ABSTRACT

Title of Thesis: THERMAL IMPACT STUDY OF AN UNDERGROUND STORMWATER MANAGEMENT SYSTEM

Poornima Natarajan, Master of Science, 2008

Directed By: Professor Allen P. Davis
Department of Civil and Environmental Engineering

Increase in stream temperature by heated stormwater runoff from impervious surfaces is a serious environmental problem. An underground storage/slow release facility is a versatile stormwater best management practice (BMP) for buffering high flows. Temperature reductions in underground storage BMPs, however, have not been quantified. A field study on an underground storage facility was undertaken to characterize its effect on stormwater runoff temperatures. In colder months, when the runoff temperature ranged from 5 and 15°C, small or no temperature change was observed. Runoff produced during summer storm events, with event mean temperatures over 20°C, exhibited mean temperature reductions of 1.6°C through the BMP. While statistically significant, the reductions were not sufficient to cool the summer runoff discharges below the Maryland Class III temperature standard (20°C) 100% of the time. The results indicate that underground facilities can moderate high runoff temperatures, but that a more efficient design is needed.

THERMAL IMPACT STUDY OF AN UNDERGROUND STORMWATER MANAGEMENT SYSTEM

By

Poornima Natarajan

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2008

Advisory Committee:
Professor Allen P. Davis, Chair
Professor Oliver J. Hao
Professor Richard H. McCuen

© Copyright by
Poornima Natarajan
2008

ACKNOWLEDGEMENTS

I would like to thank Maryland State Highways Administration (SHA) for supporting this research project. Thanks to Karen Coffman of SHA, Christopher Brooks and Kimi Will of McCormik Taylor Inc., and other SHA people for their support at various stages of the project. I extend my sincere thanks to Dr. Allen Davis for providing me with an opportunity to work with him and for his continuous mentoring, support, and encouragement throughout this research. I would like to thank Dr. Richard McCuen for the invaluable guidance and help he has provided during the course of this research. Thanks to Dr.Oliver Hao for his being a part of the advisory committee. My heartfelt love and thanks to my parents and my sister Suhasini, who have always stood by me and have been a constant source of motivation. Finally, hearty thanks to all my friends, who have directly and indirectly helped me in making this work possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

Over the past several centuries, forests have been cleared to satisfy the growing demand for land and fuel of the burgeoning world population. Natural land covers have been replaced by large agricultural lands and urban areas. The world urban population is expected to almost double by 2050, increasing from 3.3 billion in 2007 to 6.4 billion in 2050 (United Nations 2008). Globally, the proportion of the population that resides in urban areas is expected to rise from 50% in 2008 to 70% in 2050 (United Nations 2008). The sustained increase in urbanization has resulted in large scale replacement of pervious land cover by impervious areas such as roads, driveways, sidewalks, parking lots, and rooftops. Replacement of the natural land cover by impervious surfaces and infrastructure has resulted in the "urban heat island effect." Many US cities have been found to have air temperatures 3.3 to 4.4°C (6 to 8°F) warmer than the surrounding rural regions (US Department of Energy, 1996).

Imperviousness impacts the quality and quantity of water from a watershed by reducing infiltration and increasing the runoff volume and pollutant loadings during storm events. Hydrologic modification in a watershed associated with urbanization can affect physical, chemical, and biological conditions of the receiving waters (Paul and Meyer 2001; Wang et al. 2003). Increased frequency of flooding and peak flow volumes, increased sediment loadings, loss of riparian habitat, changes in stream channel width and depth, decreased base flow, and increased stream temperatures are some of the impacts of urban runoff on streams.

Stream warming due to urbanization has been a problem of growing concern in recent years. In summer, the average stream temperature was found to increase by as much as 5–8°C in a watershed in Long Island, New York, associated with urbanization (Pluhowski 1970). A study by Galli (1990) on thermal and dissolved oxygen impacts to aquatic life associated with urbanization and representative best management practices (BMPs) in Maryland showed that stream temperature increases by 0.14°F (0.08°C) for each one percent increase in watershed imperviousness. The aquatic biota were affected for connected imperviousness greater than 10% (Schueler 1994). Sensitive species such brook trout ceased to exist for watershed impervious cover beyond 4% in Maryland (Stranko et al. 2008).

Streams that receive urban stormwater runoff have been found to have elevated temperatures (Galli 1990; USEPA 1999; Walsh et al. 2003). Increased stream temperatures by heated runoff have been noted as a severe and prevalent problem in Maryland (Boward et al. 1999). Common urban impervious surfaces have high thermal capacity and absorb solar radiation. As stormwater runoff is conveyed over black asphalt roadways and access areas, heat is transferred to the runoff via conduction, thereby raising its temperature. Summer is the period of concern when ground temperatures are highest and when intense direct sunlight will greatly increase the temperature of the black-colored asphalt (Figure 1). Runoff temperatures from urban impervious areas as high as 29°C have been measured in Dane County, Wisconsin (Roa-Espinosa et al. 2003).

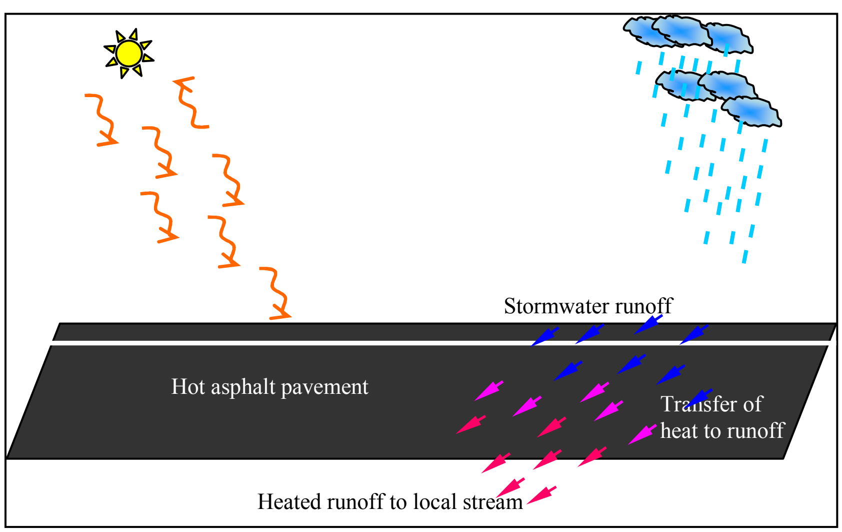


Figure 1-1. Schematic diagram showing the transfer of heat to stormwater runoff

The discharge of high-temperature water can have negative impacts on local streams receiving the runoff, raising stream temperatures, causing direct impact to aquatic organisms that cannot withstand higher temperature. Cold-water species such as trout are extremely sensitive to temperature and are stressed at high temperatures. The Maryland state Class III standard for natural trout waters and Class IV standard for recreational trout waters have been established as 20ºC (68ºF) and 24ºC (75ºF), respectively (USEPA 1988b).

An increase in stream temperature has a direct impact on the dissolved oxygen level. The solubility of oxygen in water decreases at higher temperatures, which results in lower levels of dissolved oxygen. Additionally, as the temperature increases, the metabolic rate of aquatic organisms rises, which causes an increase in the demand for dissolved oxygen. Also, photosynthesis and plant growth increase with higher water temperatures. The consumption of oxygen by bacteria during decomposition of dead plants further depletes the dissolved oxygen level in the stream (Paul and Meyer 2001).

Best management practices such as wetlands, dry detention ponds, grass swales, and sand filters are widely employed control measures for removing pollutants in urban stormwater runoff. While the need to control thermal pollution by storm runoff has been recognized in many research studies, limited studies have investigated the thermal sensitivity of BMPs. Galli (1990) studied the effects of stormwater BMPs, specifically an infiltration facility, an artificial wetland, an extended detention dry pond, and a wet pond, on water temperature. The study results demonstrated the thermal enhancement of the outflow from the BMPs. A thermal balance study on an on-stream wetpond in Ontario yielded similar results. The large surface area of the pond exposed to solar radiation and the lack of surrounding vegetation resulted in the thermal enhancement of the pond during the dry-weather seasons (Van Buren et al. 2000a). However, small reductions in runoff temperatures were observed in bioretention facilities located in trout sensitive regions in North Carolina (Jones et al. 2007).

Another versatile stormwater best management practice is an underground storage and slow release facility. These detention facilities attenuate peak flows. However, evaluation of the temperature mitigation in such underground storage BMPs has not been performed. The ambient temperature in an underground storage is cooler than the surface ground temperature, and extended detention of the inflow runoff should aid in heat loss. Thus, it can be hypothesized that reductions in the temperature of incoming stormwater runoff should occur in an underground storage BMP. Hence, the temperature of runoff discharged from the BMP into the receiving waters or streams will be relatively low.

In order to test the hypothesis, a thermal impact study was conducted in two underground storage BMPs in Timonium, Maryland. The objectives of this study were to quantify the impact of underground storage on the temperature of runoff from a highway and to develop a simple heat transfer model. In order to achieve these objectives, the first task was to set up and monitor stormwater runoff flows and temperatures into and out of the underground storage BMP. The data obtained were employed to quantify the temperature mitigation in the BMP and to develop the heat transfer model. The model, formulated as a set of differential equations, when solved numerically would predict the temperature of the runoff at the outlet of the facility. This will enable the determination of the efficiency of underground stormwater storage facilities in mitigating runoff temperature. While the outflow from this specific BMP may not be directly discharged into an active trout stream, the data and performance results obtained from this research should be applicable to other similar BMPs in trout sensitive regions. The impact of these BMPs in managing high temperature concerns in highway applications can hence be quantified for future design, analysis, and implementation.

Chapter 2

BACKGROUND

2.1 Urbanization and Land Development

Impervious surfaces like, roads, driveways, parking lots, and rooftops have increased due to expanding urbanization. In 2002, urban land in the United States was less than 3% of total land area, but housed 79% of the U.S. population (Lubowski et al. 2006). Urban and suburban lands (residential, commercial, industrial, and institutional) constitute nearly 16% of Maryland and are concentrated in the Washington-Baltimore metropolitan area (Boward et al. 1999). Based on the 2000 Census, the population of Maryland has been projected to increase by 33% between 2000 and 2030 (US Census Bureau statistics Sep 29, 2008). With the increase in population, urban sprawl is expected to further expand to accommodate the new population.

2.2 Imperviousness and its Impacts on Runoff Quantity and Quality

Watershed imperviousness imparts hydrologic modifications in the catchment; reduced infiltration, increased surface runoff, decreased lag time, increased peak flow volumes, and lower dry weather stream flow. Due to urbanization, increase in direct runoff to streams up to five times that of pre-urban periods has been witnessed in Long Island, New York (Seaburn 1970). In addition to the impact on water quantity, urbanization has an effect on the quality of the runoff. Impervious surfaces accumulate pollutants which are washed off during storm events and eventually delivered to the receiving waters. *The National Water Quality Inventory: 2000 Report to Congress* has identified urban runoff as one of the leading sources of water quality impairment in surface waters (USEPA 2005).

2.2.1 Effects of Imperviousness on Stream Ecosystem

The impact of watershed imperviousness on the stream ecosystem is manifold. Physical, chemical, and biological processes in the receiving waters are affected due to urbanization (Booth and Jackson 1997; Paul and Meyer 2001; Elliott et al. 2004 Walsh et al. 2004; Bernhardt and Palmer 2007). The term "urban stream syndrome" has been used to describe the consistently observed ecological degradation of streams draining urban land (Walsh et al. 2005). Urban-induced flashy hydrographs, decreased baseflow, channel instability, elevated levels of sediments, metals, nutrients, pesticides, fecal coliforms and other contaminants, stream warming, riparian deforestation, and decline in biodiversity in streams have been well documented by various researchers.

Imperviousness is considered as a valuable indicator of the impact of urbanization in a watershed on aquatic systems (Schueler 1994). In western Washington, approximately 10% effective watershed imperviousness yielded demonstrable loss of aquatic system function (Booth and Jackson 1997). Similar results have been reported for trout streams in Maryland and Wisconsin (Galli 1990; Wang et al. 2003). Urbanization is considered one of the more serious immediate threats to the brook trout populations in Maryland. For a watershed of impervious surface area of 0.5%, substantial reduction in brook trout population was observed, while for imperviousness greater than 4%, brook trout is expected to be completely eliminated (Butowski et al. 2006; Stranko et al. 2008). Figure 2-1 illustrates the extreme sensitivity of brook trout to upstream imperviousness in Maryland.

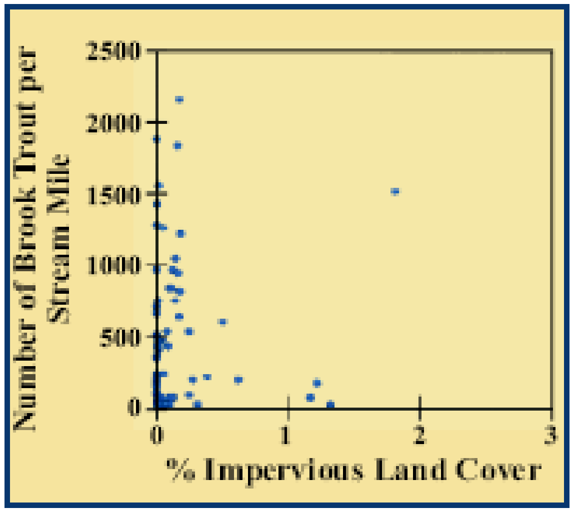


Figure 2-1. Sensitivity of brook trout population to percentage watershed imperviousness (Source: Boward et al. 1999)

2.3 Stream Warming

Research studies have indicated that imperviousness has a direct impact on, and high correlation with, the stream temperature (Galli 1990; Booth and Jackson 1997; Schueler 2003; Wang et al. 2003). Stream temperature enhancement has been attributed to a range of urban factors, including the clear cutting of vegetation from stream banks, introduction of ponds and lakes, increased stormwater runoff to streams, and a reduction in the amount of ground-water inflow (Pluhowski 1970; USEPA 1999). Pluhowski (1970) observed 5-8°C increase in mean stream temperatures during summer in a study in Long Island, New York.

Galli (1990) performed continuous water temperature monitoring in six headwater urban streams in the Piedmont portion of Maryland's Anacostia basin. The watershed imperviousness ranged between 0 and 60%. The study showed that the stream temperature increased by 0.14°F for each one percent increase in watershed imperviousness. The study findings on the effect of urbanization on stream temperature supported the work of Pluhowski (1970); urbanized Lower White Oak was typically 4-15°F warmer than undeveloped, forested Lakemont tributary (Figure 2-2). The study revealed that as the level of watershed imperviousness increased, the size of storm required to produce large fluctuations in stream temperature decreased. The streams became increasingly responsive to stormwater runoff inputs with the increase in watershed imperviousness. Study by Wang et al. (2003) in trout streams in Wisconsin and Minnesota predicted 0.25°C increase in water temperature for each one percent increase in imperviousness.

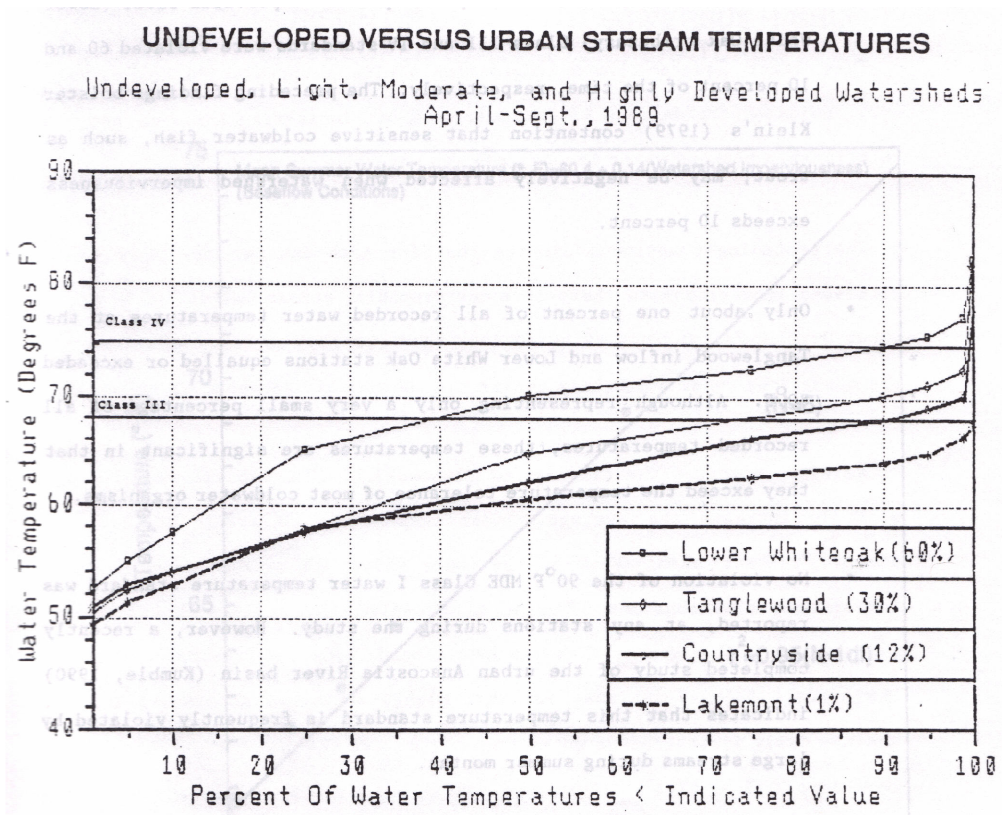


Figure 2-2. Effect of development on six headwater stream temperatures in Maryland (Source: Galli 1990)

Section 303(d) of the Clean Water Act addresses the thermal pollution of receiving waters. The section states that "*each State shall estimate for the waters identified as impaired the total maximum daily thermal load required to assure protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife*" (Federal Water Pollution Control Act, USEPA). Temperature Total Maximum Daily Loads (TMDLs) are being developed to protect coldwater stream habitats, especially in the Pacific Northwest (Kieser et al. 2003).

2.3.1 Response of Stream Biota to Stream Warming

Many research studies on the effects of elevated stream temperature on aquatic biota have been conducted. Biotic integrity and species diversity are severely impaired at higher water temperatures. Fish growth, metabolic rate, egg maturation, spawning, incubation success, distribution and migration patterns, and resistance to diseases, parasites, and pollutants are influenced by temperature regimes (Armour 1991; Schueler 2003; Butowski et al. 2006). Hogg and Williams (1996) observed that a 2-3.5°C water temperature increase in a stream in Ontario, Canada caused decrease in the total animal densities, smaller size and altered sex ratios in the stream invertebrates, and increase in the growth rates of amphipoda.

2.3.1.1 Temperature Sensitivity of Trout

When general temperature requirements are considered, fish can be grouped into cold water, cool water, or warm water categories (Armour 1991). Increased water temperature may preclude temperature sensitive cold water species such as salmon and trout. Alteration in thermal regimes can change the relative distribution and population of the species; cool water and cold water species may be completely extirpated and replaced by more tolerable species (USEPA 1999).

Comprehensive study on Maryland streams, named the Maryland Biological Stream Survey, conducted by the Maryland Department of Natural Resources from 1995 to 1997, showed that the streams most affected by urbanization are in the Baltimore-Washington Metropolitan portions of the Patapsco and Potomac Washington Metro river basins (Boward et al. 1999). The survey estimated the current brook trout population in Maryland streams to be about 300,000, which once numbered more than 3 million. The study cites that one of the most important reasons for the decrease in brook trout population is water temperature. Due to the clearing of trees for urban development, previously forested streams have been exposed to direct sunlight, combined with the input of heated runoff from impervious surfaces and warm water discharges from ponds and lakes. Consequently, only few streams have temperatures cool enough to support brook trout, particularly in the eastern half of the state (Boward et al. 1999). Figure 2-3 depicts the historic change in the population of brook trout in the state of Maryland.

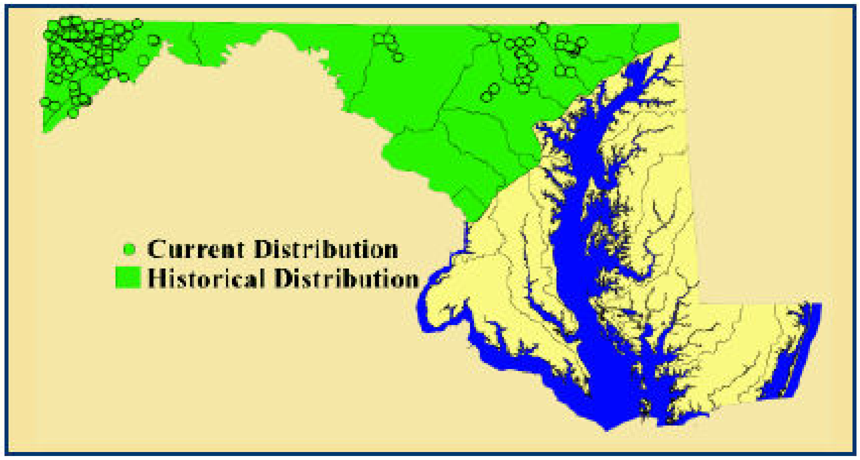


Figure 2-3. Current and historical distribution of brook trout in Maryland (Source: Boward et al. 1999)

2.3.1.2 Temperature Requirements of Trout

Trout are adapted to cooler waters and may become stressed in warm waters. Baldwin (1951) identified 14^{o}C as optimal water temperature for brook trout. The upper lethal water temperature limit for hatchlings is 20^{o}C and approximately 25^{o}C for juveniles and adults. Brown trout have an optimum temperature range of 7 to 17ºC and become stressed at temperatures above 19ºC (Roa-Espinosa et al. 2003). Table 2-1 provides a summary of the temperature regimes for trout species.

