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RAINWATER HARVESTING:

A SUSTAINABLE SOLUTION TO

STORMWATER MANAGEMENT

A Thesis in

Civil Engineering

by

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ABSTRACT

In most urban areas, conventional stormwater management has led to increasing environmental and economical problems. It is becoming increasingly important to better utilize the limited amount of available water resources as global population growth and climate change are forecasted to increase water stresses such as flooding and drought. Locally in the Borough of State College and at the University Park Campus of The Pennsylvania State University (Penn State), stormwater flooding has caused infrastructure damage and environmental ecosystem damage in terms of erosion, sedimentation, flooding and potential pollution. Stormwater can be viewed either as an expensive threat to environmental protection and social wellbeing, or it can be viewed as an opportunity to promote micro-watershed sustainable development through the use of decentralized stormwater solutions such as rainwater harvesting (RWH).

The overall goal of this thesis is to demonstrate how RWH is a sustainable solution to stormwater management. Therefore, a study was conducted to investigate whether RWH could mitigate future climate change effects on stormwater runoff and help restore natural pre-development stormwater flow patterns, hence improving stormwater quantity and quality before the runoff enters receiving waters. RWH also was tested to determine whether it was a financially feasible answer to stormwater management.

In order to conduct an urban stormwater impact assessment, hydrologic discharge data were collected from an outlet storm-sewer in the East Campus Drainage Area (ECDA) at Penn State and used to calibrate the Storm Water Management Model (SWMM). Also, a financial comparison between a RWH system and the implementation of a green roof on a building under construction at the university with a conventional subterranean stormwater facility was assessed. Through the simulation of five storm events, the ECDA-SWMM hydrologic results indicate that RWH at Penn State has the ability to decrease stormwater quantity peak runoff by 52.7% and total volume runoff by 46.1%. This resulted in a potential decrease of possible future flooding events, a decrease of potential constituents of water quality pollution, and assisted in water conservation. Results from the financial analysis indicate that Penn State could realize savings of between $10 million to $30 million over the next 30 years by investing in RWH in future buildings instead of green roofs and conventional stormwater management facilities.

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Chapter 1

INTRODUCTION

Conventional stormwater management relies on expensive and centralized infrastructure systems, such as large, expensive stormwater pipes and detention ponds that concentrate and transport rainfall (and potential pollutants) to receiving bodies of water. For example, at The Pennsylvania State University, University Park campus (Penn State) and in the Borough of State College (SCB), stormwater is managed through pipes and ponds, which may result in environmental degradation to receiving waters because of the increased peak and total volume runoff which erodes stream banks, introduces contaminants, and increases the water temperature (CC, 2007). In some areas of the SCB, peak stormwater flow and total runoff volume currently exceed piping capacity resulting in infrastructure property damage (Hopkins, 2002; Smeltz, 2005). Increasing pipe size to mitigate this problem is expensive and only exacerbates downstream ecosystem damage. According to the U.S. Environmental Protection Agency (EPA) and the Intergovernmental Panel on Climate Change (IPCC), the frequency of high intensity rainfall events leading to flooding can be expected to increase in the future because of climate change(CIER 2008; UCS, 2008). This will result in greater runoff to receiving waters and less infiltration for aquifer recharge if not addressed by proper management. Hence, there is an urgent need to take a more holistic and sustainable approach to the management of stormwater runoff.

1.1 Thesis Objective

This thesis seeks to determine whether stormwater runoff, when managed sustainably through rainwater harvesting (RWH), can become a valuable resource and not a financial and environmental liability. The sustainable management of stormwater requires a different approach from the conventional conveyance and disposal paradigm. It is proposed here that if stormwater is treated as a resource, and managed through the use of properly engineered decentralized stormwater harvesting systems, the resulting benefits will be multiple: decreased stormwater runoff peak and volume with the associated environmental impact and reduced demand for potable water. Stormwater harvesting can be a key to sustainable water resource management as it reduces aquifer depletion, potable water costs, non-point pollutant discharge, and future flooding events that could potentially cause infrastructure damage. Using the East Campus Drainage Area (ECDA) at Penn State as a case study, the potential for RWH will be evaluated from both engineering and economic perspectives.

1.2 Goals

This thesis is organized around the following specific goals:

1) Define sustainability and its role in stormwater management in the 21st century.
    a. Discuss global sustainability in terms of water and wastewater
    b. Review the literature of the progression of stormwater management throughout time
    c. Discuss economic instruments for stormwater policies
2) Review the literature of state-of-the-art rainwater harvesting technology. Explain how reusing stormwater benefits the following:
    a. Stormwater flooding concerns
    b. Water quality issues
    c. Water conservation concerns

3) Project future increases in severe precipitation events.
    a. Discuss the science of climate change and its relationship with the hydrological cycle
    b. Summarize future climate change effects on precipitation in the Northeastern USA, the Mid-Atlantic region, and Pennsylvania
    c. Discuss the potential problems facing local stormwater infrastructure because of future climate change scenarios
4) Collect runoff discharge data from the ECDA on the Main Campus Basin and use these data to calibrate a numerical model for decision-making.
    a. Develop a computer-based modeling tool that can produce good estimates of the rainfall/runoff observed storm events
    b. Run a sensitivity analysis with the ECDA model to identify important parameters for the model calibration
    c. Explain limitations of the ECDA model simulations
5) Using building roof area data, calculate the volume potential of harvested rainwater for Penn State given current average rainfall rate (i.e., 100% RWH potential).
    a. Analyze the harvesting potential by implementing the RWH scenario through diversions on building rooftops within the ECDA model
    b. Evaluate the hydraulic and hydrological effects that RWH would have on the ECDA
    c. Discuss how RWH can mimic nature by running the ECDA model in a pre-developed scenario

6) Determine the monetary value of harvested rainwater.

    a. Discuss the potential water savings from collecting and reusing stormwater in the ECDA

    b. Perform a financial analysis of the benefits if Penn State implemented RWH in new building infrastructure

    c. Predict future stormwater regulations and the attendant economic benefits of RWH if implemented in certain scenarios

Chapter 2

LITERATURE REVIEW

2.1 Sustainability

2.1.1 Global Sustainability

"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."

- Bruntland (1987)

Sustainability is a broad concept that provides a critical link between the future life on earth with the present actions of mankind. The need to embrace sustainability has never been greater than it is now, given the 21st century's rapidly increasing economic and environmental pressures. Figure 2.1.1 shows that by the year 2050, the global population will number over 9 billion people (Sophocleous, 2004). In the next 12 years, the world's middle class will grow from 30% to 52% (Naim, 2008). Given the social implications resulting from these pressures, purely technical solutions are no longer sufficient (ASCE, 1998). Sustainable development requires a systems approach, and multi-disciplinary and multi-participatory global leadership. Sustainability is as much an ethical as it is a technical concept; it must therefore embrace traditional cultures and value systems in each and every community around the world, and technical solutions must be culturally appropriate. By understanding and practicing sustainability at the local level, we may begin to overcome the challenges of the diminishing quantity of fresh water resources and the rising levels of human consumption. This thesis is based on this premise and focuses on sustainability and water resources, specifically through appropriate and sustainable stormwater management at the local level.

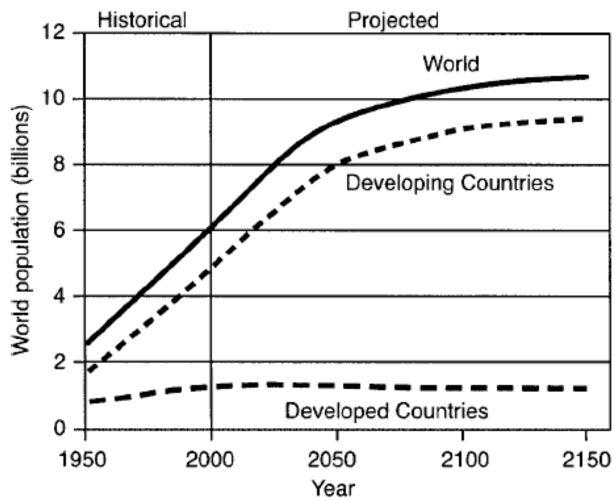


Figure 2.1.1: Historical and projected world population (Sophocleous, 2004).

2.1.2 Water Sustainability

Providing access to potable water in the 21st century is becoming an increasing challenge, and a lack of available water resources is already affecting a large amount of the world's population. Currently, over 1.1 billion people live without clean drinking water, 2.6 billion people lack adequate sanitation, and over 3,900 children die every day from waterborne diseases (UN, 2003). Water scarcity levels, as displayed in Figure 2.1.2, are projected to spread to many parts of the world as compared to the 1995 levels. As climate change increases, so will the likelihood of more frequent draughts, faster desertification, and more widespread water shortages. With the shared responsibility of the world's most essential necessity, many countries, including countries in the Middle East, Asia, and Africa, have been on the brink of war over water. Water is a global humanitarian need that will have to be addressed by the world community in order to circumvent catastrophic effects. The social and institutional components associated with water resource management must seek a common and sustainable vision for our water that will share the responsibility of deterring future environmental impacts such as water pollution, desertification or flooding. The complicated water challenges this world faces are opportunities to be solved with a mixture of innovative technology and a passion to improve human life.

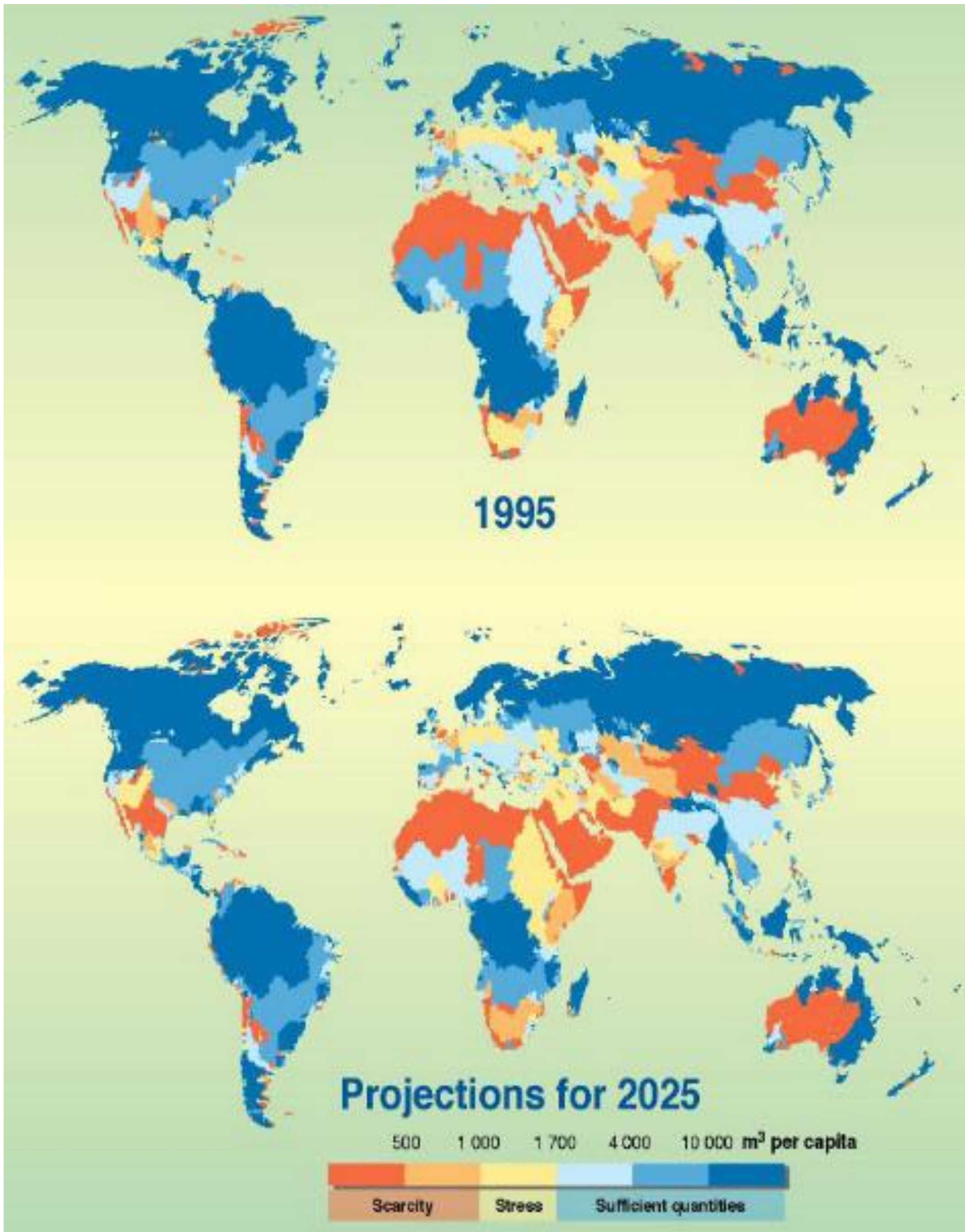


Figure 2.1.2: World 1995 and 2025 freshwater supply: Annual renewable supplies per capita per river basin (UNEP, 2007).

2.1.3 Stormwater Sustainability

Increased urbanization has caused drastic changes in hydrologic flow through the engineered alteration of land and water resources (Pierpont, 2008). Although most developed countries enjoy clean water and sanitation, their urban water systems still lack a comprehensive approach to sustainable stormwater management (Malmqvist et al., 2006). Sustainable stormwater management should strive to naturalize the built environment with the goal of reaching predevelopment flow conditions through the conservation of green space, the use of green infrastructure, and innovatively engineered systems. This chapter will discuss the ancient history of stormwater management, the progression from conventional to sustainable stormwater management in the United States, and the future challenges faced by the stormwater field due to climate change, and will suggest a free market economic solution for stormwater management through the implementation of decentralized engineered rainwater harvesting systems.

2.2 The History of Stormwater Management

2.2.1 Surface Water Runoff

Surface water runoff is created when pervious or impervious surfaces are saturated from rain, snowmelt, or melting ice (Durrans, 2003). Pervious surface areas can naturally absorb water until a point of saturation after which a greater amount of the rainwater runs off and travels via gravity to the nearest stream. This point of saturation is dependent on soil type, topography, flora and fauna, and evapotranspiration (Pierpont, 2008). In urban land use, where impervious surfaces blanket the natural environment, the hydrological process of surface water runoff patterns become more complex and unnatural, often causing infrastructure damage and the impairment of receiving waters by pollutants (Ragab at el., 2003). The need for stormwater management conveyance systems developed as a result of thousands of years of human experiences with destructive floods. The next section will discuss how stormwater infrastructures arose in ancient societies.

2.2.2 Stormwater Management in Ancient History

Water management infrastructure is an essential component of the built environment. For thousands of years, quality of life was directly correlated to flood control because floods would destroy both food crops and livestock. This required even very ancient societies to have some technique or strategy to manage and control rainwater (Koutsoyiannis at el., 2008). As far back as 3000 years ago, the ancient civilizations of Assyria and Babylonia had combined wastewater and stormwater sewage systems (Durrans, 2003). Figure 2.2.1 shows a picture of the water infrastructure of the ancient Roman city Volubilus, in North Africa, built in the 3rd century, B.C.

Figure 2.2.1: Water infrastructure in Volubilis, a 2000-year-old Roman city in Morocco (Stone slabs over stormwater culvert).

Underneath the stone pavings, a box culvert was implemented to transport stormwater and wastewater from household uses. Water infrastructure has served centralized cities worldwide and has provided the basic human needs of sanitation, clean drinking water, and flood prevention.

2.2.3 Conventional Stormwater Management

Conventional stormwater management requires the construction of an expansive and expensive centralized infrastructure system to transport runoff efficiently and rapidly. This approach often results in financial and environmental liability in the forms of infrastructure flooding damage and the externalization of possible stormwater pollution costs. Potential stormwater pollution externalities costs include the public recreation value of fishing or avoided permitting and mitigation costs. Beginning in the 1920s, stormwater management and flood prevention were implemented in a linear fashion, assuming that stormwater was a waste and not a resource (Durrans, 2003). With the help of gravity, stormwater was "disposed" of through streets, gutters, pipes, and channels, with its final destination being detention ponds and receiving waters. This allowed for drainage to occur in urban developments and the control of infrequent flooding events. Figure 2.2.2 shows the conventional view of centralized stormwater management. Every urban setting has only two types of drainage systems: major systems, designed to manage 100-year storm events; and minor systems, designed to manage 2- to 25-year storm events (Grigg, 2003). The conventional and cost-effective solution to reducing peak flows and total volumes up until recent years was to build larger detention ponds. Detention ponds had an adverse effect on the environment because they disrupted natural drainage paths, failed to improve the stormwater quality resulting from constituents of non-point pollution, and caused channel degradation complications (Durrans, 2003). This one-dimensional view that stormwater is a nuisance and its management acts as a service for urban communities to simply reduce flood damage, traffic delays, and citizens' inconvenience is at odds with an environmental understanding that rainwater can be utilized as a valuable resource.

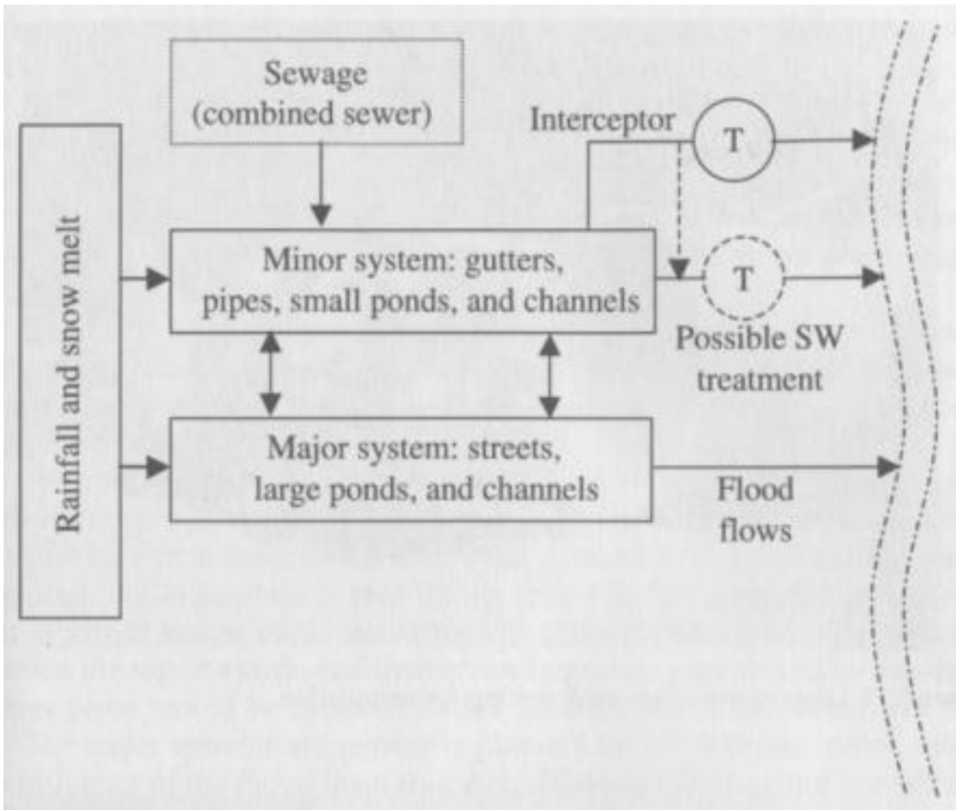


Figure 2.2.2: Schematic representation of conventional stormwater management (Grigg, 2003).

As environmental degradation worsened through the practice of these conventional stormwater practices, stormwater management regulations were promulgated and began to impact how stormwater was handled. Regulations promulgated as part of the 1987 Clean Water Act (CWA) Amendments (i.e., Phase I and II of the National Pollutant Discharge Elimination System (NPDES)) required the control of runoff quantity and quality, which sparked innovative solutions and progressive goals that helped reduce the negative impacts on aquatic ecosystems. The regulations address runoff quantity in order to control flooding, change in streambed morphology, and to decrease base flows; they address quality because of the potential for deleterious effects from nutrient and sediment transport and pollutant loading. These quantity and quality impacts affect ecological habitats, public health, safety, and recreation in local watersheds. The CWA regulations led to a transition to the use of Best Management Practices (BMPs), which are discussed later in this chapter. Elements of urban infrastructure are characterized by "long lifetimes," with buildings and roads lasting more than 100 years. Much of the existing stormwater infrastructure is in an advanced stage of aging and will need significant funding in the near future to be replaced and updated (Anderson, 2005; EPA, 2007). This need to update existing infrastructure offers an enormous opportunity for a paradigm shift in stormwater management, with new infrastructure designed in a sustainable manner (Malmqvist et al., 2006). With the advancement of urban runoff modeling programs and the availability of predevelopment flow data, sustainable stormwater development starting at the micro scale, through accumulation, can have a macro beneficial effect with the ultimate goal of "no discharge" (i.e., predevelopment flow).

2.2.4 Environmental Effects of Stormwater Discharges

In the past, stormwater management was practiced in a anthropocentric - human centered – manner and as a result has had a profound effect on the environment. As suburban sprawl has exploded in the last 20 years, so too has the increase in imperviousness over the forest, pasture and range lands, and cropland which those suburban developments replaced. This has affected local hydrological cycles by producing more surface runoff and decreasing the base flow, interflow, and depression storage (Davis et al., 2006). Studies have shown a direct correlation between water quality of streams and imperviousness and have revealed that communities with more than 10% imperviousness cause the streams in watersheds to become physically unstable, thereby producing an increase in erosion and sedimentation damage (EPA, 1996).

Surface water and aquatic ecosystem quality has increased dramatically over the last 25 years because of the prevention of point source constituents of pollution such as industries and sewage treatment plants (Roebuck, 2007). Potential stormwater non-point source pollution, which was not regulated strictly until recently with the implementation of NPDES Phase II stormwater regulations, is now becoming increasingly recognized as the largest source of water quality impairment in the United States (Andoh et al., 2001). As runoff travels through impervious land, it absorbs natural and human-made pollutants that eventually discharge into receiving rivers, lakes, wetlands, and coastal waters and can even directly infiltrate into aquifers through sinkholes. Urban stormwater accounts for approximately 40% of the constituents of pollution which results in the country's lakes, rivers, and estuaries not being clean enough to meet basic uses such as swimming or fishing (Schueler, 1994). Stormwater runoff pollution is multifaceted and arises from stormwater volume quantity and quality; these are explained below.

Water Quantity

Excessive stormwater quantity may produce streambank erosion and change the morphology of the stream bed (Wynn, 2004). Stormwater quantity is commonly controlled in developments by assuring that post-development peak runoff discharges are equal to or lower than pre-development runoff discharges. Even though the peak runoff is controlled on post-development discharges, the amount of evapotranspiration, baseflow, interflow and groundwater recharge would be lower than the pre-development state. Also, during the construction stages of developments, soils may become compacted and have less infiltration capacity than in post-development environments. This means that during construction the amount of stormwater could possibly increase in quantity because less rainwater is evaporating or infiltrating. Specific impacts may include "flooding, erosion, sedimentation, temperature and species succession, dissolved oxygen depletion, nutrient enrichment and eutrophication, toxicity, reduced biodiversity, and the associated impacts on beneficial water value uses" (Wagner et al., 2007).

Water Quality

Water quality concerns vary regionally and are a function of factors such as land use, air pollution, vehicle density, and population density (Fletcher et al., 2007). The main pollutants produced by stormwater (and conventional stormwater management) are suspended solids, oxygen-demanding matter, bacteria, nutrients such as nitrogen and phosphorus, and heavy metals. Suspended solids typically originate from the first flush runoff of a surface due to a rain event. Suspended solids cause an increase of turbidity, which lowers the amount of light penetration in water and directly affects ecosystems in numerous ways, but primarily by lowering the amount of dissolved oxygen (DO) in the water. It is important to maintain a higher DO level in or to better sustain aquatic life. Stormwater picks up organic matter from animal feces and combined sewer overflows (CSOs) and typically lowers the DO levels in receiving surface waters. Pathogenic bacteria in CSOs have caused detrimental human health effects and have caused beaches to be off limits because of health safety issues. Some examples of diseases associated with waterborne infections in CSOs are gastroenteritis and hepatitis (EPA, 2001a).

Nitrogen and phosphorous originate primarily from agricultural runoff but may also come from household usage of fertilizers, pesticides, and herbicides (Adams and Papa, 2000). Another major pollutant is thermal enrichment. Thermal enrichment occurs when surface water is heated as it gets transported through conventional stormwater drainage, or when wastewater at an elevated temperature is discharged to a lower temperature receiving water. Thermal changes can detrimentally affect receiving waters, especially rivers and streams that are cold water fisheries where just the slightest increase in temperature can affect the dissolved oxygen concentration (the solubility of oxygen is a function of temperature, its solubility decreasing with increasing temperature) and change the entire ecosystem.

Best Management Practices

In the past, stormwater management consisted of "end-of-pipe" treatment methods, meaning that the runoff would quickly drain from landscapes to a centralized treatment facility. Conventionally, most stormwater plans consisted of one centralized best management practice (BMP) such as a detention pond to lower the stormwater quantity rushing into receiving waters. A BMP is any program, technology, process, criteria, operating method, measure, or device that controls, prevents, removes, or reduces constituents of stormwater pollution (DOT, 2004). BMPs include permeable or porous pavement, infiltration basins, infiltration trenches, rain gardens, bioretention ponds, dry well and seepage pits, constructed filters, vegetable swales, infiltration berms and retentive grading, vegetated green roofs, and rainwater harvesting (DEP, 2006). Rainwater harvesting will be discussed in more detail as an example of how a stormwater BMP works.

Low Impact Development

Low impact development (LID) is a relatively recent approach to stormwater management that focuses on the minimization of runoff and onsite treatment. LID is a strategy that incorporates a number of stormwater runoff BMPs distributed throughout the entire site in order to maintain the site's predevelopment hydrologic regime. The goal of LID is to use "source control" techniques that encourage effective storage, infiltration, evaporation and groundwater recharge. The LID concept is based primarily on five concepts, which include: (1) conservation and minimization, (2) storage, (3) conveyance, (4) landscaping, and (5) infiltration (DER, 2002). The principle of conservation and minimization refers to the preservation of existing vegetated areas in urban settings. LID encourages storage of runoff volume in order to minimize the peak runoff rates and also to convey stormwater runoff to vegetated areas which helps mitigate the runoff rate. LIDs can be more cost effective than traditional stormwater management when evaluated using whole life cycle analysis. If implemented correctly, LIDs have the ability to eliminate all conventional stormwater infrastructure by managing discharge in a decentralized location and dealing with rainfall where it lands (Saravanapavan et al., 2005).

2.2.5 Economic Instruments for Stormwater Policy

"The problem of stormwater runoff management grows apace with continued urbanization, yet the management tools for this growing non-point source problem have not fully kept pace."

-Thurston et al. (2002)

In order for environmental quality to improve, a market must be created to offer incentives to reduce the quantity and improve the quality of an environmental externality. Ordinarily, this can be achieved in one of three ways: (1) measuring the emissions of pollutants into the environment and charging for them, (2) promoting the use of technological advances to decrease the inputs, or (3) measuring the ambient concentration and creating an economic system to achieve this level. Non-point constituents of pollution are complicated and generally cannot be regulated by mechanisms (1) and (3) because the externalities are usually stochastic and are non-observable. Instead, hydrologists must model emissions in order to estimate possible pollution based on certain practices. The two major mechanisms that are commonly used for public policy in controlling urban stormwater runoff are a Monetary Fee Mechanism and a Stormwater Trading Mechanism.

Monetary Fee Mechanisms

One way to improve stormwater control is to create fees that are commensurate with the degree of water degradation. This is known as the "polluter pays principle," for it forces polluters to provide monetary compensation for the ecological damage they are creating. One method is to create a stormwater utility that generates revenues by correlating the percentage of imperviousness at either a parcel level or at a regional level with receiving water degradation (Cyre, 2000). Some communities have done this by instituting either a flat rate or a compounding rate based on imperviousness. This non-market tax internalizes good practices through emission charges. The revenue that is generated can be used to invest in improvements in the communities' stormwater infrastructure. This drives homeowners or business owners to invest in technology such as BMPs or LIDs to stop polluting and also creates an efficient market through a varied difference in control costs between large polluters and small polluters (Doll and Lindsey, 1999). For stormwater management, many transaction costs are incurred in acquiring all the data one needed to evaluate and assess a monetary valuation for the watershed.

