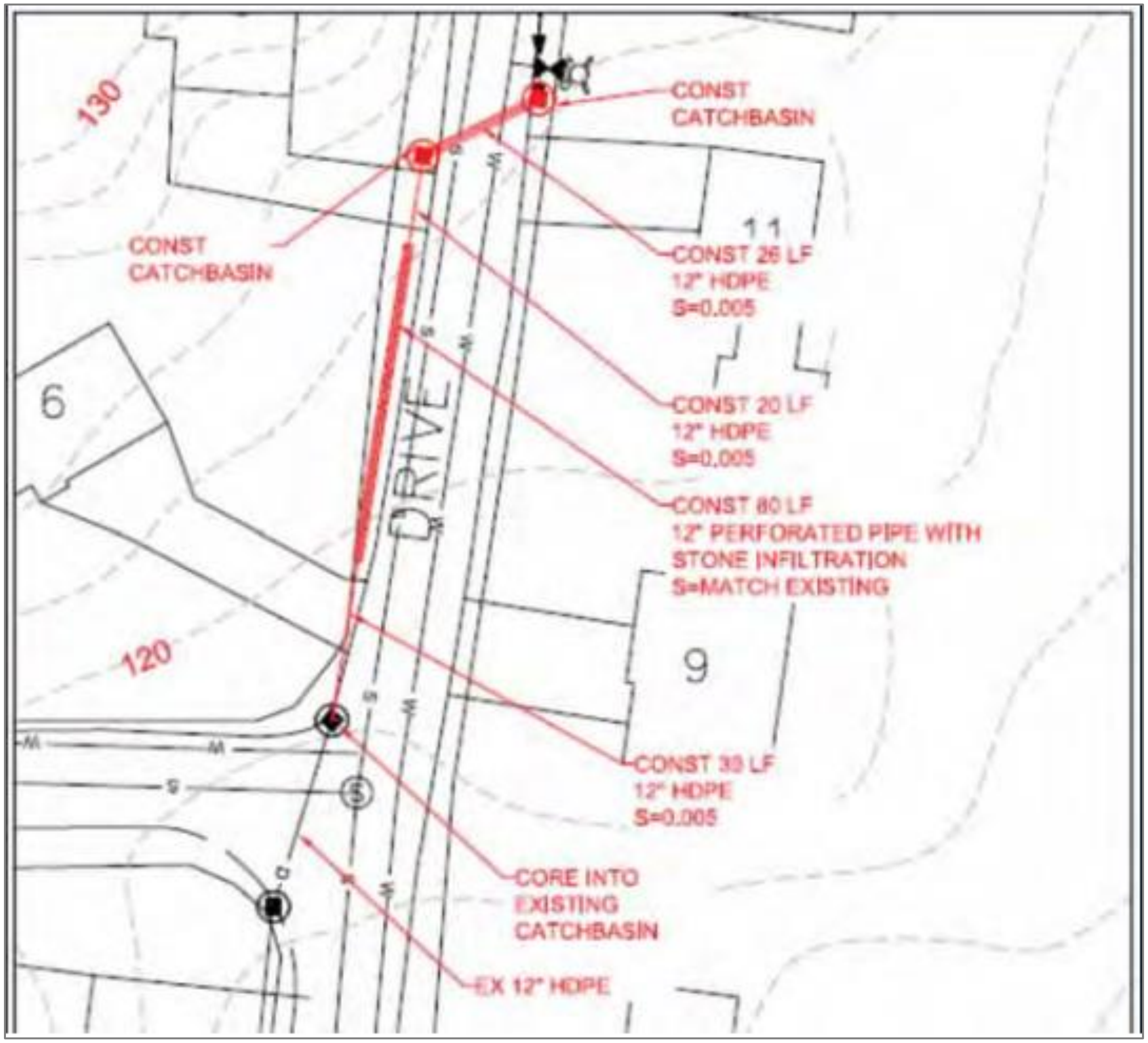

Figure 70: Hillcrest Infiltration Trench site layout

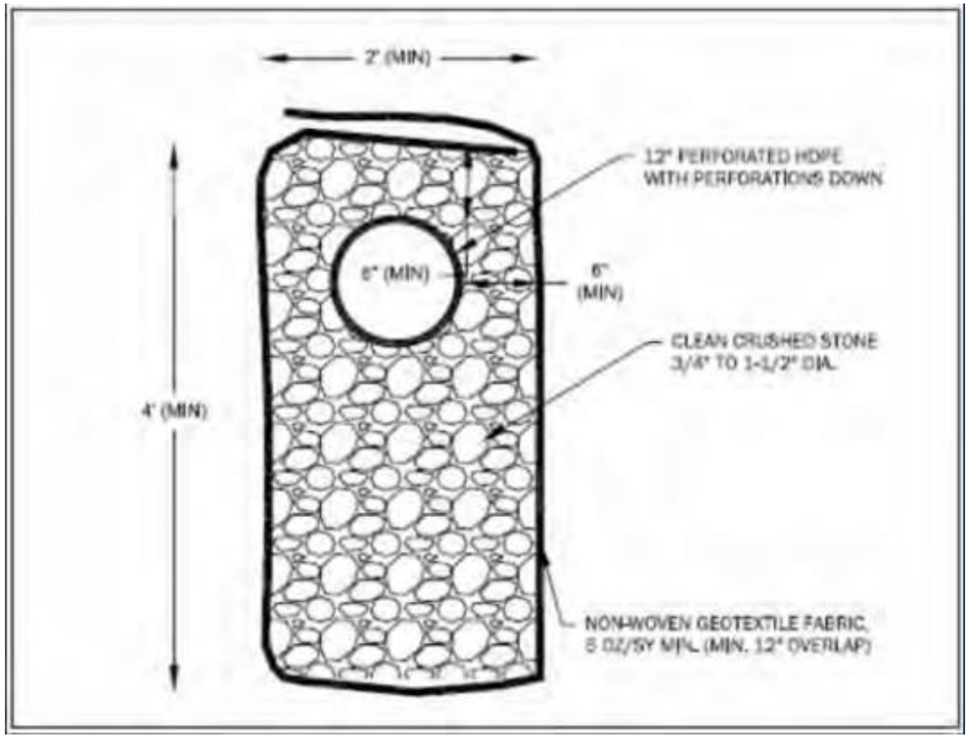

Figure 71: Hillcrest Infiltration Trench section view

Kettlebell Subsurface Gravel Filter