Table 2-1. Summary of temperature requirements and regimes for trout

Requirement/Criteria	Temperature (°C)	Reference
Growth and survival	11 - 16	Baldwin (1951); Raleigh (1982); Drake and Taylor (1996)
Optimal water temperature for brook trout	14 (Maximum 14.4)	Baldwin (1951); MacCrimmon and Campbell (1969)
Optimal water temperature for brown trout	7 - 17	Roa-Espinosa et al. (2003)
Spawning of brook trout	19	Hokansen et al. (1973)
Egg maturation and development	4.5 – 11.5	MacCrimmon and Campbell (1969)
Upper lethal water temperature limit	Hatchlings: 20 Juveniles and adults: 25	MacCrimmon and Campbell (1969)
Experimental LT50 (temperature at which 50% population survive) for trout	Brook : 25.2 Brown: 26.2 Rainbow: 26.6	Grande and Andersen (1991)
Maryland Class III standard for natural trout waters	20	USEPA (1988b)
Maryland Class IV standard for recreational trout waters	24	USEPA (1988b)
Maximum daily mean temperature (for brown trout)	22	Rossi and Hari (2007)
Maximum temperature for 100% survival exposure time (for brown trout)	1- minute: 28 10-minutes: 26.5 1-hour: 25	Rossi and Hari (2007)
Change in temperature at the beginning of storm event	≤ 7	Rossi and Hari (2007)
Maximum daily temperature in winter	≤ 12	Rossi and Hari (2007)

Procedures to evaluate the temperature regimes of salmon, namely maximum weekly temperature that should not be exceeded, short-term maximum survival temperature, upper and lower incipient temperatures, and lethality of exposure time based on the acclimation temperature have been proposed by Armour (1991). The Maryland state Class III standard for natural trout waters and Class IV standard for recreational trout waters have been established as 20ºC (68ºF) and 24ºC (75ºF), respectively (USEPA 1988a). The U.S EPA has placed limitations on the daily and weekly average temperatures, and exposure times in marine and freshwater streams (USEPA 1988b).

2.3.2 Other Impacts of Stream Warming

In addition to the previously discussed effect on aquatic biota, stream temperature directly influences the level of dissolved oxygen in the water. At higher temperatures, the solubility of oxygen in water decreases, resulting in lower levels of dissolved oxygen. The rise in metabolic rate of aquatic organisms at higher temperatures causes an increase in the demand for dissolved oxygen. Also, photosynthesis and plant growth increase with higher water temperatures. The consumption of oxygen by bacteria for decomposing dead plants further depletes the dissolved oxygen level in the stream (Paul and Meyer 2001).

2.3.3 Thermal Enhancement of Streams by Stormwater Runoff

Streams receiving storm runoff from urban impervious surfaces have been found to have elevated temperatures (Galli 1990; Booth and Jackson 1997; Boward et al. 1999; USEPA 1999; Walsh et al. 2004; Wang et al. 2003; Walsh et al. 2005). Stream warming due to heated runoff has been reported as a severe and prevalent problem in Maryland (Boward et al. 1999). Summer is a critical period when discharge of heated runoff can lead to a short-term spike in the stream temperature at the beginning of a storm (Rossi and Hari 2007). This is because summer storms are usually characterized short heavy storms, typically more frequent in afternoon.

Common impervious surfaces have high thermal capacity and absorb solar radiation. During summer, the ground temperatures are highest and intense direct sunlight will greatly increase the temperature of the black-colored asphalt. Pavement temperatures can reach as high as $60^{o}C$ in summer (Rossi and Hari 2007). As stormwater runoff is conveyed over heated black asphalt roadways and access areas, heat is transferred to the runoff via conduction, thereby raising its temperature. Heated stormwater runoff flowing into the local stream would cause negative impact on its ecosystem.

2.4 Thermal Impact Study of Best Management Practices (BMPs)

Thermal impacts of treatment processes on urban stormwater runoff can be considered to be under-monitored and under-researched. Generally, little or no consideration is placed towards temperature mitigation in the design aspects of the BMPs (Jones et al. 2007). Although the need for control measures to mitigate urban stormwater thermal enhancement has been emphasized, limited studies have investigated the performance of BMPs in reducing runoff temperature. The majority of such studies performed have focused on wetlands, wet and dry detention basins (Galli 1990; Van Buren et al. 2000a; Sherwood 2001; Kieser et al. 2003), and few on infiltration and bioretention facilities (Galli 1990; Jones et al. 2007).

2.4.1 Runoff Temperature Mitigation Wetponds and Wetlands

Galli (1990) performed a study on four representative BMPs including an infiltration facility, artificial wetland, extensive detention dry pond, and a wetpond in Maryland. Inflow and outflow temperatures were monitored and violation of temperature standards during both baseflow and stormflow conditions was evaluated. The study revealed that none of the four monitored BMPs reduced the runoff temperature and in fact contributed to the increase in outflow temperature. The BMPs ranked in order of temperature mitigation performance were infiltration-dry pond, artificial wetland, extensive detention dry pond, and a wetpond (Table 2-2 shows the delta-T and standard violations). Based on the observed runoff temperatures, trout cannot be expected to survive at the outfall of any of the four BMPs.

Table 2-2. Summary of BMP temperature performance in Maryland (Source: Galli 1990)

Table 16 Summary: BMP Temperature Performance1/

Parameter	Infiltration-Dry Pond	Extended Detention Wetland	Extended Detention Dry Pond	Wet Pond
	BMP Type			
Average Baseflow Delta-T (°F)	2.6	3.9	5.5	9.7
Maximum Baseflow Delta-T (°F)	7.6	8.7	9.7	15.1
Average Stormflow Delta-T (°F)	2.3	2.4	5.2	8.5
Maximum Stormflow Delta-T (°F)	5.0	7.8	11.2	14.0
Average Total Delta-T (°F)	2.5	3.2	5.3	1.1
Maximum Total Delta-T (°F)	7.6	8.7	10.9	9.1
Percent Baseflow Violation of MDE Temperature Stds. - Class III (68°F)	8	60	50	77
- Class IV (75°F)	1*	15	10	35
- Class I (90°F)	0	0	0	0
Percent Stormflow Violation of MDE Temperature Stds. - Class III (68°F)	18	57	48	64
- Class IV (75°F)	0	5	15	25
- Class I (90°F)	0	0	0	0
Maximum observed outflow water Temp (F)	77.7	80.8	81.9	82.6

1/ - Total Delta-T values shown represent combined baseflow and stormflow temperatures (i.e., all flow conditions).

* - Class IV violation result of defacto extended-detention control.

Van Buren et al. (2000a) performed the thermal energy balance of an on-stream stormwater management pond in Kingston, Ontario. The pond received runoff inflows from a parking lot and a creek having drainage areas of 12.6 *ha* and 4500 *ha*, respectively. During the dry-weather days, net radiation and heating of the baseflow owing to the large exposed surface area of the pond, along with the lack of surrounding vegetation, resulted in increased pond temperature. During rainfall events, the parking lot runoff contributed to the thermal enhancement of the receiving waters and the thermal output was greater than the input. Also, the average surface water temperature was 3.6ºC higher than that at the pond bottom. The study illustrated that the per-area thermal energy contribution of the parking lot was 30 times higher than that of the upstream catchment area consisting of residential and forested land use.

Sherwood (2001) studied the effectiveness of a naturally vegetated stormwater detention basin in reducing the chemical loading and temperature of runoff from a residential development located in Monroe County, New York. The facility did not have a significant thermal impact on the runoff. During summer storms, the maximum inflow and outflow runoff temperatures were observed to be similar, the mean outflow temperature being 0.5°C (0.9°F) higher than the mean inflow temperature.

2.4.2 Runoff Temperature Mitigation of Bioretention Facilities

Recently, a thermal impact study was conducted on six BMPs located in trout sensitive regions in Western North Carolina (Jones et al. 2007). Four bioretention facilities, one wetland and a wetpond were monitored for inflow and outflow temperatures. The BMPs received stormwater runoff from asphalt parking lots with or without any shading by trees or vegetation. During the summer months, the mean effluent runoff temperature was significantly higher than the mean influent temperature in both the wetland and wetpond. The water temperature remained above the 21°C threshold in the deeper waters in the wetpond throughout the period. The outflow from the wetpond was warmer than that from the wetland ($p<0.05$). Unlike the wetland and wetpond, the bioretention facilities cooled the inflow runoff, although not below the 21°C threshold. Infiltration of runoff through the bioretention area aided in the loss of heat to the surrounding soil. Further, the study found that runoff conveyed through a buried metal pipe exhibited a temperature reduction of up to 6°C.

2.4.3 Thermal Impact of Other BMPs

Porous pavement has been observed to provide some thermal mitigation (USEPA 2000). Temperature mitigation in rock cribs has been studied in Dane County, Wisconsin (Roa-Espinosa et al. 2003). The field data indicated that the rock crib (volume 255 m^3) filled to capacity aided in effective mitigation of the runoff temperature until the initial volume of the crib was completely replaced by the runoff. The rock crib did not reduce inflow temperature after the volume was replaced.

2.4.4 Underground Stormwater Storage Facilities

An underground storage and slow release facility is another versatile stormwater best management practice. In ultra-urban settings, where surface space is a constraint, underground detention systems provide the best alternative to surface detention/retention ponds (Roberts 1997). These systems are mainly designed to address the quantitative aspect of stormwater runoff by attenuating peak flows. The outflow from underground storage facilities is controlled by orifice and/or weir combinations. However, the ability of these facilities to reduce runoff temperature has not been investigated.

2.4.5 Summary of Performance of Various BMPs in Temperature Mitigation

Wetponds and wetlands have been found to serve as a source of thermal pollution in most of the studies. The large surface area of wetponds exposed to direct solar radiation and lack of shading result in increase in water temperature. Shading by vegetation and riparian buffers can help reduce temperature to some extent, but the outflow temperature might still be harmful to the receiving waters (Galli 1990; Van Buren et al. 2000a). Bioretention facilities and grass swales have the potential to reduce runoff temperature. With regards to design considerations, Jones et al. (2007) pointed out that bioretention facilities with inadequate depth and not designed to capture the first flush may cause additional heating of the runoff. In general, stormwater BMPs promoting infiltration and providing sufficient shading to detained runoff can mitigate runoff temperature (Kieser et al. 2003). The performance of BMPs such as parallel pipe and baseflow diversion systems, multiple-port release wet ponds, sand and peat filters, and conveyance systems in mitigating temperature are yet to be evaluated (Galli 1990). No research study has reported on potential thermal mitigation in underground storage facilities.

2.5 Thermal Impact Study of Underground Stormwater Storage BMP

Underground storage systems have not been monitored for stormwater runoff temperature mitigation. Since these BMPs have been designed as slow release facilities, the runoff is stored in the underground pipes for some period. During this detention period, the runoff can lose some heat by various heat transfer mechanisms. Hence, the BMP might be capable of reducing the temperature of urban storm runoff.

2.5.1 Heat Transfer Mechanism in Underground Storage Facilities

During summer storms, the runoff from highway and other impervious surface is typically heated due to the convective transfer of heat from the hot impervious surface. The heated runoff flows into the underground pipes, where the ambient temperature is cooler than the high air temperature outside, specifically in summer. In case the underground storage pipes have some stored volume of water between storms, its temperature is expected to be same as the ambient underground temperature. The pipe buried underground is also expected to be at the surrounding soil temperature.

The runoff flowing into the underground system can lose heat by three main mechanisms. Convective heat transfer in fluids is comprised of two mechanisms: diffusion (by random molecular motion) and advection (by bulk motion) (Incorpera and DeWitt 1990). As the heated runoff from highway flows into the storage system, it comes into contact with the pipe, surrounding air and already-stored runoff, if any, all at a lower temperature. If any water is stored in the pipe, the warmer inflow runoff mixes with the cooler stored water resulting in buffering of the temperature.

A temperature gradient exists between the pipe wall and the inflow runoff. As runoff is conveyed through the pipe, convective heat transfer will occur between the flowing water and the pipe surface. The convective heat flux *q"*, is proportional to the temperature difference between the surface (T_p) and the fluid (T_w) and is of the form:

$$q'' = h(T_p - T_w) \tag{2-1}$$

The proportionality constant *h,* called the convective heat transfer coefficient, is a function of the nature of the flow motion and the thermal properties of the material (Incorpera and DeWitt 1990). This suggests that the thermal conductivity of the pipe material will control the rate of heat transfer between the flowing runoff and the pipe; the higher the conductivity, the greater the heat transfer and hence more reduction in the runoff temperature. The runoff will be cooled by the surrounding air as well. Some heat might be conducted through the pipe to the surrounding soil.

The detention time of runoff in the pipes will have an influence on the total heat transfer. Longer retention time will allow for further cooling of runoff. However, the retention time of runoff in the system depends on the volume received from the storm event. As more runoff flows in, the stored water flows out, and this may limit the net heat loss. The temperature of inflow runoff varies depending on the season. Hence a seasonal variation in temperature reduction in the BMP is expected.

2.6 Modeling of Thermal Mitigation in BMPs

Thermal enrichment of runoff passing over heated asphalt pavement is well established and has been modeled (Xie and James 1994; Van Buren et al. 2000b; Roa-Espinosa et al. 2003; Herb et al. 2006). Regression models for predicting stream temperatures as a function of watershed characteristics, land use, solar inputs, and inflows from upstream channel and/or runoff from a stormwater control also have been developed (Huebner and Soutter 1994; Weatherbe 1995;

Schroeter et al. 1996; LeBlanc et al. 1997; Wehrly et al. 1998). The Thermal Urban Runoff Model (TURM) was developed by the Dane County Land Conservation Department to predict the impact of urban development on stream temperature and tested successfully in the Token Creek watershed in Dane County, Wisconsin (Roa-Espinosa et al. 2003).

Thermal impact of best management practices have been also been modeled. Van Buren et al. (2000a) modeled an on-stream stormwater management pond in Kingston, Ontario by using a thermal energy balance approach. Assuming that the pond is completely mixed, the average pond temperature was estimated as a function of the thermal energy stored in the pond. A routine in the TURM model accounts for the gain or loss of heat from the passage of water through swales, detention basins, and rock cribs. TURM predicted that cooling of the runoff passing through a rock crib and grass swales (Roa-Espinosa et al. 2003). Herb et al. (2007), at the St. Anthony Falls Laboratory (Minnesota), developed hydro-thermal models to simulate temperature mitigation of surface runoff in wetland basins. The simulations predicted the wetland complex to reduce runoff temperature by 2.6 °C, on average for Minnesota climate conditions, compared to unmitigated runoff from an asphalt parking lot.

To summarize, many models have been developed to predict runoff and stream temperatures. Thermal impact of BMPs has been modeled for limited types of BMPs. Since heat transfer models will measure the performance of the BMP in reducing runoff temperature, modeling the thermal impact of a BMP will yield useful information regarding the employment of BMPs for mitigating temperature of urban stormwater runoff for various imperviousness conditions.

Chapter 3

METHODOLOGY

3.1 Site Description

Several underground stormwater management facilities in Maryland were investigated to determine their suitability for inclusion in this study. The sites were evaluated based on the size of drainage area, percentage imperviousness, asphalt vis-à-vis concrete pavement, number of inflow points, accessibility of inlet and outlet points, and safety at the site. Two BMPs, BMP 3007 and BMP 3008, both located along I-83 northbound, north of Seminary Avenue in Baltimore County (Figures 3-1 to 3-4), were chosen for the study. Both the BMPs are located within the Maryland State Highway Authority right-of-way. A pavement sensor is located in I-695 at I-83 N, at a distance of approximately 3.22 *km* (2 miles) from the two BMPs. The sensor measurements include rainfall intensity, air temperature, pavement temperature and other weather parameters such as relative humidity, dew point, and wind speed and direction.

BMP 3007 and BMP 3008 were both modified to have two inflow points by blocking one inlet in each facility and redirecting the runoff into their respective downstream inlets. The drainage area to BMP 3007 is 1.07 *ha* (2.64 acres), of which 66% is impervious. BMP 3008 has a contributing drainage area of 1.23 *ha* (3.04 acres) and impervious fraction of 43%. The characteristics of the drainage areas of the two BMPs, including SCS curve number and time of concentration (T_c), are summarized in Table 3-1.

In each BMP, the underground storage system consists of six HDPE pipes, each 122 *cm* (48 *in.*) in diameter. The outflow is controlled by a 3.8 *cm* (1.5 *in.*) orifice. The total length of pipes in BMP 3007 and BMP 3008 are 166 *m* (544 *ft*) and 188 *m* (616 *ft*) respectively, their corresponding storage capacities being 210 m^3 (7419 ft^3) and 236 m^3 (8316 ft^3).

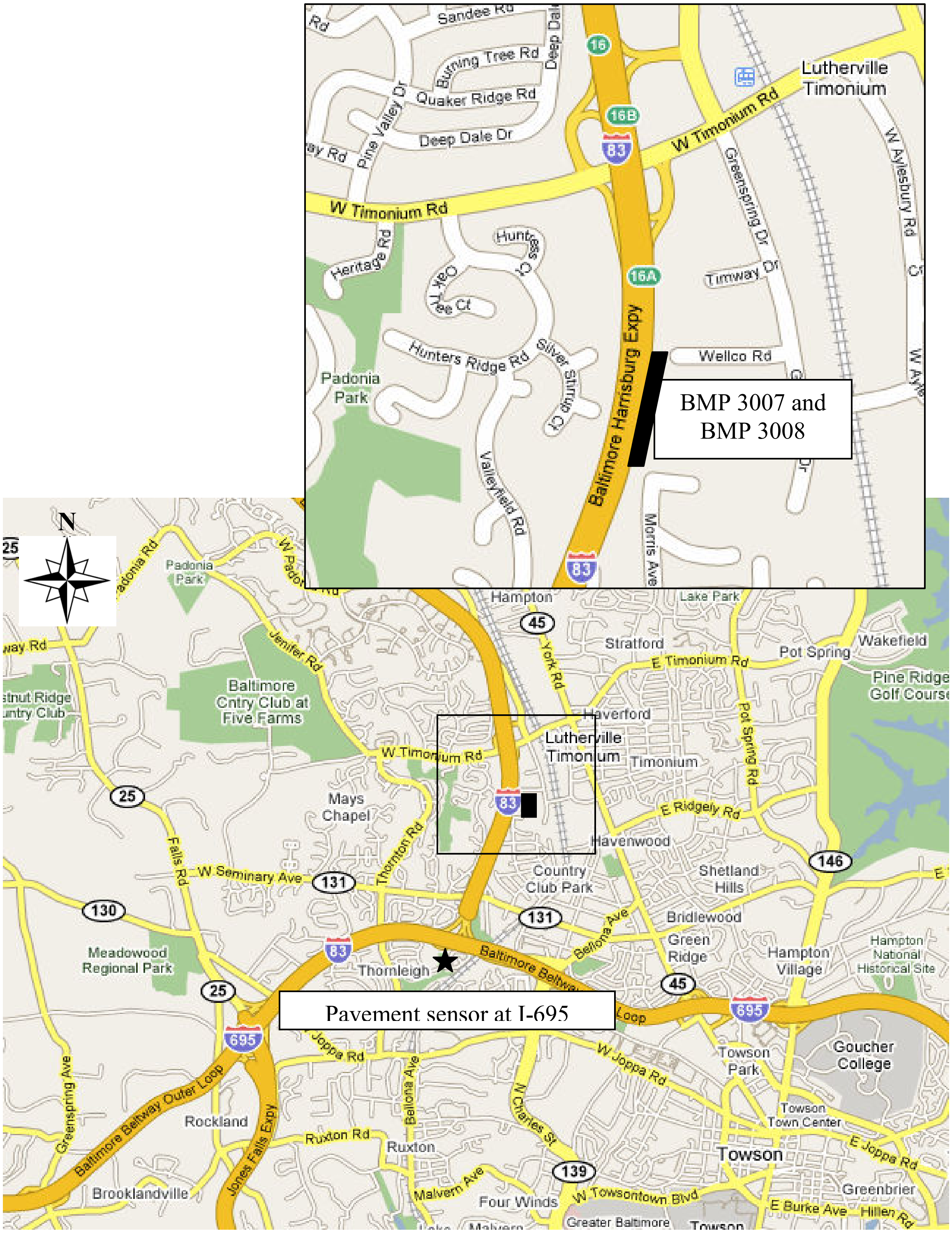


Figure 3-1. Map location of I-83 study sites BMP 3007 and BMP 3008
(Source: <www.maps.google.com>)

Figure 3-2. Study site BMP 3007 behind the noise wall along I-83 NB

Figure 3-3. Study site BMP 3008 along I-83 NB

Figure 3-5. Inlet I-43 of BMP 3008 along I-83 NB

Table 3-1. Drainage characteristics of BMP 3007 and BMP 3008

BMP	Structure Number (or Inlet)	Drainage Area (*ha*)	Curve Number	Tc (*hr*)	Impervious Area (*ha*)	% Impervious
3007	I 3-5	0.12	98	0.10	0.12	100%
	I 3-4			*blocked*		
	MH 3-3	0.95	62	0.10	0.58	61%
	Total	**1.07**	**66**		**0.70**	**66%**
3008	I 4-3	0.05	98	0.10	0.05	100%
	I 4-1			*blocked*		
	MH 4-3	1.18	81	0.38	0.48	41%
	Total	**1.23**	**82**		**0.53**	**43%**

The study sites are located within the Patapsco river watershed (MD stream designation 02-13-09). The outlet of BMP 03007 is approximately 900 *ft* upstream of a tributary of Roland Run. The two BMPs discharge into this tributary of Roland Run, which ultimately drains into the Patapsco River.