Stormwater Trading Mechanisms

Urban stormwater credit trading mechanisms are used to provide developers, engineers, and designers with incentives to manage stormwater in a sustainable manner in order to protect the overall quality of the aquatic resources (Woodward and Kaiser, 2002). Stormwater emissions directly affect the rival value goods associated with them. This means that the total sum of all the stormwater produced in an urban setting and its entire associated economic, social, and environmental values are summed in order to determine a fixed environmental protection baseline emission. Most trading schemes in the United States have to do with nutrient loadings and water temperature. By implementing a market-based mechanism to improve the water quality of a watershed, higher polluters are allowed to use a stormwater quantity rationing by allowing them to purchase water quality improvements from smaller producers to offset their urban runoff and at the same time all participants are performing in an economic optimality.

According to Thurston et al. (2002), in order to create a successful stormwater credit trading market, the following must exist:

1) A precise target in environmental improvement or stormwater runoff must be specified through reduction or detention of specific stream parameters.
2) A shared responsibility of stormwater mitigation between the entire watershed being analyzed.
3) A cost differentiation between large, high control cost polluters and individual, low control cost polluters because the monetary difference creates "opportunities in cost reduction that large, centralized approaches miss because they are essentially 'end of pipe' rather than source-reduction in nature."

This last point is extremely important because it differentiates trading credits from monetary fee mechanisms, thus yielding higher cost advantages to the large polluters.

Abatement Trading Credits

Stormwater abatement trading credits are an economic tool that provide promotion of onsite abatement for individual property owners by lowering their stormwater fees. With this increase in revenues gained from the fees of selling stormwater credits, onsite centralized BMPs can be utilized (Thurston et al., 2002). When environmental damage has been done to a watershed, smaller BMPs spread through a community can be built sustainably by a system of abatement trading credits giving economic incentives to control stormwater runoff in a cost-efficient way.

2.3 Rainwater Harvesting

For thousands of years, RWH was integrated into ancient cultures all over the world, from the Negev desert region in Israel to the Anti Atlas region in Morocco, and from the Mayan Civilizations in Central America to the isolated Pacific Island of Fiji (Gould and Nissen-Peterson, 1999). With the increasing intensity of water droughts and shortages projected worldwide and an escalation of floodwater occurring from intense storm events, the ancient practice of RWH is gaining significant public policy attention in regions of the world such as the Gold Coast of Australia, Germany and Sub-Saharan Africa. Developing an effective stormwater management system is imperative to help prevent the detrimental results from the increase of flooding. RWH has been shown to unravel these flooding-related stormwater problems as well as provide a resource for water-stressed regions (Coombes and Kuczera, 2001a; Fewkes and Warm, 2000; Ragab et al., 2003). It is estimated that over 100 million people in the world currently utilize RWH (Heggen, 2000). In the U.S., only about 250,000 RWH systems had been installed by start of the 21st century (Krishna et al., 2005).

2.3.1 What is Rainwater Harvesting?

RWH, in the broadest sense, is a technique that collects and stores roof runoff to be used for non-potable sources within domestic, commercial, institutional and industrial sectors in lieu of drinking water. Five controllable components are associated with RWH: (1) catchment surface, (2) conveyance system, (3) filter, (4) storage tank(s), and (5) water pump(s). The catchment surface dictates how much rainfall can be collected and therefore what size storage tank is needed. Conveyance systems are required to transfer rainwater from the roof to the storage tanks. Every inch of rain has the capacity to produce about 623 gallons of water per 1000 square feet of roof area. The main focus of the filter is to decrease the concentration of contaminants (i.e., atmospheric particulates, tree leaves, and animal manure) from the first flush of a rain event from being conveyed directly into the cistern. Storage tanks can vary from a small above-ground 65-gallon tank to large underground tanks that are able to store thousands of gallons of rainwater. A well-designed storage tank allows particles to settle and prevents algae and bacterial growth (Fewkes, 2006; Konig, 2001). Pumps are used to distribute rainwater to its end uses either directly or indirectly depending on the type of RWH system.

Three types of RWH systems are able to convey rainwater to buildings for non-potable uses, including gravity fed, directly pumped, or indirectly pumped (Roebuck, 2007). Gravity-fed RWH systems require that cisterns be located on top of the roof of a building in order to provide the amount of pressure head to be used for toilet flushing. In the indirectly pumped RWH system, stormwater is pumped to a second holding tank typically located on the roof and then water is conveyed to toilets through the use of gravity. Directly pumped RWH skips the holding tank and pumps water directly to the needed destination (Leggett et al., 2001). A diagram of an indirectly pumped RWH system is displayed in Figure 2.3.1. The advantages of using an indirectly pumped RWH system include:

1) Provides water for non-potable uses in case of pump failure because it relies on gravity to distribute water to toilets.

2) More energy efficient because the water pump can run at full flow rather than only running at times when the supply is needed (EA, 1999).

3) Can be connected to a backup water main pipe in case the water level at the header tank runs low and needs to be supplemented by potable water.

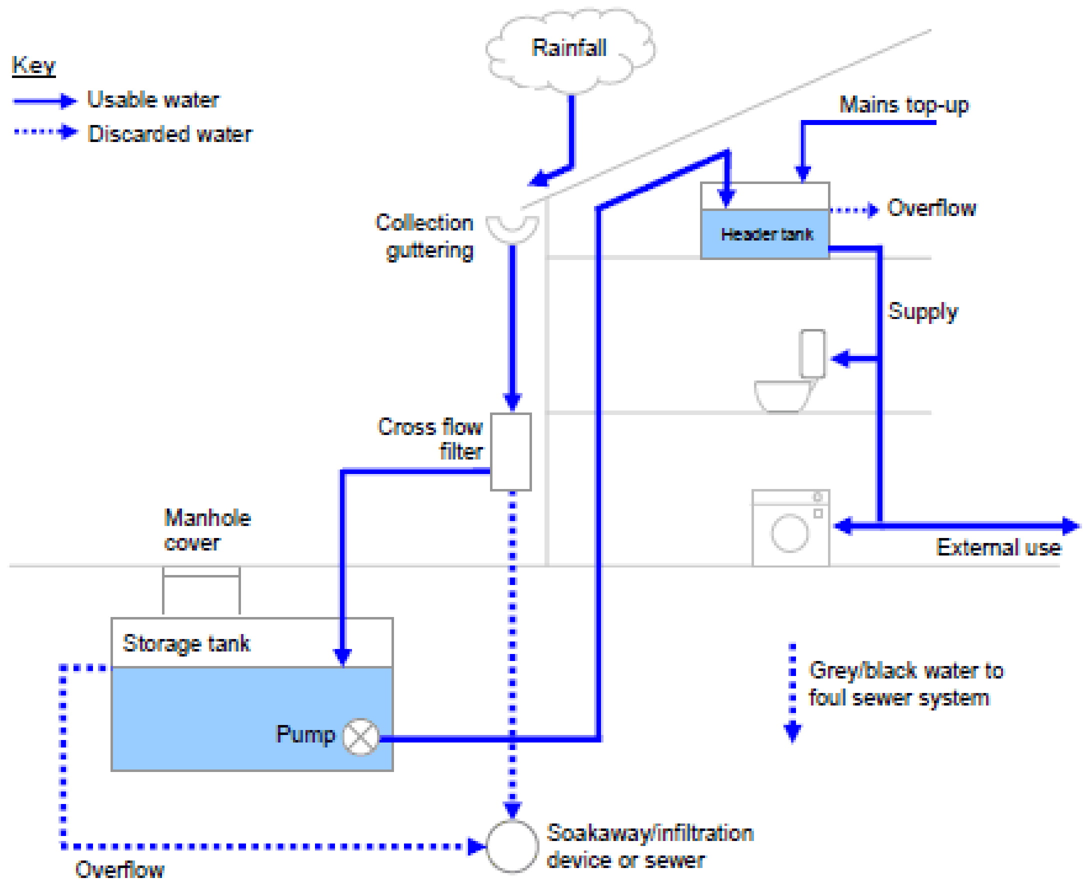


Figure 2.3.1: Indirectly pumped RWH system schematic (Roebuck, 2007).

Rainwater Harvesting Prevents Flooding

Rainwater harvesting reduces the load on stormwater piping systems, thereby preventing flooding of existing infrastructure by decreasing the peak runoff (Bucheli et al., 1998; Fewkes and Warm, 2000). By increasing the number of decentralized rainwater harvesting units, municipalities can install smaller and less expensive stormwater management systems. Also, decreasing stormwater discharges to a central municipal system increases the life cycle of the stormwater management system by extending the service life of the infrastructure assets and decreasing replacement costs (Coombes et al., 2000). Rainwater collection benefits stormwater infrastructure by making roof runoff independent from conventional centralized stormwater conveyances and by decreasing stormwater infrastructure corrective and/or restoration costs.

Rainwater Harvesting Reduces Depletion of Drinking Water Resources

Rainwater collection is not only a solution to problems caused by stormwater runoff; it also decreases the demand on public water supplies which in turn reduces the demand for new reservoir and well construction (Lallana et al., 2001; Leggett et al., 2001). Potable water provided by a municipality is used by consumers for both potable and non-potable purposes. RWH can supplement both these potable and non-potable water uses, but rainwater must be properly filtered and treated to be used for consumption because untreated it does not meet typical drinking water standards. Coombes et al. (2001b) modeled RWH for a community in Southern Australia and concluded that rainwater tanks are able to provide a viable alternative source of water and decreases the demand for potable water by 50%. RWH also could help reduce the peak demand for potable drinking water (Lallana et al., 2001).

Rainwater Harvesting Reduces Pollutant Loading to Receiving Waters

As discussed earlier, stormwater negatively affects the ecosystems of receiving waterways through the introduction of pollutants and the erosion of stream banks. In the Penn State University area, this is important because part of the university discharges its stormwater to a cold water fishery area and a small increase of water temperature could devastate the trout population in Spring Creek. Some of the key factors that influence roof runoff quality include roof material (roughness, age, and chemical characteristics), size and inclination of roof, precipitation intensity of event, pollutant concentration in the rain, and wind patterns. For example, changes in wind patterns from climate change also could increase the amount of sediment debris on rooftops, which could further degrade the quality of receiving waters (Arthur and Wright, 2005). Rainwater collection decreases the volume and rate of stormwater that flows into the receiving waterways and acts as a buffer for stormwater quality control.

2.4 Climate Change and its Effects on Precipitation

2.4.1 Climate Change

Greenhouse gasses occur naturally in the earth's atmosphere and help to protect the planet and sustain life by trapping solar energy. Without these gasses, the earth's average temperature would be about 30º C (86º F) lower than we currently experience (i.e., about 15º C) making life on earth as we know it impossible (Matondo et al., 2004). The global energy cycle receives incoming short wave (~0.5 um) solar radiation. Some energy reflects back into the atmosphere off clouds, high albedo surfaces (e.g., snow), and aerosols (e.g., sulphuric acid droplets formed from volcanic eruption or sulphates formed from industries or forest fires). The remainder of the incoming energy is absorbed by the earth's surface and atmosphere. Eventually, the earth's surface releases the energy back into space as long-wave (~10 um) infrared radiation. As this energy departs, clouds and greenhouse gasses absorb and trap some of it (Hengeveld, 2005). This energy cycle balance within our atmosphere is responsible for providing life to the world's ecosystems, changes in seasons, wind patterns, ocean currents, and the global water balance that controls the interaction between precipitation, evapotranspiration, runoff, and evaporation.

Anthropogenic influences, such as the combustions of hydrocarbons and deforestation, can increase the amount of carbon dioxide, nitrous oxide, methane, and sulphates in the earth's thin layer of atmosphere if their emission rates exceed the ability of the various sinks on the earth to absorb these gasses. If exceeded, a resulting enhanced greenhouse effect traps outgoing solar radiation and causes warming to occur on the earth and climates to change nonlinearly. Changes in land use, such as urbanization, create carbon cycle disturbances that enhance the greenhouse effect by modifying land albedo values by increasing the amount of imperviousness (e.g., heat island effects from asphalt cities) (UNEP, 2007).

Since the industrial revolution in the mid-19thcentury, the anthropogenic driving forces of hydrocarbon combustion and deforestation have increased the amount of excess greenhouse gasses in the atmosphere. This was proven beyond a reasonable doubt by modeling natural drivers of global warming and anthropogenic drivers of global warming, over time (IPCC, 2007). Man-made carbon dioxide has had the strongest role in increasing the amount of greenhouse gasses in the atmosphere, most of which have come from fossil fuel use and land-use change. Fossil fuel use mainly has been due to applications in transportation, heating, cooling, industry, and agricultural farming. Land use changes, including urbanization, deforestation, and agricultural applications, have caused methane and nitrous oxide to increase.

The Intergovernmental Panel of Climate Change (IPCC) published a report in 2007 which was written by over 450 lead scientific authors from 130 countries and has been peer reviewed by over 2500 scientific experts. Table 2.4.1 presents the key direct observations and future projections from the latest IPCC report (IPCC, 2007). These scientists agreed, with 90% certainty, that humans are at fault for increasing global temperatures and causing climate change

Table 2.4.1: Key observations and future projections from the 2007 IPCC report (IPCC, 2007).

Key Direct Observations from 2007 IPCC Report	**Key Future Projections from the 2007 IPCC report**
Carbon dioxide levels have increased from 280 parts per million (ppm) to 379 ppm since the industrial revolution.	Probable temperature rise *likely*, between 1.8º C and 4º C.
The global average air temperature has increased by 0.74º C (0.56º C-0.92º C) in the past 100 years.	Possible temperature rise *likely*, between 1.1º C and 6.4º C.
11 out of the past 12 years have been among the warmest years in recorded history.	Sea level *likely* to rise by 28-43 cm
Since the 1980's, average atmospheric water vapor content has risen because warmer air can hold more water vapor.	Arctic summer sea ice disappears in second half of century
Mountain glaciers and snow cover have decreased.	Increase in heat waves *very likely*
Global sea levels have increased at a rate of 1.8 mm (1.3 mm - 2.3 mm).	Increase in tropical storm intensity *likely*
Extreme > 99% probability of occurrence, *Extremely likely* > 95%, *Very likely* > 90%, *Likely* > 66%, *More Likely than not* > 50%, *Unlikely* < 33%, *Very unlikely* < 10%, *Extremely unlikely* < 5%,	

2.4.2 Climate Change and the Hydrological Cycle

Modifying the global energy cycle directly affects the world's water resources. Global warming increases the amount of land evapotranspiration and ocean evaporation, which in turn causes longer and more frequent droughts in some parts of the world and higher intensity precipitation in other parts through the increase in moisture availability and cloud cover (Hengeveld, 2005). Average precipitation is predicted to increase between 5-20% in certain regions of the world and will cause greater extremes in weather than we have now, with stronger and more intense rainfall (Houghton et al., 2001). The rate of heavy precipitation, or rainfall intensity, is expected to increase at a greater rate than that of average precipitation. This will cause extreme rainfall events to occur more often. Ashley et al.

(2005) stated that climate change and urban sprawl are increasing the frequency of worldwide flooding. The stormwater infrastructure of urban areas will fail to control a greater runoff volume and flooding will become more persistent (Semadeni-Davies et al., 2008). For example, in the United Kingdom, what is presently considered a 20-year storm is predicted to occur once every 3-5 years in the next century (Hengeveld, 2005). Understanding how climate change affects different regions of the world is imperative for the implementation of appropriate adaptation strategies.

2.4.3 Regional Climate Change Effects on Precipitation

Climate change has begun to affect patterns of precipitation, runoff and evapotranspiration regionally in the Mid-Atlantic Region. As temperatures around the region increase, models are predicting that the Mid-Atlantic states will see more frequent and more intense rainfall that will increase flood frequencies and amplitudes (EPA, 2001b). Regionally, studies have assessed different models and have shown that precipitation overall will increase from 5-20% (CIER, 2008; UCS, 2008). Ashley et al. (2005) stated that because of climate change, "flood risks may increase by a factor of almost 30 times and that traditional engineering measures alone are unlikely to be able to provide protection… [since] urban storm drainage assets have relied on past performance of natural systems and the ability to extrapolate this performance." Human activities change the environment of local regions which also affects the hydrological cycle. Urban sprawl in the Mid-Atlantic Region continues to affect the hydrological cycle through loss of pervious surfaces, which prevents rainwater from infiltrating naturally. In the past 100 years in the United States, average precipitation has increased; though precipitation events are fewer in number, they are more extreme. Figure 2.4.1 shows how the proportions of heavy rainfalls (95th and 99th percentile) have increased significantly in most areas of the world, including the eastern United States

(Groisman et al., 2005). Snowmelt also has been occurring earlier across many parts of the Mid-Atlantic Region (Hengeveld, 2005). Fisher et al. (1999) conducted a study that took into consideration two models and concluded that by 2030, precipitation will increase from -1% to 8% and by 2095 precipitation will increase from 6-24%. These numbers indicate a major human impact on the local hydrological cycle of the Mid-Atlantic Region. Choi and Fisher (2003) concluded that precipitation in the Mid-Atlantic Region would increase from 13.5% to 21.5%, an increase that is especially notable since a 1% rise in annual precipitation enlarges catastrophic losses by as much as 2.8%.

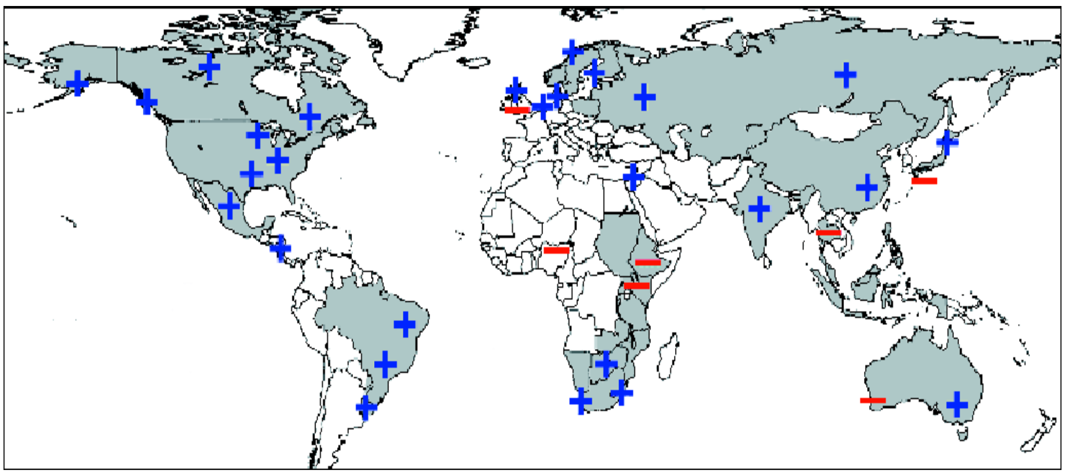


Figure 2.4.1: Proportion of heavy rainfalls for the past 100 years: Regions of disproportionate changes in heavy (95th) and very heavy (99th) precipitation (Regions with a blue plus sign signify increase in precipitation and regions with a red negative sign signify a decrease in precipitation) (Groisman et al., 2005).

Pennsylvania

Since the start of the 20th century, Pennsylvania has seen its average yearly temperature rise by 1.2º F and precipitation increase between 10% and 20%. The United Kingdom Hadley Centre's climate model, HadCM2, predicts that temperatures in Pennsylvania will rise between 2-9º F and this will cause precipitation to jump 50% in the fall, 20% in the winter and summer, and 10% in the spring (EPA, 1997). Buda and DeWalle (2002) concluded that the state's annual precipitation would increase by 5%. Warmer temperatures will cause the larger quantity of snow to melt sooner in spring, which will reduce the amount of stream flows in the summer and fall. This is significant because snowmelt floods caused over $320 million worth of damage in 1996 in Pennsylvania (Buda and DeWalle, 2002).

Susquehanna River Basin

The Susquehanna River basin has been negatively affected as population has increased and the water quality and quantity has been altered in the area. With climate change causing more frequent and more intense storms, the Susquehanna River basin will be prone to more flooding. As the Susquehanna River basin is already listed as one of the most flood-prone river basins in the country, more snowmelt floods and hurricane floods will occur from the warming temperatures in the area (American Rivers, 2005). Reed et al. (2006) stated that “the global climate system has interacted with the regional terrestrial hydrology in important yet unquantified ways.” Historically, the hydro-climatic variability and the change in the area’s human land use has had negative effects on the ecosystems that exist in the basin area.

Chapter 3

METHODS

This chapter provides information on the collection of the data used in the analysis of stormwater discharged from the East Campus Drainage Area (ECDA).

3.1 Study Area

The East Campus Drainage Area (ECDA) is part of the Main Campus Basin, which is one of the four watershed basins Penn State maintains and preserves (Figures 3.1.1 and 3.1.2). With a total of 129 acres, the ECDA makes up a third of the Main Campus Basin and has an intensively developed land use with 66.2 acres (51.1%) of the area impervious. Buildings make up the largest percentage of the total imperviousness in the ECDA with 21.7 acres (16.8% of the total area), compared to roads (7.78 acres or 6.01%), parking (18.3 acres or 14.1%), sidewalks (14.0 acres or 10.8%), and impervious sports areas (4.39 acres or 3.39%). This is significant because buildings are the ideal catchment surface for rainwater harvesting.

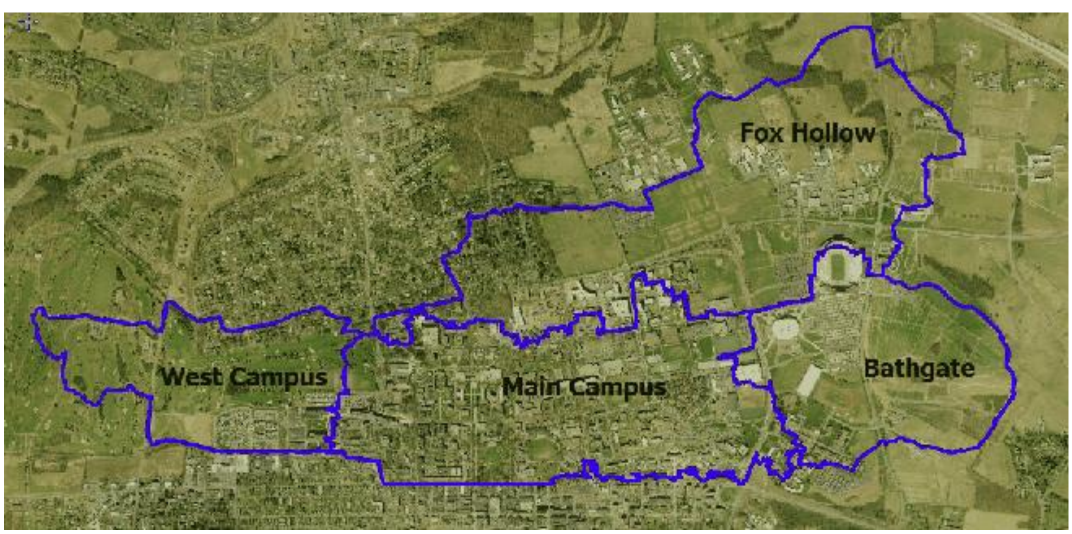


Figure 3.1.1: The four watershed basins Penn State regulates and maintains super-imposed over topography (PSU, 2007a).

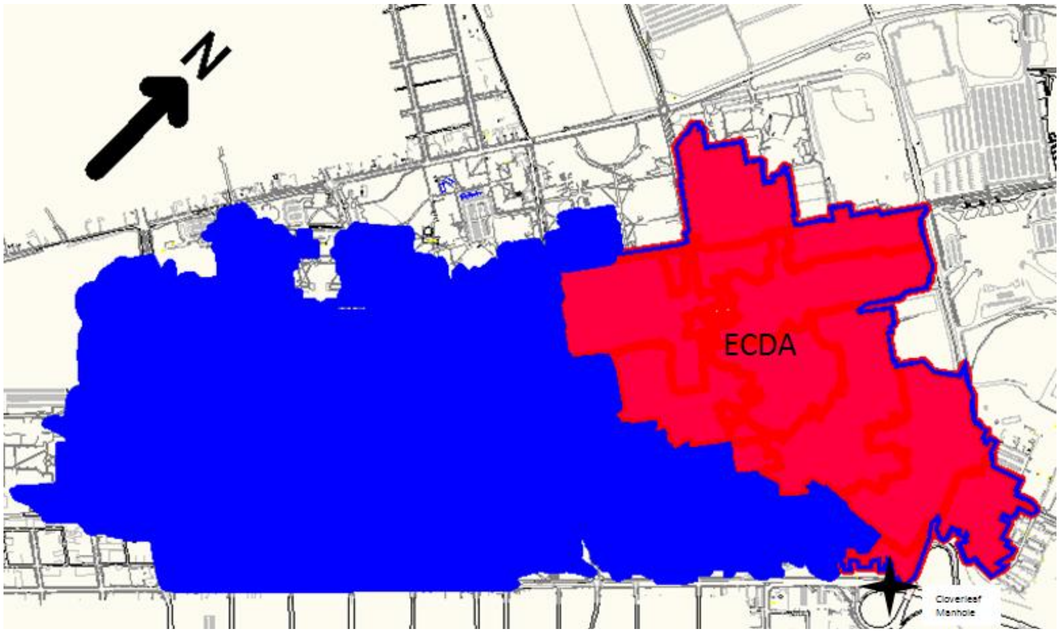


Figure 3.1.2: The ECDA (red) located within the borders of the Main Campus basin (blue).

The Main Campus stormwater management utility is a 100% gravity flow system that is maintained by Penn State University, which works closely with the State College Borough because they share discharge right-of-ways (PSU, 2007b). The ECDA discharges stormwater into the University Park Storm Drain System at the University Drive – College Avenue cloverleaf manhole on the southeast corner of campus (see Figures 3.1.2 and 3.1.3). The watershed outlet at the University Drive cloverleaf manhole discharges into the Duck Pond, which then flows into Slab Cabin Run, and thence into Spring Creek, before finally entering and travelling down the Susquehanna River to the Chesapeake Bay. Figure 3.1.4 shows the Spring Creek watershed in detail. Penn State is concerned about the direct impingement stormwater runoff has on the local watershed and promotes the use of conservation design practices. Both the Spring Creek and Susquehanna Watersheds are forecasted to continue developing and growing; therefore, stormwater runoff quantity and quality must be observed closely and managed sustainably.

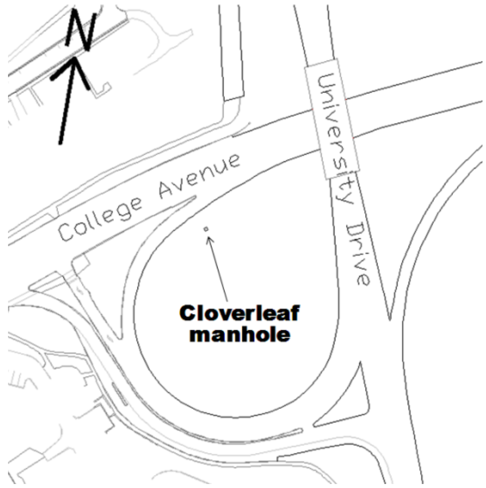


Figure 3.1.3: Location of University Drive – College Avenue cloverleaf manhole.

Figure 3.1.4: Location and watersheds within the Spring Creek Basin, Centre County, Pennsylvania (Fulton et al., 2005).

3.2 Data Sets and Data Collection

3.2.1 Weather Data

Weather data for the ECDA were obtained from the Penn State Meteorology Department, which has a University Weather Station (part of the National Weather Station network), located within the borders of the Main Campus Watershed at Walker Building. Weather parameters including barometric pressure, daily average air temperature, precipitation, humidity and winds are recorded using in 5-minute intervals a Davis Monitor II observing system. The monitoring system uses a tipping bucket rain gauge to record rainfall, also in small increments. Table 3.2.1 lists detailed information about the University Weather Station.

Table 3.2.1: Detailed information about the University Weather Station at Penn State University.

Station COOP-ID	36-8449
Location	40.79N 77.86W
Elevation	1181 ft
Data in Archive	1882 to present

3.2.2 Water Usage Data

Records of water usage data were obtained from the Office of the Physical Plant (OPP) at Penn State. The 2005-2007 average water volume pumped from eight wells in two different well fields at University Park was 2.28 million gallons per day or a total of 835 million gallons of clean drinking water per year. With a population of over 41,000 at University Park, the average water consumption equates to 54 gallons/person/day. Even though enrollment rates have increased steadily over the past 30 years and new construction projects are initiated each year, Penn State actually has decreased its total yearly water consumption by 27% from 1981 to 2006 (PSU, 2000). The reduction in water consumption can be attributed to water efficiency improvements (i.e., low flow toilets, urinals and shower heads) and updating the efficiency of the West Campus Steam Plant, which accounts for 9% of the total water consumption on campus (PSU 2007b).