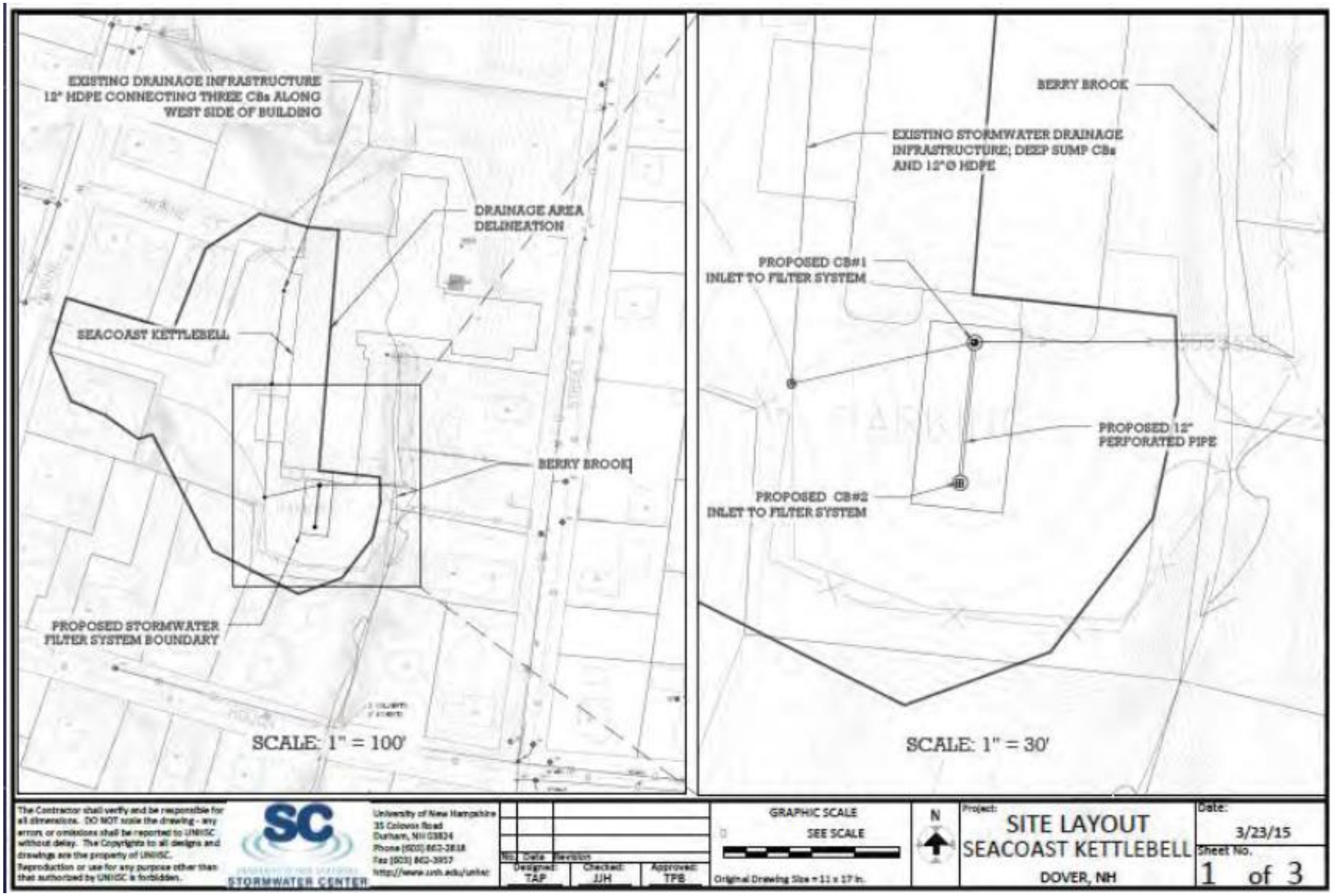

Figure 72: Kettlebell Subsurface Gravel Filter site layout

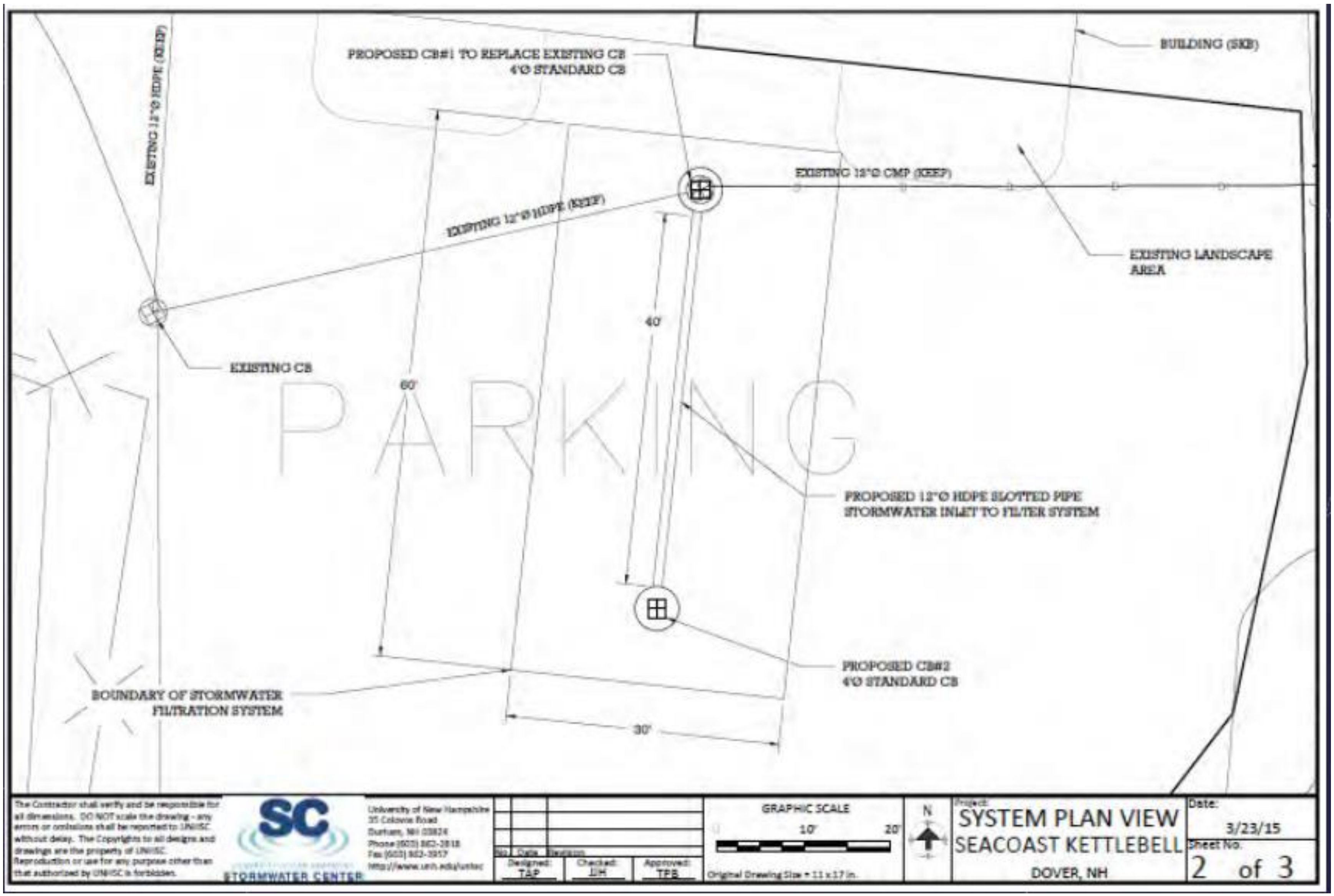

Figure 73: Kettlebell Subsurface Gravel Filter system plan view

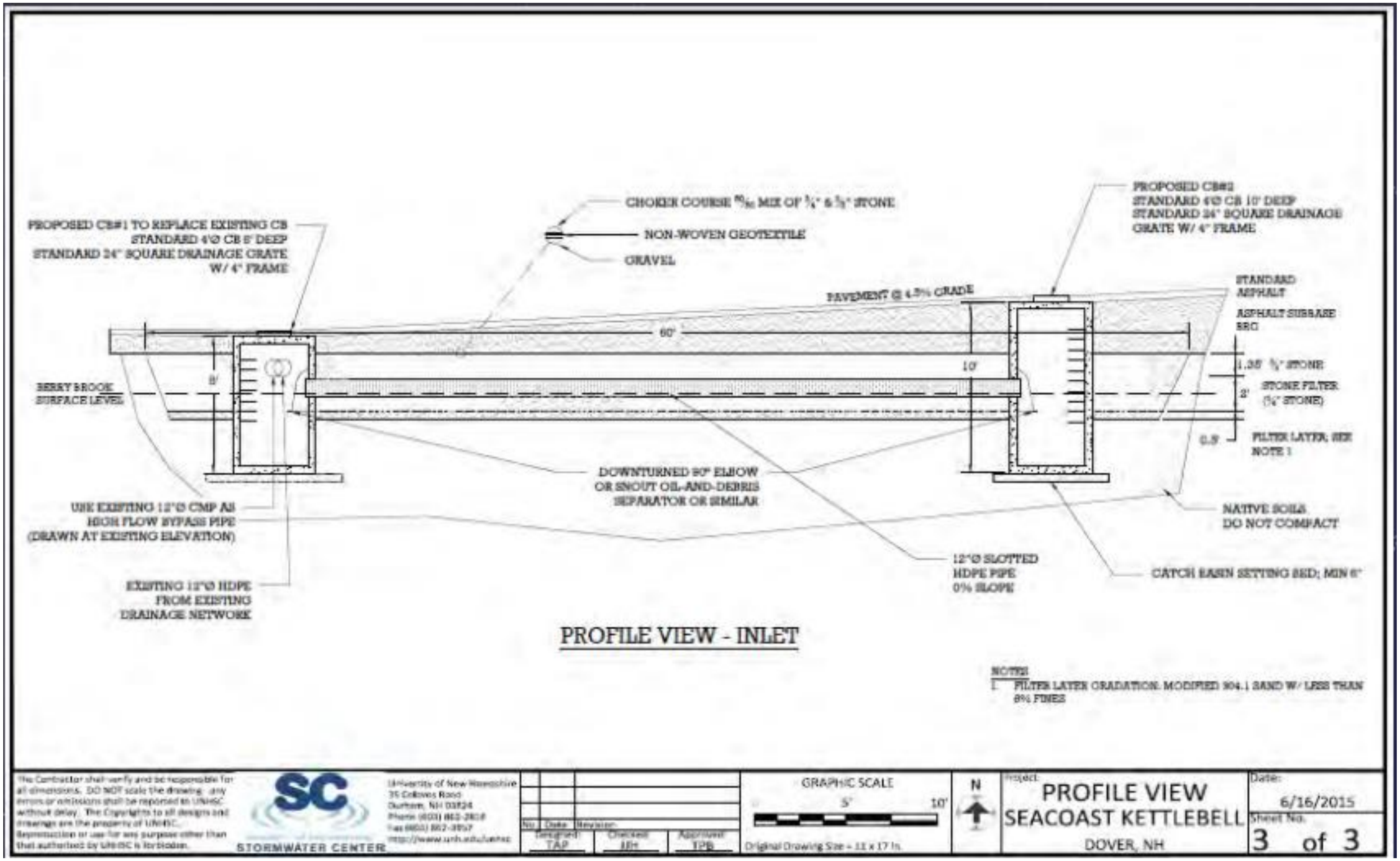