3.2 Monitoring and Sampling

Monitoring equipment was installed in BMPs 3007 and 3008 in September 2007 to continuously measure and record flow depth, conductivity and temperature of stormwater runoff at the inflow and outlet points, air temperature, and rainfall depth. The sensors are manufactured by Global Water Instrumentation, Inc. (Gold River, CA). A Global Water FL16 flow logger was installed to record the stormwater runoff flow rate and temperature at the BMP inflow and outflow pipes. The probe has an operating temperature range of -40 to +85°C. The sensor works in depths as low as 1.9 *cm* (3/4 *in.*) and can be programmed to suit the pipe characteristics. Conductivity measurements were made using a conductivity sensor (WQ301) working over the range of 0-5000 microsiemens/cm. The sensors were placed in the inlet pipes (Figure 3-6) and their loggers in a weather-proof box (Figures 3-7). A 15.2 *cm* (6 *in.*) tipping bucket rain gauge (RG 200) was installed to record the rainfall at the site at two minute intervals. The temperature sensor (WE700), capable of operating in the temperature range of -50 to +50°C, was installed to record air temperature. The air temperature sensor was mounted on a post and housed in a ventilated solar shield having high reflectiveness, low heat retention and low thermal conductivity in order to protect it from direct sunlight effects (Figure 3-8).

The conductivity sensor, air temperature sensor and rain gauge were connected to individual data loggers (GL500-2-1 USB model) capable of recording over 81,000 readings. The data logger can be programmed to sample at the desired interval from 1 second to multiple years. The instruments are battery powered and operate on a Windows-based software interface. The data stored in the logger’s memory were retrieved by downloading as a file into a laptop.

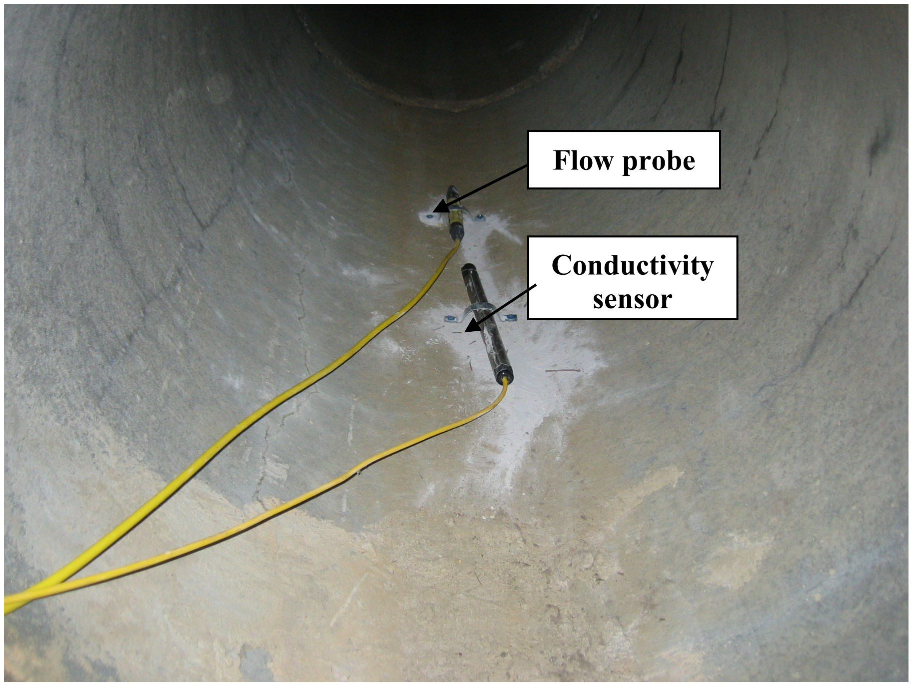


Figure 3-6. Flow and conductivity sensors installed in the inlet pipe at MH 4-3 of BMP 3008

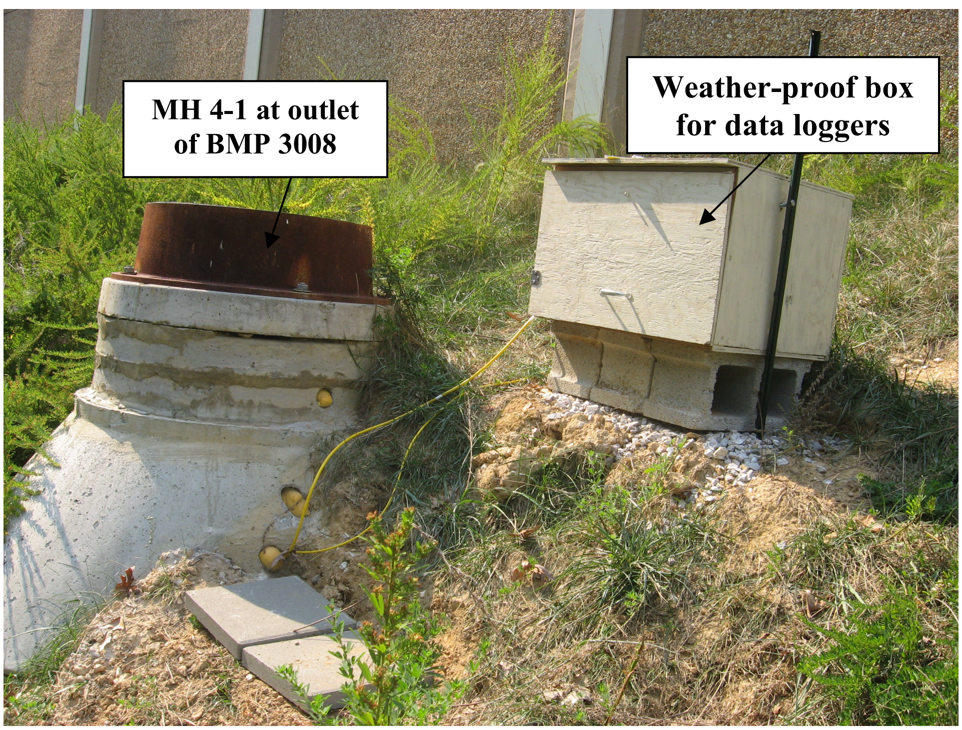


Figure 3-7. Set up of instruments at the site

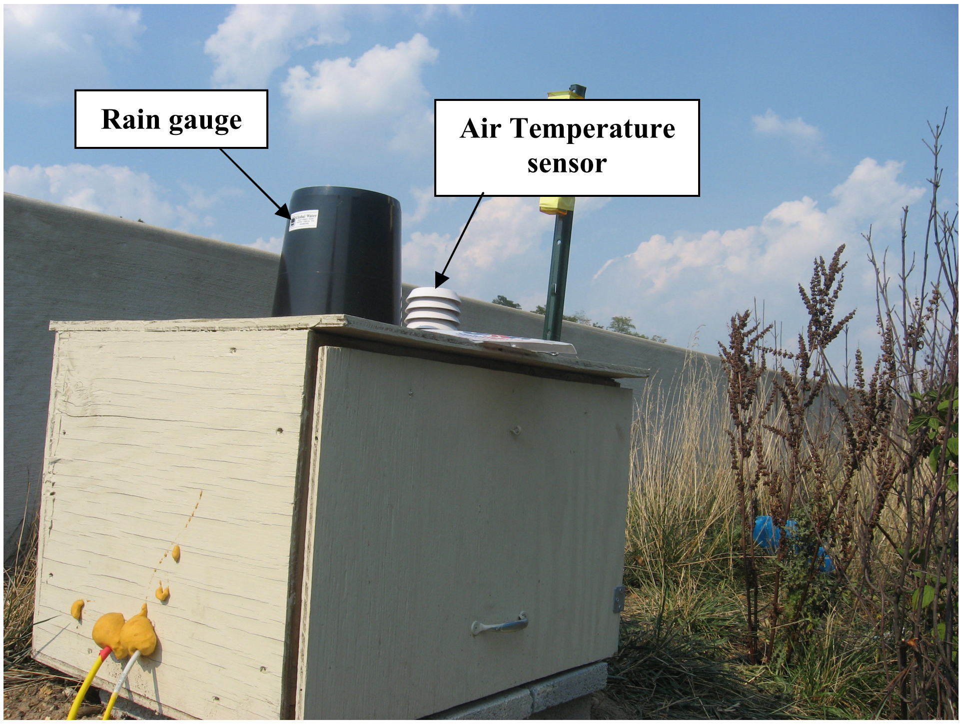


Figure 3-8. Rain gauge and air temperature sensor installed at the site

Each probe was programmed to continuously record data at two-minute intervals. It was proposed to collect data for as many rainfall events as possible, placing importance on data obtained during late spring, summer, and early fall, when high temperatures are most critical.

3.3 Data Collection

Runoff flow, temperature, and conductivity were monitored from the end of September 2007 through September 2008. Several initial installation problems occurred at the site. Rainfall data for the months September to November 2007 were lost due to calibration error in the rain gauge. The probes at one inlet in each of the two BMPs did not record any flow during the storm events until December 2007. As a measure to capture most of the runoff from the highway, it was proposed to install weirs in the inlet pipes to increase the flow depth. The installation of weirs and replacement of non-functional units was completed in February 2008. Flow and temperature data were lost at the outlet of BMP 3008 due to malfunctioning of the flow probe from March 2008. Hence, BMP 3008 data were not considered for analysis. In total, 70 events were recorded since equipment installation. However, due to the initial problems encountered at the site, it was necessary to exclude data collected for BMP 3007 from September 2007 until the reinstallation in February 2008.

3.4 Data Quality Assurance and Quality Check

3.4.1 Rainfall Data

As a measure of quality check, rainfall depths recorded at the I-83 site were compared to the recordings at a weather station in Timonium, Maryland. The weather station, located at a distance of approximately 6 miles from the study site, measures rainfall rate, air temperature, and other weather parameters such as humidity, dew point, pressure, and wind speed at 5-minute increments. The data recorded at the weather station are accessible through the web (*<http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=KMDTIMON1&month=10&day=19&year=2007>*). The total rainfall depth recordings at the site and the weather station were found to be in good agreement for most of the events.

3.4.2 Flow Data

The inflows observed at the two inlets of BMP 3007 were found to be unrealistic. This was because the inflow into the system was much higher compared to the observed outflow, resulting in volume imbalance. Additionally, the inflows exceeded those reasonable for rainfall depth and drainage area. It is essential to achieve flow balance in the system to perform data analysis of any kind. It was thus necessary to simulate the runoff into the BMP.

3.4.2.1 Simulation of runoff

TR-55 was employed to simulate the runoff from the area draining each of the inlets based on the rainfall depth recorded at the study site (USDA 1986). The method employed for runoff simulation has been outlined in Appendix A. Simulations using weighted curve number, computed based on cover type of the drainage area (Table 3-1), produced small or no runoff for the range of rainfall recorded at the site. However, the probes installed in the inlet pipes had responded to these storm events. This suggested that a modification was required in the approach adopted to simulate runoff. It is reasonable to assume that runoff is generated from the impervious area only and the rainfall occurring over the grassy/pervious area is completely infiltrated for most common events. Based on this assumption, runoff to an inlet was computed using the fraction of impervious area as contributing drainage area and the corresponding curve number of 98 as input. Simulations were performed for a number of storm events and the simulated runoffs compared to the observed inflows.

The simulated flows matched the trend of the observed flow but were of significantly lower magnitudes. The simulated runoff and observed flow at the two inlets of BMP 3007 during a rainfall event on April 28, 2008 is shown for comparison in Figures 3-9a and 3-9b. The simulated inflows and observed outflow at BMP 3007 during the same event is shown in Figure 3-9c. The simulated inflows and observed outflow yielded flow balance in the storage system for most of the storm events. This suggested that the approach adopted for simulating runoff was acceptable. Inflows to each inlet of BMP 3007 were simulated using rainfall data for all the storm events and utilized for all data analyses.

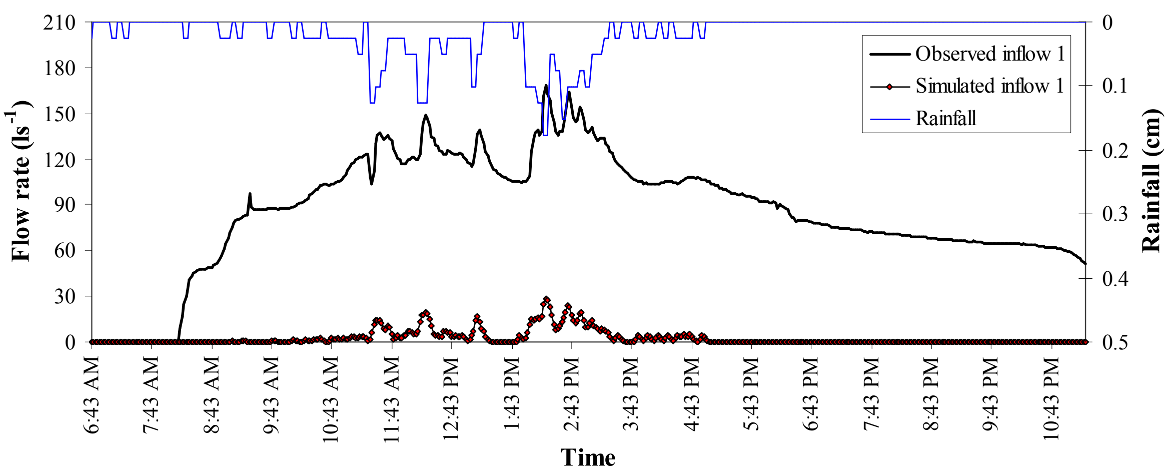


Figure 3-9a. Plot of simulated and observed inflow at inlet 1 of BMP 3007 on April 28, 2008, storm event

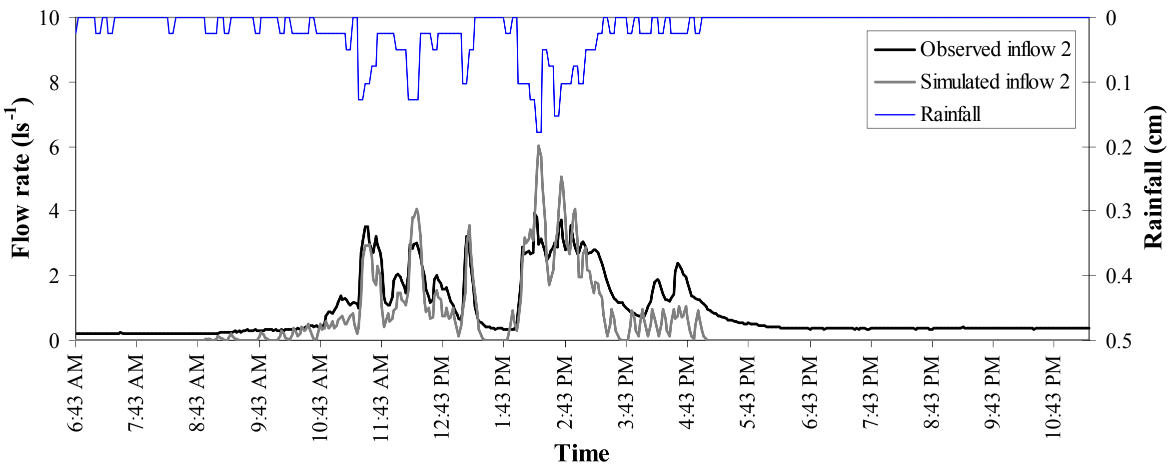


Figure 3-9b. Plot of simulated and observed inflow at inlet 2 of BMP 3007 on April 28, 2008, storm event

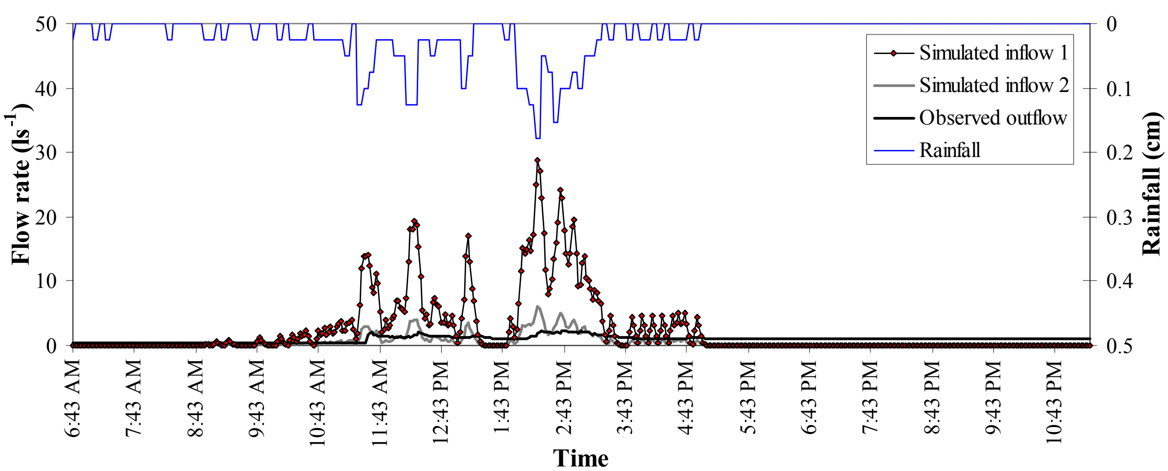


Figure 3-9c. Plot of simulated inflows and observed outflow at BMP 3007 on April 28, 2008, storm event

3.5 Data Analyses

Complete data sets for flow, temperature, and rainfall were available beginning February 2008. In total, 56 storm events occurred between February 22 and September 30, 2008, and were considered for data analyses.

3.5.1 Event Mean Temperature

For each storm event, the total thermal energy (E) present is calculated as:

$$E = \int_0^{T_d} QT\rho C_{pw} dt \tag{3-1}$$

where Q is the measured stormwater flow rate, T is the water temperature, ρ is the density of water and C_{pw} is the specific heat capacity of water. T_d is the duration of storm event. Substituting the flow and temperature observed at the inlets and outlet, the total thermal energy in and out can be obtained respectively.

The event mean temperature (EMT) is defined and calculated similarly as:

$$EMT = \frac{\int_0^{T_d} TQdt}{\int_0^{T_d} Qdt} \tag{3-2}$$

The EMT represents the temperature that would result if the entire storm event discharge were collected in one container. Since EMT weights discrete temperature measurements with flow volumes, EMT aids in the comparison of temperatures between inflow and outflow and among different events. By combining the events on a monthly (or seasonal) basis, the flow-weighted mean monthly (or seasonal) temperature can be computed for each month (or season). Additionally, peak input and output temperatures can be evaluated for each storm. The event mean temperature and peak temperature at the inlet and outlet are metrics employed to evaluate the reduction in temperature achieved in the underground system.

3.5.2 Exceedence of Threshold Temperature

In the present study, two temperature thresholds were considered, namely optimal water temperature for brook trout of 14°C (57.2°F) and the Maryland State Class III temperature standard of 20°C (68°F). Volume of water and time exceeding these two temperature thresholds at the inlet and outlet are evaluated for each storm. This demonstrates the possibility of the trout being subjected to stress if the runoff from highway and outflow from BMP were to be directly introduced into the stream. Also, an understanding of the performance of the system in abating temperature can be achieved.

3.6 Heat Transfer Model

3.6.1 Model Formulation

The impact of the underground storage BMP in mitigating stormwater runoff temperature can be estimated using a heat transfer model. The underground storage system consists of parallel pipes of diameter 122 *cm* (48 *in.*). For the purpose of modeling, the pipes are considered as a single storage pipe of 122 *cm*, and of length equal to the combined lengths of all pipes in the system. This pipe will be modeled as a set of completely mixed tank reactors (CSTR) in series. In this design, it is assumed that the water flowing in is instantaneously and completely mixed with the stored water and hence the temperature of water is uniform over the volume in a given CSTR.