3.2.3 Flow Data

Stormwater quantity data were collected from the 60 in. diameter Main Campus stormwater pipe and the 48 in. diameter East Campus stormwater pipe using a Hach Sigma 930 flow meter located at the cloverleaf manhole. The Hach Sigma 930 flow meter records the water depth (in inches) with a submerged pressure transducer and water flow velocity (in feet per seconds, fps) using sound waves and applying the Doppler principle (Hach Company, 2006). The data logger recorded water depths and velocity readings for stormwater discharges in both pipes in 5-minute intervals for the study period beginning 6/06 and ending 12/07. Figure 3.2.1 shows the author collecting data at the cloverleaf manhole with the Hach Simga flow meter. The sampling setting of 5 minutes, instead of every 15 minutes, was chosen in order to capture more precise hydrographs. The water depth data are used to calculate cross-sectional areas of flow, which were combined with flow velocities to provide the volumetric flow rates of stormwater through the pipes (See Appendix A.1). The flow meter was intended to simultaneously collect discharge data from both the 60 in. diameter Main Campus stormwater pipe and the 48 in. diameter East Campus stormwater pipe (Figure 3.2.2). The flow meter connected to the 60 in. diameter Main Campus pipe was not calibrated correctly and therefore the data collected could not be used. For this reason, the thesis scope was narrowed such that the study area was restricted to the ECDA.

The 48 in. diameter East Campus runoff data could not be used directly because the 48 in. diameter pipe had a 6 in. diameter coaxial pipe running within it. In order to convert the measured height and velocity readings to discharge, the effective area had to be

Figure 3.2.1: Collecting data at the cloverleaf manhole in winter 2007.

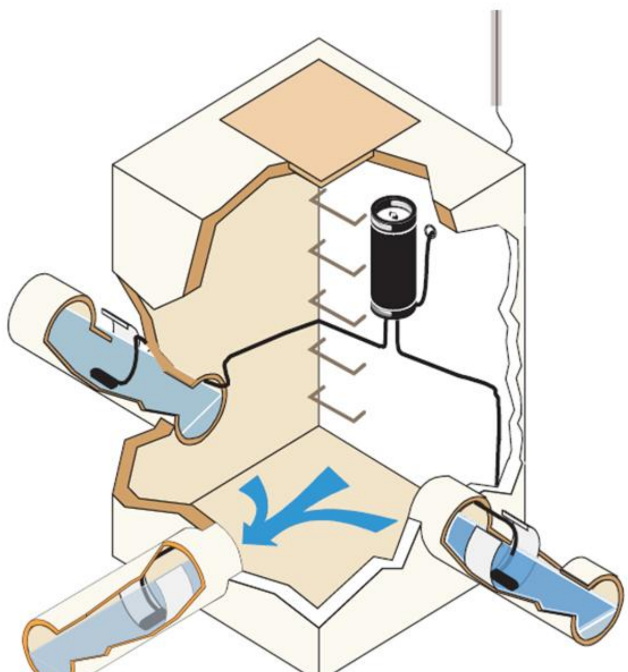


Figure 3.2.2: Depiction of the flow meter positioned to read two different stormwater pipes at the cloverleaf manhole (Hach, 2006).

calculated for both stormwater pipes. In the case of the 48 in. diameter pipe with the coaxial pipe inside it, the effective area of the 6 in. diameter pipe had to be subtracted from the 48 in. diameter pipe in order to calculate the correct runoff values. (See Appendix A.2 for effective area calculations for a pipe with a coaxial pipe inside it.) The 6 in. diameter coaxial pipe carries stormwater from the stormwater detention facility (the Duck Pond) back through the ECDA to cool the Breazeale Nuclear Reactor. The Breazeale Nuclear Reactor pumps 340 gallons per minute of water through the 6 in. diameter pipe to cool the 1 MW thermal reactor in its 71,000 gallon tank. After the water is used at the Breazeale Nuclear Reactor, it is released directly into the East Campus Drainage Area stormwater system at a fairly constant rate. The Combustion Lab and the Research Boiler Lab also use stormwater from the 6 in. diameter return pipe for research purposes, but do so at irregular times, and then release this water directly into the 48 in. diameter stormwater pipes (personal communication with M. Morlang, Breazeale Safety Representative (Morlang, 2008)). For this study, the water discharged by these two buildings is presupposed to be insignificant.

After the effective area flow of the 6 in. diameter pipe is subtracted to calculate the correct runoff flow, the water that is used by Breazeale also must be subtracted in order to correct total measured flow to represent just stormwater runoff flow from precipitation. The Breazeale flow was fluctuates consistently; therefore, the average runoff flow from the Breazeale Nuclear Reactor was calculated by averaging the constant discharge in the 48 in. pipe during periods when no rain events occurred. This gave the runoff data during storm events a near to zero discharge baseline in order to accurately represent runoff from storm events. Figure 3.2.3 graphically depicts the relationship between the corrected runoff flow data (Raw data – Breazeale flow) versus the raw flow data collected (Breazeale flow + Runoff flow).

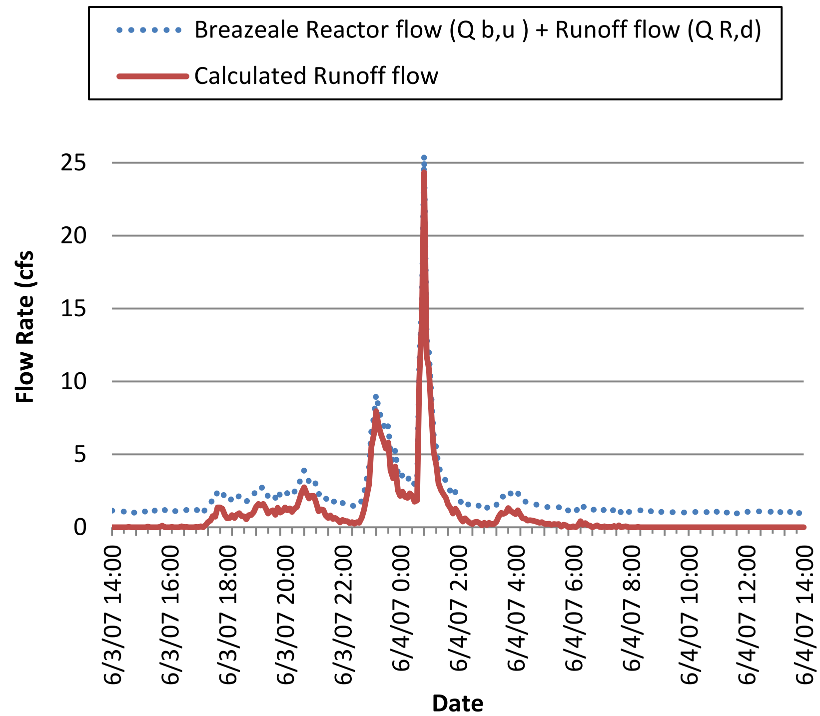


Figure 3.2.3: Breazeale Reactor flow versus calculated runoff flow.

3.3 Model Selection, Description, and Development

3.3.1 Model Selection and Description

In order to investigate potential hydrological benefits that RWH systems could provide to Penn State, the USEPA Stormwater Management Model (SWMM) was chosen as the urban stormwater management simulation tool with which to model and simulate the ECDA. Stormwater flow and precipitation data were collected for specific events between 6/06 through 12/07. These storm specific data were used to calibrate the SWMM model in order to test RWH, given broad and general precipitation scenarios.

Other common hydrologic and hydraulic urban models that were considered were TR-55 (Soil Conservation Service), HEC-HMS (U.S. Army Corps of Engineers), MOUSE (Danish Hydraulic Institute) and HydroWorks (HR Wallingford Ltd.) (Barco et al., 2008).

These models are all advanced, computer assisted, lumped rainfall-runoff models that can link together a number of different size sub-catchments, with varying topographic features, in order to create a single network that can simulate stormwater quantity or quality for a given watershed (Huber and Dickinson, 1998; Lee et al., 2008).

The SWMM model was chosen because it is widely accepted by engineering consultants around the world; free to download (and thus readily available to municipalities and engineering firms); provides output for thorough analysis; and is more widely used than other available urban runoff quantity/quality models for stormwater planning, analysis, and design (Barco et al., 2008; Lee et al., 2008; Nix, 1994; Wurbs, 1995). SWMM was first introduced in 1973 and has undergone five subsequent upgrades (Rossman, 2004). SWMM 5.0 is a physically based, deterministic model, which depends on the estimation of many initial parameters (Barco et al., 2008). It is capable of providing either single-event or continuous-storm-event simulations when analyzing the rainfall/runoff relationship (Rossman, 2004). Figure 3.3.1 depicts how SWMM is capable of simulating hydrologic processes such as infiltration and overland flow on a collection of sub-catchment areas while routing runoff through a system of hydraulic stormwater structures such as pipes, channels, storage/treatment devices, pumps and regulators (Rossman, 2004).

A SWMM hydrologic model for the ECDA was used to analyze runoff hydrographs under three scenarios as a function of time: past, present and future. The present scenario was analyzed first in order to set up a rainfall/runoff model which could be calibrated for the ECDA using the collected observed data. The calibrated parameters from the present model then were used to simulate past and future rainfall events.

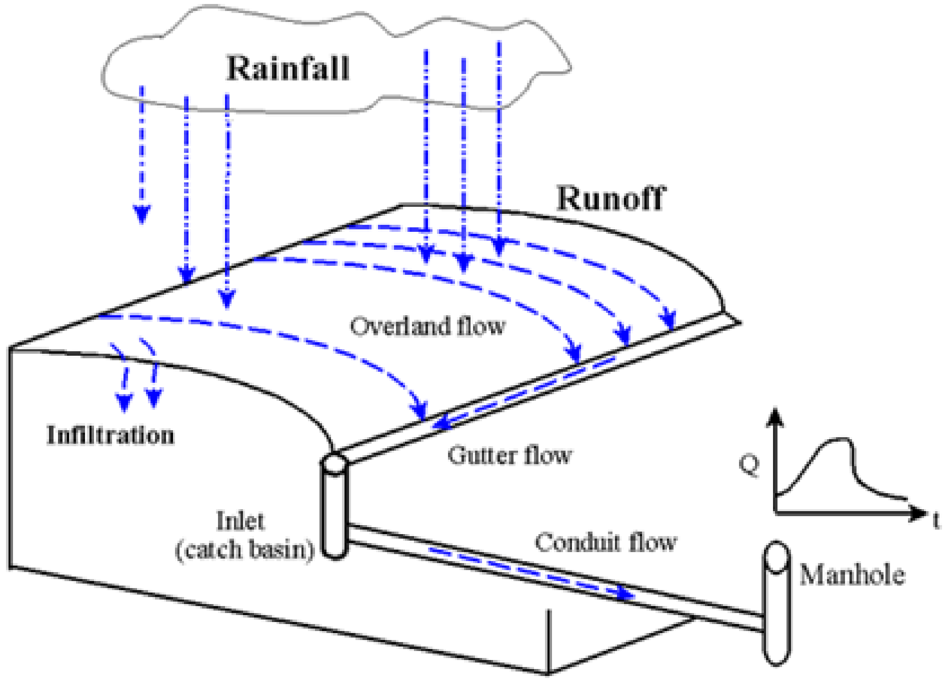


Figure 3.3.1: SWMM sub-catchment runoff/routing diagram (Rossman, 2004).

3.3.2 ECDA-SWMM Model Development

The ECDA was represented using the ECDA-SWMM in its current physical state by including all of the land use information discussed in this chapter (See Appendix B.1 for the ECDA-SWMM input data). The drainage area was spatially represented by dividing the ECDA into 53 sub-catchments. A large number of sub-catchments were used to better increase the spatial detail of the model and to more effectively simulate the use of RWH and its hydrological impacts. The sub-catchments were divided into groupings that shared similarity in physical characteristics, land uses, and drainage patterns (i.e., direction of flow). Buildings were grouped and delineated as separate sub-catchments within the catchment area that contained them. By delineating the buildings as separate from the parent sub-catchments, a stormwater storage node (i.e., RWH cisterns) could easily be added to the buildings in order to model the effect RWH would have on stormwater peak flow rates and volumes. This will be discussed in more detail later in the Chapter 4.

ECDA-SWMM Input Parameters

The input parameters that drive a SWMM model and which characterize the ECDA include the watershed's meteorological, hydrology, and pipe hydraulics data. The meteorological data includes precipitation, evaporation and daily average air temperature and were discussed previously in Section 3.2.1. The ECDA-SWMM model used rainfall data as the driving input and used the kinematic wave routing method to conduct a hydrologic rainfall/runoff event simulation. The catchment hydrology is dictated by the associated parameters of the sub-catchments which include total area, width of overland flow, average overland slope, percent impervious area (%), pervious and impervious Manning roughness, soil saturated hydraulic conductivity and drying time, Curve Number for pervious areas, percent impervious area with no depression storage (%), and pervious and impervious depression storage depth. A few of these sub-catchment parameters are explained in greater detail:

- The "width of overland flow" parameter was calculated by dividing the total area of each sub-catchment by the average overland flow length a drop of water would travel in that particular sub-catchment (Rossman, 2004).
- The "percent of non-building impervious area" describes the impervious area created by roads, sidewalks and parking, and not by buildings.
- The percent impervious area with no depression storage is the amount of impervious area that does not allow ponding to occur (i.e., sloped impervious surfaces).

The hydraulics of the stormwater management utilities were dictated by parameters provided in the OPP CAD map of the ECDA nodes and links, which included the manhole's invert elevations and maximum water depth; the conduit's shape, length, and diameter; and the pipe roughness. For each of the storage unit nodes, stage/storage and stage/discharge graphs were created in order to simulate the proper detention of flow associated with each stormwater facility by graphing the depth of water/storage volume and depth of water/discharge relationships for each storage facility.

The following hydraulic conditions were used to build the ECDA-SWMM model:

- 39 Junction Nodes
- 4 Storage Unit Nodes (3 subsurface detention facilities and 1 surface detention pond)
- 44 Conduit Links
- 1 Outfall (Cloverleaf Structure)
- 1 Rain Gauge (located in the Main Campus Drainage Area)

Table 3.3.1 clarifies the fixed hydrology and hydraulic input parameters that were utilized for the ECDA-SWMM model. For the Manning's n and depth of depression storage parameters, the higher ends of the accepted values were selected because the stormwater pipes have aged and some impervious surfaces such as sidewalks, impervious sport areas and some roads and parking lots allow stormwater to overflow onto pervious surfaces. Also, Appendix B.2 shows the ECDA-SWMM node/link map representation of the ECDA.

In order to properly analyze possible stormwater effects under different precipitation and storage scenarios, a runoff model must be able to produce good estimates of runoff hydrographs (Tsihrintzis and Sidan, 2008). In the following chapter, the current physical state parameters discussed in this chapter are run through a sensitivity analysis of the ECDA-SWMM model using a specific storm event and then three to six storm events are calibrated to match the observed runoff data.

Table 3.3.1: Hydraulic and hydrology parameter input data.

Parameter Name	**Accepted Values**	**Value Used in ECDA-SWMM Model**
Manning's n for Corrugated Metal Pipes	0.019-0.032 (Durrans, 2003)	0.032
Manning's n for Concrete Pipes	0.011-0.013 (Durrans, 2003)	0.013
Impervious Areas Depth of Depression Storage (in)	0.050-0.100 (ASCE, 1992)	0.100
Pervious Areas (lawns) Depth of Depression Storage (in)	0.100-0.200 (ASCE, 1992)	0.200
NRCS CN for Pervious Areas	based on hydrological soil group and land use description	71.0
NRCS CN for Impervious Areas	98.0	98.0
Soil Saturated Conductivity (in/hr)	7.00	7.00
Drying Time (days)	4.00	4.00

Chapter 4

RESULTS AND ANALYSIS

4.1 Precipitation Data

During the one-year analysis period of this study (2007), 33.8 in. of total rainfall data were cataloged at the University Weather Station on the Main Campus Watershed. Table 4.1.1 shows the monthly percent difference between the 100-year average rainfall data and the observed rainfall data of 2007. For the 2007 data, rainfall in the Main Campus Watershed was 11.9% less than the 100-year average, including differences in rainfall of -50.9% in May and -40.7% in September. This less-than-average rainfall in the fall of 2007 prompted the Department of Environmental Protection to declare a drought watch in most of the Commonwealth of Pennsylvania, including Centre County (DEP, 2007; Dvorak, 2007).

Table 4.1.1: 1882-1990 average monthly precipitation for State College, PA, average monthly observed data for 2007, and the percent difference.

Month	2007 Observed Rainfall (in.)	100-year Average Rainfall data (in.)	Percent Difference relative to the 100-year Average Rainfall Data (%)
January	2.12	2.74	-22.6
February	1.14	2.54	-55.1
March	2.94	3.34	-12.0
April	3.45	3.30	4.55
May	1.95	3.97	**-50.9**
June	2.61	4.01	-34.9
July	3.32	3.74	-11.2
August	4.55	3.40	33.8
September	1.76	2.97	**-40.7**
October	2.35	2.86	-17.8
November	3.85	2.85	35.1
December	3.80	2.67	42.3
Total	33.8	38.4	-11.9

The decrease in precipitation in 2007 in the Main Campus Watershed was accompanied by a lesser number of larger volume rain events and also decreased the amount of higher intensity storm events. The 2007 rainfall data were broken into 122 precipitation events in which 46 of the rainfall events had less than 0.05 in. of rain total. Precipitation events of less than 1/20th of an inch (0.060 in.) rarely generate runoff, meaning that for this study, only the 76 events that produced 0.060 in. of rain or greater were studied and analyzed (Zhang and Hamlett, 2006).

Intensity-duration-frequency (IDF) curves for State College were produced using current data available at the National Oceanic and Atmospheric Administration (NOAA) website (NOAA, 2008). The probabilistic relationship between the precipitation duration, rainfall intensity, storm return periods and the 76 precipitation events are represented graphically in Figure 4.1.1. The 76 precipitation events then were broken down to 1-, 2-, 5-, 10-, 25-, and 100-year period events. As Figure 4.1.1 depicts, in 2007, the largest return event was a 1-year precipitation event and, therefore, all the rest of the 75 rainfall events are below the 1-year event curve.

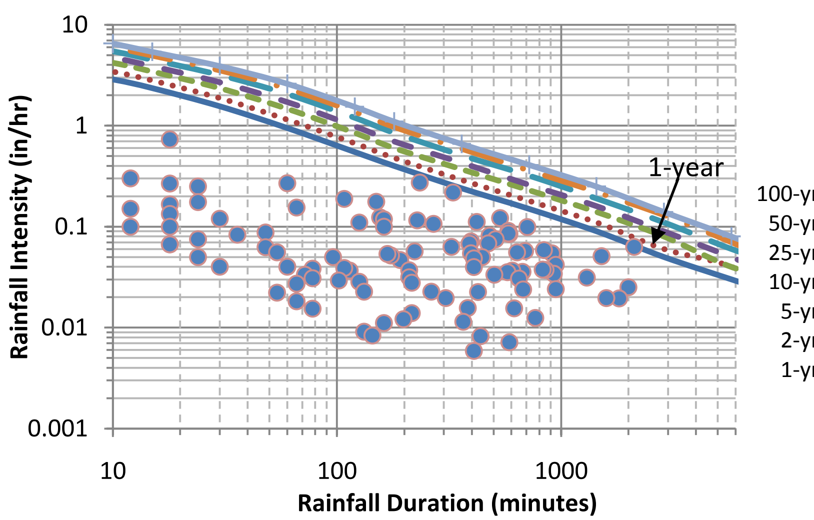


Figure 4.1.1: Intensity Duration Frequency Curves (IDF) for State College, PA, with the 76 precipitation events larger than 0.05 in. rainfall depth that fell in 2007 on the Main Campus Watershed (NOAA, 2008).

4.2 Validation of the Rainfall Runoff Storm Event Data

The measured stormwater discharge, collected from the cloverleaf outlet structure, was plotted under rainfall hyetographs in order to verify the data to make sure the observed timing of runoff data matched the timing of the rainfall data. Figure 4.2.1 shows that the timing of the stormwater peak runoff flow for the 7/11/07 storm event matches the timing of the highest 5-minute intensities of the rainfall events. This visual validation of the storm events data was implemented for all the storm events prior to calibration, which will be discussed in greater detail in the next section.

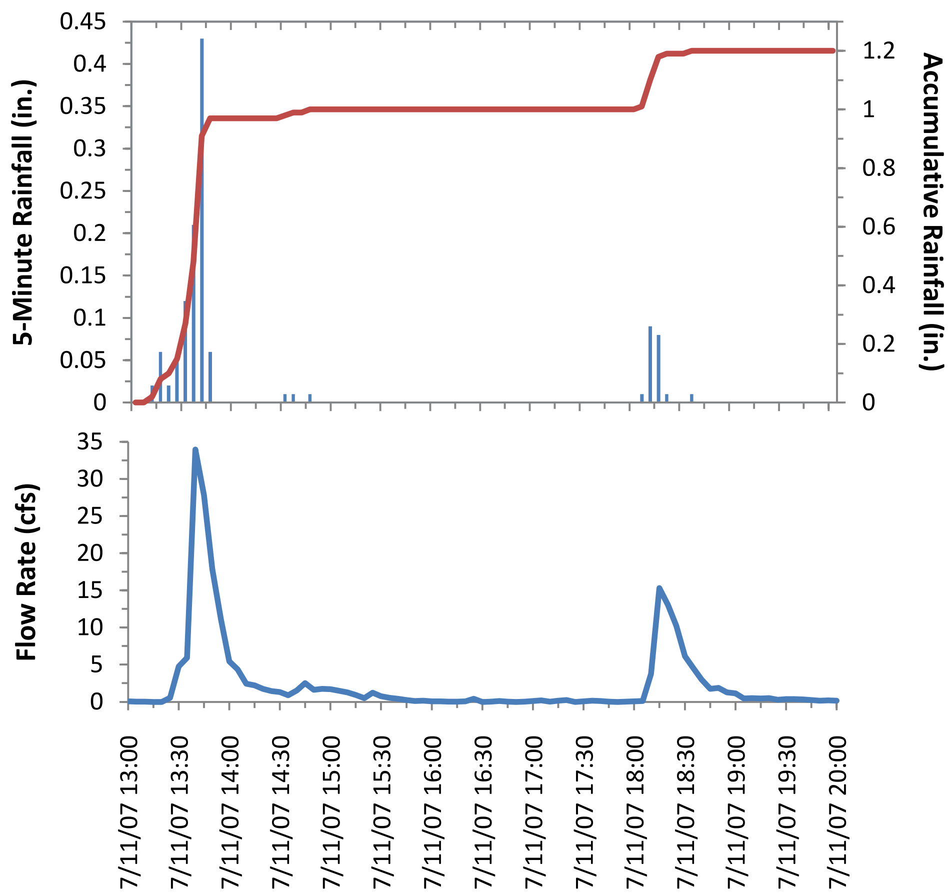


Figure 4.2.1: ECDA observed rainfall validation: Rainfall hyetograph versus observed runoff for the 7/11/07 storm event.

4.3 ECDA-SWMM Model Development Results

4.3.1 ECDA-SWMM Sensitivity Analysis

A sensitivity analysis was performed in order to evaluate the significance of each modeling parameter. The 6/22/06 and 6/23/06 storm events were used to systematically determine which model parameters have a significant effect on the surface runoff. For this analysis, a significant effect means that if a certain parameter was adjusted by ± 100%, the output results would show changes greater than ± 5%. The sensitivity analysis results for the two storms were almost identical and therefore validated the use of the sensitivity analysis for multiple storm events. Figures 4.3.1 and 4.3.2 show the sensitivity of the runoff volume and runoff peak flow results to various percentage changes in the parameters for the 6/22/06 event. The sensitivity analysis examined the following parameters: percent of non-building imperviousness, impervious depression storage depth, pervious depression storage depth, slope, width of overland flow, percent of impervious area with no depression storage, pipe roughness coefficient, soil saturated conductivity, and curve number. The sensitivity analysis was performed by adjusting each parameter by +/- 25%, 50%, 75% and 100%. Parameters not shown in Figures 4.3.1 or 4.3.2 including the curve number, soil saturated conductivity, and pervious depression storage depth, were also analyzed. These parameters did not show significant changes in the model outputs. Although these parameters were adjusted the maximum of ± 100%, the peak flows and runoff volumes in the ECDA-SWMM model simulation results were not affected greater than ± 5%, which was this study's parameter for determining significant effects. The curve number is typically the parameter which has the greatest impact on peak volume rates in a sensitivity analysis; however, it did not have a significant effect on the ECDA-SWMM model because the ECDA is a highly urbanized catchment area with a high impermeability percentage (Davis et al., 2006). Possibly, the curve number did not influence the model's results because the two storms that were used for the sensitivity analysis were both moderate rainfall events resulting in minimal runoff. Similarly, the soil saturated conductivity and pervious depression storage depth both are associated with infiltration and therefore do not play an influential role in the ECDA-SWMM model because of its high imperviousness (Nix, 1994).

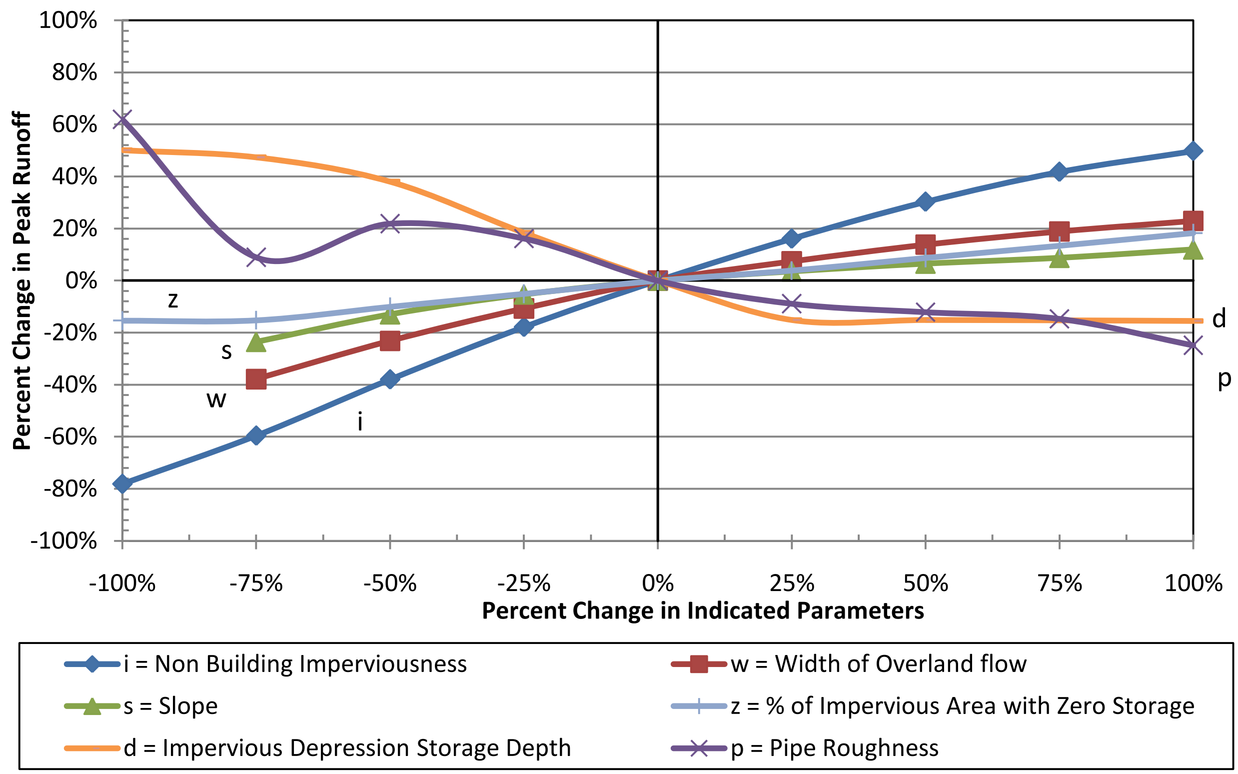


Figure 4.3.1: Pre-calibration peak runoff sensitivity analysis of the ECDA-SWMM model using the 6/22/06 storm event.

The pre-calibration peak runoff sensitivity analysis shows a linear change with all of its parameters except for the pipe roughness. Decreasing the pipe roughness parameter by 75% caused the peak runoff to decrease, while it was expected to have increased linearly. An explanation for this decrease is feedback in one or more of the 44 pipe conduits causing the runoff to be restricted therefore decreasing the peak runoff. Ideally, it would be possible to change the pipe roughness one conduit at a time and then run separate simulations in order to look for feedback in each pipe. Given that the model runs as a whole entity and there are many pipes feeding into each other, finding the confining combination of interacting pipes would be difficult.