Figure 74: Kettlebell Subsurface Gravel Filter profile view

Lower Horne Street Bioretention

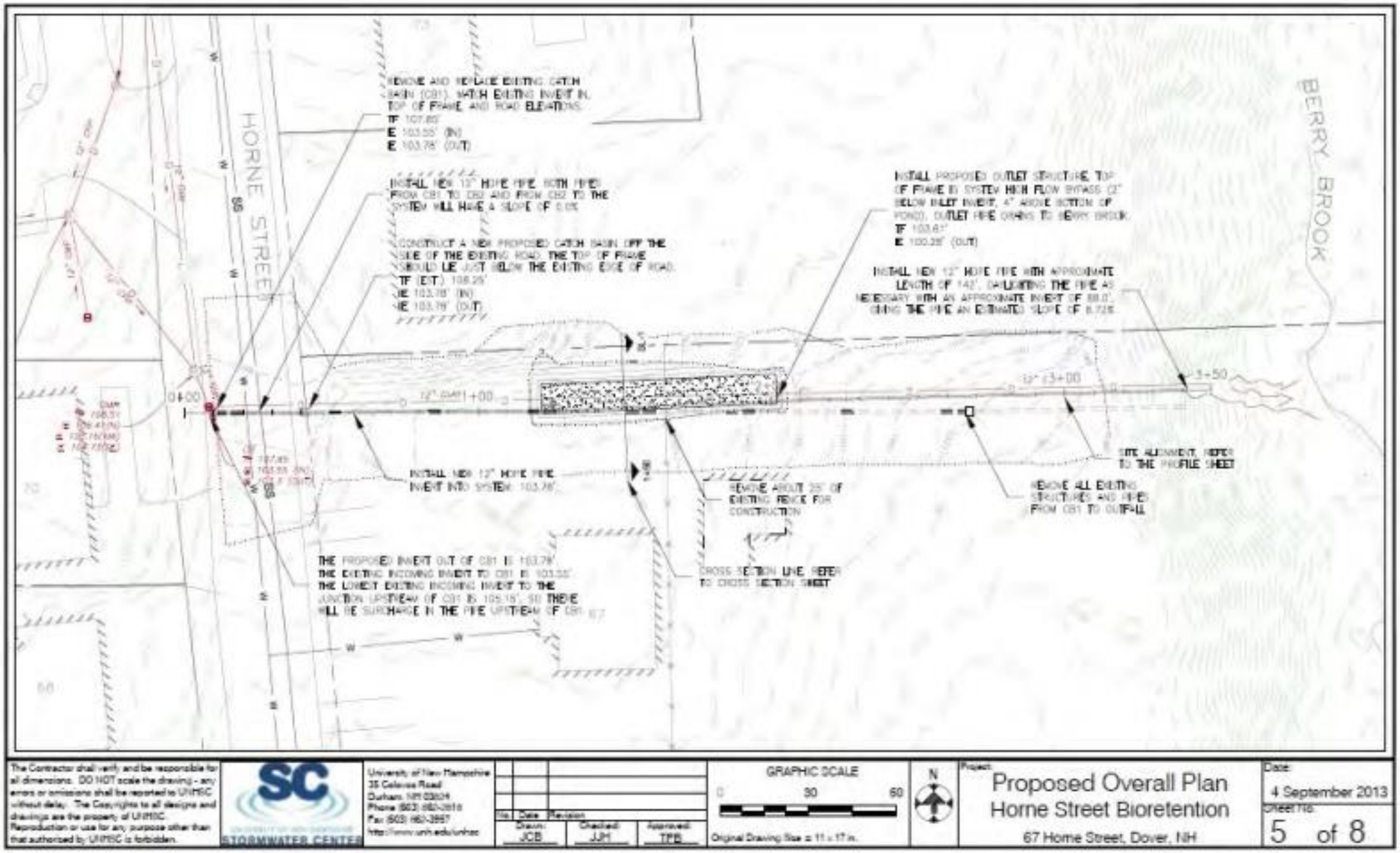

Figure 75: Lower Horne Street Bioretention overall plan

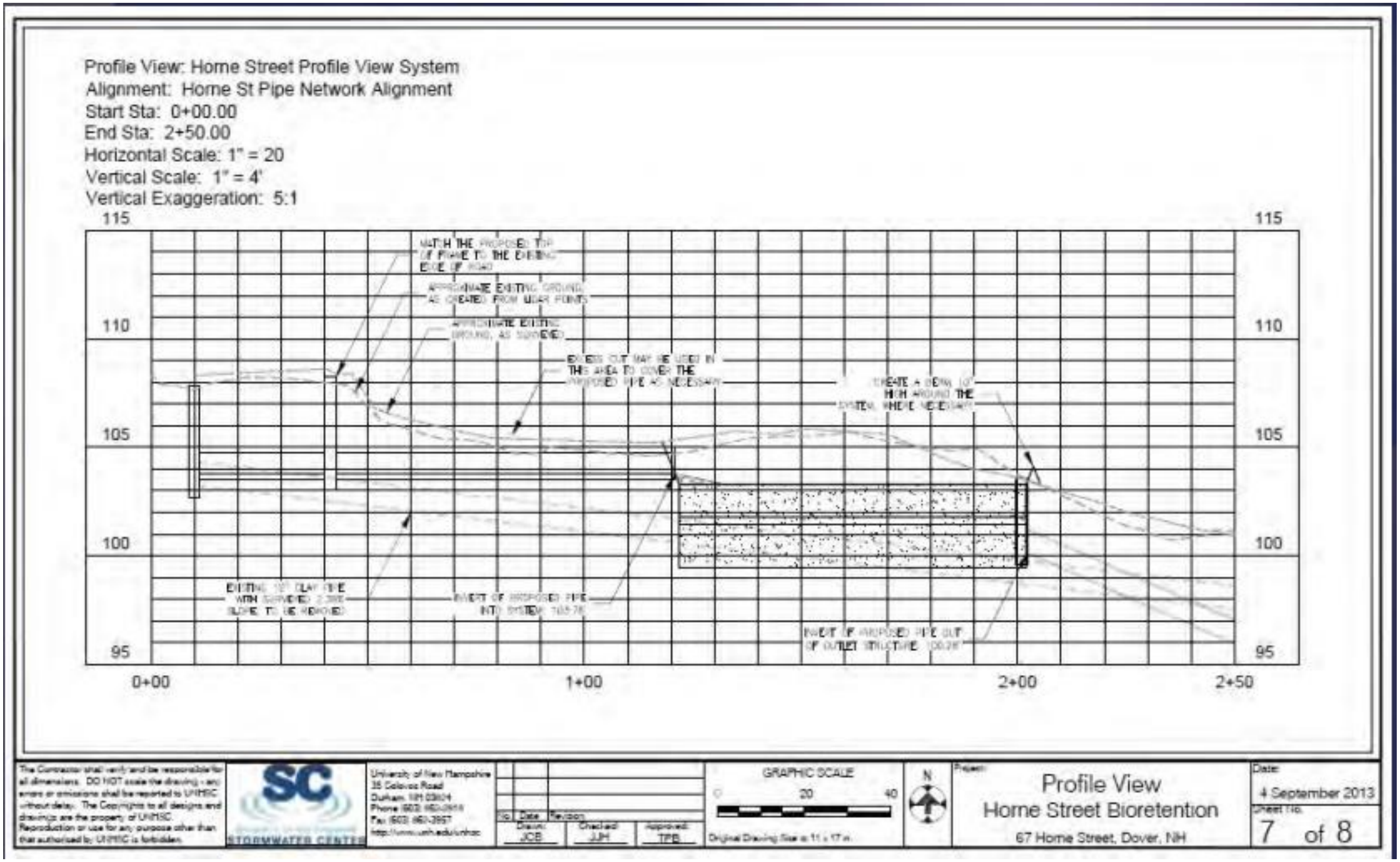