For each CSTR, knowing the initial volume (V) of water stored, the equation below can be solved for θ (Figure 3-9):

$$V = \frac{R^2}{2}(\theta - \sin\theta)L \tag{3-3}$$

The flow depth in the storage pipe can be calculated using:

$$h = R\left(1 - \cos\frac{\theta}{2}\right) \tag{3-4}$$

The outflow is calculated based on the flow depth assuming that it is controlled by a weir or orifice using:

$$Q_o = \frac{2}{3}C_d\sqrt{2gh}^3 = \frac{2}{3}C_d\sqrt{2g}\left[R\left(1 - \cos\frac{\theta}{2}\right)\right]^{\frac{3}{2}} \tag{3-5}$$

or for orifice $$Q_o = C_d a\sqrt{2gh} = C_d a\sqrt{2gR\left(1 - \cos\frac{\theta}{2}\right)} \tag{3-6}$$

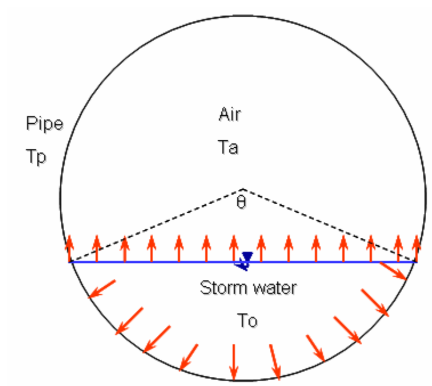
where R is the radius of the storage pipe (m), θ is the angle subtended by the water surface at the center of the pipe (radians), L is the length of one CSTR (m), h is the flow depth, which is the head over the weir or upstream head above the center of the orifice (m), C_d is the coefficient of discharge, a is the area of the orifice (m^2), d is the diameter of the orifice (m), and g is the acceleration due to gravity (ms^{-2}).

The storage in the pipe is calculated by solving the flow balance differential equation:

$$\frac{dV}{dt} = Q_{in1} + Q_{in2} - Q_0 \tag{3-7}$$

where Q_{in1} and Q_{in2} are the two inflow rates (m^3s^{-1}), and Q_0 is the computed outflow rate (m^3s^{-1}).

In the summer, the runoff flowing into the underground pipe is at a higher temperature compared to the water stored in the pipe, if any. Heat is transferred from the inflow water to the stored water by convection. As water flows through the pipe, heat will be transferred to the pipe walls from the runoff by convection. Some heat transfer might occur to surrounding air in the pipe. The heat transfer phenomenon occurring in the pipe is shown by a simple diagram in Figure 3-10. For simplicity, it is assumed that conduction of heat through the pipe wall and to the surrounding soil is negligible.



T_o = Temperature of stored water
T_a = Temperature of air
T_p = Temperature of pipe

Initial condition: $T_o = T_a = T_p$

Figure 3-10. Schematic diagram of heat transfer in the storage pipe and air

Taking into consideration these heat transfer terms, the heat balance for the system is given as:

$$\text{Heat energy stored} = \text{Heat in} - \text{Heat out} - \text{Heat loss} \qquad (3\text{-}8)$$

The heat loss term includes the heat transferred to the pipe wall and the surrounding air. Although, the heat loss to the air is likely to be very small due to the poor thermal conductivity of air, the water-air heat transfer term is taken into consideration.

The volume of water stored in the pipe is the control volume for performing the heat balance. The change in heat energy in the system per unit time can be expressed in the form of a differential equation as:

$$\frac{dE}{dt} = V_w \rho_w C_{pw} \frac{dT_o}{dt} = Q_{in1}\rho_w C_{pw} T_{in1} + Q_{in2}\rho_w C_{pw} T_{in2} - Q_o \rho_w C_{pw} T_o - U_a A_a (T_o - T_a) - U_p A_p (T_o - T_p)$$

(3-9)

where T is the temperature (°C), ρ_w is the density of water (kg m^{-3}), C_p is the specific heat capacity of water (J kg^{-1}°C^{-1}), U is the overall heat transfer coefficient (J s^{-1} m^{-2} °C^{-1}), A is the surface area in contact (m^2), and M is the mass (kg). Subscripts '*a*', '*p*' and '*w*' denote air, pipe and water, respectively.

The change in air and pipe temperature can be obtained by a heat balance on the surrounding air and that on the pipe:

$$M_a C_{pa} \frac{dT_a}{dt} = U_a A_a (T_o - T_a) \qquad (3\text{-}10)$$

$$M_p C_{pp} \frac{dT_a}{dt} = U_p A_p (T_o - T_p) \qquad (3\text{-}11)$$

where,

$$A_a = 2RL \sin\frac{\theta}{2} \qquad (3\text{-}12)$$

$$A_p = R\theta L \qquad (3\text{-}13)$$

$$M_a = \rho_a R^2 \left[\Pi - \frac{\theta - \sin\theta}{2}\right] L \qquad (3\text{-}14)$$

$$M_p = \rho_p A_p k \qquad (3\text{-}15)$$

Here, k is the thickness of the storage pipe (m). By solving the differential equations (3-9, 3-10 and 3-11) simultaneously by a numerical approach, the outflow temperature can be obtained along with the air and pipe temperature. The constants used in the above equations are listed in Table 3-3.

Table 3-3. Constants and parameters of the heat transfer model

Parameter/Constant		Value	Units	Reference
Data	Q_i		m^3s^{-1}	
	T_i		°C	
Constants	g	9.8	ms^{-2}	Gibson (1952)
	ρ_w	1000	kg m^{-3}	Incorpera and DeWitt (1990)
	ρ_p	950	kg m^{-3}	Matweb (Jun 27, 2007)
	ρ_a	1.247	kg m^{-3}	Incorpera and DeWitt (1990)
	C_{pw}	4186	J kg^{-1}°C^{-1}	Incorpera and DeWitt (1990)
	C_{pp}	2200	J kg^{-1}°C^{-1}	Matweb (Jun 27, 2007)
	C_{pa}	1012	J kg^{-1}°C^{-1}	Incorpera and DeWitt (1990)

3.6.2 Implementation and Programming

Based on the CSTR-in-series design of the system, the pipe is divided into ‘n’ number of CSTRs of equal lengths L. The first reactor in the series receives two inflows, as observed in the study sites. The outflow from the first reactor is the input to the second reactor and so on. The flow from one reactor to the successive one, except to the last, is assumed to be controlled by a weir. The outflow from last reactor is controlled by a 3.8 *cm* (1.5 *in.*) orifice, as existing in the study sites. A simple schematic of the underground storage system and the model design is shown in Figure 3-11.

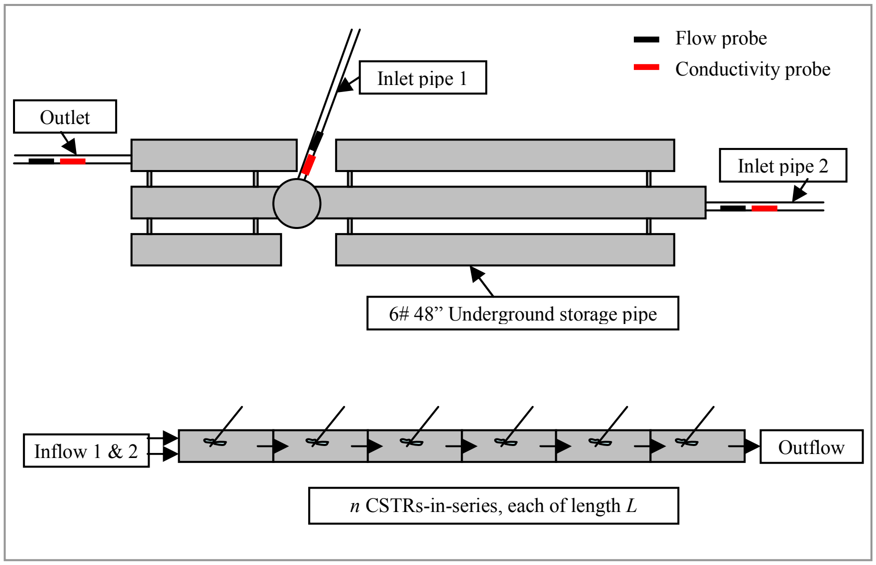


Figure 3-11. Schematic representation of the underground system and the model design

For each reactor, the volume and temperature differential equations, developed in the previous section, are solved numerically by the Runge-Kutta method in Matlab. Runoff inflow and temperature observed at the site and constants (discharge coefficients, density and thermal constants) are the inputs to the model. The model assumes that the stored water (if any), pipe wall and air have the same initial temperature, which is specified as an input. In the water balance module, the model computes the outflow rate and the storage in the system. In the second module of the code, the model predicts the temperature of runoff at the outlet as a function of time. The model results can hence be used to quantify the reduction in temperature of runoff.

3.6.3 Model Evaluation

Evaluation of the heat-transfer model is essential to determine the prediction accuracy of the model. The observed and model-predicted outflow temperature should be compared for a number of events to determine whether the model underpredicts or overpredicts the temperature. The bias and relative bias in the model predictions can yield the level of prediction accuracy of the model.

Chapter 4

RESULTS AND DISCUSSION

4.1 Field Study

4.1.1 Event Characterization

Measurements for 56 storms included rainfall depths that ranged from 0.15 to 8.64 *cm* (0.06 to 3.4 *in*.) and were recorded at the study site from February through September 2008. The total rainfall depth and duration of each storm event are given in Table 4-1. The highest rainfall depth of 8.64 *cm* (3.4 *in*.) was recorded on September 27, 2008. The duration of this event was nearly 18 hours. The majority of the storm events ranged from 0.25 to 1.52 *cm* (0.1 to 0.6 *in.*) (see Table 4-1). Totally, nine events had measured rainfall depths greater than 2.54 *cm* (1 *in.*) during the monitoring period. The summer storms were characterized by intense short-duration rainfall.

The volume-duration-frequency characteristics of the storm events included in the analyses were compared to the distribution of rainfall in 15 stations in Maryland (Kreeb and McCuen, 2003). The purpose of the comparison was to ensure that the rainfall data chosen for data analyses were representative of those expected in the state of Maryland. The Kreeb and McCuen study, conducted for 15 stations in Maryland, was based on 10352 storms. Table 4-2 shows the frequency of storms events of given volume and duration at the Timonium study site. The statistics for the 15 stations in Maryland are also included in Table 4-2 for comparison.

On comparing the two frequency distributions, the number of storms measuring rainfall depths between 0.025 and 0.254 *cm* may be considered to be under-represented in the data collected. About 16% of the storm events fall in the rainfall depth range 0.025 to 0.254 *cm* at Timonium compared to nearly 33% in the historical data. The frequency of storms that measured rainfall depths between 0.255 and 0.635 *cm* is higher at Timonium in comparison to that in the 15 stations in Maryland. Frequency of storms that measured rainfall depths in the ranges of 0.636 to

1.27 *cm*, 1.271 to 2.54 *cm,* and that greater than 2.54 *cm* at Timonium are similar to that of historical data. Taking into consideration the smaller sample size and sampling variation involved in the present study, it can be concluded that the rainfall data chosen for analysis adequately represents Maryland and is unbiased.

Table 4-1. Rainfall data for Timonium site from February until September 2008

Event Date	Rainfall Depth, *cm* (*in.*)	Event Duration, *hr*	Event Date	Rainfall Depth, *cm* (*in.*)	Event Duration, *hr*
2/26/2008	0.25 (0.10)	2.60	5/31/2008	1.09 (0.43)	3.77
2/26/2008	0.25 (0.10)	1.50	6/3/2008	0.15 (0.06)*	0.97
3/4/2008	0.99 (0.39)	3.30	6/4/2008	0.99 (0.39)	2.60
3/5/2008	0.56 (0.22)	2.13	6/4/2008	0.84 (0.33)	0.97
3/5/2008	0.13 (0.05)	1.60	6/4/2008	0.10 (0.04)*	1.47
3/7/2008	1.37 (0.54)	9.50	6/10/2008	1.80 (0.71)	2.93
3/8/2008	0.71 (0.28)	10.17	6/28/2008	0.38 (0.15)	0.47
3/16/2008	0.66 (0.26)	6.87	6/29/2008	0.18 (0.07)*	0.13
3/18/2008	0.18 (0.07)*	2.90	6/30/2008	0.48 (0.19)	0.17
3/19/2008	1.42 (0.56)	7.27	7/6/2008	0.48 (0.19)	0.37
3/20/2008	0.28 (0.11)	1.40	7/9/2008	1.50 (0.59)	0.50
4/1/2008	0.28 (0.11)	4.53	7/13/2008	3.10 (1.22)	12.20
4/3/2008	1.47 (0.58)	12.27	7/23/2008	3.66(1.44)	5.10
4/6/2008	0.58 (0.23)	5.57	7/30/2008	0.99 (0.39)	0.30
4/11/2008	0.48 (0.19)	0.70	8/2/2008	0.28 (0.11)	1.13
4/13/2008	0.15 (0.06)*	1.30	8/2/2008	0.56 (0.22)	0.27
4/20/2008	0.53 (0.21)	0.93	8/13/2008	2.92 (1.15)	2.50
4/20/2008	4.17 (1.64)	3.53	8/28/2008	0.20 (0.08)*	0.37
4/21/2008	0.76 (0.30)	1.13	8/29/2008	2.01 (0.79)	12.67
4/26/2008	0.64 (0.25)	4.03	8/30/2008	0.30 (0.12)	0.37
4/28/2008	3.12 (1.23)	10.17	9/05/2008	0.46 (0.18)*	4.07
5/9/2008	3.12 (1.23)	14.33	9/06/2008	3.81 (1.50)	8.30
5/10/2008	0.46 (0.18)	5.03	9/12/2008	2.44 (0.96)	10.10
5/12/2008	4.72 (1.86)	26.63	9/25/2008	0.84 (0.33)	3.87
5/16/2008	1.19 (0.47)	9.53	9/26/2008	0.56 (0.22)	0.27
5/18/2008	0.46 (0.18)	4.67	9/26/2008	0.71 (0.28)	8.03
5/20/2008	0.53 (0.21)	2.73	9/27/2008	8.64 (3.40)	17.90
5/20/2008	0.56 (0.22)	1.13	9/30/2008	0.71 (0.28)	3.47

- indicates events falling below the rainfall threshold value of 0.25 *cm* (0.10 *in.*)

Table 4-2. Rainfall data recorded at the I-83 site from February until September 2008

	Event Duration	Rainfall Depth, *cm* 0.025-0.254	0.255-0.635	0.636-1.27	1.271-2.54	2.54 <	Total Timonium, MD	15 Stations, MD*
	1 hr	0.0536	0.1429	0.0357	0.0179	0.0000	0.2500	0.3290
	2 hr	0.0714	0.0357	0.0179	0.0000	0.0000	0.1250	0.0756
	3 hr	0.0357	0.0357	0.0179	0.0179	0.0179	0.1250	0.0627
	4-6 hr	0.0000	0.1071	0.0714	0.0000	0.0357	0.2143	0.1234
	7-12 hr	0.0000	0.0179	0.0714	0.0536	0.0357	0.1786	0.1818
	13-24 hr	0.0000	0.0000	0.0000	0.0357	0.0536	0.0893	0.1616
	24< hr	0.0000	0.0000	0.0000	0.0000	0.0179	0.0179	0.0659
Total	Timonium, MD	0.1607	0.3393	0.2143	0.1250	0.1607	1.0000	1.0000
	15 Stations, MD*	0.3288	0.1461	0.2131	0.1747	0.1373	1.0000	

* Kreeb and McCuen (2003)

BMP 3007 received very small volumes of inflow during storm events measuring rainfall depths less than 0.25 *cm* (0.10 *in.*). However, the volumes were not large enough to produce measurable outflows from the underground systems. Hence, a threshold rainfall depth value of 0.25 *cm* was fixed and only rainfall events equal to or greater than the threshold value were considered for the analyses. During large storm events, outflow from the storage system continued for long periods, up to two days after the event. Smaller storm events of rainfall depth less than 0.25 *cm* occasionally occurred during these periods. Hence, events that had rainfall depths less than the threshold depth and preceeded by large storm events were not eliminated. A total of seven events were eliminated from the record, thereby reducing the storm sample size from 56 to 49 (Table 4-3). Runoff flows to the inlets were computed for each of the selected storm events by the TR-55 method (see Appendix A).

Table 4-3. Total number and rainfall depths of events recorded and selected for analysis in each month at Timonium

Month	Events		Events	
	Total	Total Rainfall Depth , *cm*	Above Threshold*	Total Rainfall Depth, *cm*
Feb-08	2	0.51	2	0.51
Mar-08	9	6.30	8	6.12
Apr-08	10	12.19	9	12.04
May-08	8	12.14	8	12.14
Jun-08	8	4.93	5	4.50
Jul-08	5	9.86	5	9.86
Aug-08	6	6.25	5	5.97
Sep-08	8	17.73	7	17.27
Total	56	69.90	49	68.40

*includes storms below threshold but preceded by large storm events

4.1.2 General Observations

The general characteristics of flow, temperature, and conductivity during all of the storm events are discussed in this section. A storm event is accompanied by a decrease in the air temperature prior to the start of the event. After the rain started, runoff took about 6 to 10 minutes (inlet 2 and inlet 1) from the highway to flow into the underground facility. Since the pavement is warm at the beginning of the storm, an initial spike was observed in the temperature of the inflow. The inflow temperature gradually decreased as the storm progressed due to the cooling of the pavement. The average detention time of the inflow in the storage facility was between 15 and 20 minutes. The outflow temperature was more uniform compared to the inflow temperature and was observed to follow the trend of the inflow temperature until the inflow ceased.

The conductivity measurements support the start and stop of the inflow to the system. An initial spike was observed in inflow conductivity due to the first-flush phenomenon. The lag time between inflow and outflow conductivity peak was observed to be similar to that of temperature. The level of conductivity in the stormwater runoff was found to have seasonal variations. High levels of conductivity in the inflow runoff were measured during winter due to the use of salts to melt ice and snow on the highway. The concentration of salts in the runoff decreased in spring and a further decrease was observed in summer.

Factors such as impervious cover and intensity, duration, time of the day, and season of occurrence of the rainfall event have an effect on the inflow temperatures. The fraction of impervious area in the drainage area of an inlet influenced the inflow temperatures at that inlet. The inflow temperatures recorded at the inlet drained by a larger fraction of impervious area were at least 1°C higher than at the inlet having smaller impervious fraction for most of the events during summer. During large storm events, the BMP received inflow at a higher rate and the runoff was quickly conveyed through the BMP. The shorter detention time in the BMP had some impact on the reduction observed in the runoff temperature. The time of the day determined the air temperature and the pavement temperature and hence influenced the runoff temperature. During cooler months, when the air temperature was low, the runoff exhibited low temperature. In summer, most of the events occurred in hot afternoons and produced warm runoff.

The general observations are illustrated for the June 30, 2008, storm (Figure 4-1). The total rainfall depth recorded during this event was 0.48 *cm* (0.19 *in.*). The total duration of the event was 10 minutes. The air temperature was around 34°C one hour prior to the rainfall event and dropped by 8°C at the start of the event. BMP 3007 received inflow six minutes after the start of rain. The highest inflow temperature of 21.7°C (71°F) was recorded during this event. The inflow temperature gradually reduced as the event progressed. Outflow from the system was observed six minutes after the runoff inflow began. The time lag between peak inflow and outflow temperatures was around ten minutes. The outflow temperature remained lower than the two inflow temperatures throughout the event and then gradually approached the ambient underground temperature. High inflow runoff conductivity was measured when the inflow began and then gradually decreased to almost zero conductivity. This is because the salts on the highway are washed-off during the first few minutes of the storm.