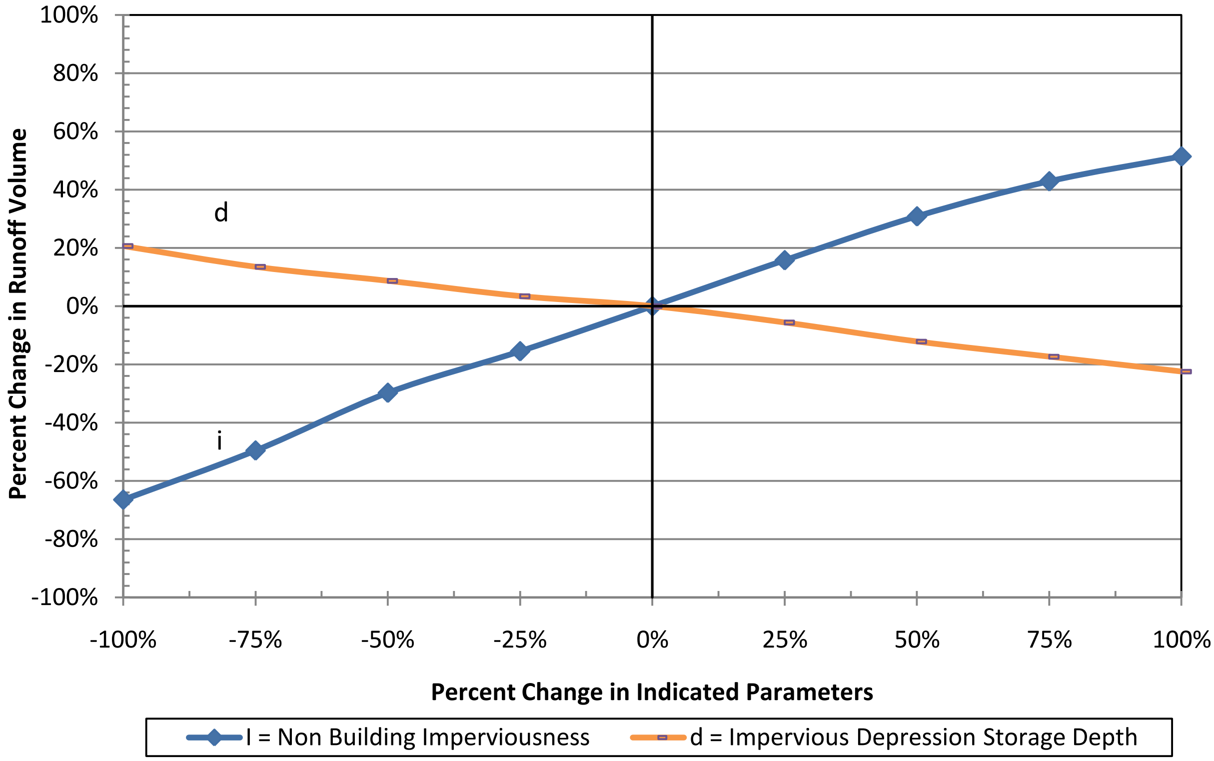


Figure 4.3.2: Pre-calibration runoff total volume sensitivity analysis of the ECDA-SWMM model using the 6/22/06 storm event.

The sensitivity analysis in Figure 4.3.1 depicts that the peak runoff is most sensitive to changes in non-building imperviousness, width of overland flow, slope, and pipe roughness coefficient. Figure 4.3.2 shows that the ECDA-SWMM model runoff volume results are most sensitive to changes with the non-building imperviousness parameter and the impervious depression storage depth parameter. These were the same parameters that were most sensitive in a SWMM model study done by Barco et al. (2008). The four parameters that were used in the next section to calibrate the ECDA-SWMM model are the non-building imperviousness, impervious depression storage depth, slope and width of overland flow. These results from the sensitivity analysis allowed a more systematic and focused approach to the calibration of the ECDA-SWMM model because the four parameters that have a noteworthy effect on the model outputs are known and can be adjusted and utilized for a specific reason (Lee et al., 2008).

4.3.2 ECDA-SWMM Model Calibration

Understanding the primary modeling objective is necessary in order to discern the interconnection between the "path to model calibration" and the data observed. The ECDA-SWMM modeling objective in this thesis was to successfully calibrate and simulate between three to six storm events and come within a margin of error of ± 10% of the observed data . In order for a model to be credible and conclusive, between three to six storms need to be "reasonably well calibrated" (Nix, 1994). Single storm events with less than 0.10 in. of rainfall were not simulated because this diminutive amount of precipitation would not produce a large enough runoff peak and/or runoff volume to be constructively evaluated (Tsihrintzis and Sidan, 2008). Data from 29 storm events with more than 0.10 in. of rainfall were then organized and prepared to be utilized by formatting them into precipitation input files for the ECDA-SWMM model. Next, the ECDA-SWMM model was run to simulate the peak flows and runoff volumes for the 29 storm events. Calibration simulations were performed on a trial-and-error basis with the 29 storm events, and five storm events were chosen to be utilized for this study because they successfully simulated within a range of error of ± 10% of the observed data. Appendix B.3 lists all 29 storm events observed, uncalibrated and calibrated peak runoff, and total runoff volume data.

After calibrating all the storm events, resulting in only five out of the 29 storm events falling within a range of error of ± 10% of the observed data, the ECDA-SWMM model demonstrated that it is not a generally fair representation of the observed data.

Although this may be significant in other studies, the model is not being used here to predict the accuracy of future storm events; it is being used as a vehicle to simulate future generalized RWH scenarios.

For a visualization of the divergence between observed and simulated results, the calibrated and observed peak and total runoff then were normalized by dividing each simulation run by its observed counterpart. See Appendix B.4 for the results of all 29 storm events. Figure 4.3.3 presents normalized data (i.e. simulated/observed) in a graphical form. Data for the five selected storm events are presented as calibrated and non-calibrated normalized points as a function of total rainfall. The remaining 24 storm events are presented as calibrated and non-calibrated normalized points as a function of total rainfall. Running averages of the 24 storm events not selected for this analysis show a non-linear relationship between rainfall and model accuracy; however, this running average illustrates that the general positive effect of calibration on all 29 storm events. The next section of this chapter first will show the uncalibrated simulation of the five uncalibrated storm events selected and then compare the deviation with the rest of the 29 simulated storm events.

4.3.3 Uncalibrated Simulations for Five Selected Storm Events

The uncalibrated simulations for the five selected storm events were run using the ECDA-SWMM model and then the predicted outputs were compared to the observed total runoff volume, the runoff peaks, and the runoff peak timing. Figure 4.3.4 (a-e) on page 51 shows that the simulated peak runoff timing for the five simulated storm events agrees well with the observed peak flow. The simulations also show that in all five storm events, the simulations over-predict the peak rates and quantity of the runoff.

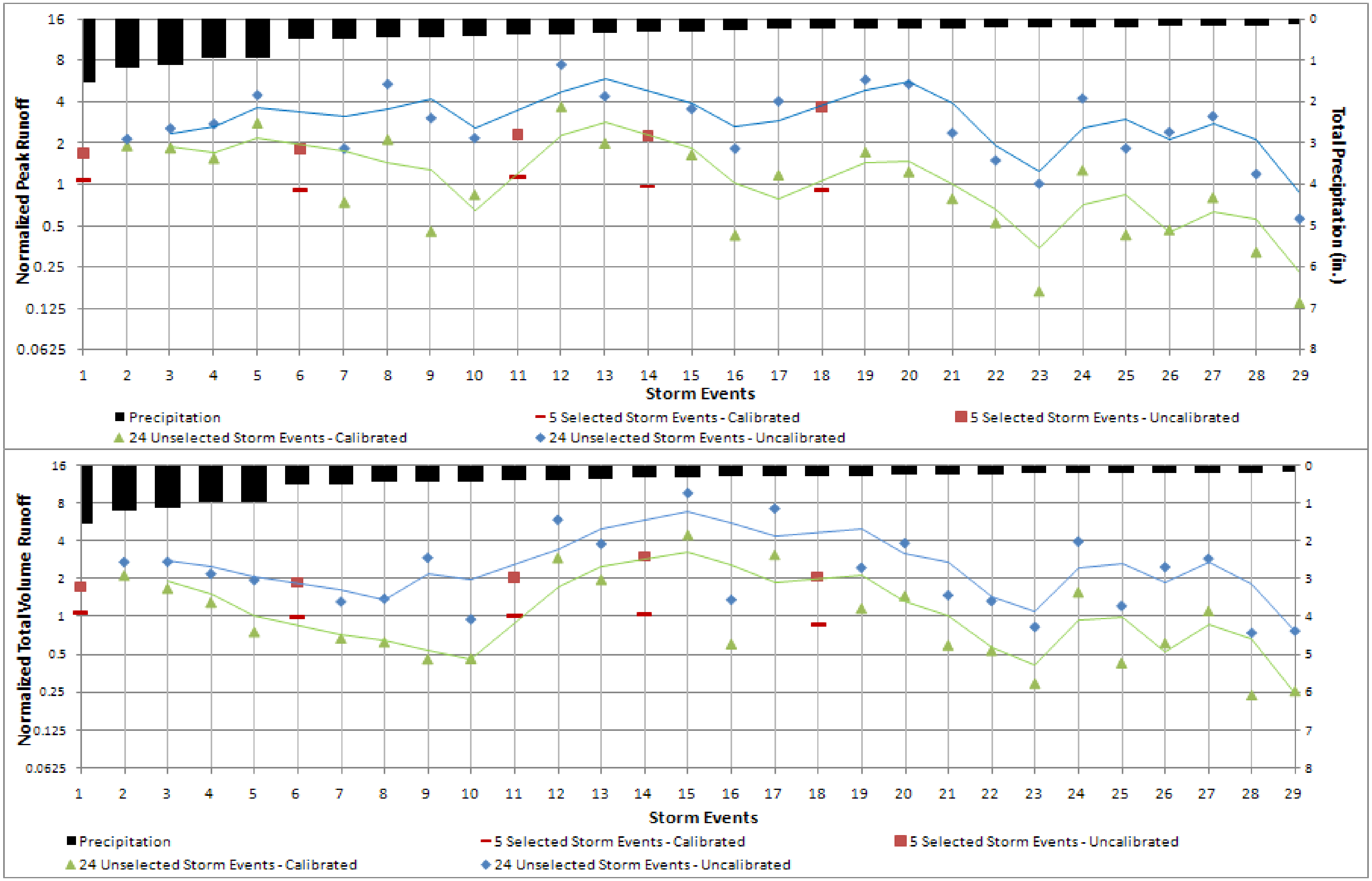


Figure 4.3.3: Normalized peak runoff and normalized total volume runoff for all 29 storms.

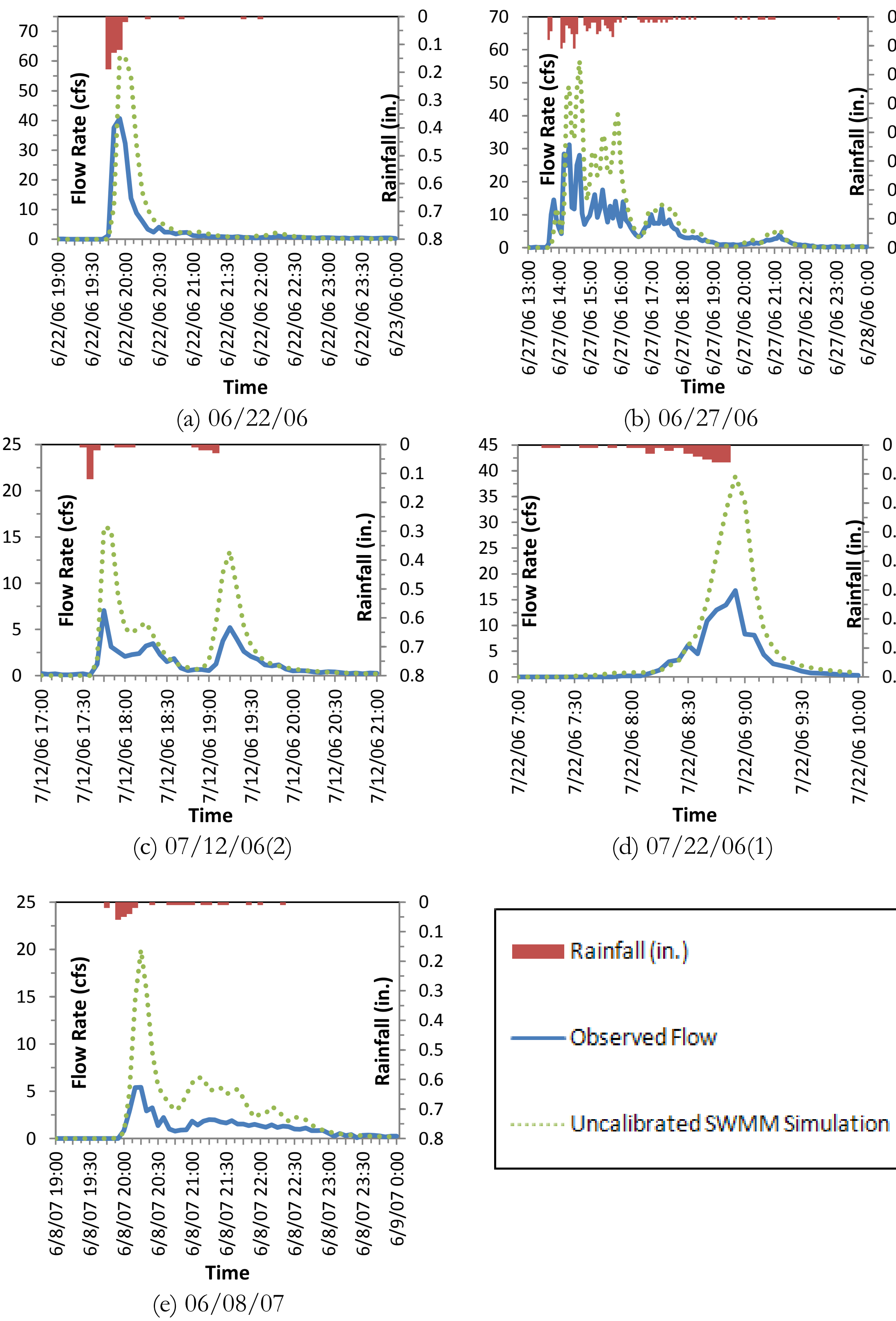


Figure 4.3.4: ECDA-SWMM uncalibrated simulations for five selected storm events.

4.3.4 ECDA-SWMM Uncalibrated Error Analysis

The flow peak and total volume error were calculated using the normalized percentage error (NPE) using the following equation:

$$NPE_{X_i} = \frac{X_{s_i} - X_{o_i}}{X_{o_i}} * 100 \quad \text{(Eq. 4.3.1)}$$

where X is either the peak runoff (Q_p) or the total runoff volume (V_T); the subscripts s and o indicate whether observed quantities are simulated or observed, and the subscript i is a numerical index meaning the ith storm. The NPE of the five storm events then was compared to the mean normalized percentage error (MNPE) of all 29 storm events with more than 0.10 in. of rainfall using the following equation:

$$MNPE_X = \frac{1}{M} \sum_{i=1}^{M} NPE_{X_i} \quad \text{(Eq. 4.3.2)}$$

where M is the number of storms simulated (Tsihrintzis and Sidan, 2008).

The results of all five selected storm simulations and their associated rainfall, NPE error, and MNPE error characteristics are shown in Table 4.3.1; Appendix B.5 shows the results from the 29 storm events. Storm events with a one or two in the parenthesis were multiple peaking storm events that were split up in order to isolate peak runoff flows. The multiple peaking storm events were analyzed as separate storm events only if they had a gap of no rain greater than three hours.

Table 4.3.1: Summary of the five uncalibrated storm events.

Storm Event	Total Rainfall (in.)	Uncalibrated V_T NPE (%)	Uncalibrated Q_p NPE (%)
6/22/06	0.50	86.3	68.6
6/27/06	1.52	73.6	81.7
7/12/06(2)	0.26	108	128
7/22/06 (1)	0.38	106	132
6/8/07	0.32	204	269
$MNPE_X$ (%)		116	136

The five uncalibrated storm events selected had a MNPE error of 116% (V_T) and 136% (Qp), compared with the 29-storm MNPE error of 168% (V_T) and 197% (Qp). The over-simulation by the ECDA-SWMM model compels limitations to the precision of the model or the accuracy of the data observed. In order to check the validity of the simulated volume results of the storm events, the theoretical physical maximum amount of runoff volume was calculated using Equation 4.3.3:

$$Maximum\ Total\ Runoff\ Volume = Total\ Rainfall * Drainage\ Area \qquad \text{(Eq. 4.3.3)}$$

Using the Maximum Total Runoff Volume for all 29 storms, the Observed Runoff Coefficient K_o and the Simulated Runoff Coefficient K_s were calculated using the following equations:

$$Observed\ Runoff\ Coefficient(K_O) = \frac{1}{M}\sum_{i}^{M}\frac{Observed\ Total\ Runoff\ Volume_i}{Maximum\ Total\ Runoff\ Volume_i}$$

(Eq. 4.3.4)

$$Simulated\ Runoff\ Coefficient(K_S) = \frac{1}{M}\sum_{i}^{M}\frac{Simulated\ Total\ Runoff\ Volume_i}{Maximum\ Total\ Runoff\ Volume_i}$$

(Eq. 4.3.5)

where M is the number of storm events used and *i* implies the *i*th storm event.

Results for this analysis are shown in Appendix B.6. The K_s coefficient was 0.233 or twice the K_o coefficient of 0.116. Interestingly, the results from this analysis showed that the observed (K_o) and simulated (K_s) runoff coefficients had deviations similar to the ECDA-SWMM normalized uncalibrated and calibrated total volume model simulations. The average normalized uncalibrated total volume percentage for the 29 storm events was 2.68 and the average normalized calibrated total volume percentage was 1.19 (see Appendix B.4). Both error analyses show similar deviations of the observed, uncalibrated simulations being about twice as much as the simulated calibration; therefore, the accuracy of the data and the model simulations could show limitations in this study. The model was calibrated using five storm events that took place over a relatively brief period of time. Given the limited nature of the data used in calibration, care should be exercised in extrapolating model simulations beyond these data. The observed data in the 29 storms could be underestimated for the following reasons:

- The stormwater pipe network is aging and possibly leaking runoff.
- The East Halls drainage network has a slope that runs in the opposite direction of the surface topography and therefore runoff may overflow to a different drainage area than indicated in the 2004 pipe diagrams.
- The ECDA-SWMM model was constructed using CAD files from 2004 and does not take into account any new infiltration BMPs that may have been implemented in the last four years.
- There could be an unknown number of dry wells in the ECDA that were drilled sometime in the past that percolate stormwater directly to the baseflow or groundwater.
- The Karst topography in the area may be allowing a greater amount of the overland flow to infiltrate more rapidly into the groundwater table.

4.3.5 Calibration Exercise and Simulations of the Five Selected Storm Events

In order for the ECDA-SWMM model to more accurately mimic the observed watershed behavior, a calibration was performed using the appropriate parameters that were discussed in the sensitivity analysis. The five selected storm events from Section 4.3.2 were used in this calibration exercise. The total precipitation ranged from 1.52 in. to 0.260 in. for the five selected storm events. The ECDA-SWMM model shows versatility by running calibrations using storm events with precipitation that differed by over an inch. Also, the ECDA-SWMM model appears capable of evaluating typical summer thunderstorms because all five modeled storm events occurred in summer conditions during the months of June and July. The calibration is limited to a fixed number of storms that occurred only in a fixed number of months during the summer season. The ECDA-SWMM model calibration was performed in the following sequence:

1) The runoff "volume" parameters were calibrated in order to best match the simulated runoff volume to that of the observed (Nix, 1994). This was done by adjusting the non-building imperviousness (i) and the impervious depression storage depth (d).
2) The "peak and shape" parameters were calibrated in order to match the simulated runoff peak to the observed. Width (w) and slope (s) were used as the parameters to adjust the peak and shape of the hydrograph. In some cases, adjusting the peak parameters altered the volume as well, suggesting that those parameters needed to be readjusted until the calibrated runoff was within ± 10% of the observed data.
3) Once the calibration of one storm was completed the same process was performed on the remaining four storm events until all five storm events were within ± 10% of the observed peak and volume. Tables 4.3.2 though 4.3.5 show a step-by-step process of the calibration of all five storms.

The storm event on 7/22/06 was chosen to be calibrated first because it had a relatively low total precipitation and therefore would be more sensitive to changes in parameters because adjusting parameters from smaller storm events causes more significant changes in the results as compared to larger storm events. Table 4.3.2 shows each run calibrated for the 7/22/06 storm event and the specific parameter that was adjusted.

Table 4.3.2: ECDA- SWMM calibration of the first storm event on 7/22/06 (1).

7/22/06 (1) - 0.38 in.										
		Percent of Estimated Values (%)								
Run #		1	2	3	4	5	6	7	8	9
i		100	75.0	50.0	50.0	50.0	40.0	40.0	40.0	40.0
d		100	100	100	125	150	150	175	175	175
w		100	100	100	100	100	100	100	50	50
s		100	100	100	100	100	100	100	100	50
	Obs.	Simulated								
Volume (ac-ft)	0.730	1.51	1.26	1.02	0.953	0.895	0.807	0.747	0.699	0.672
Peak (cfs)	16.8	39.0	32.3	25.5	25.0	24.5	21.7	20.7	18.5	17.2
NPE V_T (%)		106	73.2	39.9	30.6	22.6	10.6	2.33	-4.25	-7.95
NPE Qp (%)		132	92.3	51.7	48.8	45.9	29.3	23.56	10.37	2.48

The first run is the starting point of this exercise and is the uncalibrated simulation for the 7/22/06 storm event. In runs #2, #3, and #6 the non-building imperviousness was decreased by 60% in order to decrease the total runoff volume, because according to the sensitivity analysis the ECDA-SWMM runoff volume was most sensitive to this parameter. The non-building imperviousness can be decreased this much (i.e., 60%) in the model calibration because it can be argued that some non-building impervious surfaces are not directly connected to the stormwater network. For example, some impervious surfaces such as sidewalks, impervious sport areas and some roads and parking lots allow stormwater to overflow onto pervious surfaces. The next variable that was adjusted was the impervious depression storage parameter. In modeling runs #4, #5, #7 the depression storage was increased by 75% to a value of 0.175. After run #7, the NPE total volume (V_T) had decreased to a mere 2.33% over the observed data; however, the NPE peak flow (Qp) still had not reached an acceptable level of within ± 10%, so the width and slope parameters were chosen to calibrate the model. These two parameters are more abstract because they are difficult to measure and therefore are excellent parameters to use in the calibration (Nix, 1984). After run #9, the 7/22/06 storm event had been calibrated to a deviation of less than ± 10% and therefore the next storm event then was able to be calibrated.

The same calibrated parameter values that were used in run #9 on the 7/22/06 storm event then were used to simulate the storm event on 6/22/06 in run #10. After calibrating the remaining parameters with this storm in runs #10 through #13, the updated parameters (depression storage (d) decreased to 150%, and width (w) increased to 60%) allowed the model to effectively simulate the other four storm events within ± 10% of the observed data. Tables 4.3.3 through 4.3.5 present the calibration sequence for the remaining three storm events. Table 4.3.6 presents the summary of the calibrated simulation results for the five storm events that were analyzed.

Table 4.3.3: ECDA- SWMM calibration of the 6/22/06 and 7/22/06 (1) storm events.

6/22/06 - 0.5 in.						**7/22/06 (1) - 0.38 in.**		
		Percent of Estimated Values (%)						Percent of Estimated Values (%)
Run #		10	11	12	13	Run #		14
I		40.0	40.0	40.0	40.0	i		40.0
D		175	150	150	150	d		150
w		50.0	50.0	40.0	60.0	w		60.0
s		50.0	50.0	50.0	50.0	s		50.0
	Obs.	Simulated					Obs.	Simulated
Volume (ac-ft)	1.27	1.24	1.18	1.22	1.26	Volume (ac-ft)	0.730	0.738
Peak (cfs)	40.7	34.6	33.6	33.1	36.3	Peak (cfs)	16.8	18.8
NPE V_T (%)		-2.43	-7.06	-4.16	-0.940	NPE V_T (%)		1.10
NPE Qp (%)		-15.0	-17.4	-18.6	-9.96	NPE Qp (%)		11.9

Figure 4.3.5 shows the hydrographs for all five calibrated storms events. In comparison to Figure 4.3.4, the calibrated storm events greatly decreased the modeled total runoff volume and runoff peak rate to within an error of ±10%. While doing so, the stormwater peak timing seemed to have become less accurate. Nevertheless, the ECDA-SWMM model still was able to predict and simulate the peak timing within 15 minutes. Also,

the timing of the observed peak flows slightly preceded the timing of rainfall. This is possible since the recording rain gage is located outside of the ECDA watershed, thereby experiencing rain at a different time than within the ECDA watershed.

Table 4.3.4: ECDA- SWMM calibration of the 6/27/06 and 7/12/06 (2) storm events.

6/27/06 - 1.52 in.			**7/12/06 (2) - 0.26 in.**		
		Percent of Estimated Values (%)			Percent of Estimated Values (%)
Run #		15	Run #		16
i		40.0	i		40.0
d		150	d		150
w		60.0	w		60.0
s		50.0	s		50.0
	Obs.	Simulated		Obs.	Simulated
Volume (ac-ft)	4.38	4.69	Volume (ac-ft)	0.460	0.404
Peak (cfs)	31.2	33.0	Peak (cfs)	7.06	6.41
NPE V_T (%)		7.05	NPE V_T (%)		-12.2
NPE Qp (%)		5.92	NPE Qp (%)		-9.22

Table 4.3.5: ECDA- SWMM calibration of the 6/8/07 storm event.

6/8/07 - 0.32 in.		
		Percent of Estimated Values (%)
Run #		17
i		40
d		150
w		60
s		50
	Obs.	Simulated
Volume (ac-ft)	0.210	0.220
Peak (cfs)	5.41	5.17
NPE V_T (%)		4.29
NPE Qp (%)		-4.40

Table 4.3.6: Summary of the five calibrated storm events.

Storm Event	**Total Rainfall (in.)**	**Calibrated V_T NPE (%)**	**Calibrated Q_p NPE (%)**
6/27/2006	1.52	7.05	5.92
6/22/2006	0.5	-9.96	-0.94
7/22/06 (1)	0.38	1.1	11.9
6/8/2007	0.32	4.29	-4.4
7/12/06 (2)	0.26	-12.2	-9.22
$MNPE_X$ (%)		-1.94	0.64

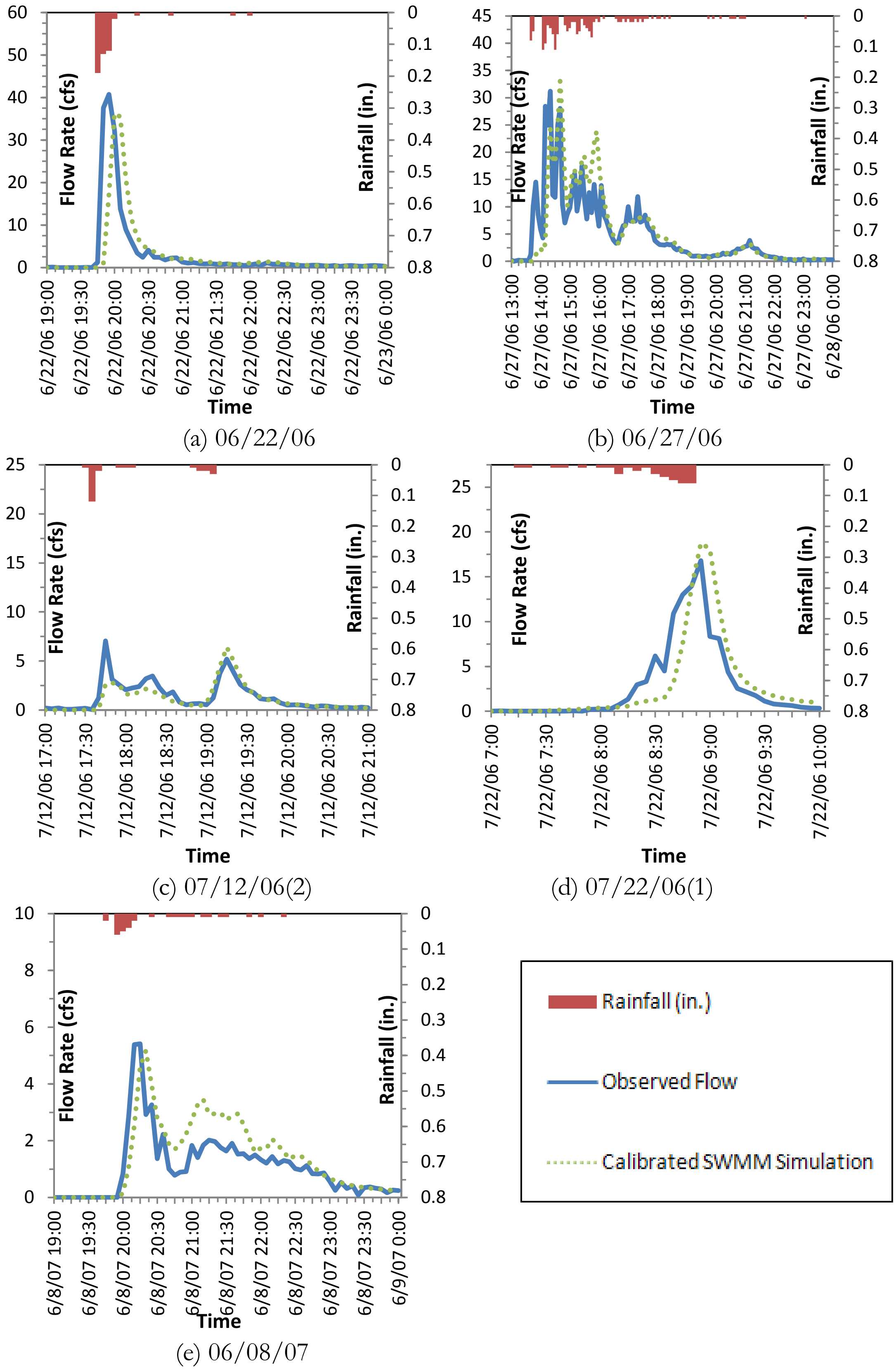


Figure 4.3.5: ECDA-SWMM calibrated simulations for five selected storm events.