Figure 76: Lower Horne Street Bioretention profile view

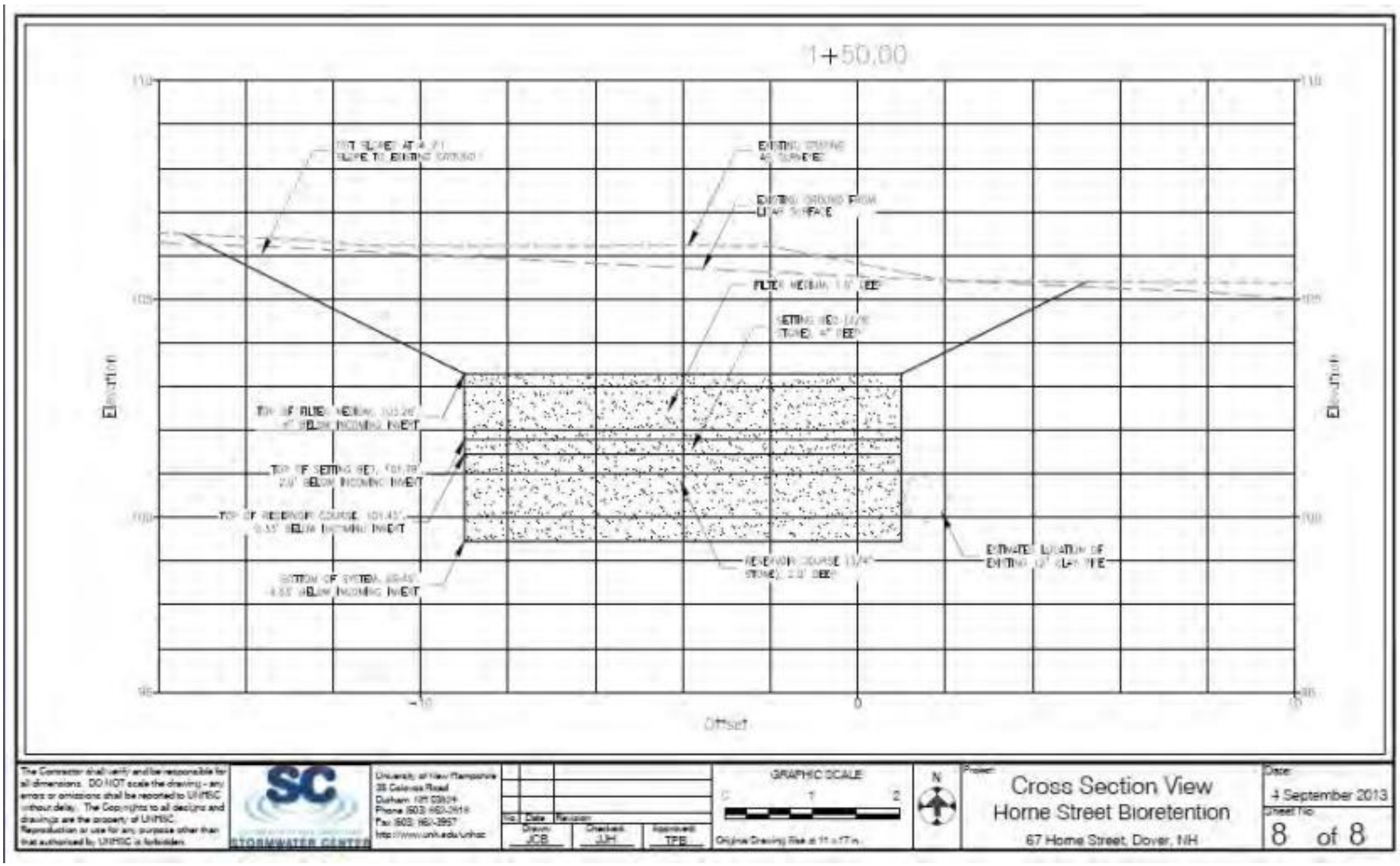

Figure 77: Lower Horne Street Bioretention cross section view

Upper Horne Street Bioretention