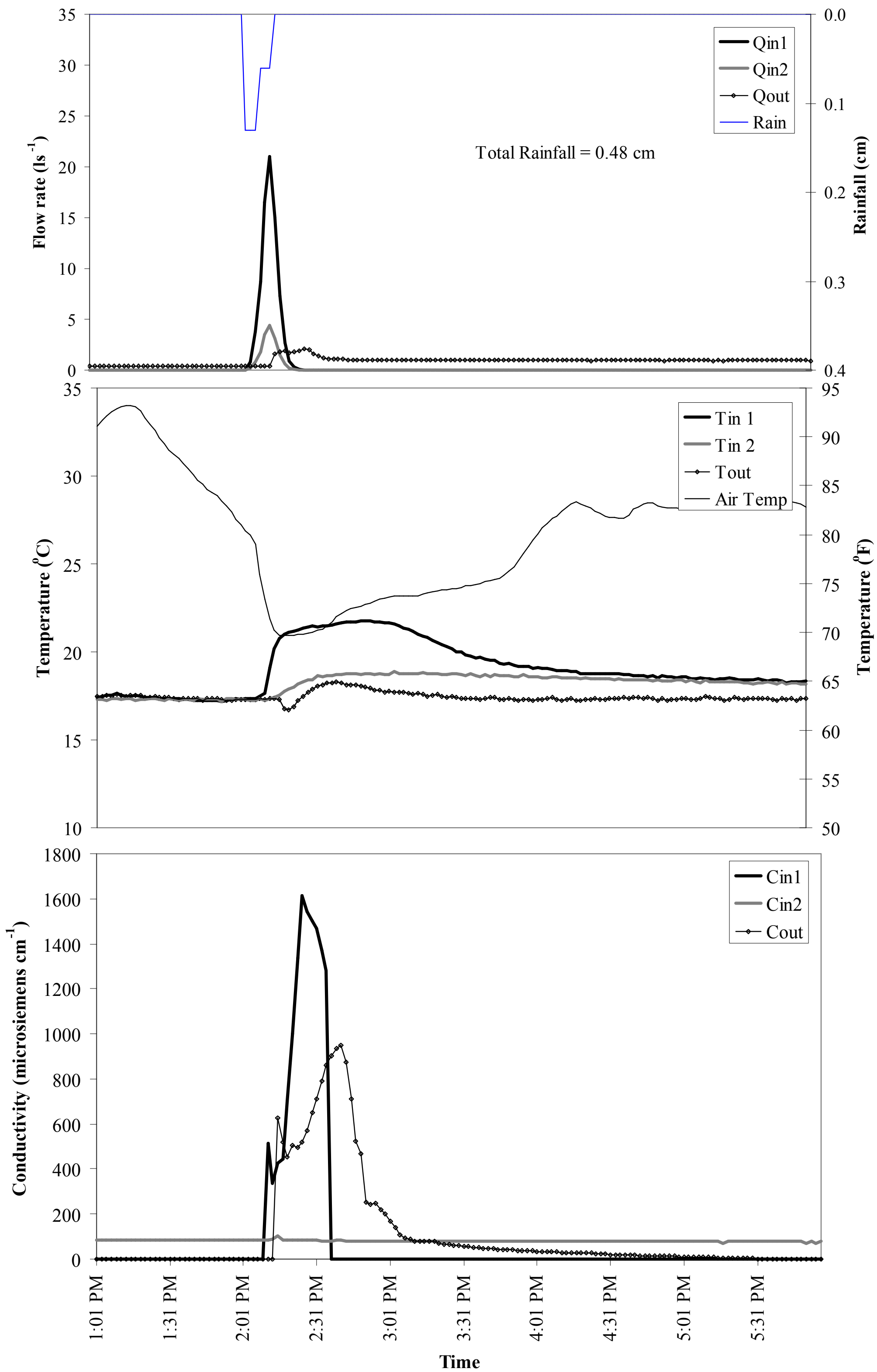


Figure 4-1. Plot of flow, temperature and conductivity of BMP 3007 on June 30, 2008 storm (Flow, temperature, and conductivity measurements are plotted at two-minute intervals and rainfall is plotted at six-minute intervals)

4.1.3 Analyses and Characterization of Runoff Temperatures

During the monitoring period, the inflow and outflow runoff temperatures exhibited seasonal variation. The inflow temperatures ranged between 3.0 and 11.0°C (38 and 52°F) during the months of February and March 2008. The outflow temperatures showed small or no difference from the inflow temperatures during these months. The inflow temperatures increased in the following months, and very high inflow temperatures were observed in June and July 2008. Some reduction in the temperatures was observed during the warmer periods. July was the hottest month and the runoff temperatures gradually decreased in the following months.

4.1.3.1 Maximum, Minimum and Mean Monthly Temperatures

The maximum, minimum, and flow-weighted mean inflow and outflow temperatures were computed for each storm (Appendix B). As mentioned earlier, two temperature thresholds, namely optimal water temperature for brook trout of 14°C (57.2°F) and the Maryland State Class III temperature standard of 20°C (68°F) for natural trout waters, were considered for evaluating the performance of the BMP. On some occasions, the upper limit of the optimum temperature range for brown trout, 17°C (62.6°F), was exceeded. Hence, the 17°C limit was considered as an additional check to evaluate the BMP.

In order to depict the overall temperature reduction achieved in the underground storage BMP, the storm events were combined on a monthly basis. The computed monthly temperatures along with the monthly rainfall depths are summarized in Table 4-4a. ΔT was computed as the difference between the flow-weighted mean monthly outflow and inflow temperatures (Table 4-4b). This value is a measure of the temperature reduction achieved in a particular month. Hence, a negative ΔT would suggest that the underground storage BMP aids in the reduction of the runoff temperature. However, the effectiveness of the BMP is based on the temperature reduction meeting defined goals.

Table 4-4a. Summary of maximum, minimum, and flow-weighted mean monthly temperature at inlet and outlet of BMP 3007

Month	Number of events	Inlet 1 Temperature			Inlet 2 Temperature			Inflow Temperature*			Outflow Temperature		
		Maximum	Minimum	EMT	Maximum	Minimum	EMT	Maximum	Minimum	EMT	Maximum	Minimum	EMT
		°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Feb-08	2	5.0	3.3	4.7	5.5	5.2	5.4	5.5	3.3	4.8	5.1	3.9	5.0
Mar-08	8	9.5	4.7	7.5	10.1	5.5	7.6	10.1	4.7	7.5	10.7	5.3	7.6
Apr-08	9	14.0	4.9	11.4	13.3	5.8	11.0	14.1	4.9	11.4	14.1	5.1	9.7
May-08	9	14.5	8.8	11.6	16.2	8.2	11.5	16.2	8.2	11.6	15.5	9.0	11.5
Jun-08	5	21.5	14.3	16.3	19.7	11.3	14.8	21.5	11.3	16.0	18.3	8.3	15.5
Jul-08	5	24.1	18.7	21.0	21.2	17.3	20.0	24.1	17.3	20.8	22.4	16.5	19.4
Aug-08	5	20.9	17.0	18.8	20.2	16.6	18.6	20.9	16.6	18.7	20.5	17.3	18.5
Sep-08	6	20.8	14.3	18.2	20.4	15.0	18.1	20.8	14.3	18.1	21.1	14.1	17.6
Total	49												

*Inlet 1 and Inlet 2 combined

Table 4-4b. Mean reduction of temperature in each month in BMP 3007

Month	**EMT in**	**EMT out**	**ΔT = EMT out – EMT in**
	°*C*	°*C*	°*C*
Feb-08	4.8	5.0	0.2
Mar-08	7.5	7.6	0.1
Apr-08	11.4	9.7	-1.7
May-08	11.6	11.5	-0.1
Jun-08	16.0	15.5	-0.5
Jul-08	20.8	19.4	-1.4
Aug-08	18.7	18.5	-0.2
Sep-08	18.1	17.6	-0.6

Figure 4-2 shows the flow-weighted mean monthly inflow and outflow temperatures computed for the monitoring period. The optimum temperature ranges for brook trout and brown trout, and the MD Class III temperature level are shown in the figure. In Figure 4-2, a clear trend of increasing monthly mean temperatures is evident from February through July and then a decrease from August to September. While there was little or no difference between the mean inflow and outflow temperatures for the months February to May, reductions exhibited in June and July were 0.5°C and 1.4°C, respectively. The temperature difference again became small in August and September.

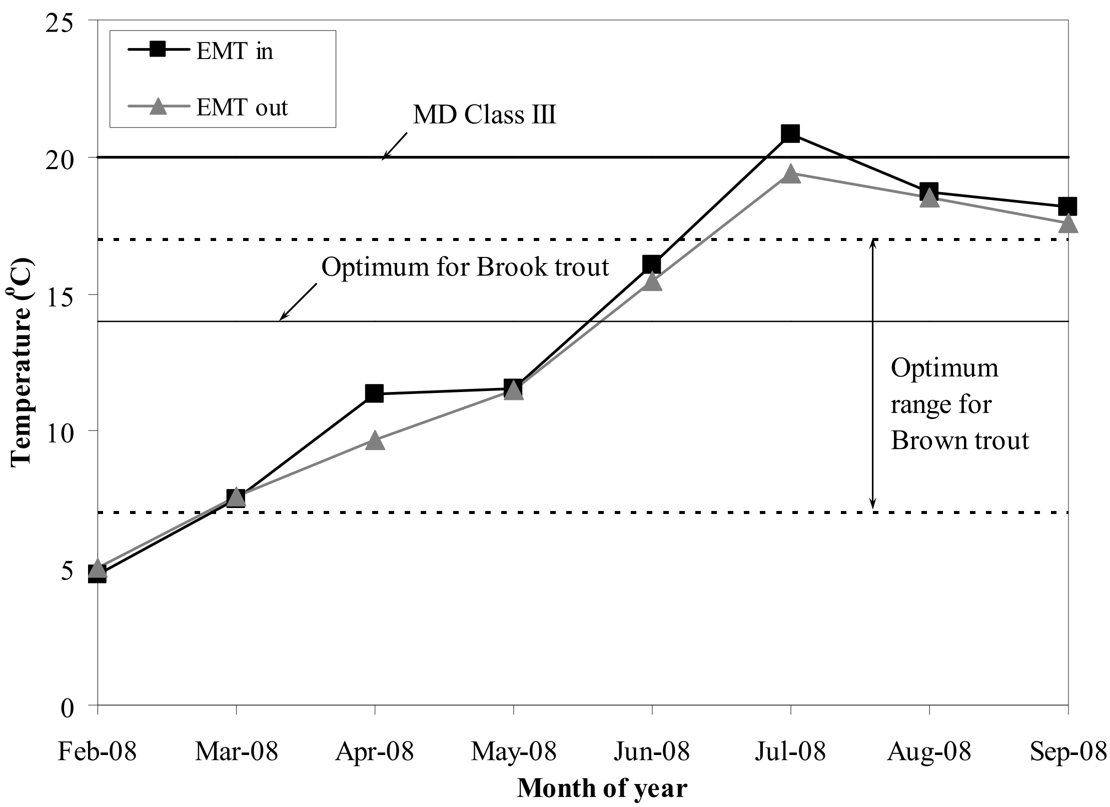


Figure 4-2. Flow-weighted mean monthly temperatures for BMP 3007

The mean temperature of outflow runoff (see Table 4-4a) was slightly higher than that of inflow during February and March, which resulted in a positive ΔT. The ΔT for April and May were small and negative (Table 4-4b). It can be hypothesized that during colder months, the outside air temperature is lower than the ambient underground temperature. Hence, little or no reduction in temperature occurs. It was observed that the air temperature was approximately 7.2°C (45°F) or less and the ambient underground temperature approximately 4.4°C (40°F) in February and early March. The inflow temperatures ranged between 3.0 and 7.0°C (37 and 45°F). In most of the events, the outflow temperature was at least higher 0.3°C greater than the inflow temperature during the major part of the storm. Thus, the computed mean outflow EMT was greater than that of inflow. Since the ΔT values for these months are small, they can be considered to be insignificant. Also, the observed inflow and outflow temperatures fall within the optimum temperature range for survival of trout. This suggests that although the BMP is not effective in reducing the temperature during colder months, the outflow temperatures are not detrimental to trout.

The inflow and outflow temperatures that exceeded the two threshold temperatures were recorded during the 2008 summer (Table 4-4). In June, the flow-weighted mean temperatures at the inlet and outlet were 16.1°C (60.9°F) and 15.5°C (59.9°F), respectively. Both the mean inflow and outflow temperatures exceeded the optimum temperature of 14°C for brook trout but were lower than the Maryland Class III threshold (Figure 4-2).

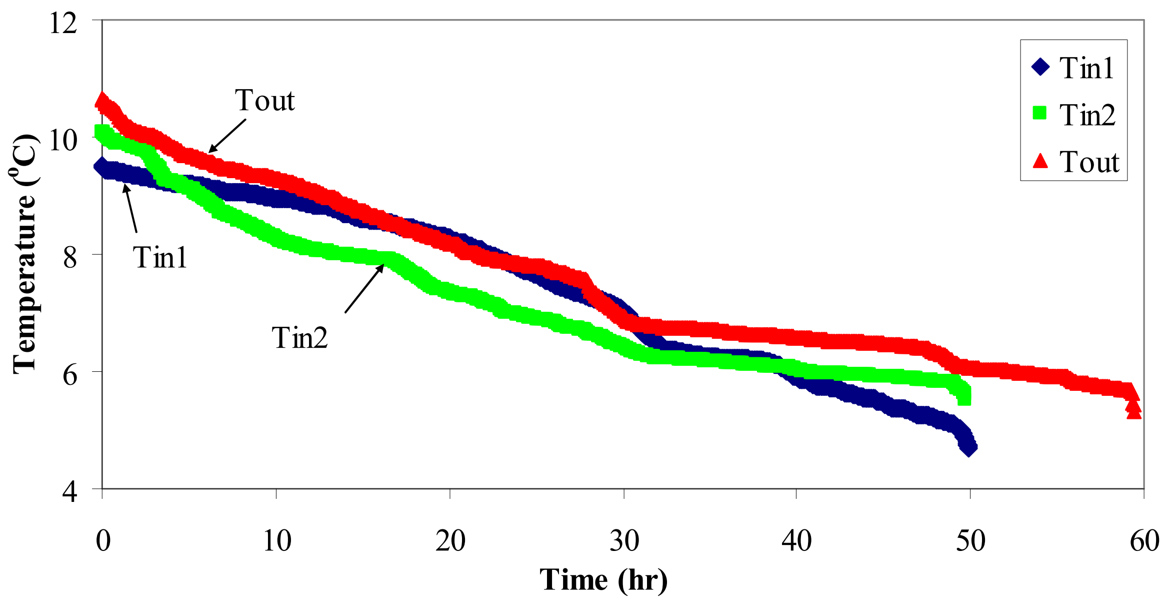
A further increase in inflow temperature levels was observed in July. During this month, the inflow temperature ranged between 17°C and 25°C (63°F and 77°F). The high temperature range occurred because the majority of the storm events happened in late afternoon when the air and pavement temperatures were very high. The highest inflow temperature of 24.1°C (75.5°F) was observed in the July 13, 2008, storm. This was the only instance when the runoff temperature exceeded the Maryland Class IV standard of 23.8°C (75°F) for recreational trout waters. The flow-weighted mean inflow and outflow temperatures were computed as 21.7°C (71°F) and 19.7°C (67.5°F), respectively, for this month. However, the mean outflow temperature surpassed the 14°C optimum temperature threshold and is only 0.3°C less than the Maryland Class III threshold (Figure 4-2).

The maximum and mean temperatures observed in August and September were lower than those of July. During these two months, the inflow temperature ranged between 14°C and 21°C (57.2°F and 70°F). The maximum inflow and outflow temperatures observed during these months were greater than the two threshold temperatures. The reduction in runoff temperatures observed during these months was small. As seen in Table 4-4b, the flow-weighted mean outflow temperature was only 0.2°C less than the mean inflow temperature in August and about 0.6°C lower in September. Although the mean inflow and outflow temperatures were at least 1.6°C lower than the MD Class III threshold, the temperatures were higher than the 14°C threshold in both months.

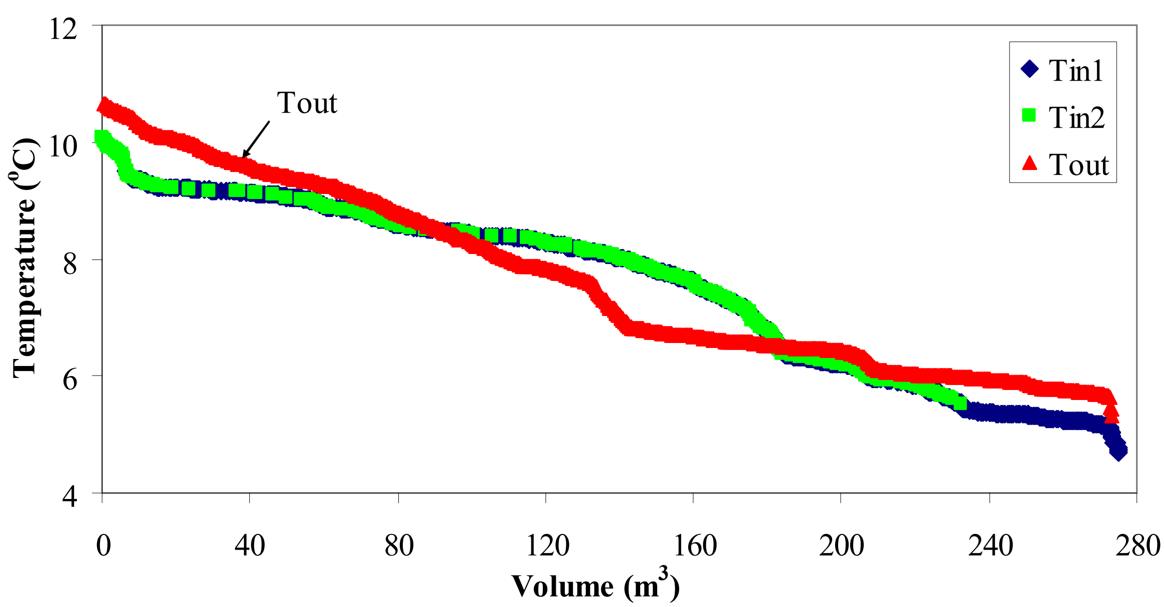
4.1.3.2 Time of Exposure and Volume Analysis

The exposure time to the inflow and outflow temperatures and the respective exposure volumes were computed for each storm event. For the exposure time analysis, the temperature data (2-minute intervals) at the two inlets were ranked from the highest to the lowest and plotted. For the volume analysis, the two inflow temperatures were combined and ranked from the highest to the lowest and their corresponding cumulative volumes were calculated based on flows determined over 2-minute intervals. For ease of representation, the events were combined on a monthly-basis and the time and volume of inflow and outflow water exceeding the two temperature thresholds are shown in the plots. Since summer is the critical period, more importance was placed on summer rainfall events.

Firstly, the results of the analyses performed on storms recorded in a colder month are presented. Eight storm events occurred in March, with rainfall durations ranging between 1.4 and 10.2 hours. On combining the flows from these events, BMP 3007 received inflow cumulatively for nearly 50 hours during the month. Figure 4-3a is a time-based plot of the inflow and outflow temperatures.



(a)



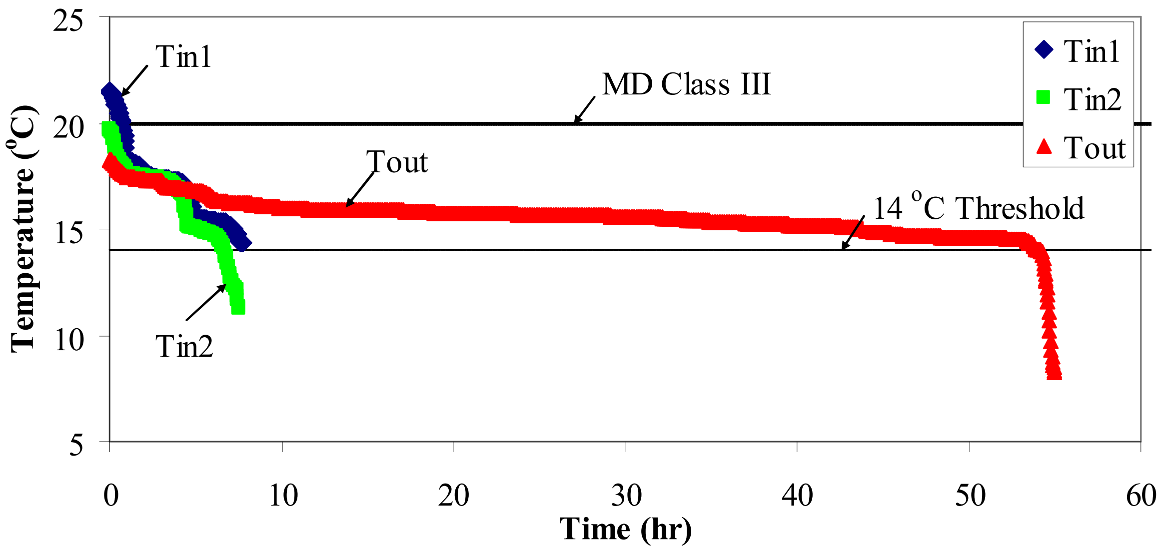
(b)

Figure 4-3. a. Time-based and **b.** Volume-based plots of inflow and outflow temperatures of BMP 3007 in March, 2008 (All data points are plotted at 2-minute intervals)

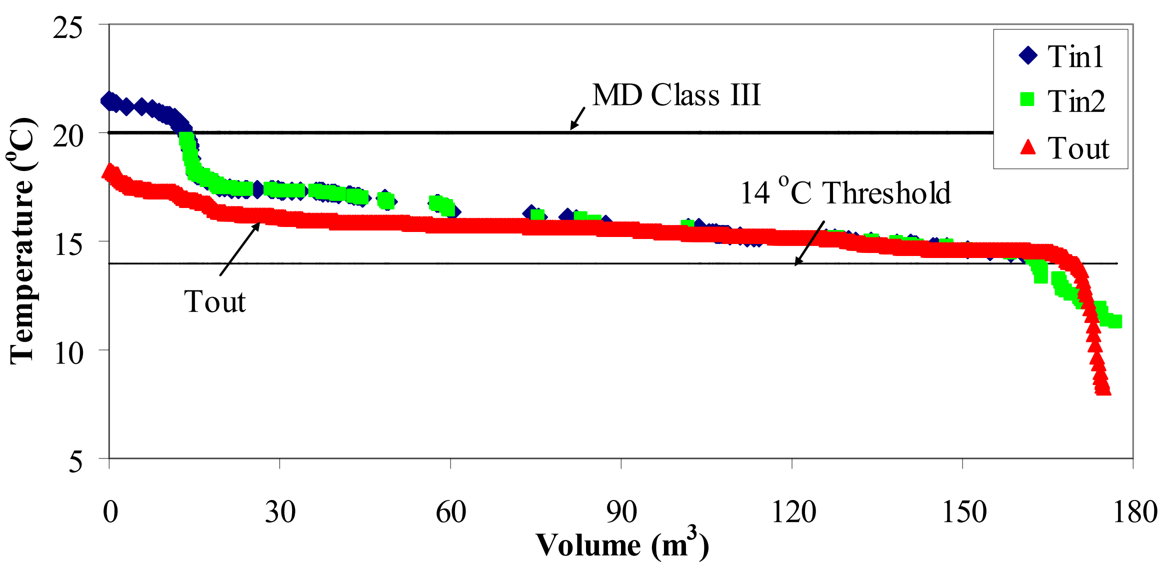
As can be seen in Figure 4-3a, the outflow temperature was at least 0.5^{o}C higher than the inflow temperature during most of the month. While the maximum outflow temperature was 10.7^{o}C (51.3°F), the maximum inflow temperature was 10.1^{o}C (50.2°F). The combined volume of flow to inlet 1 and inlet 2 from the eight storms was 275 m^3. Of this, almost 90 m^3 outflow volume was nearly 0.6^{o}C higher than the inflow volume for the temperature range 10.7 to 9^{o}C (Figure 4-3b). The inflow temperature was cooled almost 2^{o}C in the lower temperature ranges. However, it is evident that both inflow and outflow temperatures lie well within the optimum temperature ranges of the trout species. Although the reduction in temperature is not considerable, if either the inflow or the outflow volume were to be introduced to the stream, no stress is expected to occur.