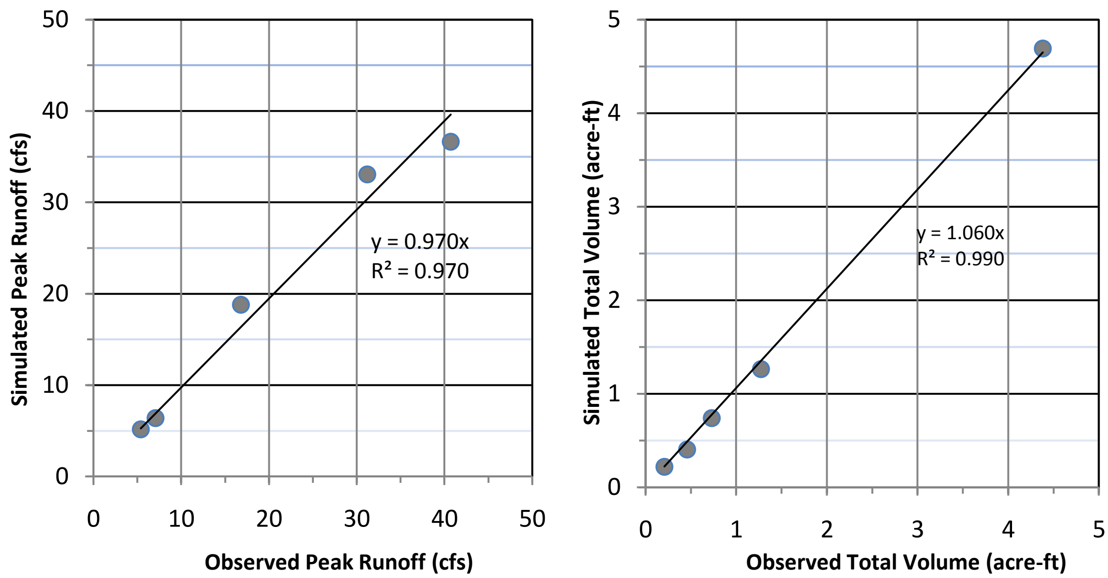


Figure 4.3.6: Calibrated simulation peak and total volume runoff versus observed peak and total volume runoff for the 5 storm events.

Figure 4.3.6 shows that the calibration regression for the five storm events analyzed had a coefficient of determination (r^2) of 0.970 for the peak runoff and 0.990 for the total volume. By having r^2 values so close to 1.00, the relationship between the observed and simulated variables shows small variability and therefore the ECDA-SWMM model simulations are statistically well representative of the observed values.

4.4 Analysis of Three Scenarios Using the ECDA-SWMM Model

Scenario 1: Current State Scenario With the use of RWH: The watershed was represented by incorporating the utilization of 100% potential RWH. The ECDA-SWMM model was used to simulate the effect on stormwater runoff due to a decrease in effective impervious area through the use of rainwater catchment systems represented by SWMM storage nodes.

Scenario 2: Future Climate Change Scenario With and Without RWH: This scenario incorporated current features (i.e., parking lots, etc.) and simulated climate change and the predicted future increases in precipitation by inputting a greater total rainfall amount in the calibrated storm events within the ECDA-SWMM model. The RWH scenario then was run with the increased rainfall storm events in order to test whether RWH was able to mitigate the effects caused by climate change and the resulting stormwater runoff.

Scenario 3: Pre-Colonial Scenario: The watershed was considered pristine and undeveloped with wooded groundcover and permeable soils.

4.4.1 Scenario 1: Current State Scenario With the use of RWH

Through the use of RWH, this scenario illustrates the sustainable benefits Penn State could gain if it was to incorporate RWH systems in the ECDA. Two of these benefits include improved stormwater management (i.e. decrease in peak flow, total runoff volume) and the conservation of potable water. To begin with, rainwater was selected to be collected and supplement only non-potable water in this analysis because more complex RWH systems (i.e., systems that utilize rainwater for drinking) are more difficult and expensive to implement. For the ECDA RWH scenario, the only non-potable uses considered include toilet flushing and landscape irrigation. In order to determine the RWH potential, the hydrologic potential must be compared to the water demand (Hicks, 2008).

ECDA Water Usage Analysis

A proper analysis of the water usage in the ECDA is an important component to modeling the use of RWH. Each building on campus is equipped with its own separate water meter to maintain an accurate account of the water used in gallons. The 2005-2007 average total water consumption in the ECDA was 2.29 MG/day and accounted for 13% of the total water used at Penn State(PSU, 2006; PSU, 2007b; PSU, 2008a);. Penn State is in many ways like a small town, meaning that there are different types of buildings with different design codes for water usage. Furthermore, water demand varies with the type of building, and therefore buildings in the ECDA were categorized by sector in order to determine the amount of water used for flushing toilets and landscape irrigation. The types of buildings in the ECDA include academic and research buildings, sports facilities, common facilities and student residential housing. The percentages of each building sector are shown below in Figure 4.4.1, with academic and research buildings making up the largest percentage of buildings in the ECDA (i.e., 47%).

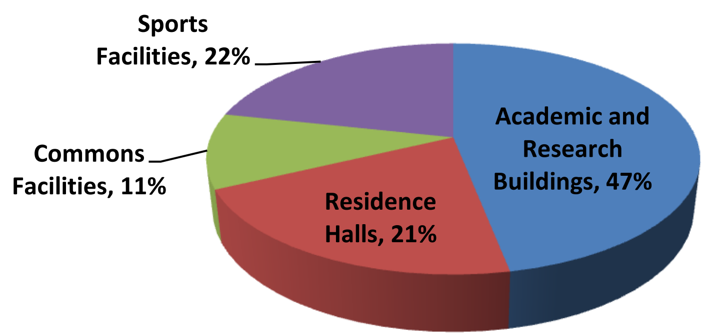


Figure 4.4.1: Percent of building types in ECDA.

Figure 4.4.2 shows that the largest water-consuming buildings are residence halls, which consume more than 50% of all the potable water in the ECDA.

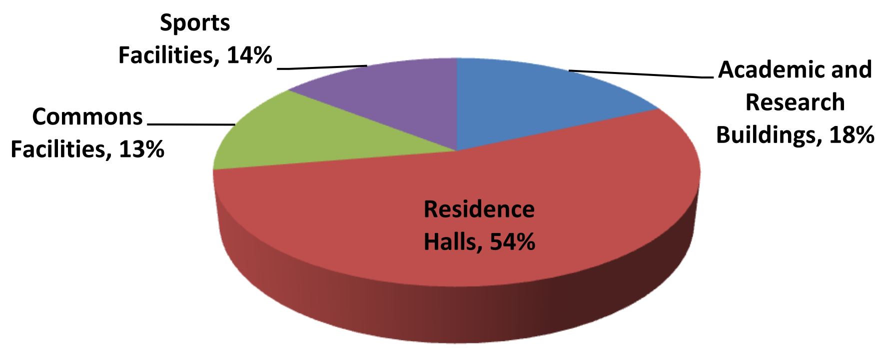


Figure 4.4.2: Percent of water usage by building sector in the ECDA.

Even though water usage data was provided for each building on the ECDA, the percentage of water used for potable and non-potable sources is not measured separately at

Penn State. Therefore, the percentage of water used for non-potable uses was estimated to be 86% for commercial buildings and 78% for domestic buildings based on previous research (AWWARF, 1999; PI, 2003). For this analysis, the common facilities, sports facilities, and academic and research buildings were grouped together in order to for them to have water consumption characteristics similar to typical commercial facilities, and residential hall water usage were selected to behave comparably to that of typical residential structures. The water end use of a commercial building might vary in some cases. For example, a sport facility might use more water for irrigation, yet an academic and research building could utilize more water for toilet flushing, but since both end uses were grouped as non-potable, there is no conflict in their being grouped in the same sector. A water assessment case study performed by Stanford University found that toilet flushing and landscape irrigation can account for over 30% of the water used on a college campus (SU and MWM, 2003).

Figure 4.4.3 shows the 100% potential monthly RWH yield in comparison with the 3-year average monthly water usage. Hypothetically, if the ECDA was able to collect 100% of the rainwater that fell on building rooftops, then it would be possible to supplement between 14-46% of the drinking water demand and utilize rainwater for 100% of flushing and irrigational needs. The higher end drinking water demand of 46% is well below the selected non-potable water usage for commercial and domestic buildings of about 80%.

It is only possible to collect 100% of rooftop rainfall by designing building-specific cisterns of adequate volume. With the water supply/demand data of the buildings on the ECDA, an analysis of the hydrological stormwater impact and potential is explained in the next section.

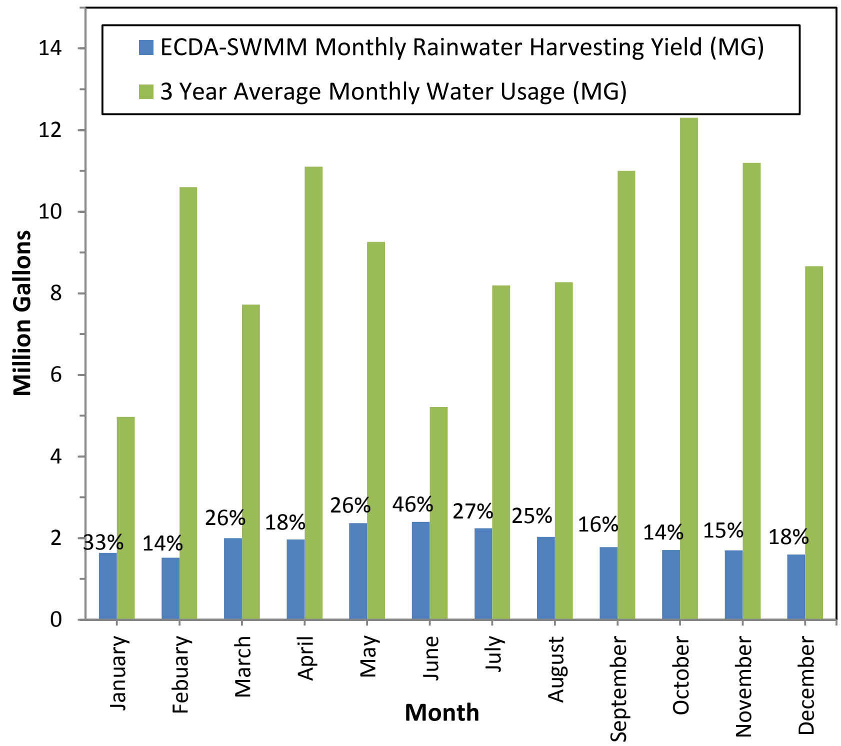


Figure 4.4.3: ECDA RWH yield versus water usage
based on averaged monthly precipitation.

ECDA-SWMM Model Simulation with 100% RWH Potential

The five storm events that were calibrated with the ECDA-SWMM model in Scenario (1) were utilized to run the RWH simulation. First, the ECDA-SWMM model was adjusted by adding storage nodes that would collect and store the flow from the separate building nodes in order to represent the storage tanks of RWH. Since 100% of the amount of RWH yield makes up between 14-46% of the monthly water, it was accepted that 100% of the collected rainfall could be utilized for flushing toilets and irrigation in the ECDA buildings each month. Therefore, the storage nodes were designed to detain 100% of the stormwater produced from each storm event. Figure 4.4.4 shows the results of the RWH simulation. Table 4.4.1 shows the percentage differences of total runoff and peak flow rates between the calibrated simulation and the RH simulation.

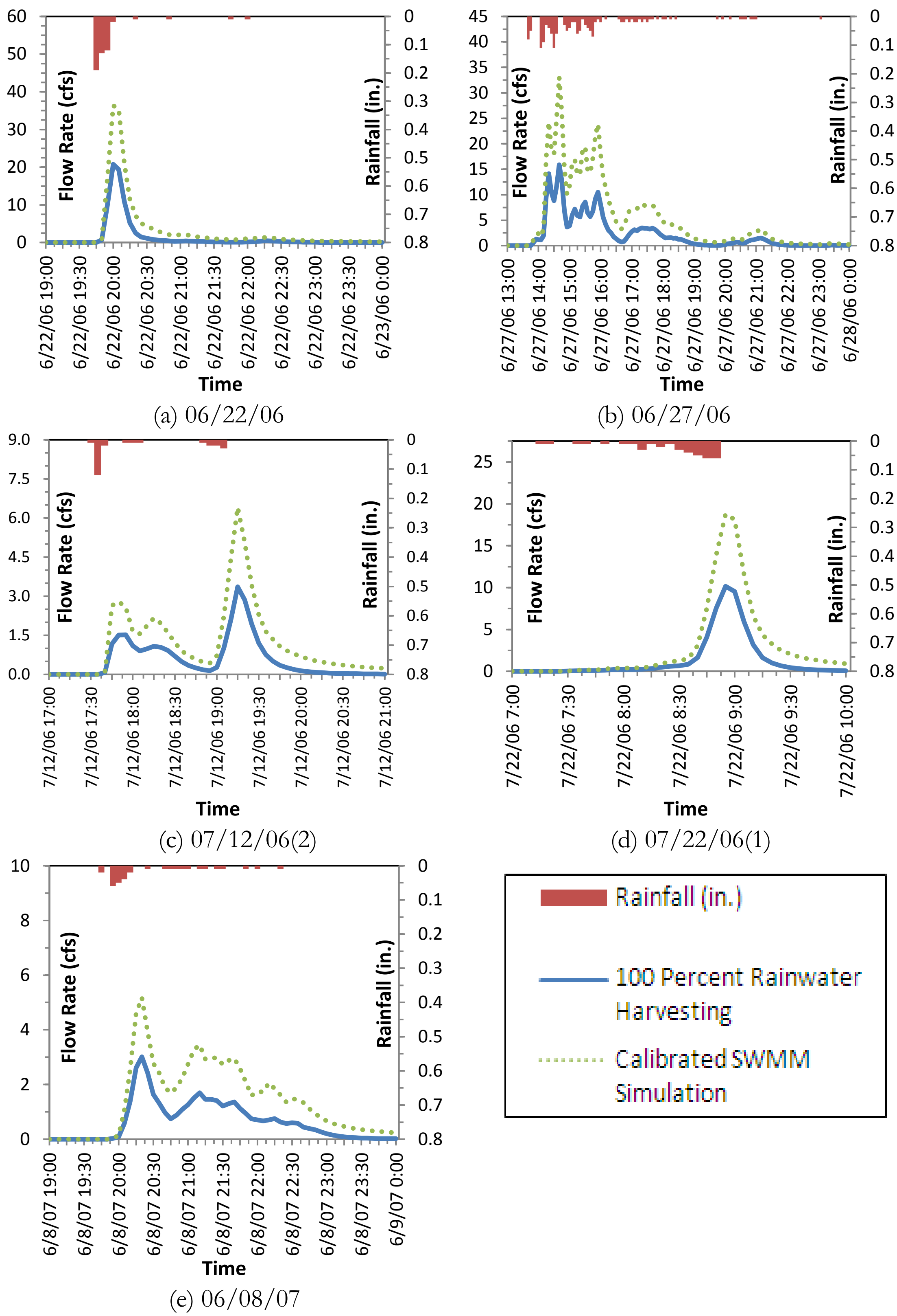


Figure 4.4.4: ECDA-SWMM simulations with 100% RWH.

Table 4.4.1: Percent decrease in total volume and peak runoff through 100% RWH.

Storm Event	Calibrated V_T (ac-ft)	Calibrated Q_p (cfs)	100% RH V_T (ac-ft)	100% RH Q_p (cfs)	V_T Percent Decrease (%)	Q_p Percent Decrease (%)
6/22/06	1.26	36.7	0.560	20.8	-55.6	-43.3
6/27/06	4.69	33.0	1.98	15.9	-57.8	-51.9
7/12/06 (2)	0.404	6.41	0.192	3.36	-52.5	-47.5
7/22/06 (1)	0.738	18.8	0.352	10.2	-52.3	-45.9
6/8/07	0.219	5.17	0.120	3.01	-45.2	-41.7
		Percent Decrease in Runoff (%)			**-52.7**	**-46.1**

Application of the RWH scenarios in the ECDA shows that the percentage of peak flow and total volume reduction was consistent with all five storm events at about 50%. The actual decrease of total volume through RWH is -52.7% and for the peak flow is -46.1%. This would not only help stormwater quantity problems, since 100% of the runoff from buildings would be collected (representing 44% of the impervious land on ECDA), the stormwater quality would increase because there would be a reduction in stormwater pollutant loading.

4.4.2 Scenario 2: Future Climate Change Scenario With and Without RWH

On a global scale, climate change will cause temperatures to rise leading to significant problems throughout the hydrological system, with droughts in some areas of the world and flooding in others. As discussed in Section 2.4.3, predictions for Pennsylvania indicate that an increase of precipitation could result in storm events of greater intensity that will occur more frequently. The more intense and more frequent precipitation events will cause a shift in IDF curves and therefore fundamentally change how stormwater is managed. As population continues to increase, urbanization will add complexity to the problem with the corresponding increase in impervious area. Stormwater management plans should begin incorporating sustainable forms of controls in preparing to adapt to these changes. Table

4.4.2 shows the summary of the literature review of climate change and its effect on precipitation in Pennsylvania.

Table 4.4.2: Predicted range of climate change impacts in Pennsylvania relative to current historical averages (see Chapter 2 of this thesis) (UCS, 2008; CIER, 2008).

	2020s (2010-2039)	**2050s** (2040-2069)	**2080s** (2070-2099)
Change in Average Annual Temperature	2.5° F increase	4.0-5.5° F increase	5.0-8.5° F increase
Change in Maximum Summer Temperature	2-3° F increase	2.0-7.0° F increase	3.0-12° F increase
Change in Average Annual Rainfall	5.0% increase	5.0-12% increase	12-20% increase
Change in Average Annual Snowfall	50% decrease	50-100% decrease	75-100% decrease

The main objective of this scenario is to examine the hydraulic impact to the urban drainage system resulting from climate change. Simulations were performed using the five storm events that were calibrated with the ECDA-SWMM model. For this scenario, an increase amount of precipitation of 20% was selected in order to take into consideration the worst case scenario in the impact of climate change on stormwater management. This assumption was analyzed by increasing the precipitation of each storm event by 20% for the 5-minute interval rainfall data for each of the five storm events. The increase of precipitation for the five storm events is displayed in Table 4.4.3.

Table 4.4.3: Climate change (CC) scenario 20% increase on the rainfall of the five storm events.

Storm Event	**Rainfall (in.)**	**20% Increase in Rainfall (in.)**
6/22/06	0.500	0.600
6/27/06	1.52	1.82
7/12/06 (2)	0.260	0.312
7/22/06 (1)	0.380	0.456
6/8/2007	0.320	0.384

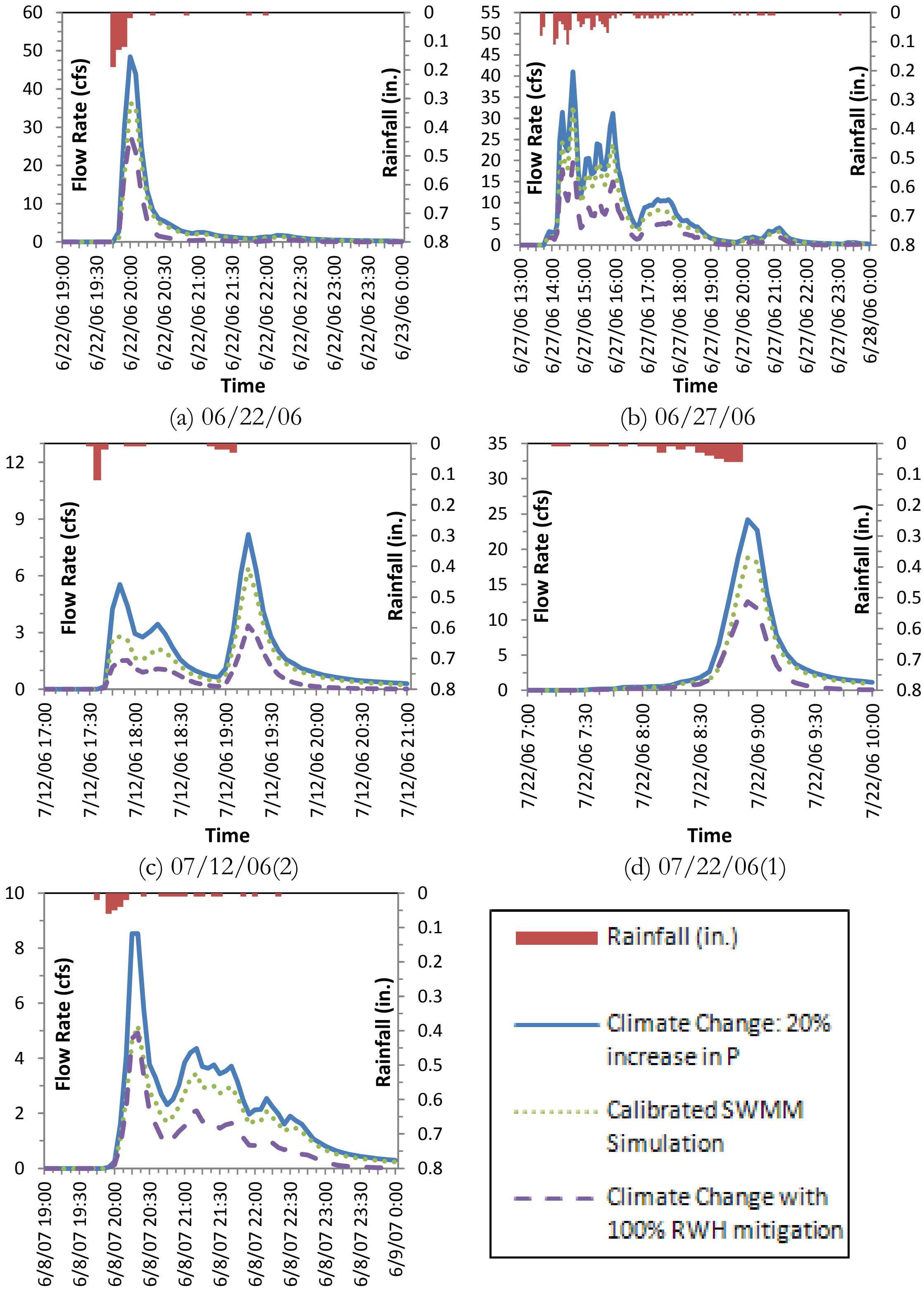
In order to determine if this climate change scenario could be mitigated by RWH, the RWH ECDA-SWMM model was run using the increased precipitation data. The runoff hydrographs comparing the simulations of future climate change effects on precipitation with the use of RWH (in purple) and without the use of RWH (in blue) are shown in Figure 4.4.5. The calibrated simulation from Section 4.3.2 is shown (in green) as the current condition scenario with no increase in precipitation in order to illustrate the potential affect climate change could have on stormwater peak runoff and total volume. Table 4.4.4 shows the results of running the ECDA-SWMM model with this increased precipitation.

Table 4.4.4: Climate change (CC) scenario with 20% increase in precipitation.

Storm Event	Calibrated V_T (ac-ft)	Calibrated Q_p (cfs)	CC V_T (ac-ft)	CC Q_p (cfs)	V_T Percent Increase (%)	Q_p Percent Increase (%)
6/22/06	1.26	36.7	1.63	48.4	29.4	31.9
6/27/06	4.69	33.0	6.01	41.0	28.1	24.2
7/12/06 (2)	0.404	6.41	0.570	8.19	41.1	27.8
7/22/06 (1)	0.738	18.8	0.972	24.2	31.7	28.7
6/8/2007	0.219	5.17	0.333	8.53	52.1	65.0
		Percent Increase in Runoff (%)			**36.5**	**35.5**

In the climate change scenario, the peak runoff and total volume would increase by about 35%. Results from the simulation produced by the ECDA-SWMM model of combining the climate change scenario's adjusted rainfall storm events and the RWH scenario from section 4.4.1 are listed in Table 4.4.5, which shows the hydraulic effect RWH would have on peak runoff and total volume discharge in storm events affected by future climate change increases in precipitation.

RWH can be viewed as a sustainable solution to difficulties of stormwater management in the coming years. This section reveals that even though stormwater quantity (peak and total volume runoff) possibly could be increased by 35% because of climate change, RWH still would be able offset this increase by decreasing total volume flows by



(a) 06/22/06 (b) 06/27/06

(c) 07/12/06(2) (d) 07/22/06(1)

(e) 06/08/07(1)

Figure 4.4.5: ECDA-SWMM simulations with a 20% increase in precipitation from future climate change scenarios and the mitigation of stormwater through 100% RWH.

Table 4.4.5: Climate change – RWH (CC-RWH) scenario with 20% increase in precipitation and 100% RWH potential.

Storm Event	CC V_T (ac-ft)	CC Q_p (cfs)	CC-RWH V_T (ac-ft)	CC-RWH Q_p (cfs)	V_T Percent Decrease (%)	Q_p Percent Decrease (%)
6/22/06	1.63	48.4	0.730	28.2	-55.2	-41.8
6/27/06	6.01	41.0	2.68	19.5	-55.5	-52.4
7/12/06 (2)	0.570	8.19	0.192	3.36	-66.3	-58.9
7/22/06 (1)	0.972	24.2	0.454	12.6	-53.3	-48.0
6/8/07	0.333	8.53	0.173	4.91	-48.0	-42.3
		Percent Decrease in Runoff (%)			**-55.7**	**-48.7**

-55.7% and peak flows by -48.7%. The increased runoff of the future climate change scenario does not significantly decrease the percentage of stormwater quantity that RWH is able to mitigate because the more stormwater produced just increases the amount of rainwater collected and reused.

4.4.3 Scenario 3: Pre-Colonial Scenario

One goal of sustainable development is to have zero impact on the environment. Goals of this type are seen in other environmental disciplines; for drinking water the Maximum Contamination Level Goals for many contaminants is zero. This would be similar to setting a goal for stormwater of zero impact from pre-construction levels by minimizing the detrimental impacts of stormwater discharge (i.e., no temperature changes, no sedimentation loading, no erosion damage, no increase in Biological Oxygen Demand, etc.). When planning or evaluating a stormwater management design, it is important to quantify the "zero" impact as a benchmark; one way that can be done is by assessing the pre-colonial runoff and stream conditions before the impact of imperviousness. Pre-colonial conditions represent an example of the natural flow of runoff and could be a zero discharge aspiration to be emulated as an innovative approach to sustainable stormwater management to minimize the environmental impact of stormwater discharge. In this section, the East

Campus Drainage Area's stormwater runoff was evaluated based on its pre-development conditions and then modeled using the calibrated ECDA-SWMM model.