Figure 78: Upper Horne Street Bioretention drainage area

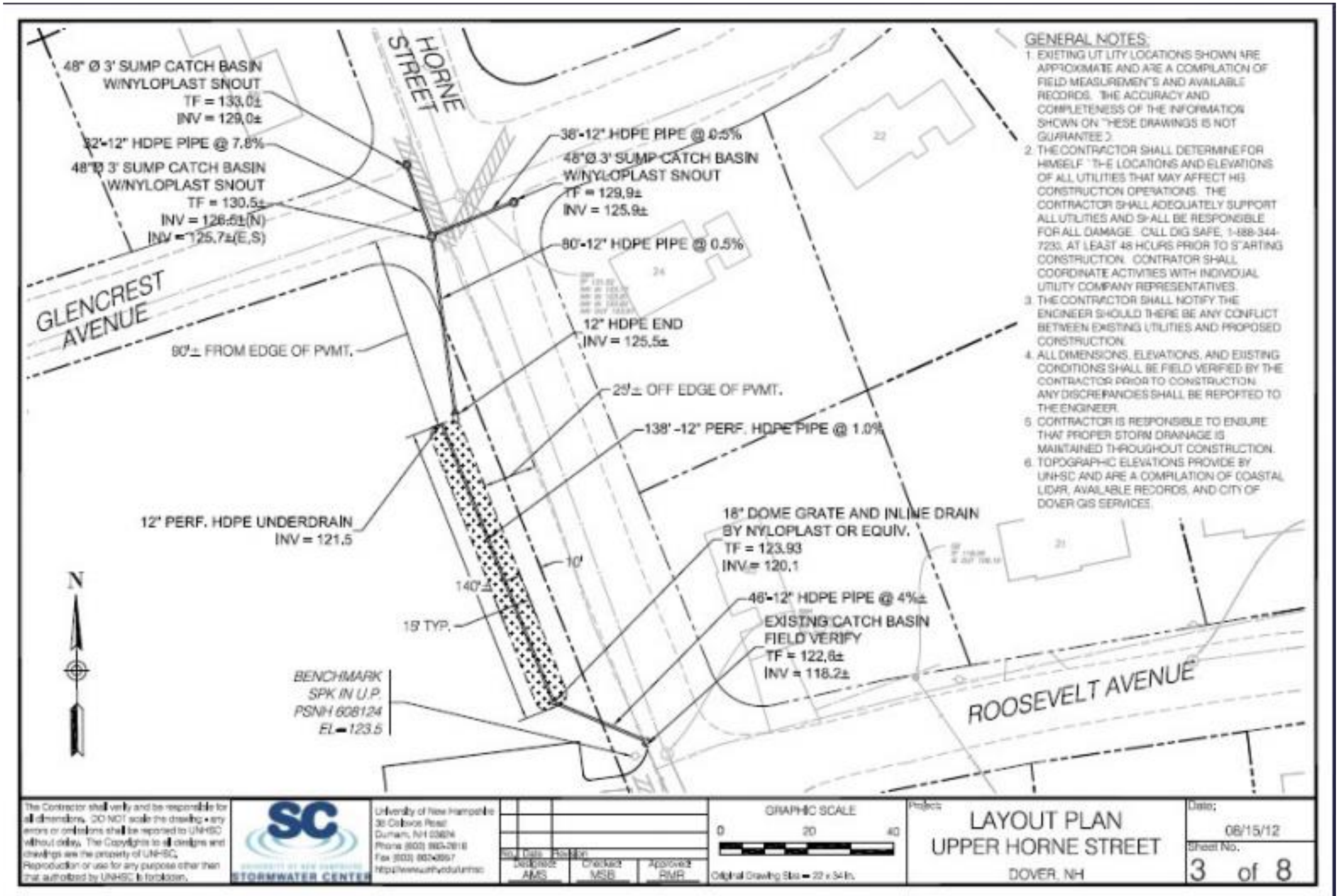

Figure 79: Upper Horne Street Bioretention layout plan

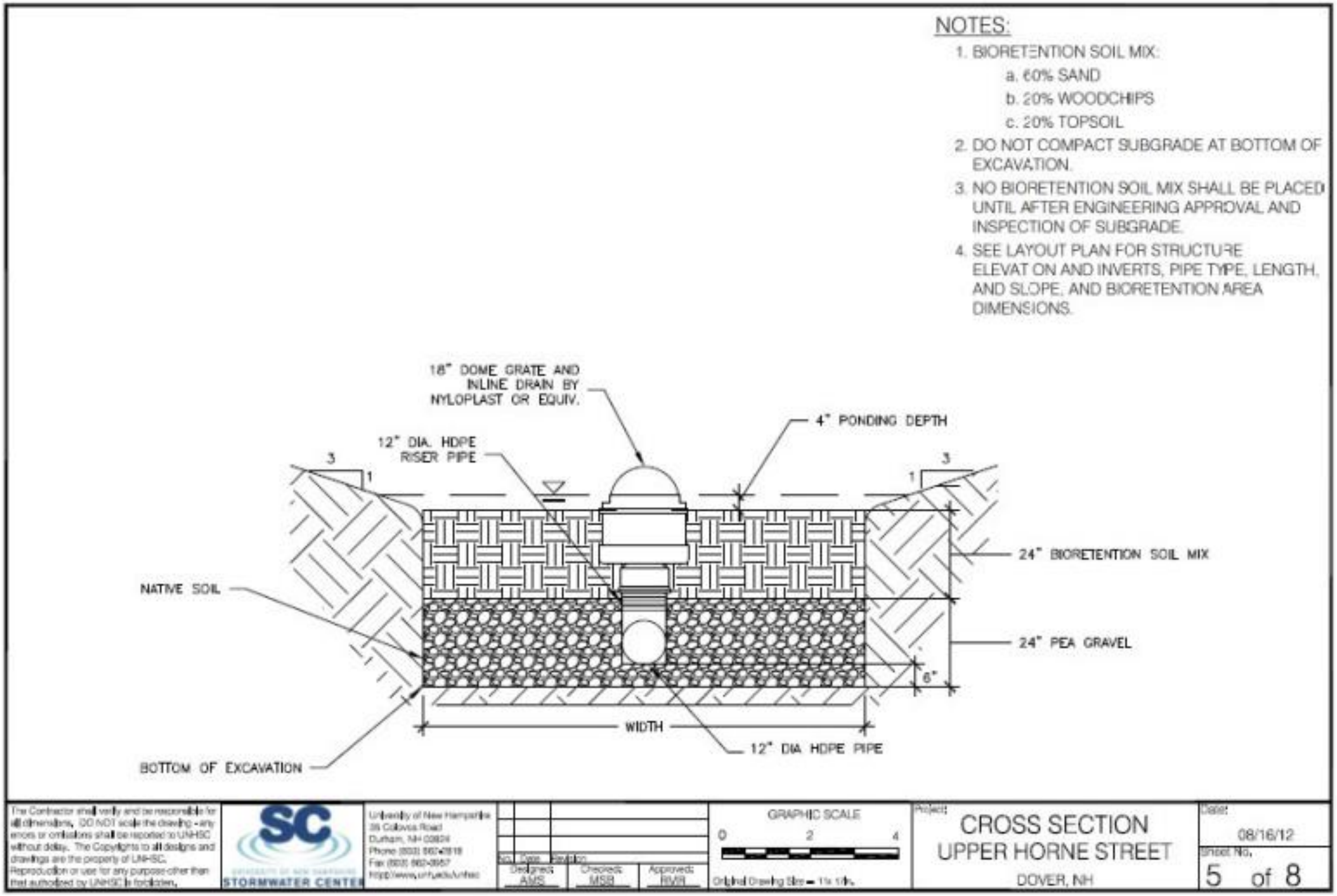

Figure 80: Upper Horne Street Bioretention cross section