The inflow temperature range increased in summer 2008 and high inflow temperatures were recorded during this period. The monthly flow and temperature for the month of June 2008 are shown in Figure 4-4. BMP 3007 received runoff for nearly ten hours from the five storms that occurred during this month. About 14 m^3 of the total runoff volume measured temperature greater than 20^{o}C (68^{o}F) for a period of nearly 45 minutes. The storage system cooled this volume by at least 2^{o}C. Runoff measuring temperature in the range 16 to 14^{o}C was cooled by less than one degree. The inflow and outflow volumes were at the same temperature for most of the period in this month.

July was a hot month, with air temperatures measuring close to 32.2^{o}C (90^{o}F) before most events. Five storm events occurred during this month of which two storm events measured rainfall depths greater than 2.5 *cm* (1 *in.*). The duration of these events ranged from 0.3 to 12.2 hours. The facility received a combined runoff volume of 515 m^3 from the five events for a period of 20 hours in this month (Figure 4-5). Of the total volume, nearly 285 m^3 of runoff had measured temperatures in the range from 20 to 24^{o}C (68 to 75.2 ^{o}F) for a period of 13 hours. During this period, the runoff was cooled by nearly 2^{o}C. Of the total outflow volume, around 70 m^3 exhibited a temperature greater than 20^{o}C and exited the system in 13 hours. The flow of a large volume of high temperature runoff into the local stream for a certain period can be much more lethal than small flow volumes of the same temperature in the same period. For the rest of the month, the outflow was cooled to remain under the 20°C threshold but higher than the 17°C threshold.

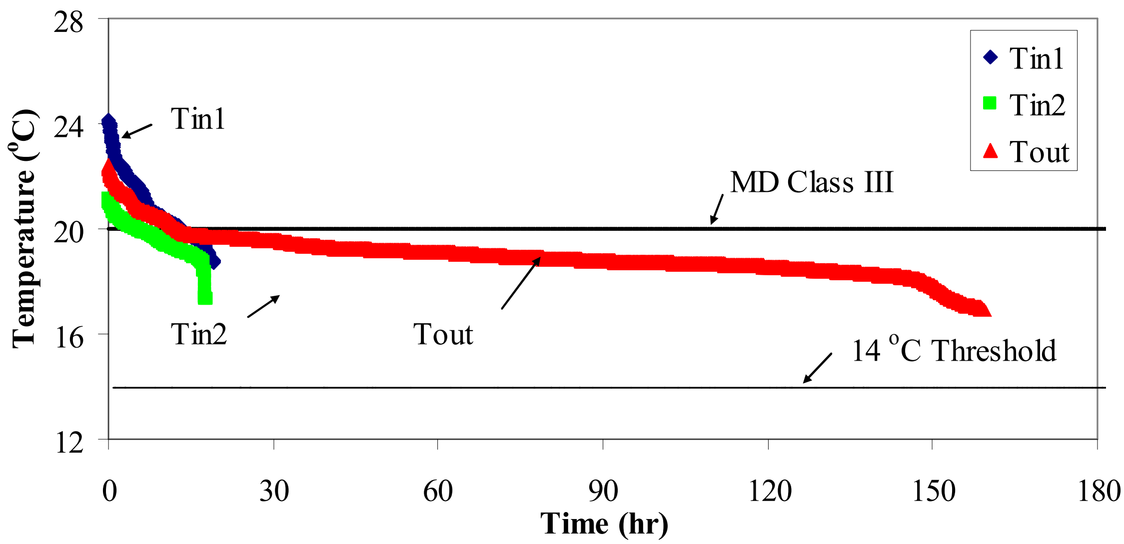


(a)

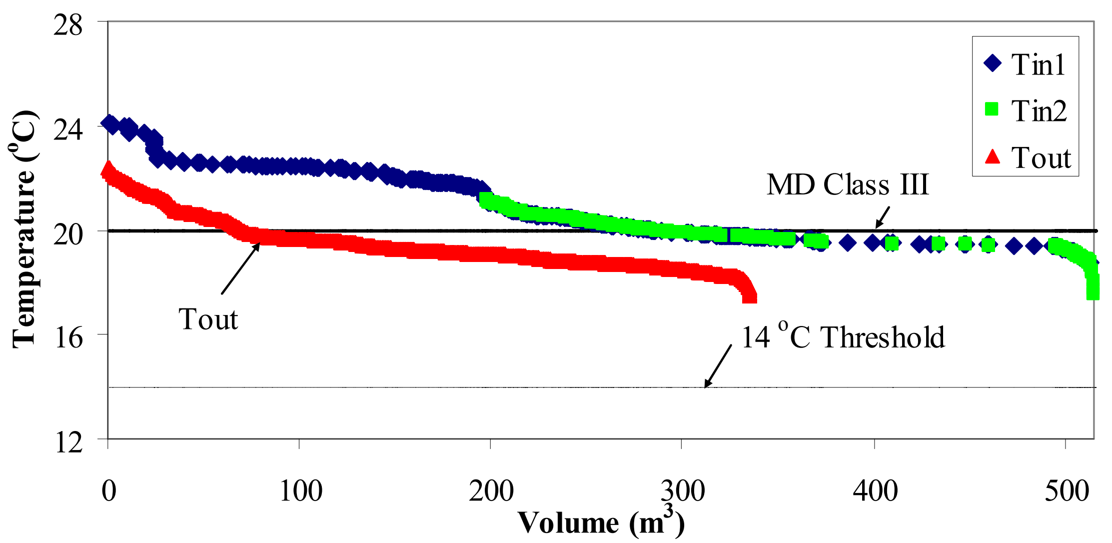


(b)

Figure 4-4. a. Time-based and **b.** Volume-based plots of inflow and outflow temperatures of BMP 3007 in June, 2008 (All data points are plotted at 2-minute intervals)



(a)

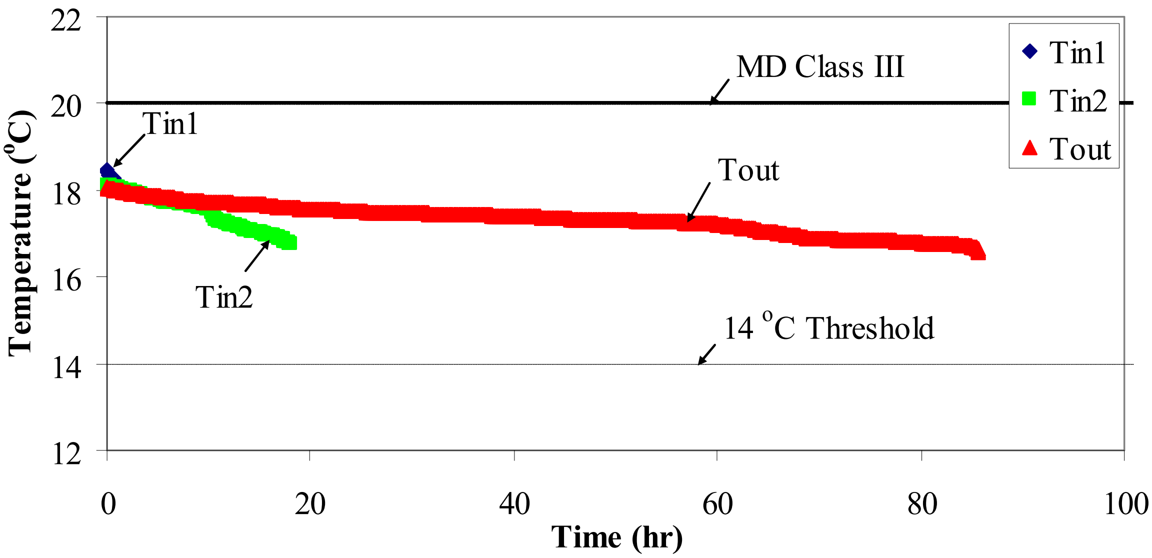


(b)

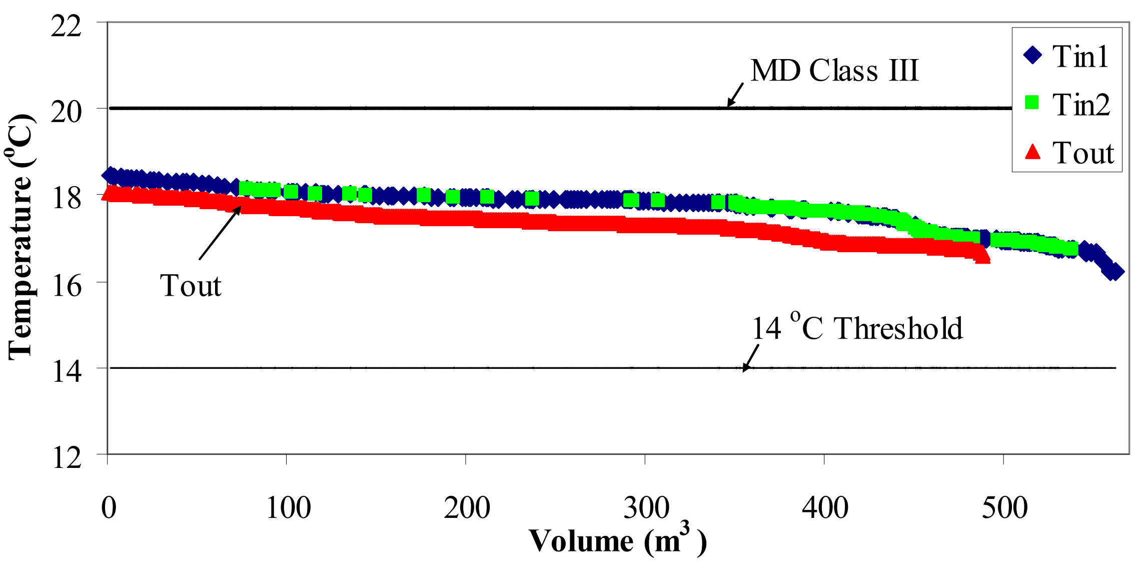
Figure 4-5. a. Time-based and **b.** Volume-based plots of inflow and outflow temperatures of BMP 3007 in July, 2008 (All data points are plotted at 2-minute intervals)

In the month of August, out of the six observed events, only one event measured a rainfall depth greater than 2.5 *cm* (1 *in.*). The six events produced a runoff volume of 13 m^3 with the measured temperatures greater than 20^{o}C for a period of 30 minutes in the entire month. During this period, mean temperature reduction of less than 0.2^{o}C was not sufficient to cool the runoff below 20^{o}C. On average, the reduction in temperature was small and the outflow remained much higher than the threshold temperature of 14^{o}C. September 2008 was the wettest month and recorded a total rainfall depth of 17.7 *cm* (7 *in.*) from eight events. The facility received a total runoff volume of 1013 m^3 over a period of around 51 hours. Of the inflow volume, 95 m^3 exceeded the 20^{o}C threshold over a period of 3.3 hours in the month.

The impact of the BMP on runoff temperatures during a high intensity storm was observable in the month of September 2008. The majority of the events recorded during this month were typically high intensity, short duration events. During large events, the detention time of the runoff in the system ranged between 6 and 10 minutes. Figure 4-6 depicts the observations for a representative storm that occurred on September 27, 2008. The event measured a total rainfall depth of 8.64 *cm* (3.4 *in.*). Outflow was recorded ten minutes after the system began receiving inflow. The BMP received a total runoff volume of 562 m^3 from the event over the duration of 18 hours. Outflow continued for more than three days. The plot shows the outflow volume until the next event which occurred on September 30, 2008. As seen in Figure 4-6, the short period of detention had little effect on the temperature. The outflow temperature is similar to the inflow temperature for a greater part of the storm.



(a)



(b)

Figure 4-6. a. Time-based and **b.** Volume-based plots of inflow and outflow temperatures of BMP 3007 for 27 September, 2008, event (All data points are plotted at 2-minute intervals)

4.1.3.3 Monthly Runoff Volume Exceedence of Threshold Temperatures

In order to evaluate the overall performance of the BMP during each month, proportions of the total monthly inflow and outflow volumes exceeding the temperature thresholds of 14°C, 17°C, and 20°C were computed and are shown in Figure 4-7. As seen in the figure, inflow and outflow temperatures did not exceed the three temperature threshold limits in February, March, and April. In May, less than 2% of the inflow volume was at a temperature greater than 14°C but lower than 17°C. The BMP did not aid in the cooling of this inflow volume. Thus, 2% of the outflow volume exceeded the 14°C threshold (Figure 4-7a). The months from February through May did not produce inflow temperatures greater than 16°C.

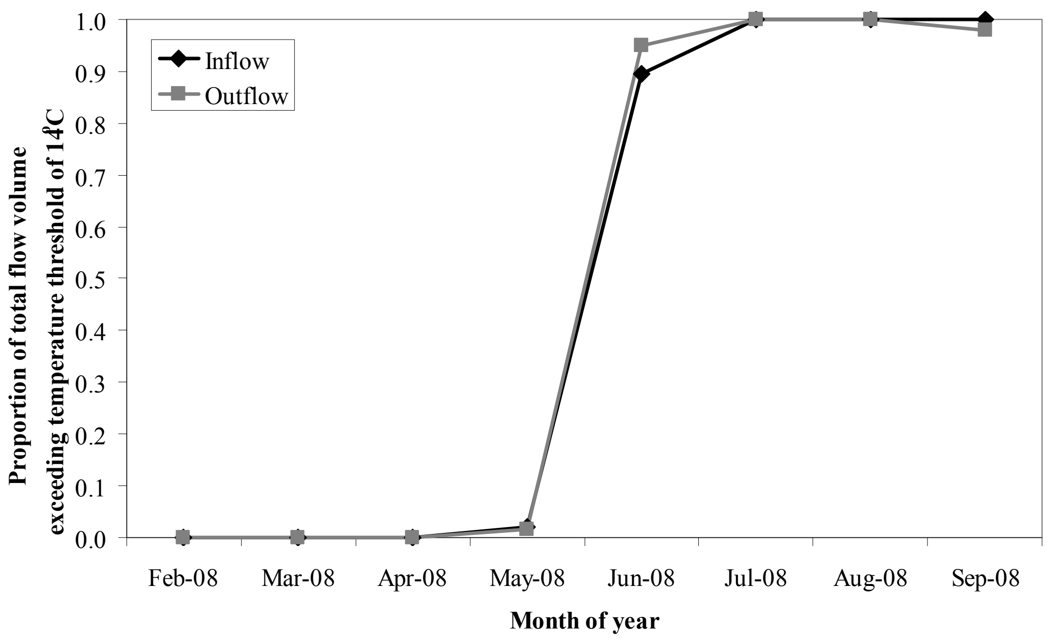


Figure 4-7a. Proportion of monthly inflow and outflow volumes exceeding 14°C threshold temperature

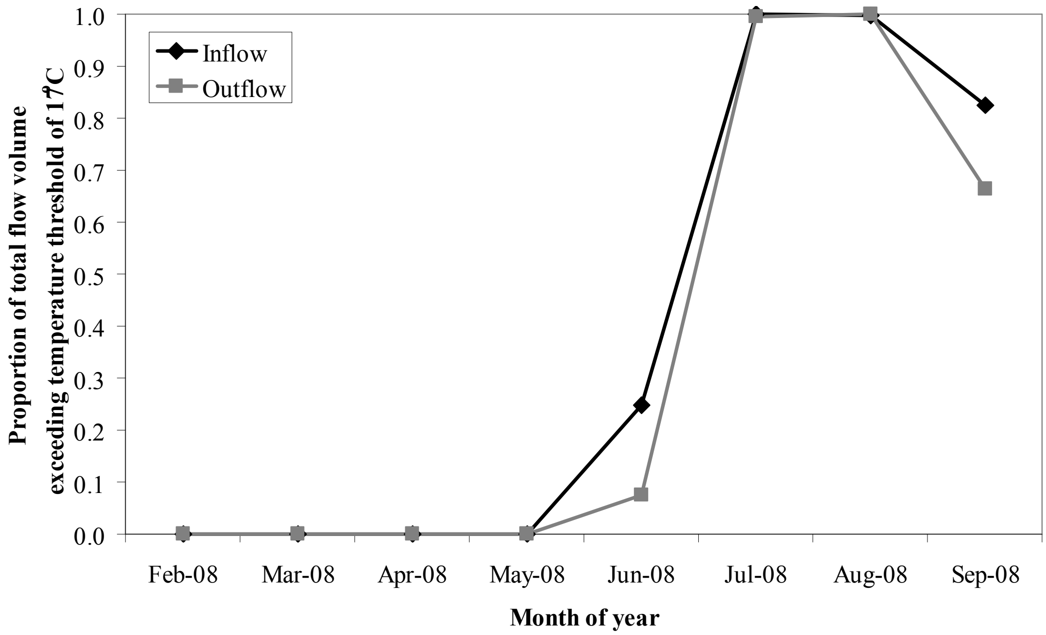


Figure 4-7b. Proportion of monthly inflow and outflow volumes exceeding 17°C threshold temperature

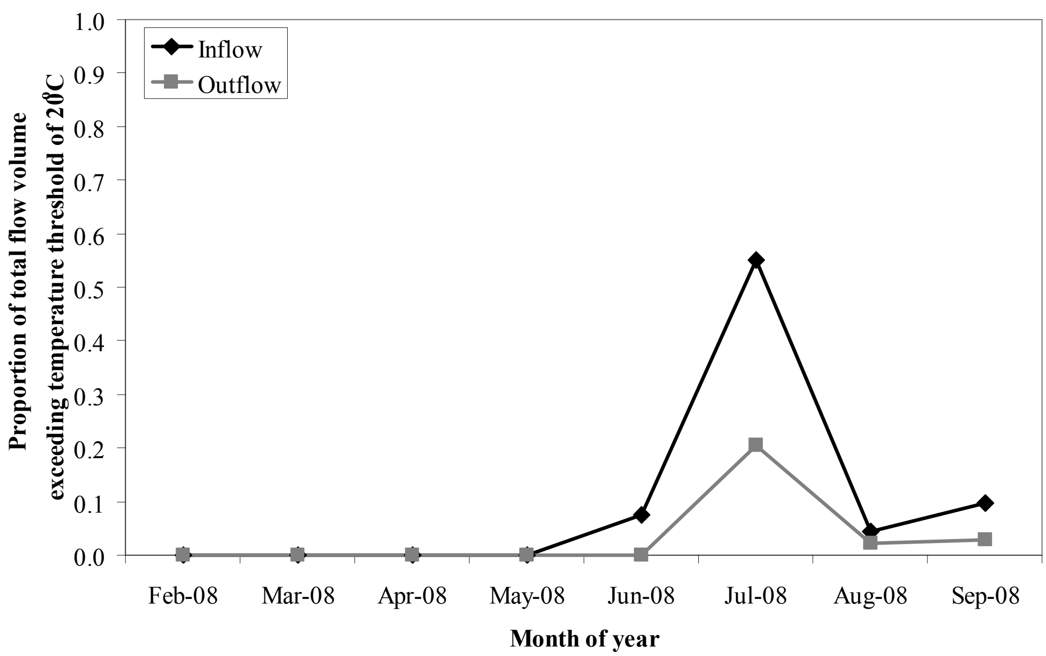


Figure 4-7c. Proportion of monthly inflow and outflow volumes exceeding 20°C threshold temperature

In June, more than 95% of inflow volume exceeded the 14^{o}C threshold, of which less than 5% of this volume was cooled to temperature below 14^{o}C. Nearly 25% of the total inflow volume was at a temperature above 17^{o}C. However, after passing through the BMP, less than 10% of the volume exceeded the 17^{o}C threshold (Figure 4-7b). The conveyance of the runoff through the BMP enabled cooling of all of the 10% inflow volume having temperatures greater than 20^{o}C (Figure 4-7c). These results indicate that the underground storage reduces higher temperatures more effectively than temperatures in the lower ranges. However, the detention of water does not completely mitigate the temperature of the runoff to desirable levels.