In the early 1800's, central Pennsylvania would have been covered by an undeveloped pristine watershed, with permeable soils and wooded groundcover. Before the rise of the metal industry in Pennsylvania, which caused the deforestation of much of the region, rainwater infiltrated naturally into the ground and overflowed at lower speeds downslope to the discharge point. This scenario was modeled as a baseline condition in order for discussion later in this thesis regarding stormwater management goals.

In order to simulate a pre-colonial scenario, several of the calibrated ECDA-SWMM model parameters were adjusted. First, the percentage of building and non-building imperviousness for all 53 sub-catchments was adjusted to 0 in order to model a pre-developed watershed without the impact that buildings, roads, sidewalks, and all other land uses have on stormwater runoff. Next, the SCS Curve Number was lowered to 55; a value set for heavy mixed woods and forests for all the sub-catchments in which brush covers the ground. All five storm events then were run with these pre-colonial conditions and the results showed that all the stormwater runoff would infiltrate giving a value of zero discharge. Even when the 1.42 in. precipitation event on the 6/27/06 storm event was used as the input, the ECDA-SWMM produced zero discharge.

In most cases, zero impact for drinking water is unattainable. Similarly, a zero discharge stormwater management philosophy would be difficult to achieve but it is being practiced as a sustainable solution to stormwater management at another drainage area on Penn State Campus. The Fox Hollow Drainage Basin at Penn State has impervious land on 28% of the drainage area but produces runoff equal to only 3% of the annual precipitation (PSU 2007a). This drainage basin shares a border with the ECDA and serves as the most progressive basin for stormwater management at Penn State. Stormwater in the Fox Hollow Drainage Basin is managed through the use of stormwater BMPs including an aggressive approach to stormwater infiltration. In order for the ECDA's stormwater management to become more sustainable, Penn State must begin trying to emulate the pre-colonial conditions by reducing the amount of stormwater runoff. One way to attempt to meet a zero discharge goal is to minimize the detrimental impact of stormwater discharge through the use of RWH on future construction projects.

When considering the benefits of RWH the true value, which includes an economic analysis on the ECDA, also must be considered. The next section illustrates the financial benefits of utilizing RWH on a sample future building project.

4.5 Financial Analysis of Rainwater Harvesting

RWH systems could have significant environmental benefits by reducing stormwater peak runoff and total volume; but in order to measure the total sustainable impact of the collection and reuse of rainwater, tangible costs must be quantified through a financial analysis. A "conservative" financial evaluation was performed instead of a full economic analysis because social and environmental "non-monetary" intangibles or externalities are discussed but are not included in the capital (Roebuck, 2007). This section evaluates three different RWH financial analyses:

1) Retrospective Water Savings Analysis: Water savings analysis through the use of RWH on 100% of buildings in the ECDA.
2) Present Financial Analysis: Comparison of the use of RWH on the Millennium Science Complex (MSC) and the proposed conventional stormwater facility.

3) Future Financial Analysis: Use of RWH instead of green roofs on future buildings that Penn State has proposed under the University Park Master Plan for future campus building infrastructure projects.

4.5.1 Retrospective Water Savings Analysis

Penn State could benefit economically through lower water bills and avoided costs of future stormwater infrastructure by having the capacity to utilize 100% of the potential RWH within the ECDA. For this hypothetical and retrospective financial analysis, the amount of water conserved and the savings from future water bills are analyzed. Table 4.5.1 shows the price of water and wastewater for the past five years; the rates of 2004-2005 are missing from the data set (PSU, 2004; PSU, 2006; PSU, 2007b; PSU, 2008a). The price of water includes the monetary value of water and also the energy used to pump the water and wastewater. There is an increasing trend of higher water prices each year; therefore the amount of money saved in annual water bills could be significant. The costs for the two utilities were selected to have identical fees for each commodity because Penn State does not separate the water and wastewater rates. Using the most current data for potable water rates ($4.19 per 1000 gallons) and assuming the 100% RWH scenario in the ECDA for a time period of one year (refer to Table 4.4.3 for 100% RWH yield monthly values), Penn State would save $96,135 in future water bills per year and also would conserve over 22.6 million gallons of fresh drinking water per year. This does not take into account the following possible intangible costs: the price of water continuing to increase, the costs of possible future flooding events, future aging stormwater infrastructure replacement costs, or potential stormwater permitting and mitigation costs (Roebuck, 2007).

The hypothetical situation of utilizing RWH in all the buildings in the ECDA (as described in Scenario 1) would not be financially beneficial because the implementation of

Table 4.5.1: University Park, PA, water and wastewater utility rates (PSU, 2004; PSU, 2006; PSU, 2007b; PSU, 2008a).

Year	Water and Wastewater Costs (per 1000 Gallons)	Price Change Since 2003 (%)
2007-2008	$8.38	33.9%
2006-2007	$7.83	25.1%
2005-2006	$7.16	14.4%
2003-2004	$6.26	--

RWH on existing infrastructures is extremely difficult and costly due to the high price and complexity of retrofitting RWH on every building in the ECDA. Therefore, the costs of constructing a RWH system are discussed in terms of a real construction project that is currently taking place at Penn State.

4.5.2 Present Financial Analysis

In September of 2008, Penn State began building the Millennium Science Complex (MSC), located on the corner of Bigler Road and Pollock Road (see the building design details used for this analysis in Table 4.5.2 and its precise location in Figure 4.5.1) on the existing ECDA (Cullerot and Whelan, 2008). The current land use for the site includes sports fields, two tennis courts and two roller hockey rinks. The new 275,600 gross square-foot (GSF) research building (99,836 ft^2 roof catchment area) will be the largest in the ECDA. The MSC will increase the total building impermeability in the ECDA from 21.74 acres to 24.03 acres and increase the total imperviousness of the ECDA by 2%. Like all buildings built at Penn State since 2004, the MSC is planned to be built to meet Leadership in Energy and Environmental Design (LEED) standards and will feature a green roof in order to reduce the stormwater impact in the ECDA. Also, an underground stormwater detention pipe system is being built and implemented in order to meet storm design standards.

Table 4.5.2: MSC building details.

Number of Stories	4
Gross Floor Area	276,000 ft^2
Total Roof Catchment Area	94,400 ft^2
Green Roof Catchment Area	50,000 ft^2
Ground Floor Patio Garden	4220 ft^2
Design Occupants	2990 people
Design Water Closets	60 toilets
Toilet Demand	1.60 Gallon/flush
Flushes/occupant	3/day
Irrigation	1.50 inches/week

Figure 4.5.1: Location of the Millennium Science Building with the five green roofs labeled (GR).

Water Balance for the Millennium Science Complex

In order to calculate the RWH potential supply, a water balance estimate must be e for the MSC. First, the monthly rainwater supply was calculated using the monthly rainfall data for State College, PA, the MSC's total roof square feet (SF), and the following equation:

$$Rainwater\ Potential\ Supply = (Precipitation) * K_{roof} * SF * 0.623 \qquad \text{(Eq. 4.4.1)}$$

where K_{roof} = 0.9 because the first 10% of rainwater typically is lost to initial abstractions such as transpiration, evaporation, and surface wetting (Hicks, 2008). The value of 0.623 was used as the precipitation unit conversion from inches of precipitation to gallons/square foot. The toilet water usage demand for the MSC was calculated by assuming that each of the "design building occupants" would flush a toilet three times a day at 1.6 Gallons per flush (Hicks, 2008). The selected irrigation water usage was calculated by assuming that the 4220 ft^2 garden would have a water demand of 1.5 in. of water per week (Hicks, 2008). Figure 4.5.2 shows the comparison of the RWH supply and the total water demand for toilets and irrigation. By collecting and utilizing 90% of the rainwater that runs off the MSC building, between 32-50% of the potable water used for flushing toilets could be conserved. This could result in up to $8700 of water savings per year at the current water rate of $4.19/1000 gallons.

The MSC currently is designed to have a green roof that will cover over an acre of the MSC's roof and will cost $1.25 million. Because green roofs can only "retain the first inch" of storm events and by code the stormwater system must be able to handle a 100-year storm event, an additional stormwater management structure must be built in order to decrease predevelopment runoff peak and volume rates (Buranen, 2008). In front of the MSC, a conventional subterranean stormwater pond for the management of the MSC's

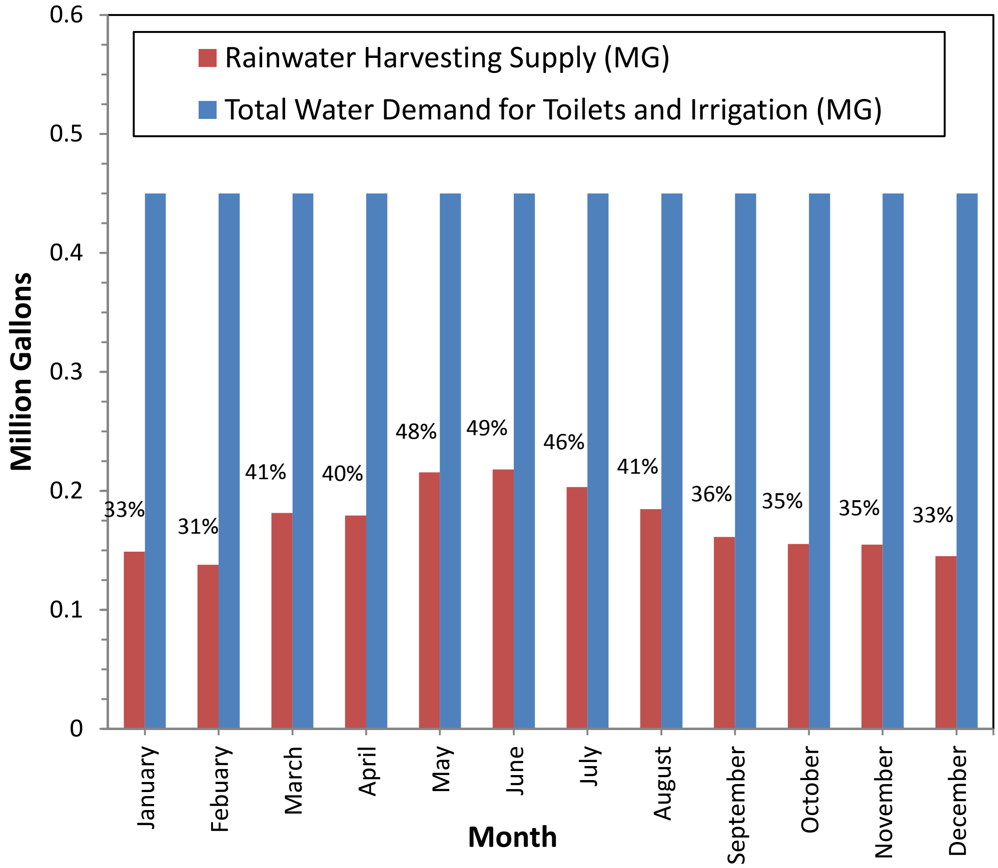


Figure 4.5.2: MSC RWH 90% yield versus calculated water usage.

stormwater is being built that consists of five 240 ft long, 48 in. corrugated steel detention pipes that run parallel to Pollock Road. This conventional stormwater detention facility was designed ignoring the green roof's retention capabilities. The costs of the purchase and installation of the corrugated steel detention pipes is compared financially to a RWH system appropriate for the MSC. For this analysis, the *Stormtank*, RWH system stormwater storage modules (Brentwood Industries, 2009) was chosen to be analyzed (See Figure 4.5.3). The *Stormtank* RWH system will be able to detain the stormwater on site for landscape irrigation and toilet flushing while also being able to handle the same volume of stormwater as the proposed conventional stormwater structures in order to meet stormwater peak and volume NPDES II regulations (Reidy, 2008).

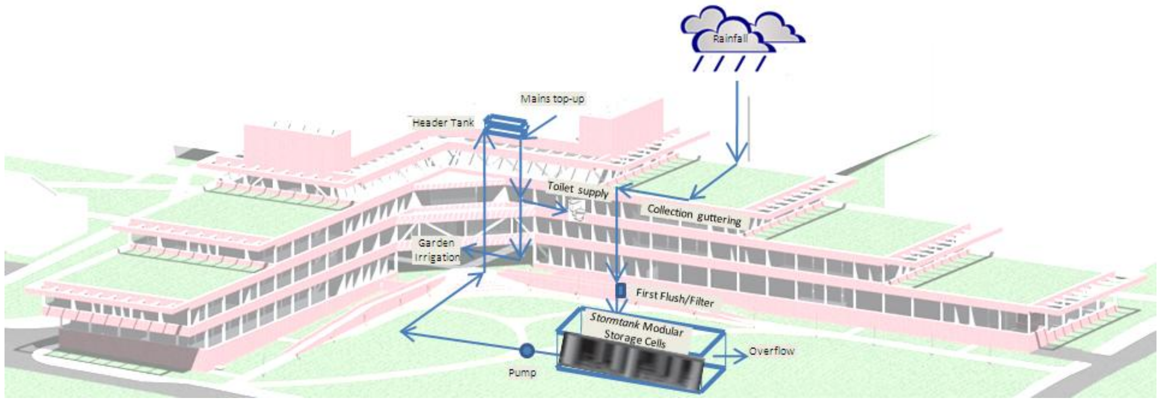


Figure 4.5.3: Schematic of the proposed MSC RWH system
(Adapted from Roebuck, 2007).

The *Stormtank* stormwater storage modular cells were selected for several reasons:

- The modular storage cells create a 97% void space allowing them to optimize the amount of water that can be stored in a smaller area. They are then wrapped with an impermeable membrane to act just like an ordinary cistern or detention structure.
- Each *Stormtank* stormwater storage modular cell can take loads up to 2.32 tons per ft^2 allowing them to be built under parking lots, streets, or recreational facilities.
- Maintenance costs are minimal.

In order to estimate the costs or savings associated with an integrated stormwater management system, detailed assumptions were made based on available data sources (see Table 4.5.3). The conventional system is designed to store up to 113,000 gallons (total volume of five 240-ft long, 48 in. corrugated steel pipes) and the modular RWH system is designed to collect up to 220,000 gallons (each *Stormtank* modular cell holds about 100 gallons). The RWH system modular detention size was estimated assuming the maximum amount of rainfall that would need to be collected in the month with the maximum amount of rainfall.

Table 4.5.3: Installation costs of RWH system and conventional stormwater system.

RWH System	Unit	Cost	Count	Total Cost
Stormtank Modular Cells (Brentwood Industries, 2009) (each cell is 36 in. * 36 in. * 18 in.)	units	$67.50	2244	$151,470.00
Stormtank Plumbing (Hicks, 2008) (i.e. overflow, potable water supply, actuated valves, and tank level sensors)	each	$2,541.60	1	$2,541.60
Geo-textile Fabric (8 oz.) (FEMP, 2003)	yd^2	$0.55	2702	$1,486.10
Geo-grid PVC Under-liner (FEMP, 2003)	yd^2	$3.83	1378	$5,277.74
Excavated Volume Needed (FEMP, 2003)	yd^3	$14.00	1638	$22,932.00
3/4 in. Crushed Stone/Backfill (FEMP, 2003)	yd^3	$12.00	972	$11,664.00
24 in. Minimum Cover (FEMP, 2003)	yd^3	$12.00	386	$4,632.00
Approx. Labor to Install System (FEMP, 2003)	hours	$70.00	178	$12,460.00
First Flush Filter (Hicks, 2008)	each	$120	1	$120.00
Tank Pump (Hicks, 2008)	each	$3,378	1	$3,378.00
10,000 Gallon Header Tank (Hicks, 2008)	each	$17,372	1	$17,372.00
Booster Pump (Hicks, 2008)	each	$1,478	1	$1,478.00
			TOTAL	$234,811.44

Conventional System	Unit	Cost	Count	Total Cost
Stormwater 48 in. diameter Detention Corrugated Steel pipes (ACE, 2005) (includes excavation and necessary backfill/cover)	linear foot	$206.50	1200	$247,800.00
Tees (FEMP, 2003)	each	$900.00	16	$14,400.00
Elbows (FEMP, 2003)	each	$700.00	8	$5,600.00
Approx. Labor to Install System (FEMP, 2003)	hours	$70.00	106	$7,420.00
			TOTAL	$275,220.00

Installation costs for the *Stormtank* modular RWH system are approximately $40,400 less expensive than the costs to install a conventional stormwater detention pipes; and the Stormtank RWH system has the potential to save about $8740/year in water costs (see Table 4.5.4). Furthermore, these estimates do not account for the costs of the sustainable stormwater management green roof structure that is being designed and built for the MSC. Table 4.5.5 shows the cost breakdown of the MSC green roof. Green roofs are estimated to cost $25 per square foot (Berghage, 2008).

Table 4.5.4: Yearly water cost savings of RWH system.

Cost of Water per 1000 Gallons	MSC yearly RWH Potential (Gallons)	Total Savings
$0.00419	2,085,425	$8,737.93

Table 4.5.5: MSC green roof size and cost.

Stormwater Structure	Unit	Cost	Count	Total Cost
Extensive Green Roof	Sq. ft.	$25.00 (Berghage, 2008)	50,000	$1,250,000

A study done by Penn State showed that a green roof "can be expected to retain 55% of Pennsylvania's annual rainfall" and is capable of improving stormwater quality by decreasing total suspended solids by 85%, and decreasing nutrient loadings of total phosphorous by 85% and total nitrate by 30% (DeNardo et al., 2003; DEP, 2006). If designed appropriately, RWH systems are able to capture 100% of the stormwater volume, thereby decreasing stormwater pollutant loadings by 100%. The total cost of the proposed stormwater system for the MSC is estimated to be about $1,581,000 (green roof + conventional stormwater structure), which is about five times the cost of an RWH system, which includes an integrated stormwater management infrastructure benefit. This benefit will be described in greater detail in the next section and in the discussion of this study.

4.5.3 Future Financial Analysis

Since 2005, Penn State has begun an institutional transformation on campus by integrating sustainable design and management of facilities by integrating conservation of energy, water, and waste. Every new building at Penn State will be built within LEED standards. With the help of the Penn State Center for Green Roof Research Institute, Penn State has achieved LEED stormwater quantity and quality design control points by installing three green roofs and preparing to install two more in the next two years. A summary of Penn State's total green roof square footage and cost information is provided in Table 4.5.6.

Table 4.5.6: Built and proposed green roofs square footage and total costs.

Building	Year Built	Building Gross Square Feet (GSF)	Roof Square Feet (SF)	Cost of Building (Dollars)	Green Roof Square Feet (GR SF)	Cost of Green Roof per SF (Dollars)	Total Cost of Green Roof (Dollars)
Root Cellar Roof	2007	4,500	4,500	Renovated	4,500	$7.00	$31,500
Forest Resources Roof	2007	92,000	33,300	$27,000,000	4,700	$25.00	$117,500
Student Health Center	2008	63,000	15,750	$26,000,000	12,500	$25.00	$312,500
Lewis Katz Building	2009	113,000	32,000	$60,000,000	22,000	$25.00	$550,000
Millennium Science Complex	2011	275,600	94,380	$172,000,000	50,000	$25.00	$1,250,000
				Total Green Roof Square Footage	93,700	Total cost	$2,261,500

One reason that Penn State is installing green roofs is to improve the stormwater quality and decrease the quantity of stormwater entering the Spring Creek Watershed. Since 2007, five of Penn State's near term construction projects have incorporated or plan to incorporate green roof technology in upcoming years. With a total of over two acres of green roofs, assuming at $25/square foot cost for all the buildings, except the Root Cellar which cost $7/square foot, construction costs of these green roofs will cost the University $2.26 million dollars. In addition, the University still has to utilize a secondary stormwater infrastructure in order to meet stormwater regulations, which adds a resultant concurrent cost (i.e., expensive detention pipes).

Since 1950, the University Park campus of Penn State has averaged about 240,000 GSF of new buildings and facilities constructed per year. In the next 20 years, it is estimated that Penn State will expand its building infrastructure by over 26%, adding about 5 million

GSF and a total of 7 million GSF by 2040 (PSU, 2008b). The future economic analysis makes the following assumptions about future building infrastructure at Penn State:

1) All future buildings will need to invest in a conventional stormwater management structure designed to limit peak flows to pre-construction levels (i.e., subterranean detention pipes).
2) Modular RWH cells meet all stormwater regulations of peak and volume difference management and maintain and protect the water quality of HQ-CWF.
3) The purchasing and installation costs of a RWH system are equal to the costs of purchasing and installing a conventional stormwater detention structure.
4) Recent stormwater infrastructure patterns show that Penn State is planning to utilize green roofs on 20% to 80% of new buildings proposed in its Master Plan (see Table 4.5.7 for the costs associated with this estimated range of green roof construction).
5) The average gross square feet (GSF) of each building is 3.5 times greater than the total roof square feet (SF). This is based on the assumption that the average building at Penn State has between three and four floors.
6) The costs of green roofs will remain at $25/square foot over time (Berghage, 2008).
7) Through the use of RWH systems, future buildings do not need green roofs in order to address possible stormwater pollution and infrastructure problems (green roof energy benefits will be discussed in the conclusion).

Table 4.5.7: Penn State's Master Plan of future building infrastructure and estimated green roof costs (PSU, 2008b).

Building Construction Projection	Total Building Gross Square Feet (GSF)	Total Roof Square Feet (SF)	Projected 20% Increase in Green Roofs (GR SF)	Cost of Projected 20% Increase (Dollars)	Projected 80% Increase in Green Roofs (GR SF)	Cost of projected 80% increase (Dollars)
20-year Building Plan	4,590,000	1,310,000	262,000	\$6,550,000	1,050,000	\$26,200,000
Future Campus Expansion Beyond the 20-year Plan (≈10 years)	2,340,000	667,000	133,000	\$3,340,000	533,000	\$13,400,000
30 Year Construction Master Plan	6,930,000	1,980,000	395,000	\$9,890,000	1,580,000	\$39,600,000

The second financial analysis demonstrated that a RWH system is financially competitive with that of a conventional stormwater detention facility. Therefore, if Penn State decided to utilize RWH systems instead of conventional stormwater infrastructure and green roofs, it could benefit by saving between \$10,000,000 and \$40,000,000 in the next 30 years or between \$300,000 and \$1,300,000 per year.

Chapter 5

DISCUSSION

5.1 Penn State Stormwater Management: Past Regulations

Penn State is confronted with the importance of having a holistic approach to its water resources because campus watersheds discharge stormwater to a High Quality Cold Water Fishery (HQ-CWF, Pennsylvania Department of Environmental Protection) and a Class A Wild Trout Stream (Pennsylvania Boat and Fish Commission) (DEP, 1999; CC, 2007). In the past, the primary objectives of stormwater management at Penn State included preventing flood damage and protecting the quality of surface water and ground water. As the University Park campus expanded to its current conditions, over 66 miles of stormwater pipes were installed and 26 subsurface detention facilities were constructed (PSU, 2007A). Stormwater regulations required peak projected stormwater flow rates from 100-year storm events to meet those of preconstruction levels (PA, 1978); water quality had to meet HQ-CWF dissolved oxygen and temperature requirements (DEP, 1999), and federal stormwater management requirements were integrated into the stormwater management program (NPDES II) (DEP, 1978; DEP, 1999; EPA, 2000). As statutory requirements, these ordinances and regulations took a central role in Penn State's plan for stormwater management.

5.2 Penn State Stormwater Management: Present Conditions

Regulations have helped drive Penn State towards a more sustainable approach to managing its water resources. Since 1983, Penn State has been pumping all of its treated wastewater to be sprayed for infiltration in a land treatment area; this eliminated discharge to

Thompson Run, a tributary to Spring Creek and helps recharge the local aquifer. Furthermore, Penn State established Water Resource Protection (WRP) Zones in order to optimize natural BMPs by minimizing development in "drainage ways, streams, Zone 1 wellhead protection areas, natural infiltration areas, major sinkholes and depressions, detention basins, and other lands that have significant impact on the University's water resources" (PSU, 2008b). These protection zones help to protect the HQ-CWF and Natural Heritage Inventory areas (WPC, 2002). Penn State currently is utilizing infiltration BMPs in order to manage its runoff from less developed parts of the watershed, such as the Fox Hollow Drainage Area. Wastewater land treatment and infiltration BMPs are examples of how Penn State practices water reuse technologies, for they both are designed to increase the amount of aquifer water recharge and also use natural systems to buffer flow to receiving waters. Figure 5.2.1 shows a simplified hydrological "water reuse cycle" at Penn State. This focus on aquifer recharge is important because water use in the area will be affected by the projected increase in population which will add to the depletion of ground water.

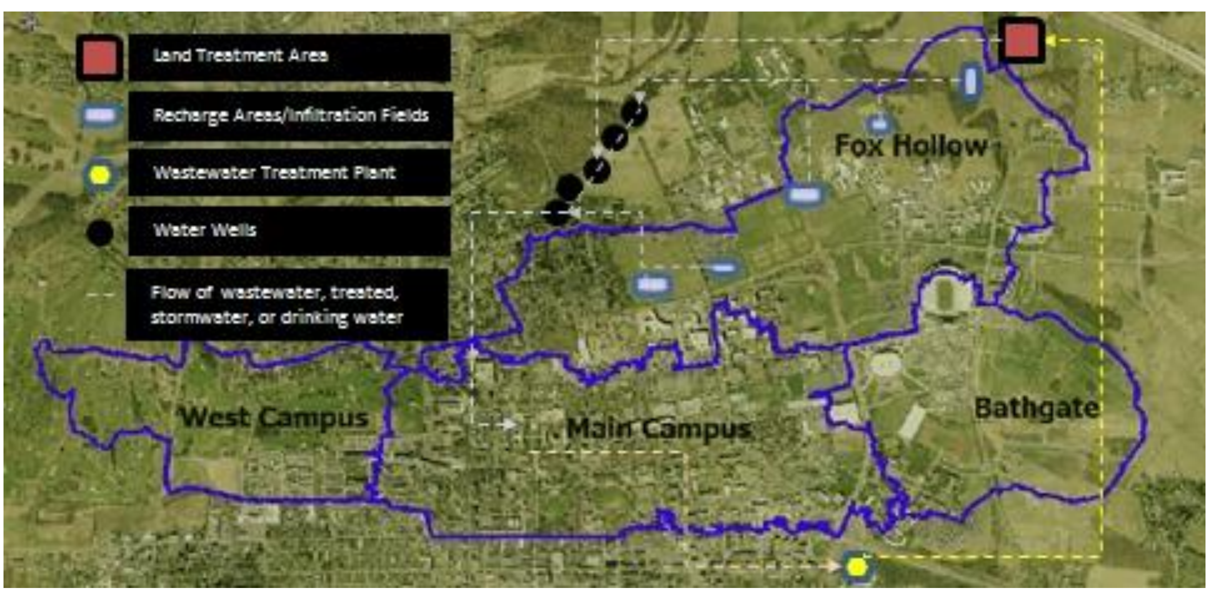


Figure 5.2.1: Simplified Penn State "water reuse cycle" at local aquifers.

Penn State has completed the necessary requirements for the NPDES Phase II stormwater program including public education and outreach, public participation and involvement, discharge detection and elimination, construction site runoff control, post-construction stormwater management in new developments and redevelopment, and has acquired the necessary NPDES permits. Minimum control measures have been incorporated into Penn State's normal operation, including utilizing and preserving natural drainage systems, using minimum structural controls, and focusing on infiltration of stormwater (PSU, 2007a). However, this regulatory compliance has been done on a "micro-watershed scale" as currently there is only a stormwater design manual for only the Fox Hollow Drainage Area, which includes only 43% of all Penn State's watersheds and 34% of its imperviousness.

Penn State has elected to go beyond mere regulatory compliance and is actively pursuing LEED certification for all new construction. In order to meet requirements to treat the first half inch of rainfall and to fulfill LEED requirements, Penn State has begun to implement green roofs on new buildings on the campus. Green roofs are able to reduce heat island effect, reduce winter heat demand, reduce stormwater volume and peak runoff for 1- in. or smaller storm events, provide a natural environment for bird wildlife, and improve aesthetics (Buranen, 2008; Carter and Jackson, 2007; Cheney, 2002). White-painted rooftops with the proper amount of insulation have the same thermo-energy benefits as green roofs for they are able to reduce heat island effects and winter heat demand in equal amounts (Gaffin et al., 2006). In terms of stormwater quantity, a great deal of research has shown that during larger storm events the substrate layer of a green roof becomes fully saturated and sheds rainfall; therefore, a green roof is not a stormwater solution to stormwater peak and volume runoff (Connelly and Liu, 2005; Liu, 2003; Moran et al., 2003).

Also, green roofs can add runoff constituents to local water sources by extracting phosphorous and nitrogen from the compost in their media during large storm events causing nitrification in rivers (Teemusk and Mander, 2007). In summary, green roofs are able to improve water quality and reduce stormwater volume and peak flows for smaller storm events, but in larger storm events after becoming fully saturated, green roofs do not have any stormwater quantity benefits and are sources of potential nutrient pollution to receiving waters.