Lowell Avenue Bioretention

Figure 81: Lowell Avenue Bioretention drainage area

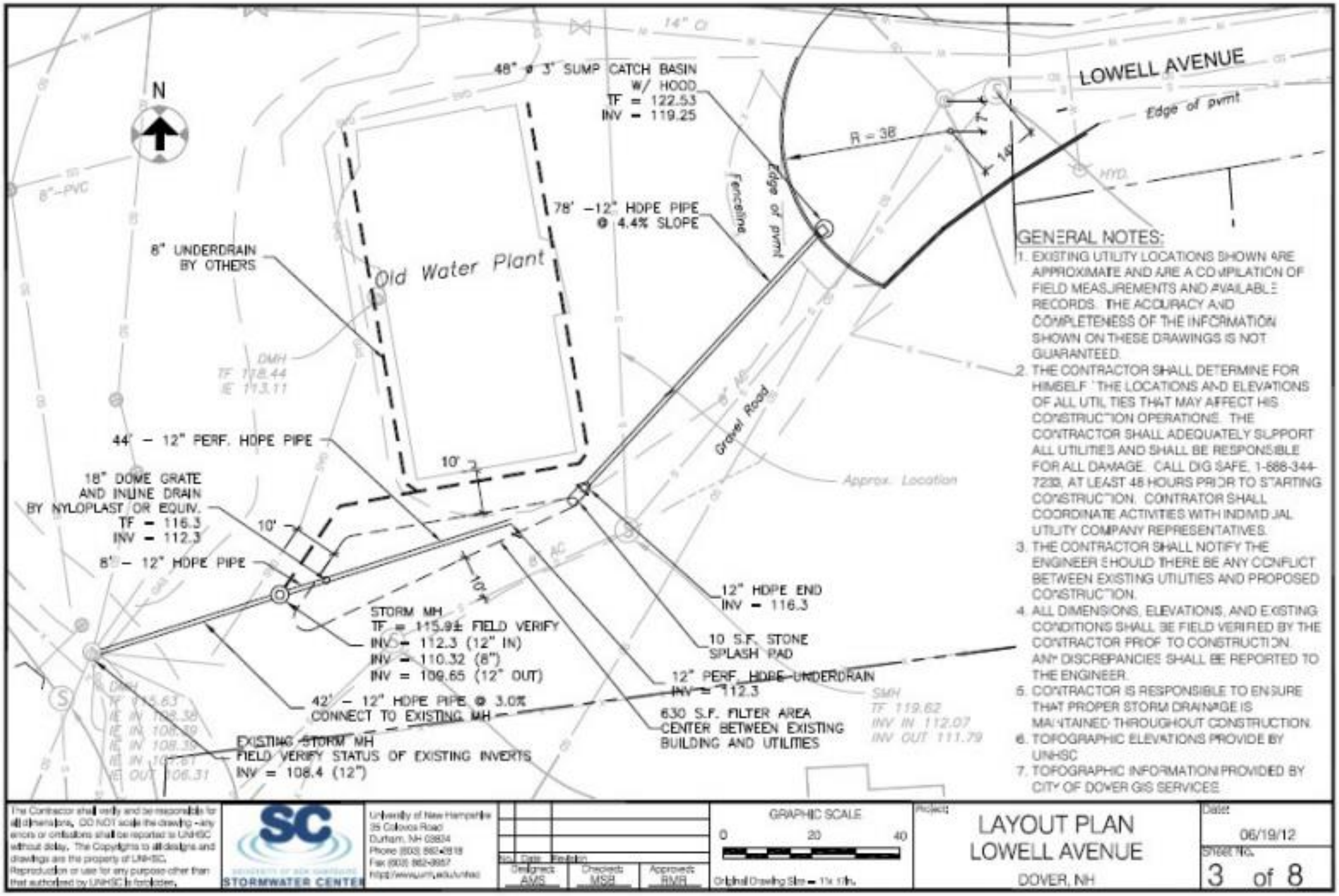

Figure 82: Lowell Avenue Bioretention layout plan

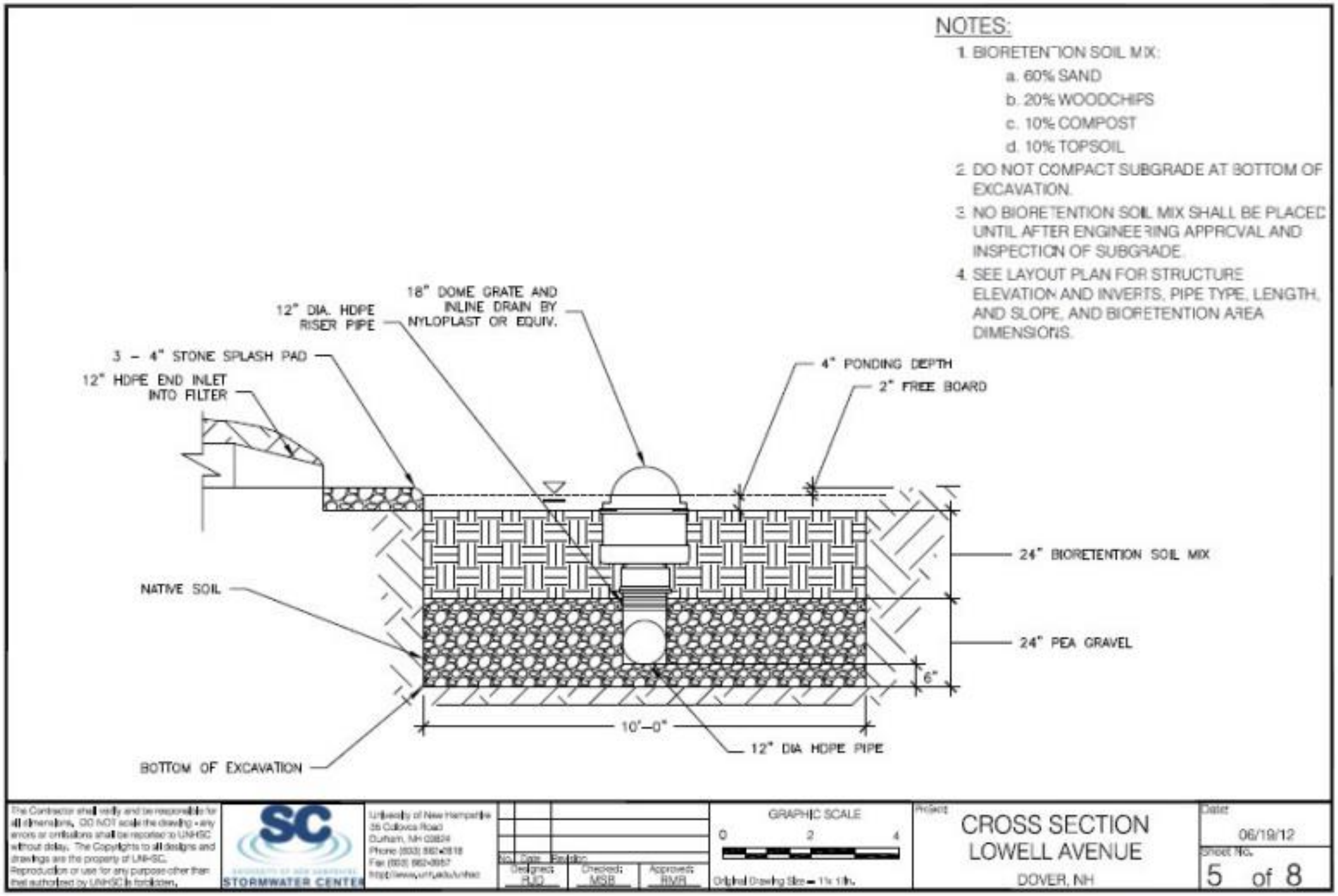