High-temperature flows capable of stressing trout were observed in July 2008. The inflow temperatures during July were in the range from 17 to 25^{o}C. This is evident in Figure 4-7, as 100% of the total inflow volume exceeded the 14^{o}C and the 17^{o}C thresholds. The temperature of this inflow volume was not reduced to below the threshold. However, significant exceedence reduction occurred at 20^{o}C. While almost 55% of the inflow volume exceeded the 20^{o}C threshold, only 20% of the total outflow volume had temperatures greater than 20^{o}C.

In August, a major portion of the total inflow and outflow volumes exhibited temperatures ranging between 16^{o}C and the 18^{o}C, thereby entirely exceeding the 14^{o}C and 17^{o}C thresholds. Less than 5% of the total inflow volume had temperatures that exceeded 20^{o}C. About 2% of the total outflow volume had temperatures that exceeded the 20^{o}C threshold and was not cooled below 17^{o}C. In September, a further decrease in the inflow temperature occurred. About 10% of the inflow volume exhibited temperatures greater than 20^{o}C and 71% of this volume was cooled below 20^{o}C. While 82% of the inflow was at a temperature higher than 17^{o}C, only about 66% of the outflow volume exceeded this threshold. Runoff was not cooled below 14^{o}C and 98% of the outflow exceeded the 14^{o}C threshold.

4.1.3.4 Summary and Mechanism of Temperature Reduction in the BMP

Based on the time of exposure and volume analysis, it can be observed that during the cooler months (March and April 2008), the inflow volumes did not violate the 14, 17, and 20^{o}C thresholds. In May, less than 10% runoff volume measured temperatures greater between 14°C and 17°C. This volume exited the system without much reduction in temperature. This may be because the ambient underground temperature is nearly the same as the runoff temperature. Therefore, the heat loss to the surrounding air and pipe can be considered to be insignificant. Any heat transfer that occurs would be by mixing of the runoff. Thus, little or no cooling of the temperature would occur.

As it gets warmer in summer, the temperature of runoff also increases. The warmer months (June, July, and August) measured runoff temperature in the range 16 to 24°C (61 to 75°F). The ambient temperature in the underground pipes was usually around 14.4°C (58°F), which is lower than the runoff temperature range. Heat loss can be expected to occur due to this difference in temperature. Any water stored from the antecedent event will be in equilibrium with the ambient temperature underground. Therefore mixing of the inflow runoff and cooler stored volume of water will result in buffering of the runoff temperature. Depending on the detention time of the runoff in the system, reduction in temperature would occur. As runoff flows through the system, it will lose some heat to the surrounding cooler air and pipe.

From the above discussion, it can be hypothesized that the BMP is more effective in mitigating higher temperatures than at lower temperatures. Figure 4-8 is a plot of the event mean inflow and outflow temperatures at BMP 3007 for events from February through September 2008. The flow and temperature at the two inlets were combined to compute the event mean inflow temperature. As seen in the figure, temperature reduction occurred when the event mean inflow temperatures were greater than 20°C. Rainfall events during June, July, and August 2008 produced event mean inflow temperatures between 20 and 23°C. During these events, the mean outflow temperature was, on an average, 2.3°C lower than the event mean inflow temperature. The distribution of the points along the 45° line in the lower temperature ranges indicates that BMP did not have any significant impact on runoff temperature during cooler periods.

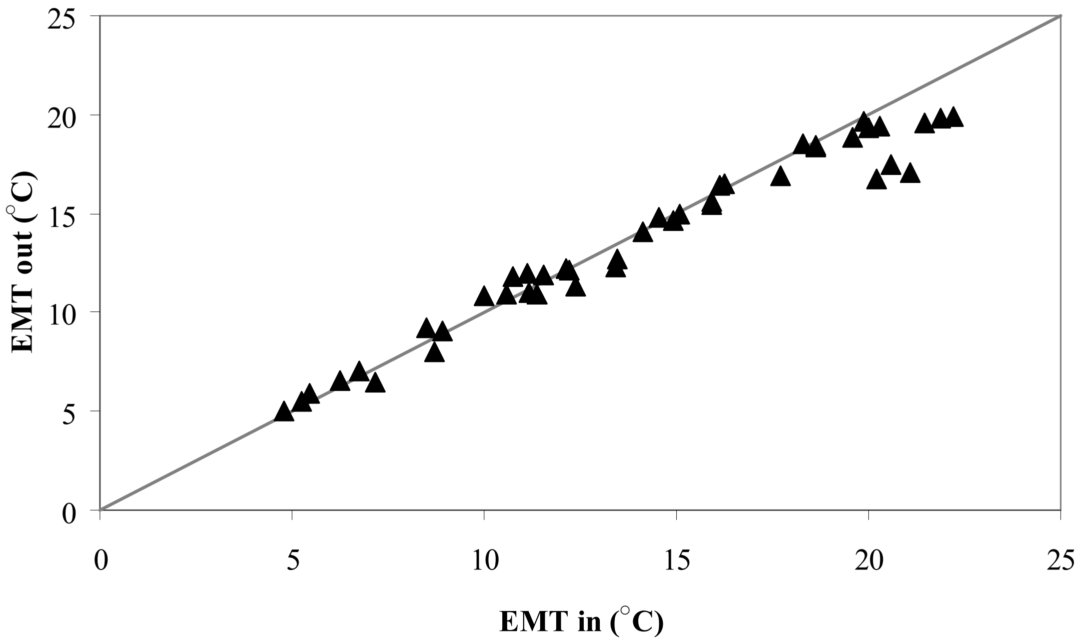


Figure 4-8. Relationship between event mean inflow and outflow temperatures at BMP 3007 for February to September 2008

4.1.3.5 Statistical Test on Temperature Reduction

To support the hypothesis on the performance of the BMP at different inflow temperature ranges, a one-sample *t*-test was performed to test the significance of the temperature reduction achieved in each month (Ayyub and McCuen 2003). The averages of event mean inflow temperatures (EMT in) and event mean outflow temperatures (EMT out) for all the events in each month were computed. The mean temperature reduction ($\mu_{\Delta T}$) was computed as the difference between the two averages (EMT out –EMT in) and was subjected to a one-sided lower *t*-test. The value of $\mu_{\Delta T}$ would be negative if the runoff temperature was reduced by the BMP. The objective of the hypothesis test was to determine whether the mean temperature reduction was significantly less than zero. Hence, rejection of the null hypothesis (H_o) would imply that the mean temperature reduction achieved is significant at the given level of significance. The results of the hypothesis test are summarized in Table 4-5.

Table 4-5. Results of *t*- test on significance of temperature reduction in BMP 3007 in each month (H_o: $\mu_{\Delta T} = 0$, H_A: $\mu_{\Delta T} < 0$)

Month	Number of events considered	Mean temperature reduction $\mu_{\Delta T}$	Rejection probability
Mar-08	6	0.04	> 0.25
Apr-08	8	0.09	> 0.25
May-08	7	-0.05	> 0.25
Jun-08	5	-1.42	0.0722
Jul-08	5	-2.22	0.0074
Aug-08	4	-0.39	0.0529
Sep-08	7	-0.15	0.2180

The mean runoff temperature reduction in March, April and May 2008 is insignificant. The rejection probability of the null hypothesis for these three months was greater than 25%. Inlet runoff temperature increased in June and the rejection probability of the null hypothesis for this month was 7.2%. The mean temperature reduction of 4.2°C in July has a rejection probability of about 0.4%, which is low. In the following months, the reduction achieved decreased and the rejection probability increased. The hypothesis test clearly indicates that the effectiveness of the BMP in reducing runoff temperature in the hotter months is much more significant than that in colder months.

A one-sided lower *t*-test was conducted on the mean temperature reduction observed during the 12 summer events producing event mean inflow temperatures exceeding the Maryland Class III standard of 20°C. The hypothesis test showed that the mean reduction of 1.6°C for the 12 events was statistically significant, with the rejection probability being less than 0.25%. This suggests that the thermal impact of the BMP is significant in summer.

4.1.3.6 Depth- Duration- Temperature Reduction Analysis

Since significant temperature reductions were observed during summer, influence of the depths and durations of the summer rainfall events on the runoff temperature was analyzed. The size of the storm determines the volume of runoff produced and the detention time in the BMP.

The detention time is critical in summer because the temperature reduction is influenced by the contact time of the runoff in the underground storage. Some observations were made during the 14 storm events that displayed significant mean temperature reduction, which occurred in June through early September 2008. Runoff produced from small storm events were detained in the facility for longer periods which resulted in significant reduction in inflow temperature. For instance, four events measuring rainfall depth in the range 0.26- 0.64 *cm* (0.11- 0.25 *in*.) and duration less than one hour, showed a mean temperature reduction of 2.7°C. During some events, the BMP received large volumes of runoff in a short period of time. At higher inflow rates, runoff is quickly conveyed through the BMP and hence the mean temperature reduction achieved in the BMP is also smaller. Two events, measuring rainfall depth greater than 2.54 *cm* (1 *in*.) and duration between 4 and 12 hours, showed a mean temperature reduction of only 0.7°C. The number of storms in other ranges of depth and duration was only one or none. Due to the small number of sample storms, the relationship between different rainfall depths and durations and mean temperature reduction could not be quantitatively characterized. With a large sample size, a rigorous analysis can be performed to determine the impact of rainfall depth and duration on runoff temperature reduction.

4.1.3.7 Temperature Exceedence Probability Plot

The exceedence probability of the observed runoff temperature and outflow temperature at BMP 3007 is shown in Figure 4-9. The temperature data (2-minute intervals) were combined for all the events during the period from February through September, 2008, and the frequency distribution analysis was performed. As can be seen in the plot, the probability of the inlet runoff temperature exceeding the 20°C threshold is about 8%. The runoff temperature exceeded the 14°C threshold 40% of the time. Only one instance of exceedence of the Maryland Class IV standard of 24°C was encountered at an inlet of BMP 3007 during the entire monitoring period. The probability of exceedence of temperatures above 20°C is less at the outlet compared to the inflow temperature. The outflow temperature exceeded the 20°C threshold approximately 3% of the time. Outflow temperature did not exceed the Maryland Class IV temperature at any instance.

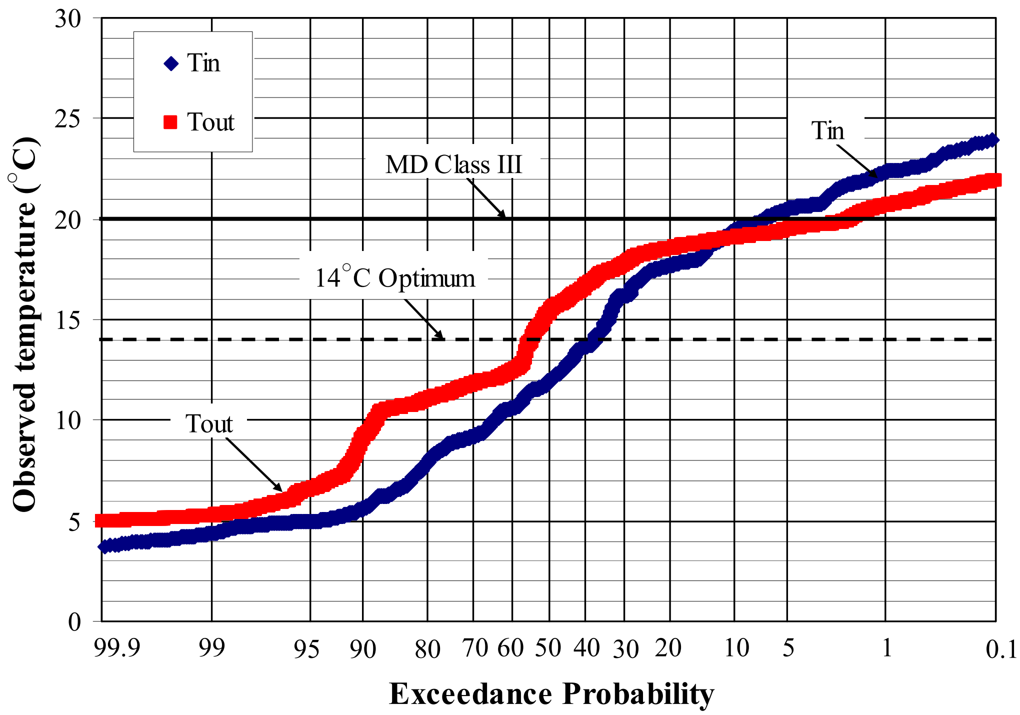


Figure 4-9. Plot showing the exceedence probability of inflow and outflow temperatures at BMP 3007 (Data points are plotted at 2-minute intervals)

The probability plot in Figure 4-9 supports the previous discussion on temperature reduction. The lower probability of outflow temperatures exceeding higher temperature thresholds compared to the inflow temperature suggests that the BMP reduced the higher runoff temperatures more effectively. However, the inflow and outflow data points on the plot are not paired and hence information on temperature reduction achieved in the system cannot be deduced from the plot.

4.1.3.8 Trout Temperature Requirements

Most events in summer produced runoff temperatures lethal to trout. The trout can withstand thermal stress depending on its acclimation temperature. Based on the acclimation temperature, the trout can survive for varying periods of time when exposed to different temperatures (Armour 1991). Sustained elevated water temperatures over 21°C (70°F) are stressful and those above 25°C (77°F) are lethal (Galli 1990). Figure 4-10 depicts the relationship between lethal temperature and time to 50% mortality of trout acclimated to different temperatures.

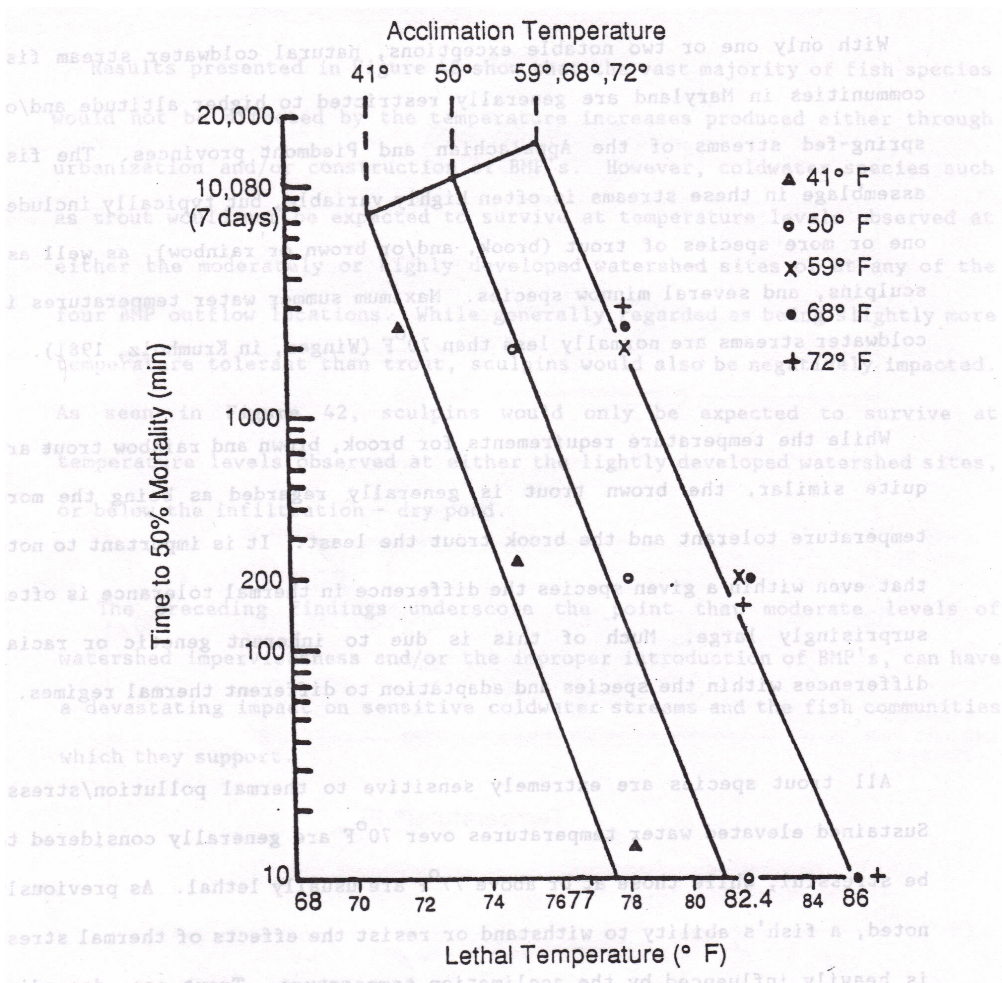


Figure 4-10. Relationship between time, acclimation temperature and 50% mortality of brown trout (Source: Elliot 1981 as referenced from Galli 1990)

As seen in Figure 4-10, brown trout acclimated at temperatures 15, 20, or 22.2°C (59, 68, or 72°F) would survive over 10 days at 24.4°C (76°F). Higher runoff temperatures were observed during July; the runoff temperature ranged between 20 to 24.1°C (68 to 75.5 °F) for a period of 13 hours. Based on Figure 4-10, brown trout acclimated to temperatures between 5 and 22.2°C (41 and 72°F) would survive at the outlet of the BMP.

4.2 Model

Simulations were performed for a number of storm events considering the underground storage system as a n-CSTR model. The simulated flow rate and observed temperature at the inlet of BMP 3007 were given as the inputs to the model. The flow module of the model involves a number of parameters, such as the number of CSTRs (n), and flow coefficients for the outlet control of each CSTR, which required calibration. The simulations performed so far have not yielded satisfactory predictions of the flow from the system. Since the model-predicted outflow does not match the observed data, it is not possible to perform the heat balance of the system.

If the system were to be considered as 1-CSTR, the outflow temperature predicted by the model was inaccurate. This is suggestive of a wrong model structure in the flow modeling; the n-CSTR model should be a better representation of the behavior of the storage system. Nonetheless, the simulations have yielded some useful results regarding the heat transfer in the system. The 1-CSTR simulations revealed that the temperature of the air and pipe do not change significantly from their initial conditions during the period of inflow. This is because the coefficients of convective heat transfer for the air and the HDPE pipe are small. This suggests that in the underground system, the heat loss to surrounding air and pipe may be small.

It is necessary to perform calibration of the various coefficients involved in the model to achieve accurate flow predictions. Once flow balance is achieved, the heat transfer in the system can be modeled.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Thermal enrichment of streams by urban stormwater runoff is a problem of serious concern, especially in summer. Underground storage and slow-release facilities are widely employed best management practices to attenuate peak flows. The purpose of this study was to determine the effectiveness of an underground storage BMP in mitigating stormwater runoff temperatures. Automated monitoring instruments were deployed in an underground storage facility in Timonium, Maryland, and flows and temperatures of runoff into and out of the facility were monitored for multiple storm events over a period of seven months.

Runoff flow and temperature data were characterized to meet the goals of this research study. As expected, the inflow runoff temperatures were observed to have seasonal variations. In cooler months, the runoff temperatures were low, from 3 to 14^{o}C. During summer, stormwater runoff that is conveyed over hot asphalt pavement exhibited temperature from 18 to 24^{o}C. In addition, the temperature of the inflow was influenced by the time of the day that the rainfall occurred. Storms that occurred during hot summer afternoons produced warmer runoff compared to storms that occurred during the night. Runoff flowing into the underground storage facility was detained for some duration depending on its volume and was released at a small flow rate.

February through May was a cooler period during which the event mean temperatures of inflow and outflow runoff were not significantly different. Although the temperature reductions were insignificant during cooler months, the temperatures were low and should be harmless to trout and other aquatic life. The temperature of runoff increased during the summer. In June and July, the event mean inflow temperature varied from 20 to 23^{o}C. A mean temperature reduction up to 4^{o}C was achieved through the BMP in summer. For rainfall events in June, the event mean outflow temperature was 1.4^{o}C less than the event mean inflow temperature, and this temperature reduction was statistically significant with a rejection probability of 7.2%. The mean temperature reduction was greatest in July (2.2^{o}C) and was found to be statistically significant with a rejection probability of 0.74%. Although reduction in runoff temperature occurred in summer, it was not sufficient to meet Maryland temperature standards for natural trout waters. Some proportion of flow from the system exceeded the threshold temperatures. The runoff temperatures were lower in August and September than in June and July. During these months, the exceedence of the Maryland temperature threshold decreased as well.

To summarize, the BMP did not have a significant impact on runoff temperatures during cooler periods. There was small or no reduction of runoff temperatures when they were less than 17^{o}C. However, runoff flowing into the system at temperatures above 19^{o}C was buffered in the cooler environment of the underground storage. For events that produced mean runoff temperatures greater than 20^{o}C, the event mean outflow temperatures were at least 1.9^{o}C lower than the event mean inflow temperatures. Hence, the BMP can be considered to effectively reduce temperature of warm runoff compared to cooler runoff. Nonetheless, the study findings demonstrate that although the underground storage facility mitigates runoff temperatures during the summer, the BMP did not aid in the reduction of temperatures below the threshold temperature 100% of the time.