5.3 Penn State Stormwater Management: Future Direction

Penn State has made considerable improvements with the management of the stormwater in the Fox Hollow Drainage Area, but could enhance its stormwater management program by implanting a sustainable macro-watershed stormwater vision for the entire University Park campus. Specifically, the Main Campus Drainage Area should implement a preventative Thompson Run stormwater management plan before the need of a curative approach in the future when problems worsen. The Main Campus Drainage Area, which is over 50% impervious, makes up 60% of the Thompson Run Drainage Area (the other 40% is located within the State College Borough). Studies by Lipton (1998) and Wilson (2001) have concluded that significant erosion and sedimentation damage from stormwater along the inlet channel are already occurring. Penn State should act swiftly to prevent even more damage; given the current degree of impervious area on the campus, the survival of trout in the receiving water is surprising and should not be taken for granted. One way to accomplish this is for Penn State to focus on the entire watershed, instead of just designing for a specific region such as the Fox Hollow Drainage Area. Also, Penn State plans to incorporate another form of water reuse by diverting the recycled wastewater for graywater by piping recycled wastewater to individual buildings and using the graywater for flushing toilets instead of pumping it to the spray fields.

Penn State has done a commendable job of exceeding regulatory minima and addressing stormwater sustainability through green technologies, LID, BMPs, LEED certification and through the implementation of water reuse technologies, green roofs, and infiltration BMPs. Moreover, the university should establish some hard goals to accompany these tools and standards. Two specific goals that will be discussed are (1) zero stormwater discharge and (2) water independence.

Penn State should continue to emphasize the importance of viewing the water cycle as a sustainably integrated philosophy rather than three different entities (stormwater, wastewater, portable water). Penn State should be setting goals towards eliminating its stormwater volume by implementing strategies such as zero discharge coming from new construction. Penn State has already lowered its water use by 27% since 1981 and in the 2007-2008 school year, 33.4 million gallons of potable water were saved through water efficiency improvements. Working towards water interdependence, Penn State could set specific goals such as 50% water reduction from groundwater sources by 2020. One way to achieve goals such as these is through the use of RWH on future Penn State buildings. For example, Penn State estimates that 155 MG of stormwater runoff discharges from its campus watershed basins each year (PSU, 2007b). With an annual water demand of about 835 MG, rainwater could provide a significant source of water for Penn State. Also, the results from this thesis show that RWH is a cost effective solution to achieve stormwater sustainability by decreasing peak runoff and total volume flows by dealing with stormwater where it falls. A financial analysis provided an example on how RWH is economically feasible (and advantageous) in comparison with conventional stormwater facilities. This analysis is conservative as it did not include the costs associated with avoided flooding, public recreation value of the cold water fishery, future water supply facilities, energy for delivering water from greater distances and stormwater pipe replacement. Table 5.3.1 compares three strategies Penn State is considering for its future sustainable water resource management plans and the rainwater harvesting proposal presented in this thesis.

Table 5.3.1: Comparison of four different water management strategies at Penn State (✚ marks signify abundant costs/benefits, + marks signify partial costs/benefits, and ▬ marks signify adverse costs/benefits).

	Strategies			
COSTS	Do Nothing (i.e. status quo)	Green Roofs	Recycled Wastewater for Graywater use	RWH
Engineered Roof		✚		+
Subterranean Pipe Structures	✚	✚	✚	✚
Pumping Station			✚	+
BENEFITS	Do Nothing (i.e. status quo)	Green Roofs	Recycled Wastewater for Graywater Use	RWH
Conserve Aquifer Water			✚	✚
Recharge Aquifer			▬	✚
Mitigate Stream Damage		+		✚
Monetary Water Cost Savings				✚

Table 5.3.1 shows a cost benefit comparison for future water management strategies by comparing conventional technologies (do nothing, green roofs, recycled wastewater) and RWH. The conventional technologies are considered a "status quo (do nothing) strategy" because no new sustainable water management is implemented and would still require expensive subterranean stormwater structures yielding no water conservation, water infiltration, or additional stormwater benefits. Through the implementation of the "green

roof strategy," Penn State would have to comply with high engineered roof costs that would require expensive large storm event-subterranean stormwater facilities in order to mitigate stream damage about 40-60% of the time. The "recycled wastewater for graywater use" strategy is another example of a centralized stormwater strategy that requires great amounts of energy to pump graywater to an extensive network of pipes. Recycled wastewater would help conserve fresh water, but at the cost of preventing that wastewater from recharging the aquifer. As Table 5.3.1 shows, RWH provides the greatest benefits when comparing the four options Penn State is considering for future management of its water resources since, at the same costs as the status quo, RWH harvesting yields all four benefits including the monetary savings of yearly water costs. Universities across the United States are beginning to implement RWH as a core stormwater management strategy. Table 5.3.2 shows a list of 12 Universities that are currently utilizing rainwater harvesting.

Even though Penn State is doing a commendable job of managing stormwater in the Fox Hollow Drainage Area, it should consider the use of RWH projects in future buildings in the Main Campus Drainage Area. Also, since Penn State shares its watershed with the State College Borough, it should work with the community to coordinate and improve their water resources management strategies.

Table 5.3.2: Twelve universities utilizing RWH on campus.

	University	Building Name	RWH End Use
1	Emory University	Whitehead Biomedical Research Building	irrigation and toilets
2	Humboldt State University	Behavioral and Social Science Building	toilets
3	MIT	incorporated in three buildings	irrigation and toilets
4	Oregon Health Sciences Univ.	Block 25	toilets, cooling energy, groundwater reclamation, and fire sprinkler backup
5	Portland State University	Epler Hall	irrigation and toilets
6	Sierra Nevada College	Tahoe Center for Environmental Sciences	toilets
7	Univ. of Florida	Rinker Hall	toilets
8	Univ. of Georgia	Tate Student Center	irrigation and toilets
9	Univ. of North Carolina	incorporated in five buildings	irrigation and toilets
10	Univ. of Texas-Houston	School of Nursing and Student Community Center	irrigation and toilets
11	Yale University	Kroon Hall	irrigation and toilets
12	Yavapai College	Chino Valley Campus Agribusiness and Science Tech Center	irrigation

5.4 Applying a RWH Paradigm Model for the State College Borough

The Borough of State College (SCB) is located in Centre County, Pennsylvania, and shares one of its drainage areas with Penn State. The Borough has four drainage areas that discharge stormwater to local tributaries, and is home to about 70,000 permanent residents. State College is composed of over 70% open space, or non imperviousness land, with the imperviousness made up of 4% sidewalks, 7% paved roads, 9% parking lots, and 10% buildings.

The stormwater problems facing the SCB include infrastructure damage from flooding, high stormwater quantity stream degradation, and water quality constituents of pollution (Lebzelter, 1998; Smeltz, 2005). In an assessment conducted in 2002, the Spring Creek Watershed had over 16.2 miles of impaired streams as a result of increased sediment loading and increased temperatures (Hughey, 2002). The Centre County Planning Commission identified 48 areas in the region that are flood prone (Hopkins, 2002). An example of a flooding site in the SCB is located at the intersection of Beaver Avenue and South Atherton Street. In the early 1990s, the SCB enacted zoning changes to prevent the Urban Village (the area west of Atherton Street) community houses from being torn down and replaced by large apartment buildings. The new zoning allowed Urban Village homeowners to build or expand a structure on their property (also known as "infill") in order to prevent the development of large apartment complexes. This infill occurred without homeowners being compelled to follow any stormwater regulations, thereby causing imperviousness to increase, which consequently caused flooding during storm events at lower elevations as stormwater conveyance capacity volume exceeded designed pipe runoff facilities and storm sewers overflowed. The high volume discharge of stormwater also has caused serious ecosystem degradation to the receiving waters. Locally, the Millbrook Marsh wetland's viability is being threatened from stormwater input (Lipton, 1998). The SCB built an underground stormwater detention facility to prevent future flooding, at an estimated remediation cost of $2 million to $4 million (Smeltz, 2005). These new infrastructure costs could result in a future increase in stormwater management costs of between 30 and 40% which are "likely to be passed on to homeowners" (Hopkins, 2002). To prevent future flooding problems, the SCB has now prohibited all infill development in the Urban Village area in order to stop the increase of stormwater volume entering the storm sewer system. This "do nothing" approach to the current stormwater problem at best simply freezes the problem in place, and does not take into consideration future possible "pollution limit" regulations to help reduce pollutants such as reducing nitrogen and phosphorous loadings to meet requirements to the Chesapeake Bay Strategy (Brenckle, 2006). To make matters worse, climate change is forecasted to increase flooding events in the region because of higher intensity rainfall which will exacerbate the SCB stormwater problem.

Much of the stormwater infrastructure in the United States is outdated and decaying; instead of investing in costly 19th century replacement infrastructure, 21st century stormwater management should incorporate sustainable design in order to deal with future climatic changes and future stricter regulations (Anderson, 2005; EPA, 2007). A social-economical-environmental solution to stormwater management is the decentralized approach of RWH. As of August of 2006, the SCB farsightedly has enacted a climate protection declaration (Resolution 944) which sets "specific goals including to establish incentives for the installation of green roofs, rainwater cisterns, and other best management practices to reduce urban runoff" (SCB, 2007). A RWH propositional paper is attached and will be presented to the State College Borough (see Appendix C).

Chapter 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary and Conclusions

This thesis has shown how RWH systems have a sustainable and positive impact on stormwater management by reducing surface runoff compared to conventional stormwater systems, decreasing potential water pollutant loadings, increasing water conservation and being cost effective. Chapter 2 laid out the foundation for the thesis by providing a literature review on sustainability, the history of stormwater management, RWH, and climate change. All of these topics are related in terms of sustainability. It was concluded that in order to circumvent troubles associated with future population growth, land use changes or urbanization, and climate change, decisions must be made in a micro scale by understanding the macro-sustainability effects. For example, locally in the Spring Creek Watershed, conventional stormwater management currently is causing environmental and financial damages in the forms of erosion, sedimentation, possible pollution and infrastructure flood cost externalization. In Chapter 3, the collected stormwater runoff data were explained and the methods of the proposed analysis were defined. In Chapter 4, the ECDA-SWMM model was calibrated and successfully simulated peak runoff and total volume from five storm events within ±10% of the observed flow. The model was utilized to run past, present and future scenarios which included a pre-colonial scenario, a RWH scenario, and a future climate change scenario with and without the use of RWH. Results from these scenarios demonstrated that RWH was able to reduce the current peak and volume flows from the ECDA by 50% and also was able to mitigate future climate change effects of increased precipitation. Finally, three RWH financial scenarios also were assessed in Chapter 4. These scenarios included: (1) a retrospective water savings analysis, (2) a financial comparison of a conventional stormwater facility being built with a RWH system, and (3) a simplified future analysis of the use of RWH facilities within Penn State's University Park Master Plan. Results from the financial analysis show that through the use of RWH systems as decentralized stormwater facilities in place of green roofs and conventional stormwater detention systems, Penn State could save between $10 and $40 million dollars in the next 30 years.

6.2 Recommendations for Future Research

Numerous avenues exist for building upon the work presented in this thesis. The suggestions for future research include the following:

(1) Further development of the ECDA-SWMM model

In order to more accurately predict hydrological discharges from the ECDA-SWMM model, runoff data should be collected at more locations throughout the drainage area so as to better understand and analyze the stormwater discharge from the ECDA and to better calibrate the ECDA-SWMM model. By collecting runoff data at different locations throughout the watershed, the reasons that the ECDA-SWMM model underestimated the observed data could be tested. The precision of the ECDA-SWMM model could be assessed by comparing the simulated results with the observed results in more than just one outfall point.

(2) Conduct a full economic analysis on RWH projects

In this thesis, a cost-benefit financial analysis was utilized in order to compare stormwater technologies. A full economic analysis should be implemented in order to consider the Life Cycle Analysis of RWH systems in comparison to other options (e.g., stormwater detention pipes, green roofs, etc.). Pumping costs, grey water pipe infrastructure costs and maintenance costs should be taken into consideration in the full economic analysis.

(3) Develop local RWH codes

With the current lack of knowledge and expertise on RWH in the engineering profession, it would be advantageous to write common technical codes that could be used by private consultants, engineers, developers and planners to design RWH systems that focuse on their use as a sustainable solution to stormwater management. Sample plumbing, electrical and building permits would help allow governments and utilities to accept RWH as an option for stormwater management.

(4) Improve and develop more specific Penn State water management goals

Penn State has a comprehensive water management program that has extensively reduced water consumption and embraced a variety of sustainable stormwater practices. The university could improve its water management program by developing specific water conservation and stormwater management goals. Through the development of specific goals, and using RWH as a tool to achieve them, Penn State could seek grants to continuously fund research in sustainable water management.

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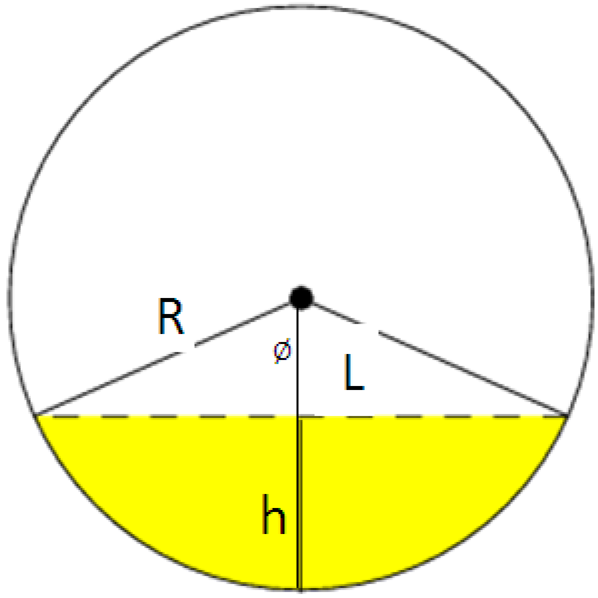
APPENDIX A

Supplementary Calculations for Chapter 3

Appendix A.1: Diagram explaining discharge calculation for the 48 in. ECDA stormwater pipe



Necessary Equations:

1. Area of a circular segment: $A = \frac{1}{2}Rs$, $s = R(2\emptyset)$
2. Area of the two isosceles triangles: $A = \frac{1}{2}(R - h)$*L
3. Effective Area of pipe water flow = Area of circular segment – Area of two isosceles triangles …

$$A = \frac{1}{2}R^2(2\emptyset) - \frac{L}{2}\ (R - h)$$

To solve for L:

1. Solve for Ø:
   - $cos\emptyset = \frac{(\mathrm{R-h})}{\mathrm{R}}$
   - $\emptyset = \arccos\frac{(\mathrm{R-h})}{\mathrm{R}}$
2. Solve for L:
   - $sin\emptyset = \frac{\mathrm{L}}{\mathrm{2R}}$ → $L = 2Rsin\emptyset$

Appendix A.2: Discharge calculation for the 48 in. ECDA stormwater pipe with a coaxial pipe inside

Assumptions:

- Coaxial water pipe is located on the bottom center of the stormwater pipe
- Water does not leak in or out of the coaxial water pipe

Calculation:

1. Effective Area of pipe water flow

$$A_{48"\,pipe} = \frac{1}{2} R_{48"\,pipe}{}^{2}(2\emptyset) - \frac{L}{2}\left(R_{48"\,pipe} - h_{stormwater}\right)$$

2. 6" pipe cross-sectional area

   - If water height is below 6"

$$A_{6"pipe} = \frac{1}{2} r_{6"\,pipe}{}^{2}(2\emptyset) - \frac{L}{2}\left(r_{6"\,pipe} - h_{stormwater}\right)$$

   1. If water is 6" or higher

$$A_{6"pipe} = \pi r_{6"\,pipe}{}^{2}$$

3. Effective Area = 48" pipe – 6"pipe

APPENDIX B

Supplementary Figures and Tables for Chapter 4

Appendix B.1: ECDA-SWMM input data

```
[TITLE]

[OPTIONS]
FLOW_UNITS          CFS
INFILTRATION        CURVE_NUMBER
FLOW_ROUTING        KINWAVE
START_DATE          07/22/2006
START_TIME          07:00:00
REPORT_START_DATE   07/22/2006
REPORT_START_TIME   07:00:00
END_DATE            07/22/2006
END_TIME            10:00:00
SWEEP_START         01/01
SWEEP_END           12/31
DRY_DAYS            0
REPORT_STEP         00:05:00
WET_STEP            00:15:00
DRY_STEP            01:00:00
ROUTING_STEP        0:01:00
ALLOW_PONDING       NO
INERTIAL_DAMPING    PARTIAL
VARIABLE_STEP       0.75
LENGTHENING_STEP    0
MIN_SURFAREA        0
NORMAL_FLOW_LIMITED  BOTH
SKIP_STEADY_STATE   NO
IGNORE_RAINFALL     NO
FORCE_MAIN_EQUATION  H-W
LINK_OFFSETS        DEPTH

[EVAPORATION]
;;Type       Parameters
;;---------- ----------
CONSTANT     0.0866

[TEMPERATURE]
TIMESERIES   072206
WINDSPEED    MONTHLY    6.14 7.05 5.15 6.21 3.62 3.37 3.03 2.71 2.79 3.63 4.48 5.33
SNOWMELT               34 0.5 0.6 0.0 50.0 0.0
ADC          IMPERVIOUS 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
ADC          PERVIOUS   1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0

[RAINGAGES]
;;             Rain      Recd.  Snow   Data
;;Name           Type      Freq.  Catch  Source
;;-------------- --------- ------ ------ ----------
```

STA01 CUMULATIVE 0:05 1.0 FILE "I:\08252006\SWMM simulations\072206A\precip072206A.dat" STA01 IN

[SUB-CATCHMENTS]

;;Name	Raingage	Outlet	Total Area	Pcnt. Imperv	Width	Pcnt. Slope	Curb Length	Snow Pack
1	STA01	393	4.69	17.28	944.5	1.3	0	
2	STA01	393	.521	100	115.3	.21	0	
3	STA01	393	5.13	15.8	1112.6	1.2	0	
4	STA01	393	2.17	100	491.5	.26	0	
5	STA01	380	1.597	21.6	186.1	1.62	0	
6	STA01	380	1.365	100	159.3	.11	0	
7	STA01	387	7.596	25.21	885.8	.86	0	
8	STA01	387	7.598	100	156.1	.1	0	
51	STA01	SF1	1.953	21.73	124	1.4	0	
52	STA01	SF1	0.346	100	45.2	.13	0	
9	STA01	375	4.974	18.61	698.5	1.39	0	
10	STA01	SF2	2.180	100	249.4	.11	0	
11	STA01	SF2	1.402	31.56	342.5	1.77	0	
12	STA01	377D	2.532	100	591	.24	0	
13	STA01	377D	5.452	21.71	754.3	1.93	0	
14	STA01	361	0.191	100	89.3	.45	0	
15	STA01	361	2.713	16.74	589	1.38	0	
16	STA01	373	6.962	8.26	506.3	1.51	0	
17	STA01	373	1.2	14.43	188.9	2.75	0	
18	STA01	373	0.113	100	73.6	.66	0	
29	STA01	359	0.606	23.1	137.7	2.12	0	
30	STA01	359	0.971	100	178.7	.23	0	
19	STA01	566B	5.058	23.92	599.1	1.18	0	
20	STA01	566B	0.674	100	117.4	.17	0	
21	STA01	363	2.131	29.2	247.3	2.07	0	
22	STA01	363	3.249	100	312.7	.09	0	
23	STA01	575.1	2.131	25.72	174.3	1.66	0	
24	STA01	575.1	0.200	100	180.4	.86	0	
25	STA01	306.2	2.727	22.63	325.5	1.59	0	
26	STA01	306.2	0.923	100	116	.12	0	
27	STA01	310.1	1.395	31.97	160.6	1.32	0	
28	STA01	310.1	0.33	100	90.8	1.58	0	
53	STA01	306	1.885	20.24	315.3	2.75	0	
54	STA01	306	0.365	100	112.1	.29	0	
31	STA01	635	2.809	23.87	129.4	.6	0	
32	STA01	635	2.235	0	194.7	.08	0	
33	STA01	SF4	10.067	10.72	1045.3	1.08	0	
34	STA01	575	1.618	100	919.6	.59	0	
35	STA01	575	5.049	13.07	645.7	1.29	0	
36	STA01	519	1.291	100	793.7	.59	0	
37	STA01	519	3.553	14.88	644.9	1.56	0	

38	STA01	471	3.17	12.48	442.4	1.85	0
39	STA01	481	1.532	13.46	311.2	4.85	0
40	STA01	481	0.22	100	191.4	1.27	0
41	STA01	301.1	2.266	0	133	2.16	0
42	STA01	301.1	0.358	100	359.7	.96	0
43	STA01	468.1	4.623	0	425.1	.4	0
44	STA01	468.3	1.968	18.13	278	4.12	0
45	STA01	468.4	2.979	19.69	294.9	2.21	0
46	STA01	468.4	0.506	100	139.1	.26	0
48	STA01	SF3	6.28	14.95	948.7	3.45	0
49	STA01	SF3	0.906	100	295.8	.31	0
50	STA01	302	1.377	18.05	207.5	1.51	0

[SUBAREAS]
;;Sub-catchment N-Imperv N-Perv S-Imperv S-Perv PctZero RouteTo PctRouted
;;-------------- ---------- ---------- ---------- ---------- ---------- ---------- ----------

1	0.012	0.15	.15	.2	25	OUTLET	
2	0.012	0.15	.15	.2	25	OUTLET	
3	0.012	0.15	.15	.2	25	OUTLET	
4	0.012	0.15	.15	.2	25	OUTLET	
5	0.012	0.15	.15	.2	25	OUTLET	
6	0.012	0.15	.15	.2	25	OUTLET	
7	0.012	0.15	.15	.2	25	OUTLET	
8	0.012	0.15	.15	.2	25	OUTLET	
51	0.012	0.15	.15	.2	25	OUTLET	
52	0.012	0.15	.15	.2	25	OUTLET	
9	0.012	0.15	.15	.2	25	OUTLET	
10	0.012	0.15	.15	.2	25	OUTLET	
11	0.012	0.15	.15	.2	25	OUTLET	
12	0.012	0.15	.15	.2	25	OUTLET	
13	0.012	0.15	.15	.2	25	OUTLET	
14	0.012	0.15	.15	.2	25	OUTLET	
15	0.012	0.15	.15	.2	25	OUTLET	
16	0.012	0.15	.15	.2	25	OUTLET	
17	0.012	0.15	.15	.2	25	OUTLET	
18	0.012	0.15	.15	.2	25	OUTLET	
29	0.012	0.15	.15	.2	25	OUTLET	
30	0.012	0.15	.15	.2	25	OUTLET	
19	0.012	0.15	.15	.2	25	OUTLET	
20	0.012	0.15	.15	.2	25	OUTLET	
21	0.012	0.15	.15	.2	25	OUTLET	
22	0.012	0.15	.15	.2	25	OUTLET	
23	0.012	0.15	.15	.2	25	OUTLET	
24	0.012	0.15	.15	.2	25	OUTLET	
25	0.012	0.15	.15	.2	25	OUTLET	
26	0.012	0.15	.15	.2	25	OUTLET	
27	0.012	0.15	.15	.2	25	OUTLET	

28	0.012	0.15	.15	.2	25	OUTLET
53	0.012	0.15	.15	.2	25	OUTLET
54	0.012	0.15	.15	.2	25	OUTLET
31	0.012	0.15	.15	.2	25	OUTLET
32	0.012	0.15	.15	.2	25	OUTLET
33	0.012	0.15	.15	.2	25	OUTLET
34	0.012	0.15	.15	.2	25	OUTLET
35	0.012	0.15	.15	.2	25	OUTLET
36	0.012	0.15	.15	.2	25	OUTLET
37	0.012	0.15	.15	.2	25	OUTLET
38	0.012	0.15	.15	.2	25	OUTLET
39	0.012	0.15	.15	.2	25	OUTLET
40	0.012	0.15	.15	.2	25	OUTLET
41	0.012	0.15	.15	.2	25	OUTLET
42	0.012	0.15	.15	.2	25	OUTLET
43	0.012	0.15	.15	.2	25	OUTLET
44	0.012	0.15	.15	.2	25	OUTLET
45	0.012	0.15	.15	.2	25	OUTLET
46	0.012	0.15	.15	.2	25	OUTLET
48	0.012	0.15	.15	.2	25	OUTLET
49	0.012	0.15	.15	.2	25	OUTLET
50	0.012	0.15	.15	.2	25	OUTLET

[INFILTRATION]

;;Sub-catchment	CurveNum	HydCon	DryTime
;;--------------	----------	----------	----------
1	82.66	0.6	4
2	98	0.6	4
3	81.67	0.6	4
4	98	0.6	4
5	85.58	0.6	4
6	98	0.6	4
7	88	0.6	4
8	98	0.6	4
51	85.58	0.6	4
52	98	0.6	4
9	83.56	0.6	4
10	98	0.6	4
11	92.3	0.6	4
12	98	0.6	4
13	85.66	0.6	4
14	98	0.6	4
15	82.3	0.6	4
16	76.58	0.6	4
17	80.74	0.6	4
18	98	0.6	4
29	86.59	0.6	4
30	98	0.6	4

```
19          87.15     0.6     4
20          98        0.6     4
21          90.71     0.6     4
22          98        0.6     4
23          88.36     0.6     4
24          98        0.6     4
25          86.27     0.6     4
26          98        0.6     4
27          92.58     0.6     4
28          98        0.6     4
53          84.66     0.6     4
54          98        0.6     4
31          87.11     0.6     4
32          71        0.6     4
33          78.23     0.6     4
34          98        0.6     4
35          79.82     0.6     4
36          96.71     0.6     4
37          81.04     0.6     4
38          79.41     0.6     4
39          80.08     0.6     4
40          98        0.6     4
41          71        0.6     4
42          98        0.6     4
43          71        0.6     4
44          83.24     0.6     4
45          84.29     0.6     4
46          98        0.6     4
48          81.09     0.6     4
49          98        0.6     4
50          83.13     0.6     4

[JUNCTIONS]
;;          Invert     Max.       Init.      Surcharge  Ponded
;;Name      Elev.      Depth      Depth      Depth      Area
;;-------------- ---------- ---------- ---------- ---------- ----------
393         1160.56    30.69      0          0          0
392         1159.64    31.37      0          0          0
387         1160.42    7.81       0          0          0
386         1157.66    19.23      0          0          0
380         1156.77    25.65      0          0          0
377         1153.92    17.88      0          0          0
377D        1170.63    13.58      0          0          0
645         1165.15    6.14       0          0          0
376         1152.12    11.31      0          0          0
375         1145.97    10.52      0          0          0
373         1133.79    9.23       0          0          0
361         1132.3     5.96       0          0          0
```

```
635            1160      5.5       0        0        0
631            1149.69    11.03     0        0        0
567.3           1139.19    6.47     0        0        0
575            1124.5     10.4      0        0        0
519            1121.11    6.19      0        0        0
359            1118.53    7.75      0        0        0
575.1           1115.65    7.83      0        0        0
310.1           1106.66    5.95      0        0        0
566B            1141.43    3.25      0        0        0
363            1122.05    2.66      0        0        0
306.1           1117.69    2.76      0        0        0
306.2           1108.18    2.6       0        0        0
306            1097.61    4.9       0        0        0
305            1095.75    6.57      0        0        0
617            1095.5     6         0        0        0
302            1073      7.04       0        0        0
468.1           1139       3         0        0        0
468.3           1118       3         0        0        0
468.4           1111       3         0        0        0
468.5           1091       0         0        0        0
468.6           1075       3         0        0        0
481            1089.4     3.1        0        0        0
471            1102.3     4.85       0        0        0
301.2           1087.9     4.8        0        0        0
301.1           1086.06    4.62       0        0        0
301            1069      4.79       0        0        0
0.12           1048      6         0        0        0

[STORAGE]
;;          Invert   Max.     Init.    Shape      Shape                  Ponded   Evap.
;;Name          Elev.    Depth    Depth    Curve       Params                  Area     Frac.
;;-------------- -------- -------- -------- ---------- -------- -------- -------- -------- --------
SF1            1172.9   0       0       FUNCTIONAL 1000    0       0       0       0
SF2            1169.46  0       0       FUNCTIONAL 1000    0       0       0       0
SF3            1100     0       0       FUNCTIONAL 1000    0       0       0       0
SF4            1151.23  2       0       FUNCTIONAL 500     .25      .8       0       0

[CONDUITS]
;;          Inlet          Outlet                    Manning    Inlet      Outlet     Init.      Max.
;;Name           Node            Node              Length     N          Offset     Offset     Flow
Flow
;;-------------- ---------------- ---------------- ---------- ---------- ---------- ---------- ---------- ----------
C1             393            392             91         0.032      0          0          0          0
C2             392            380             331        0.032      0          0          0          0
C3             387            386             385        0.013      0          0          0          0
C4             386            380             205        0.013      0          0          0          0
C8             380            377             262        0.032      0          0          0          0
C42            SF1            377             175        0.032      0          0          0          0
```