Figure 83: Lowell Avenue Bioretention cross section

Roosevelt Avenue Bioretention

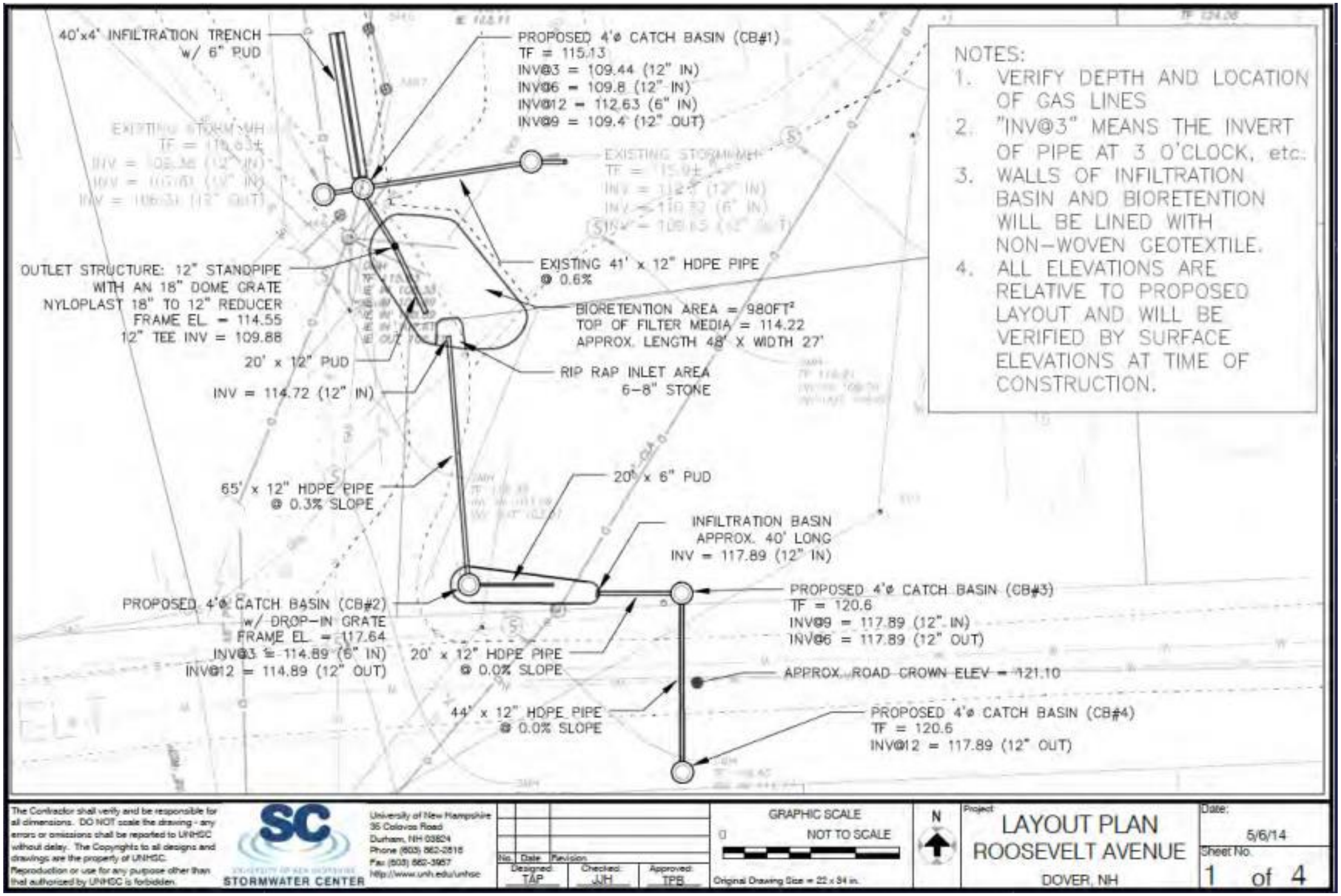

Figure 84: Roosevelt Avenue Bioretention layout plan

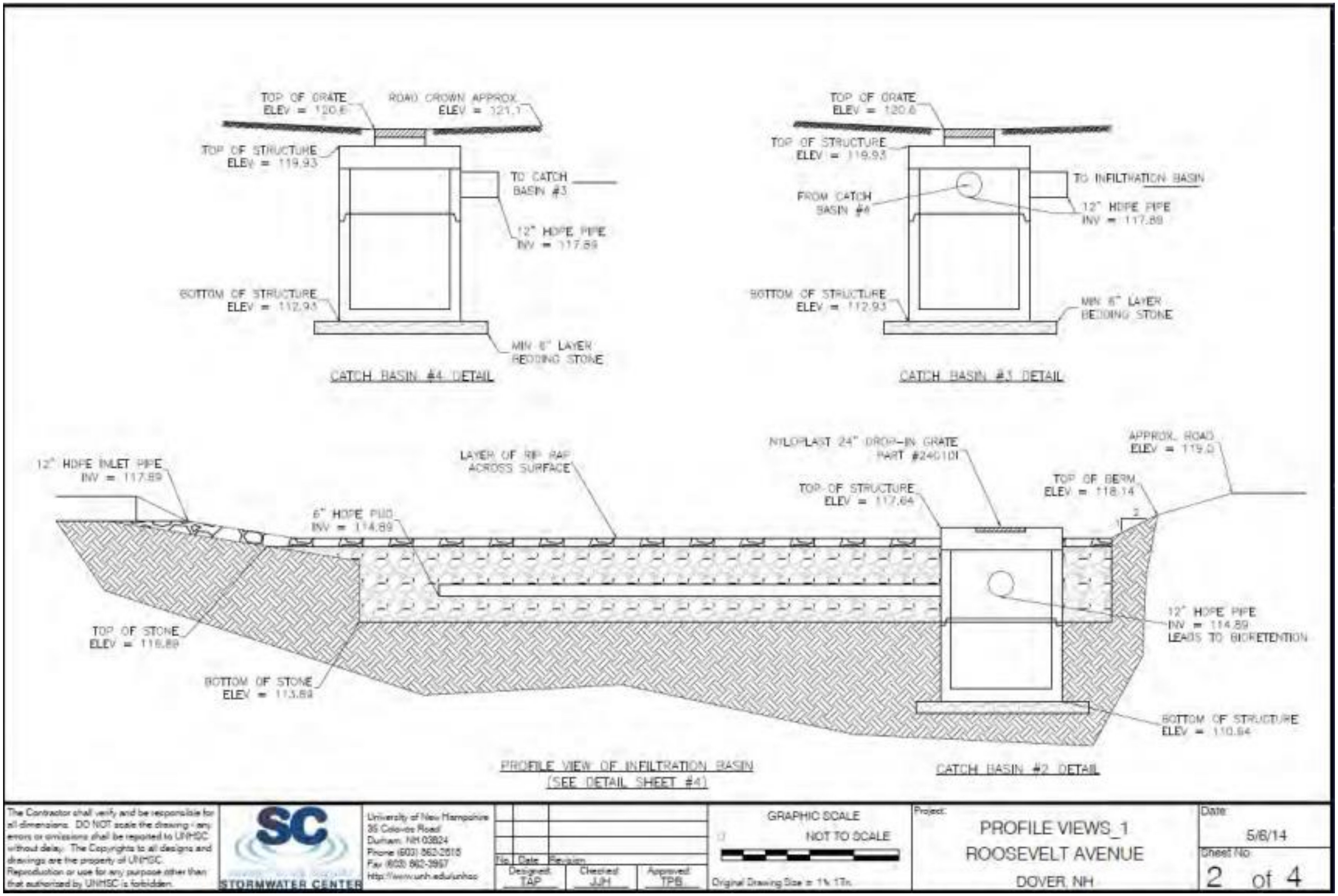

Figure 85: Roosevelt Avenue Bioretention profile view 1

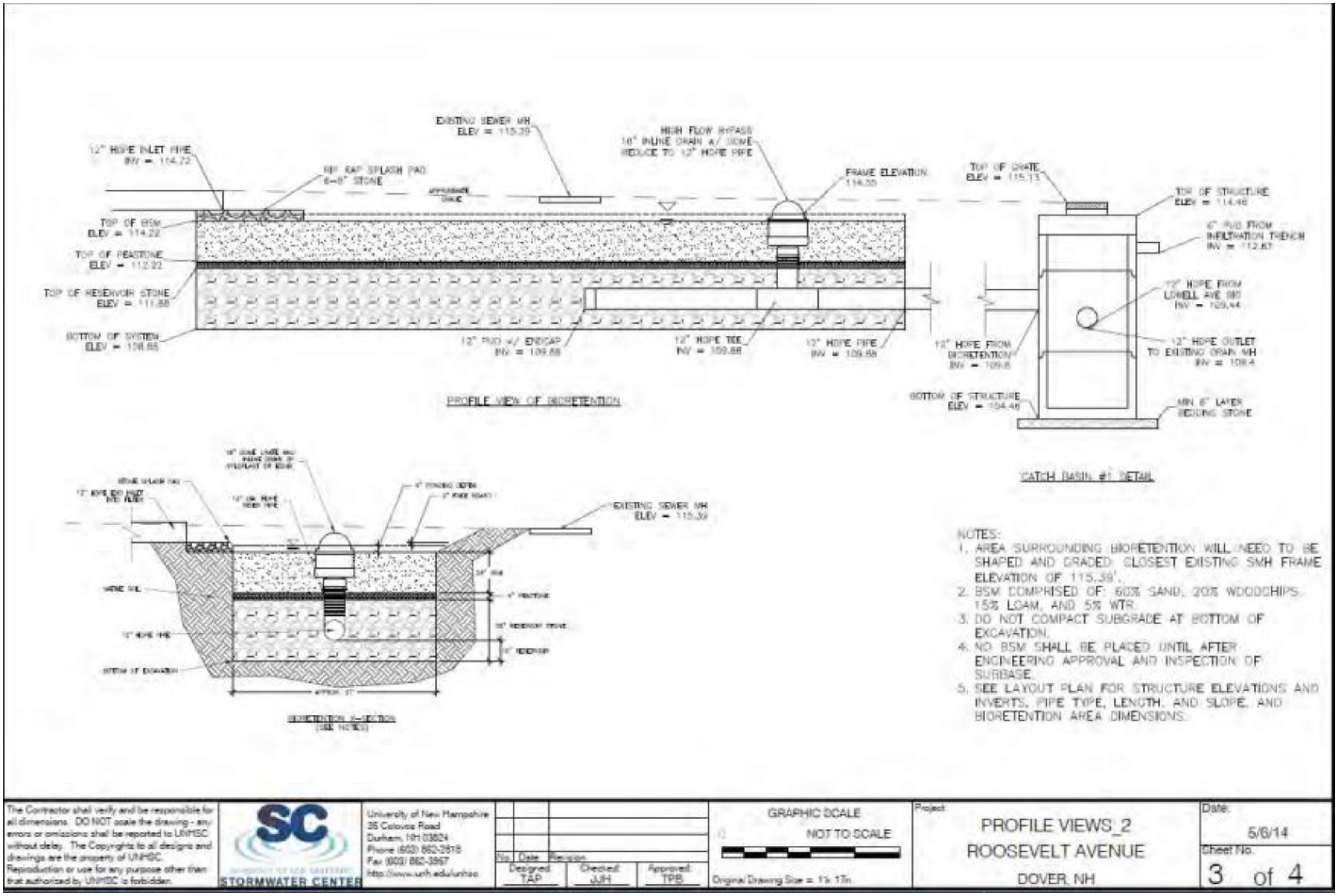

Figure 86: Roosevelt Avenue Bioretention profile view 2

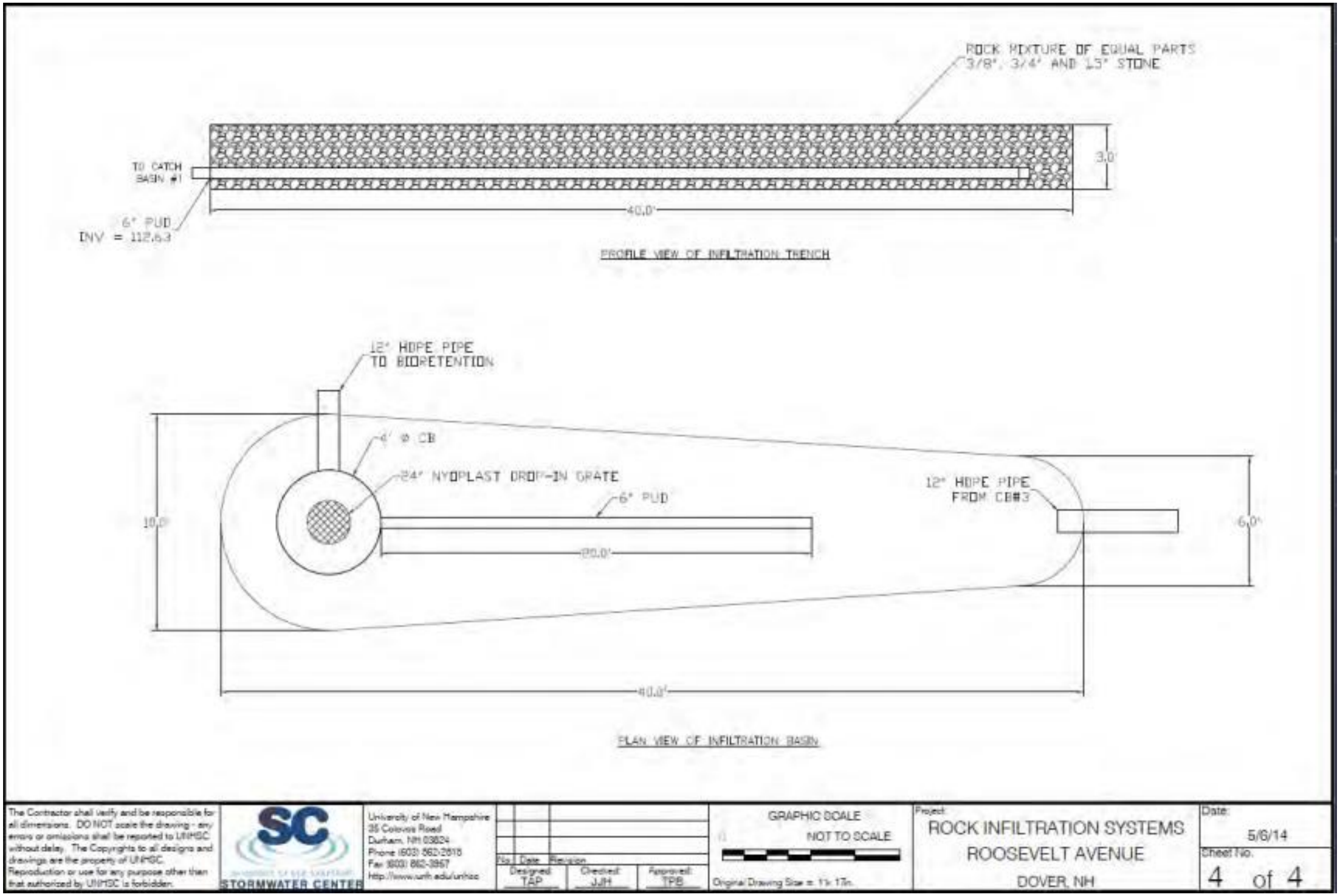

Figure 87: Roosevelt Avenue Bioretention infiltration systems