C9	377	376	149	0.032	0	0	0	0
C12	377D	645	263	0.032	0	0	0	0
C43	SF2	645	29	0.032	0	0	0	0
C10	645	376	376	0.032	0	0	0	0
C11	376	375	162	0.032	0	0	0	0
C6	375	373	267	0.032	0	0	0	0
C13	373	361	146	0.032	0	0	0	0
C15	361	359	347	0.032	0	0	0	0
C24	635	SF4	552	0.032	0	0	0	0
C25	SF4	631	45	0.032	0	0	0	0
C26	631	567.3	355	0.032	0	0	0	0
C27	567.3	519	819	0.032	0	0	0	0
C28	575	519	214	0.032	0	0	0	0
C29	519	359	112	0.032	0	0	0	0
C16	359	575.1	81	0.032	0	0	0	0
C19	575.1	310.1	277	0.032	0	0	0	0
C23	310.1	305	284	0.032	0	0	0	0
C17	566B	363	585	0.032	0	0	0	0
C18	363	306.1	225	0.032	0	0	0	0
C20	306.1	306.2	278	0.032	0	0	0	0
C21	306.2	306	241	0.032	0	0	0	0
C22	306	305	34	0.032	0	0	0	0
C38	305	302	446	0.032	0	0	0	0
C37	617	302	239	0.032	0	0	0	0
C39	302	301	101	0.032	0	0	0	0
C33	468.1	468.3	147	0.032	0	0	0	0
C34	468.3	468.4	178	0.032	0	0	0	0
C35	468.4	468.5	451	0.032	0	0	0	0
C41	468.5	468.6	253	0.05	0	0	0	0
C36	468.6	301	38	0.032	0	0	0	0
C31	481	301.2	117	0.032	0	0	0	0
C30	471	301.2	306	0.032	0	0	0	0
C32	301.2	301.1	109	0.013	0	0	0	0
C40	301.1	301	317	0.013	0	0	0	0
C0.12	301	0.12	324	0.032	0	0	0	0
C44	SF3	617	400	0.032	0	0	0	0

[XSECTIONS]

;;Link	Shape	Geom1	Geom2	Geom3	Geom4	Barrels
;;--------------	------------	----------------	----------	----------	----------	----------
C1	CIRCULAR	2	0	0	0	1
C2	CIRCULAR	3	0	0	0	1
C3	CIRCULAR	2	0	0	0	1
C4	CIRCULAR	2.5	0	0	0	1
C8	CIRCULAR	3	0	0	0	1
C42	CIRCULAR	1.25	0	0	0	1
C9	CIRCULAR	3	0	0	0	1
C12	CIRCULAR	2.5	0	0	0	1

```
C43     CIRCULAR     2.5    0    0    0    1
C10     CIRCULAR     2.5    0    0    0    1
C11     CIRCULAR     3      0    0    0    1
C6      CIRCULAR     3      0    0    0    1
C13     CIRCULAR     3      0    0    0    1
C15     CIRCULAR     3      0    0    0    1
C24     CIRCULAR     2.5    0    0    0    1
C25     CIRCULAR     1      0    0    0    1
C26     CIRCULAR     1.75   0    0    0    1
C27     CIRCULAR     2      0    0    0    1
C28     CIRCULAR     2      0    0    0    1
C29     CIRCULAR     2      0    0    0    1
C16     CIRCULAR     3      0    0    0    1
C19     CIRCULAR     3      0    0    0    1
C23     CIRCULAR     3      0    0    0    1
C17     CIRCULAR     1.5    0    0    0    1
C18     CIRCULAR     1.5    0    0    0    1
C20     CIRCULAR     1.5    0    0    0    1
C21     CIRCULAR     2.5    0    0    0    1
C22     CIRCULAR     3      0    0    0    1
C38     CIRCULAR     3      0    0    0    1
C37     CIRCULAR     1.25   0    0    0    1
C39     CIRCULAR     3      0    0    0    1
C33     CIRCULAR     1      0    0    0    1
C34     CIRCULAR     1.5    0    0    0    1
C35     CIRCULAR     1.5    0    0    0    1
C41     TRAPEZOIDAL  1.5    1    .5   0.5  1
C36     CIRCULAR     1.5    0    0    0    1
C31     CIRCULAR     1.25   0    0    0    1
C30     CIRCULAR     1.5    0    0    0    1
C32     CIRCULAR     2      0    0    0    1
C40     CIRCULAR     2      0    0    0    1
C0.12   CIRCULAR     4      0    0    0    1
C44     CIRCULAR     1      0    0    0    1

[LOSSES]
;;Link          Inlet      Outlet     Average    Flap Gate
;;-------------- ---------- ---------- ---------- ----------

[TIMESERIES]
;;Name          Date       Time       Value
;;-------------- ---------- ---------- ----------
;7/22/2006     7:05     68.4
072206          7/22/2006  7:10       68.6
072206          7/22/2006  7:15       68.7
072206          7/22/2006  7:20       68.7
072206          7/22/2006  7:25       68.7
072206          7/22/2006  7:30       68.8
```

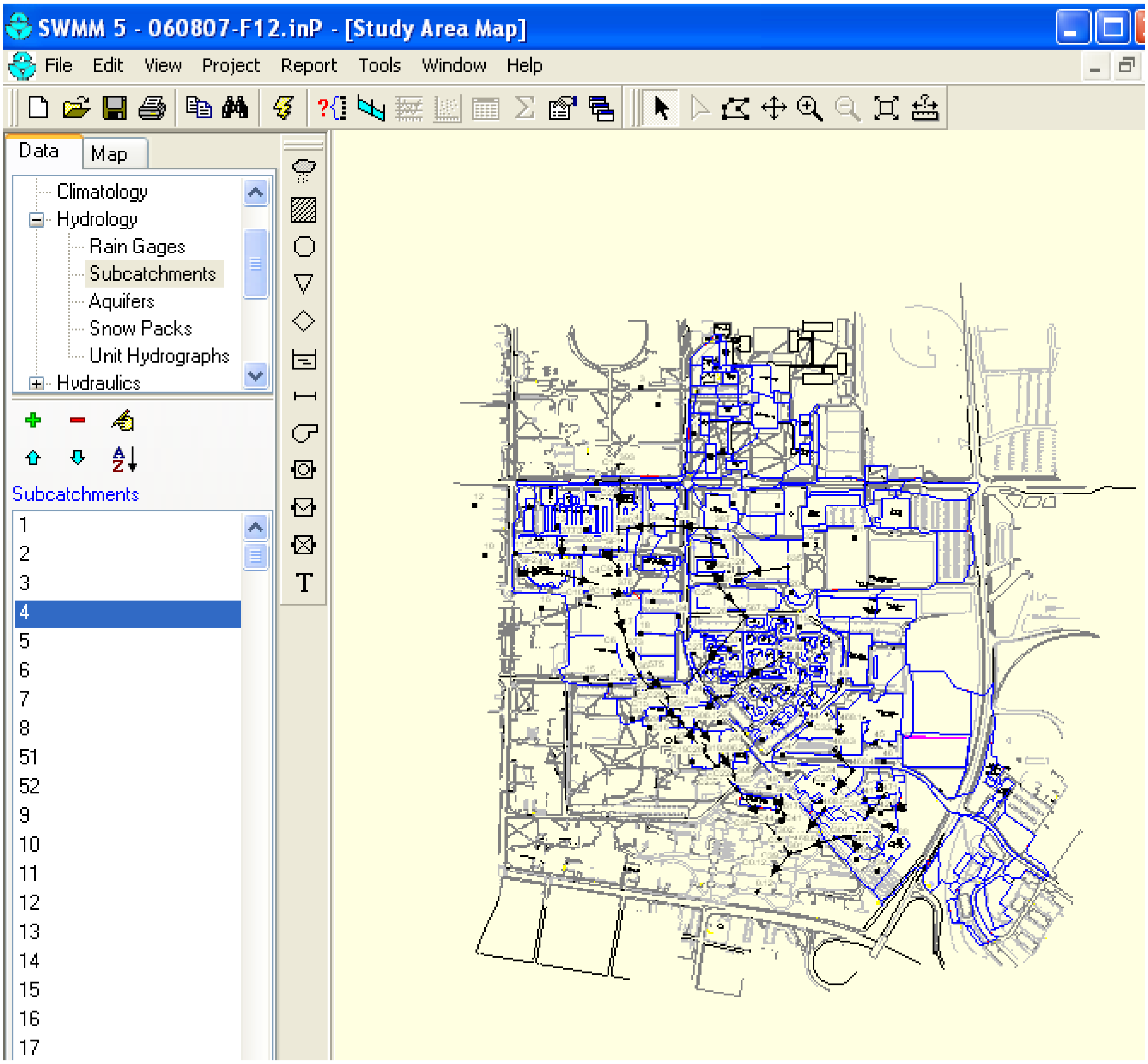
072206	7/22/2006	7:35	68.8
072206	7/22/2006	7:40	68.8
072206	7/22/2006	7:45	68.8
072206	7/22/2006	7:50	68.7
072206	7/22/2006	7:55	68.6
072206	7/22/2006	8:00	68.6
072206	7/22/2006	8:05	68.7
072206	7/22/2006	8:10	68.7
072206	7/22/2006	8:15	68.8
072206	7/22/2006	8:20	68.9
072206	7/22/2006	8:25	69
072206	7/22/2006	8:30	69
072206	7/22/2006	8:35	69
072206	7/22/2006	8:40	69
072206	7/22/2006	8:45	68.9
072206	7/22/2006	8:50	68.8
072206	7/22/2006	8:55	68.7
072206	7/22/2006	9:00	68.6
072206	7/22/2006	9:05	68.7
072206	7/22/2006	9:10	68.8
072206	7/22/2006	9:15	69
072206	7/22/2006	9:20	69
072206	7/22/2006	9:25	69
072206	7/22/2006	9:30	69
072206	7/22/2006	9:35	69.2
072206	7/22/2006	9:40	69.4
072206	7/22/2006	9:45	69.5
072206	7/22/2006	9:50	69.8
072206	7/22/2006	9:55	70
072206	7/22/2006	10:00	70
072206	7/22/2006	10:05	70.2
072206	7/22/2006	10:10	70.4
072206	7/22/2006	10:15	70.4
072206	7/22/2006	10:20	70.5
072206	7/22/2006	10:25	70.8
072206	7/22/2006	10:30	71
072206	7/22/2006	10:35	71.1
072206	7/22/2006	10:40	71.2
072206	7/22/2006	10:45	71.4
072206	7/22/2006	10:50	71.6
072206	7/22/2006	10:55	71.7
072206	7/22/2006	11:00	72.1
072206	7/22/2006	11:05	72.4
072206	7/22/2006	11:10	72.8
072206	7/22/2006	11:15	73
072206	7/22/2006	11:20	73.2
072206	7/22/2006	11:25	73.5
072206	7/22/2006	11:30	73.6

072206	7/22/2006	11:35	73.6
072206	7/22/2006	11:40	73.7
072206	7/22/2006	11:45	73.6
072206	7/22/2006	11:50	73.6
072206	7/22/2006	11:55	73.5
072206	7/22/2006	12:00	73.6
072206	7/22/2006	12:05	73.8
072206	7/22/2006	12:10	73.9
072206	7/22/2006	12:15	74
072206	7/22/2006	12:20	74.1
072206	7/22/2006	12:25	74.2
072206	7/22/2006	12:30	74.2
072206	7/22/2006	12:35	74.4
072206	7/22/2006	12:40	74.5
072206	7/22/2006	12:45	74.7
072206	7/22/2006	12:50	74.8
072206	7/22/2006	12:55	74.8
072206	7/22/2006	13:00	74.9
072206	7/22/2006	13:05	75
072206	7/22/2006	13:10	74.7
072206	7/22/2006	13:15	74.5
072206	7/22/2006	13:20	74.4
072206	7/22/2006	13:25	74.4
072206	7/22/2006	13:30	74.5
072206	7/22/2006	13:35	74.6
072206	7/22/2006	13:40	74.7
072206	7/22/2006	13:45	74.7
072206	7/22/2006	13:50	75.1
072206	7/22/2006	13:55	75.4
072206	7/22/2006	14:00	76
072206	7/22/2006	14:05	75.9
072206	7/22/2006	14:10	76
072206	7/22/2006	14:15	76.3
072206	7/22/2006	14:20	76.4
072206	7/22/2006	14:25	76.4
072206	7/22/2006	14:30	76.6
072206	7/22/2006	14:35	76.8
072206	7/22/2006	14:40	76.5
072206	7/22/2006	14:45	76.4
072206	7/22/2006	14:50	76.2
072206	7/22/2006	14:55	76
072206	7/22/2006	15:00	74.3
072206	7/22/2006	15:05	71.7
072206	7/22/2006	15:10	71
072206	7/22/2006	15:15	71.2
072206	7/22/2006	15:20	71.5
072206	7/22/2006	15:25	71.7
072206	7/22/2006	15:30	71.8

072206	7/22/2006	15:35	71.7
072206	7/22/2006	15:40	71.6
072206	7/22/2006	15:45	71.3
072206	7/22/2006	15:50	71
072206	7/22/2006	15:55	70.7
072206	7/22/2006	16:00	70.4
072206	7/22/2006	16:05	70.2
072206	7/22/2006	16:10	70.1
072206	7/22/2006	16:15	70.2
072206	7/22/2006	16:20	70.3
072206	7/22/2006	16:25	70.2
072206	7/22/2006	16:30	70.2
072206	7/22/2006	16:35	70
072206	7/22/2006	16:40	69.8
072206	7/22/2006	16:45	69.9
072206	7/22/2006	16:50	69.8
072206	7/22/2006	16:55	69.6
072206	7/22/2006	17:00	69.9

[REPORT]
INPUT NO
CONTROLS NO

Appendix B.2: ECDA-SWMM catchment, node, and link representation of the ECDA



Appendix B.3: All 29 Storm events observed, uncalibrated and calibrated peak runoff and total volume data (the 5 storms used in the ECDA-SWMM scenarios are in bold)

	Storm Event	P (in.)	Obs. Q_p (CFS)	Obs. V_T (acre-ft)	Uncal. Q_p (CFS)	Uncal. V_T (acre-ft)	Cal. Q_p (CFS)	Cal. V_T (acre-ft)
1	**06/27/06**	**1.52**	**31.2**	**4.38**	**56.7**	**7.60**	**33.1**	**4.69**
2	07/11/07	1.20	34.0	1.44	72.0	3.94	64.6	3.07
3	06/03/07	1.12	24.4	1.82	61.7	5.03	44.7	3.07
4	06/03/06	0.960	11.6	2.09	31.8	4.62	17.9	2.72
5	06/04/06	0.960	11.8	1.59	52.4	3.11	32.9	1.20
6	**06/22/06**	**0.500**	**40.7**	**1.27**	**68.6**	**2.37**	**36.7**	**1.26**
7	06/23/06	0.480	12.0	1.50	21.6	1.98	8.86	1.00
8	07/12/06	0.440	7.06	0.918	37.6	1.28	14.9	0.574
9	07/15/06	0.440	18.8	0.624	56.7	1.85	8.55	0.286
10	06/26/06	0.420	9.75	1.64	21.0	1.56	8.17	0.757
11	**7/22/06 (1)**	**0.380**	**16.8**	**0.730**	**39.0**	**1.51**	**18.8**	**0.738**
12	07/05/07	0.380	7.69	0.274	56.8	1.64	28.1	0.808
13	07/02/06	0.350	12.2	0.374	52.9	1.44	24.1	0.738
14	**06/08/07**	**0.320**	**5.41**	**0.210**	**20.0**	**0.639**	**5.17**	**0.219**
15	05/10/07	0.320	5.60	0.126	19.7	1.23	9.15	0.567
16	6/23/06 (1)	0.280	12.0	0.755	21.6	1.03	5.10	0.456
17	05/31/06	0.260	7.68	0.132	30.7	0.972	8.91	0.413
18	**7/12/06 (2)**	**0.260**	**7.06**	**0.460**	**16.1**	**0.958**	**6.41**	**0.404**
19	6/19/07 (2)	0.260	8.24	0.484	47.2	1.20	14.1	0.563
20	6/19/07 (1)	0.230	8.22	0.232	43.8	0.902	10.1	0.339
21	05/31/07	0.230	4.56	0.476	10.7	0.709	3.58	0.281
22	05/26/06	0.220	6.06	0.519	8.98	0.695	3.19	0.278
23	05/16/07	0.210	12.0	0.755	12.0	0.627	2.00	0.220
24	06/12/07	0.200	7.40	0.189	31.1	0.758	9.35	0.296
25	7/11/07 (2)	0.200	15.3	0.469	27.8	0.573	6.57	0.200
26	07/27/06	0.190	10.3	0.335	24.5	0.838	4.79	0.206
27	06/01/06	0.190	8.07	0.200	25.0	0.584	6.43	0.222
28	06/25/06	0.190	2.77	0.580	3.26	0.432	0.888	0.137
29	7/22/06 (2)	0.140	15.4	0.371	8.55	0.286	2.12	0.0943

Appendix B.4: All 29 Storm events uncalibrated, and calibrated peak runoff and total volume data normalized with the observed runoff (simulated/observed) (The 5 storms used in the ECDA-SWMM scenarios are in bold)

	Storm Event	P (in.)	Norm. Uncal. Q_p	Norm. Uncal. V_T	Norm. Cal. Q_p	Norm. Cal. V_T
1	**06/27/06**	**1.52**	**1.82**	**1.74**	**1.06**	**1.07**
2	07/11/07	1.20	2.12	2.74	1.90	2.14
3	06/03/07	1.12	2.53	2.76	1.83	1.68
4	06/03/06	0.960	2.734	2.21	1.54	1.30
5	06/04/06	0.960	4.43	1.97	2.78	0.756
6	**06/22/06**	**0.500**	**1.69**	**1.86**	**0.900**	**0.991**
7	06/23/06	0.480	1.80	1.32	0.740	0.670
8	07/12/06	0.440	5.33	1.40	2.11	0.625
9	07/15/06	0.440	3.01	2.97	0.454	0.458
10	06/26/06	0.420	2.15	0.956	0.838	0.463
11	**7/22/06 (1)**	**0.380**	**2.32**	**2.06**	**1.12**	**1.01**
12	07/05/07	0.380	7.38	5.98	3.66	2.95
13	07/02/06	0.350	4.34	3.84	1.98	1.97
14	**06/08/07**	**0.320**	**3.69**	**3.04**	**0.956**	**1.04**
15	05/10/07	0.320	3.51	9.78	1.63	4.50
16	6/23/06 (1)	0.280	1.80	1.37	0.426	0.604
17	05/31/06	0.260	3.99	7.36	1.160	3.13
18	**7/12/06 (2)**	**0.260**	**2.28**	**2.08**	**0.908**	**0.878**
19	6/19/07 (2)	0.260	5.74	2.47	1.71	1.16
20	6/19/07 (1)	0.230	5.33	3.89	1.23	1.46
21	05/31/07	0.230	2.35	1.49	0.785	0.590
22	05/26/06	0.220	1.48	1.34	0.527	0.536
23	05/16/07	0.210	1.00	0.830	0.167	0.291
24	06/12/07	0.200	4.20	4.01	1.26	1.57
25	7/11/07 (2)	0.200	1.81	1.22	0.429	0.426
26	07/27/06	0.190	2.38	2.50	0.466	0.615
27	06/01/06	0.190	3.10	2.92	0.797	1.11
28	06/25/06	0.190	1.18	0.745	0.320	0.236
29	7/22/06 (2)	0.140	0.555	0.771	0.138	0.254
Average Normalized %			2.97	2.68	1.17	1.19

Appendix B.5: Mean normalized percentage error (MNPE) for the uncalibrated and calibrated simulations of all 29 storm events

	Storm Event	P (in.)	Uncal. Q_p NPE	Uncal. V_T NPE	Calib. Q_p NPE	Calib. V_T NPE
1	**6/27/2006**	**1.52**	**81.7%**	**73.6%**	**5.90%**	**7.05%**
2	7/11/2007	1.20	112%	174%	90.1%	114%
3	6/3/2007	1.12	153%	176%	83.5%	68.2%
4	6/3/2006	0.96	173%	121%	53.8%	30.0%
5	6/4/2006	0.96	343%	96.4%	178%	-24.4%
6	**6/22/2006**	**0.50**	**68.6%**	**86.3%**	**-0.940%**	**-9.96%**
7	6/23/2006	0.48	80.5%	32.2%	26.0%	-33.0%
8	7/12/2006	0.44	432%	39.7%	110%	-37.5%
9	7/15/2006	0.44	201%	197%	-54.6%	-54.2%
10	6/26/2006	0.42	115%	-4.40%	16.2%	-53.7%
11	7/5/2007	0.38	638%	498%	265%	194.9%
12	**7/22/2006(1)**	**0.38**	**132%**	**107%**	**11.9%**	**1.10%**
13	7/2/2006	0.35	334%	284%	98.2%	97.3%
14	5/10/2007	0.32	251%	878%	63.4%	350%
15	**6/8/2007**	**0.32**	**269%**	**204%**	**-4.40%**	**4.29%**
16	6/23/06(1)	0.28	80.5%	36.7%	-57.4%	-39.6%
17	5/31/2006	0.26	300%	636%	16.0%	213%
18	6/19/2007(2)	0.26	473.4%	147%	70.9%	16.3%
19	**7/12/2006(2)**	**0.26**	**128%**	**108%**	**-9.22%**	**-12.2%**
20	5/31/2007	0.23	135%	49.0%	-21.5%	-41.0%
21	6/19/2007(1)	0.23	433%	288%	23.0%	46.1%
22	5/26/2006	0.22	48.1%	33.8%	-47.3%	-46.4%
23	5/16/2007	0.21	0.030%	-17.0%	-83.3%	-70.9%
24	6/12/2007	0.20	320%	301%	26.4%	56.6%
25	7/11/2007(2)	0.20	81.1%	22.2%	-57.4%	-57.4%
26	7/27/2006	0.19	138%	150%	-53.4%	-38.5%
27	6/25/2006	0.19	17.8%	-25.5%	-68.0%	-76.4%
28	6/1/2006	0.19	210%	192.%	-24.13%	11.0%
29	7/22/2006(2)	0.14	-44.5%	-22.9%	-86.23%	-74.6%
	$MNPE_X$		196%	168%	19.72%	18.6%

Appendix B.6: Normalized observed total volume data and uncalibrated total volume data with the maximum amount of rainfall for the ECDA

	Storm Event	P. (in.)	Obs. V_T (acre-ft)	Uncal. V_T (acre-ft)	Max V_T (acre-ft)	Obs. V_T /Max V_T	Uncal. V_T /Max V_T
1	**6/27/2006**	**1.52**	**4.38**	**7.60**	**24.3**	**0.180**	**0.313**
2	7/11/2007	1.20	1.44	3.94	19.2	0.075	0.205
3	6/3/2007	1.12	1.82	5.03	17.9	0.102	0.281
4	6/3/2006	0.960	2.09	4.62	15.4	0.136	0.301
5	6/4/2006	0.960	1.59	3.11	15.4	0.103	0.203
6	**6/22/2006**	**0.500**	**1.27**	**2.37**	**8.00**	**0.159**	**0.297**
7	6/23/2006	0.480	1.50	1.98	7.68	0.195	0.258
8	7/12/2006	0.440	0.918	1.28	7.04	0.130	0.182
9	7/15/2006	0.440	0.624	1.85	7.04	0.089	0.263
10	6/26/2006	0.420	1.64	1.56	6.72	0.244	0.233
11	**7/22/06 (1)**	**0.380**	**0.730**	**1.51**	**6.08**	**0.120**	**0.248**
12	7/5/2007	0.380	0.274	1.64	6.08	0.045	0.270
13	7/2/2006	0.350	0.374	1.44	5.60	0.067	0.257
14	**6/8/2007**	**0.320**	**0.210**	**0.639**	**5.12**	**0.041**	**0.125**
15	5/10/2007	0.320	0.126	1.23	5.12	0.025	0.241
16	6/23/06 (1)	0.280	0.755	1.03	4.48	0.169	0.230
17	5/31/2006	0.260	0.132	0.972	4.16	0.032	0.234
18	**7/12/06 (2)**	**0.260**	**0.460**	**0.958**	**4.16**	**0.111**	**0.230**
19	6/19/07 (2)	0.260	0.484	1.20	4.16	0.116	0.288
20	6/19/07A (1)	0.230	0.232	0.902	3.68	0.063	0.245
21	5/31/2007	0.230	0.476	0.709	3.68	0.129	0.193
22	5/26/2006	0.220	0.519	0.695	3.52	0.148	0.198
23	5/10/2007	0.210	0.126	1.23	3.36	0.038	0.367
24	5/16/2007	0.210	0.755	0.627	3.36	0.225	0.187
25	6/12/2007	0.200	0.189	0.758	3.20	0.059	0.237
26	7/11/07 (2)	0.200	0.469	0.573	3.20	0.147	0.179
27	7/27/2006	0.190	0.335	0.838	3.04	0.110	0.276
28	6/1/2006	0.190	0.200	0.584	3.04	0.066	0.192
29	6/25/2006	0.190	0.580	0.432	3.04	0.191	0.142
30	7/22/06 (2)	0.140	0.371	0.286	2.24	0.166	0.128
					K_o =	0.116	
						K_s =	0.233

APPENDIX C

Propositional Paper for the State College Borough

State College Borough Rainwater Harvesting Project

Brief

The State College Borough Rainwater Harvesting proposal is the development of a system that provides incentives for residential and commercial buildings to manage their stormwater on-site in a decentralized manner that reduces contribution to the borough stormwater network, manifesting multiple sustainable and positive benefits in terms of reduction of flooding events, decreasing constituents of stormwater pollution, increasing water conservation, and the treatment of rainwater as a precious resource

Background and Discussion

The State College Borough has, as a matter of good environmental policy and as part of the climate protection declaration (Resolution 944) determined to set "specific goals including to establish incentives for the installation of green roofs, rainwater cisterns, and other best management practices to reduce urban runoff" by 2012.

The stormwater problems facing the State College Borough include infrastructure damage from flooding, high stormwater quantity stream degradation, and potential water quality pollution (Lebzelter, 1998; Smeltz, 2005). The Spring Creek Watershed currently has over 16.2 miles of impaired streams as a result of increased sediment loading and increased temperatures (CC, 2007). The Centre County Planning Commission identified 48 areas in the region that are flood prone (Hopkins, 2002). The Millbrook Marsh wetland's viability is being threatened from stormwater input (Lipton, 1998). To make matters worse, climate change is forecasted to increase the amount of floodwater in the region with higher intensity rainfall exacerbating the State College Borough stormwater problem.

Technically, stormwater is a source of possible pollution and arguably a waste, and could have the same principles applied to as it as wastewater management, which attracts a disposal fee via either specific charges or through property taxes.

Environmental benefits of this proposal include:

- Reduced volume and peak flow rates to discharging water which causes erosion, constituents of pollution, turbidity and flooding.
- Reduction of erosion of water ways and consequently a reduction of maintenance requirements.
- Improved water quality through capture of first flush contaminated water.
- Reduced impact on the habitat of receiving waters through the improvement of quality of runoff.
- Increased reuse of rainwater in a decentralized manner, reducing pressure on water mains and decreasing the cost of pumping groundwater.
- Improve the health amenity and vitality of landscaping and vegetation, particularly during times of water restrictions.

Additional social and Borough benefits

- Restore natural groundwater by infiltrating additional stormwater being processed by the wastewater treatment plant.

- Improve security of groundwater.
- Reduced impact of flooding damage during storm events.
- Incentives and rewards to encourage all individuals to take action rather than only those that are environmentally conscious.
- Provide leadership to the greater State College community, including the Susquehanna River Basin, on stormwater management action.

RECOMMENDATION

It is recommended to the Borough of State College that:

1. The Borough should provide workshops and literature related to simple and cost-effective rainwater harvesting examples.

2. The Borough offer rebates of up $500 on the cost of installing a rainwater harvesting system.

3. The Borough should endorse in principle the concept of a "charge and rebate system" for stormwater runoff from residential and commercial properties to local stormwater infrastructure