5.2 Recommendations

From the data analyses and preliminary results of the heat transfer model, it can be inferred that detention time in the facility, contact surface area, and thermal conductivity of the pipe influence the temperature reduction achieved through the BMP. It would be interesting to explore the design aspects of the facility to increase the surface area and contact time of runoff to aid greater temperature reduction. Also, the performance of the underground storage facilities can be compared with other BMPs, such as sand filters and infiltration facilities to determine the effectiveness of these BMPs in reducing runoff temperatures. Other information such as the depth and temperature of runoff in the storage pipes, underground ambient temperature, and soil and pipe temperatures can be collected in future studies.

The present study covered February through September 2008. A longer period data collection covering the entire year and/or multiple years will enable more accurate characterization of the performance of the BMP during different seasons. Data collected to date indicate that summer is the critical period when runoff temperatures are high and possibly detrimental to trout. Runoff temperatures higher than the temperatures observed during the monitoring period may occur during an extreme high-temperature period. Flow and temperature data from multiple summer periods will provide a more quantitative view of the temperature reduction capacity of the BMP. In addition, with annual data, runoff temperature reductions for different depths and durations of rainfall across different seasons could be investigated.

A heat transfer model will be instrumental in understanding the temperature reduction achieved in the system. Through simulation, the performance of the storage facility during storms of different size and duration, and runoff temperature range can be analyzed. Also, the effect of the size of the facility and detention time of runoff could be analyzed through the model. The model would be a useful tool to predict the efficiency of the system in reducing runoff temperature.

It can be concluded that underground stormwater storage facilities can be employed for thermal reduction. If the underground system were absent, the warm runoff flowing into the local stream may increase the ambient stream temperature and exposure to high temperatures might stress trout and other species inhabiting the streams. However, modifying the design of the BMP to increase detention time and water contact surface area should improve the efficacy of the BMP in mitigating runoff temperatures.

APPENDIX A

Simulation of Runoff

Estimating Runoff by SCS Runoff Curve Number Method (USDA 1986)

The SCS runoff equation is

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{A-1}$$

where

Q = runoff (*in.*)

P = rainfall (*in.*)

S = potential maximum retention after runoff begins (*in.*) and

I_a = initial abstraction (*in.*)

Initial abstraction (I_a) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally correlated with soil and cover parameters. Through studies of many small agricultural watersheds, I_a was found to be approximated by the following empirical equation:

$$I_a = 0.2S \tag{A-2}$$

Substituting equation A-2 into equation A-1 gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{A-3}$$

S is related to soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10 \tag{A-4}$$

Development of Direct Runoff Hydrograph

Based on the TR-55 method, runoff from the drainage area of each inlet of the BMP was simulated for each rainfall event. A FORTRAN code developed by Dr. Richard H. McCuen (University of Maryland, College Park) was employed. The inputs required by the program are listed in Table A-1. Given the inputs, the program generates runoff (cfs) at two-minute intervals.

Table A-1. Input for runoff simulation program

Input	Input Format/ Unit	Value for BMP 3007
Rainfall depth (at 2-minute intervals)	*.txt* or *.dat* file	
Drainage area	mi^2	0.00223
Curve number	-	98
Time of concentration	*hr*	0.10
Number of rainfall ordinates	-	

In the present study, it was assumed that runoff is generated from the impervious area only and the rainfall occurring over the grassy/pervious area is completely infiltrated for most common events. Based on this assumption, runoff to an inlet was computed using the fraction of impervious area as contributing drainage area and the corresponding curve number as input.

For each event, a file containing rainfall depth (two-minute intervals) recorded at the study site was created. The simulation program was executed for each inlet of the BMP for all the storm events. The simulation performed for generating runoff to an inlet of BMP 3007 for August 13, 2008 storm event is provided as a sample.

Input

13AugRainfall.dat

```
0
0
0
0
0
0
0
0
0
0
0
0.01
0.07
0.06
0.05
0.08
0.09
0.06
0.03
0.03
0.03
0.02
0
0
0.01
0.01
0.02
0.04
0.07
0.06
0.07
0.04
0.03
0.02
0.01
0.01
0.02
0.05
0.03
0.03
0.04
0.01
0.02
0
0.01
0
```

0
0
0
0.01
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0.01
0
0
0
0
0
0
0
0
0
0

Drainage area = 0.00223

Curve number = 98

Time of concentration = 0.10

Program Output

ANALYSIS TO DEVELOP DIRECT RUNOFF HYDROGRAPH
Version 08.01

Richard H. McCuen
Department of Civil Engineering
University of Maryland
College Park, MD 20742-3021

rhmccuen@eng.umd.edu or (301) 405-1949

Storm duration (hr) = 3.463 Time increment (hr) = .0333

Rainfall depth (in.) = 1.15000 Runoff depth (in,) = .93682

-------------------- Storm runoff ------------------

.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.049	.307	.735	1.282
2.014	2.469	2.256	1.735	1.388	1.170	.833	.422
.236	.274	.413	.745	1.389	2.046	2.420	2.444
2.042	1.544	1.077	.717	.603	.912	1.317	1.378
1.400	1.290	.987	.704	.442	.304	.159	.064
.021	.083	.160	.112	.050	.018	.005	.001
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.076	.158	.111
.050	.018	.005	.001	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000							

APPENDIX B

Table B-1. Rainfall, flow, and temperature data for all rainfall events for BMP 3007 from February to September 2008

Event Date	Rainfall depth	Duration	Air Temperature	Inlet 1			Inlet 2			Outlet		
				EMT	Max	Min	EMT	Max	Min	EMT	Max	Min
	cm	*hr*	°*C*	°*C*	°*C*	°*C*	°*C*	°*C*	°*C*	°*C*	°*C*	°*C*
02/26/08	0.25	2.60	5.3	4.0	4.3	3.3	5.3	5.5	5.2	N/A	N/A	N/A
02/26/08	0.25	1.50	8.6	4.8	4.9	4.7	5.4	5.4	5.3	5.0	5.1	4.4
03/04/08	0.99	3.30	15.3	8.2	8.6	7.0	8.2	9.3	5.5	*	*	*
03/05/08	0.56	2.13	14.7	8.9	9.3	7.1	7.9	8.7	6.7	8.0	10.1	5.7
03/05/08	0.13	1.60	11.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
03/07/08	1.37	8.47	8.5	5.3	5.8	4.7	5.9	6.1	5.6	5.9	6.2	5.3
03/08/08	0.71	10.17	6.7	7.2	8.7	5.8	6.7	7.5	5.8	6.5	6.8	6.0
03/16/08	0.66	6.87	8.7	6.3	6.4	5.8	6.1	6.3	5.9	6.5	6.7	6.4
03/18/08	0.18	2.90	7.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
03/19/08	1.42	7.27	16.5	8.4	9.5	5.5	9.2	10.1	5.9	9.3	10.7	6.5
03/20/08	0.28	1.40	17.7	9.0	9.4	8.7	8.5	9.3	7.8	9.0	10.7	6.5
04/01/08	0.28	4.53	13.9	7.6	8.6	6.4	7.6	7.9	6.8	N/A	N/A	N/A
04/03/08	1.47	12.27	6.8	5.1	5.5	4.9	6.1	6.6	5.7	5.5	6.8	5.1
04/06/08	0.58	5.57	8.6	6.7	6.9	6.5	6.9	7.0	6.7	7.1	7.4	6.8
04/11/08	0.48	0.70	19.6	10.6	11.2	10.0	11.6	11.8	10.2	11.8	13.1	8.9
04/13/08	0.15	1.30	8.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
04/20/08	0.53	0.93	21.6	11.4	12.1	10.0	10.0	11.2	8.7	12.0	12.5	10.2

(contd.)

04/20/08	4.17	3.53	16.7	13.6	14.1	11.7	12.6	13.1	10.1	12.7	13.7	10.9
04/21/08	0.76	1.13	14.1	11.7	11.8	11.3	11.0	11.2	9.5	11.9	14.1	10.9
04/26/08	0.64	4.03	15.4	12.7	13.0	11.9	10.6	11.3	9.4	11.3	12.0	11.1
04/28/08	3.12	10.17	10.6	11.2	11.8	10.5	11.1	11.7	9.2	11.0	12.1	10.3
05/09/08	3.12	14.33	17.7	13.4	13.8	12.2	13.4	14.0	12.1	12.3	13.9	10.6
05/10/08	0.46	5.03	10.0	11.5	11.6	11.3	10.8	11.1	10.6	10.9	12.0	9.0
05/12/08	4.72	26.63	15.6	10.1	11.7	8.8	9.6	11.9	8.2	10.8	11.8	10.2
05/16/08	1.19	9.53	17.8	12.2	12.6	11.6	12.4	12.9	11.5	12.2	12.8	11.3
05/18/08	0.46	4.67	18.1	12.3	12.4	11.9	11.4	12.4	11.0	12.3	12.8	11.3
05/20/08	0.53	2.73	8.8	10.5	10.5	10.4	10.3	10.7	10.1	*	*	*
05/20/08	0.56	1.13	11.6	10.7	10.8	10.6	10.6	10.7	10.5	10.9	11.3	10.1
05/31/08	1.09	3.77	23.2	13.8	14.6	13.2	15.5	16.2	12.9	14.1	15.5	12.6
06/03/08	0.15	0.97	22.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06/04/08	0.99	2.60	19.8	14.8	15.6	14.3	13.2	15.2	12.1	14.8	15.8	13.8
06/04/08	0.84	0.97	27.7	15.7	17.3	14.8	16.9	18.1	14.4	15.6	17.5	14.5
06/04/08	0.10	1.47	21.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06/10/08	1.80	2.93	32.9	16.3	18.3	15.2	14.1	17.6	11.3	15.4	16.4	8.3
06/28/08	0.36	0.47	29.4	20.5	20.9	18.8	18.9	19.7	18.1	16.8	17.3	15.7
06/29/08	0.18	0.13	30.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06/30/08	0.48	0.17	28.3	21.1	21.5	20.2	17.9	18.4	17.4	17.5	18.3	16.7
07/06/08	0.48	0.37	31.0	21.7	21.9	20.6	18.0	19.2	17.3	17.0	18.8	16.5
07/09/08	1.50	0.50	31.9	22.5	22.7	21.6	20.8	21.1	19.6	19.9	22.0	17.6
07/13/08	3.10	12.20	30.8	21.8	24.1	19.6	19.9	21.2	17.4	19.6	22.4	18.0
07/23/08	3.66	5.10	23.8	19.5	19.9	18.7	19.9	20.2	19.1	18.8	20.5	16.9

(contd.)

07/30/08	0.99	0.30	31.9	22.2	22.4	20.2	20.2	20.6	19.4	19.8	22.1	19.1
08/02/08	0.28	1.13	22.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
08/02/08	0.56	0.27	25.7	20.5	20.9	19.2	19.4	20.2	19.0	19.4	20.4	18.4
08/13/08	2.92	2.50	26.9	18.5	18.9	17.5	18.6	19.5	18.0	18.4	19.7	16.6
08/28/08	0.20	0.37	22.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
08/29/08	2.01	12.67	20.0	18.8	19.2	17.0	17.7	18.5	16.6	18.4	19.4	17.3
08/30/08	0.30	0.37	28.0	19.9	20.2	19.6	19.5	19.8	19.1	19.7	20.5	18.7
09/05/08	0.46	4.07	26.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
09/06/08	3.81	8.30	24.2	20.0	20.8	19.1	20.0	20.4	18.0	19.4	21.1	18.3
09/12/08	2.44	10.10	22.8	18.2	19.0	17.5	18.8	19.1	17.1	18.5	19.5	17.7
09/25/08	0.84	3.87	15.3	14.8	15.0	14.8	15.2	16.0	15.0	14.6	15.8	14.1
09/26/08	0.56	0.27	15.8	15.0	15.1	14.3	15.7	15.8	15.5	14.9	15.3	14.2
09/26/08	0.71	8.03	19.5	16.2	16.3	16.1	16.5	16.8	16.2	16.5	16.7	16.1
09/27/08	8.64	17.90	20.0	17.8	18.5	16.2	17.7	18.1	16.7	16.9	18.1	16.3
09/30/08	0.71	3.47	20.8	15.9	16.3	15.5	17.0	17.1	16.7	16.4	16.7	16.5

Note:

Inflow was simulated using TR-55 (Appendix A)

N/A: For these events, no flow was observed

* For these events, outflow was combined with succeeding event

REFERENCES

Armour, C. L. (1991). "Guidance for evaluating and recommending temperature regimes to protect fish". U.S. Fish Wildl. Serv., *Biol. Rep.* 90 (22).

Ayyub, B. M., and McCuen, R. H. (2003). *Probability, statistics, and reliability for engineers and scientists,* 2nd Ed., CRC Press, Florida.

Baldwin, N. S. (1951) as referenced from *2006 Maryland brook trout fisheries management plan*. Maryland Department of Natural Resources, Annapolis, MD.

Bernhardt, E.S., and Palmer, M. A. (2007). "Restoring streams in an urbanizing world." *Freshw. Biol.*, 52 (4), 738–751.

Booth, D. B., and Jackson, C. R. (1997). "Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation." *J. Am. Water Resour. Assoc.*, 33 (5), 1077-1090.

Boward, D. M., Kazyak, P. F., Stranko, S. A., Hurd, M. K., and Prochaska, T. P. (1999). "From the mountains to the sea: The state of Maryland's freshwater streams". EPA/903/R-99/023. Maryland Department of Natural Resources, Monitoring and Nontidal Assessment Division, Annapolis, MD.

Butowski, N., Cosden, D., Early, S., Gougeon, C., Heerd, T., Heft, A., Johnson, J., Klotz, A., Knotts,K., Lunsford, H. R., Mullican, J., Pavol, K., Rivers, S., Staley, M., Toms, M., Kazyak, P., Klauda, R., Stranko, S., Morgan, R., Kline, M., and Hilderbrand, B. (2006). *2006 Maryland brook trout fisheries management plan*. Maryland Department of Natural Resources, Annapolis, MD.

Drake, M. T., and Taylor, W. W. (1996) as referenced from *2006 Maryland brook trout fisheries management plan*. Maryland Department of Natural Resources, Annapolis, MD.

Elliott, S., Jowett, I. G., Suren, A. M., Richardson, J. (2004). A guide for assessing effects of urbanisation on flow-related stream habitat. *NIWA Science and Technology Series,* 52.

Galli, J. (1990). *Thermal impacts associated with urbanization and stormwater management best management practices*. Metropolitan Washington Council of Governments, Washington DC.

Gibson, A. H. (1952). *Hydraulics and its applications*, 5th Ed., Constable & Company Ltd, London.

Grande, M., and Andersen, S. (1991) as referenced from *2006 Maryland brook trout fisheries management plan*. Maryland Department of Natural Resources, Annapolis, MD.

Herb, W. R., Janke, B., Mohseni, O., and Stefan, H. G. (2006). *An analytic model for runoff and runoff temperature from a paved surface*. Project Report No. 484. St. Anthony Falls Laboratory, Minneapolis, MN., Minnesota Pollution Control Agency, St. Paul, MN.

Herb, W. R., Mohseni, O., and Stefan, H. G. (2007). *A model for mitigation of surface runoff temperatures by a wetland basin and a wetland complex*. Project Report No. 499. St. Anthony Falls Laboratory, Minneapolis, MN., Vermillion River Watershed Joint Powers Organization, Dakota County, MN., Minnesota Pollution Control Agency, St. Paul, MN.

Hogg, D. I., and Williams, D. D. (1996). "Response of stream invertebrates to a global-warming thermal regime: An ecosystem-level manipulation." *Ecology*, 77 (2), 395-407.

Hokansen, K. E. F., McCormick, J. H., Jones, B. R., and Tucker, J. A. (1973) as referenced from *2006 Maryland brook trout fisheries management plan*. Maryland Department of Natural Resources, Annapolis, MD.

Huebner, R. S., and Soutter, D. G. (1994). "Predicting in-stream water quality from watershed." *Current practices in modeling the management of stormwater impacts*, W.James, ed., 1st Ed., Lewis, Florida, 65-74.

Incorpera, F. P., and DeWitt, D. P. (1990). *Introduction to heat transfer*, 2nd Ed., Wiley, New York.

Jones, M. P., Hunt, W. F., and Smith, J. T. (2007). "The effect of urban stormwater BMPs on runoff temperature in trout sensitive waters." *Proc., World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat* (CD-Rom), American Society of Civil Engineers (ASCE), Tampa, FL.

Kieser, M. S., Fang, A. F., and Spoelstra, J. A. (2003). "Predicting the impact of urban development on stream temperature using a thermal urban runoff model (TURM)." *Proc., Water Environment Federation*, National TMDL Science and Policy, (24), Los Angeles, CA. Water Environment Federation, 1716-1739.

Kreeb, L.B., and McCuen, R.H. (2003). *Hydrologic efficiency and design sensitivity of bioretention facilities.* University of Maryland, College Park, MD.

LeBlanc, R. T., Brown, R. D., and FitzGibbon, J. E. (1997). "Modeling the effects of land use change on the water temperature in unregulated urban streams." *J. Environ. Manage.*, 49 (4), 445–469.

Lubowski, R. N., Vesterby, M., Bucholtz, S., Baez, A., and Roberts, M.J. (2006). *Major uses of land in the United States, 2002*. Economic Information Bulletin, (14), United States Department of Agriculture (USDA).

MacCrimmon, H. R., and Campbell, J. C. (1969) as referenced from *2006 Maryland brook trout fisheries management plan*. Maryland Department of Natural Resources, Annapolis, MD.

Matweb, "Overview-High density polyethylene (HDPE), injection molded." <http://www.matweb.com/search/SpecificMaterial.asp?bassnum=O4000> (Jun. 27, 2007).

Paul, M., and Meyer, J. L. (2001). "Streams in urban landscape." *Annu. Rev. Ecol. Syst.*, 32, 333-365.

Pluhowski, E. J. (1970). *Urbanization and its effects on the temperature of streams in Long Island, New York.* U.S Geological Society (USGS) Professional paper 627-D.

Raleigh, R. F. (1982) as referenced from *2006 Maryland brook trout fisheries management plan*. Maryland Department of Natural Resources, Annapolis, MD.

Roa-Espinosa, A., Wilson, T. B., Norman, J. M., and Johnson, K. (2003). "Predicting the impact of urban development on stream temperature using a thermal urban runoff model (TURM)." *Proc., Urban Stormwater: Enhancing Programs at the Local Level*, EPA, Chicago, Il., 369-389. United States Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Roberts, B. (1996). "Storm-water treatment goes underground." *Civil Engineering,* 66(7), 56-57.

Rossi, L., and Hari, R. E. (2007). "Screening procedure to assess the impact of urban stormwater temperature to populations of Brown trout in receiving water." *Integr. Environ. Assess. Manage.*, 3 (3), 383-392.

Schroeter, H. O., Van Vliet, D. J., Boehmer, K., and Beach, D. (1996). "Continuous in-stream temperature modeling: integration with a physically-based subwatershed hydrology model." *Advances in modeling the management of stormwater impacts*, W.James, ed., 1st Ed., Computational Hydraulics International, Ontario, Canada, 27-48.

Schueler, T. (1994). "The importance of imperviousness" (feature article). *Watershed Protection Techniques*, 1 (3), 100-111.

Schueler, T. (2003). *Impacts of impervious cover on aquatic systems*. Center for Watershed Protection, Ellicott City, MD.

Seaburn, G.E. (1970). *Effects of urban development on direct runoff to East Meadow Brook, Nassau County, Long Island, New York.* U.S Geological Society Professional paper 627-B.

Sherwood, D.A. (2001). *Effects of a vegetated stormwater-detention basin on chemical quality and temperature of runoff from a small residential development in Monroe County, New York*. WRIR 01-4099. U.S. Geological Survey, NY.

Stranko, S. A., Hilderbrand, R. H., Morgan II, R. P., Staley, M. W., Becker, A. J., Roseberry-Lincoln, A., Perry, E. S., and Jacobson, P. T. (2008). "Brook trout declines with land cover and temperature changes in Maryland." *North Am. J. Fish Manage.,* 28 (4), 1223-1232.

United Nations (2008). Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, *World population prospects: The 2006 revision* and *world urbanization prospects: The 2007 revision*, <http://esa.un.org/unup> (Sep. 29, 2008).

U.S. Census Bureau, Population Division, "State population projections." <http://www.census.gov/population/www/projections/stproj.html> (Sep. 29, 2008).

U.S. Department of Agriculture (USDA) (1986). *Urban hydrology for small watersheds TR 55 Techincal Release 55*. 210-VI-TR-55, 2nd Ed., United States Department of Agriculture, Washington DC.

U.S. Department of Energy (1996). *Working to cool urban heat islands* (Berkeley National Laboratory PUB-775). Berkeley, CA.

U.S. Environmental Protection Agency (USEPA) (1988a). *State water quality standards summary: Maryland*. EPA 440/5-88-055. United States Environmental Protection Agency, Washington DC.

U.S. Environmental Protection Agency (USEPA) (1988b). *Temperature water quality standards criteria summaries: A compilation of state/federal criteria.* EPA 440/5-88-023. United States Environmental Protection Agency, Washington DC.

U.S. Environmental Protection Agency (USEPA) (1999). *Preliminary data summary of urban stormwater best management practices*. EPA-821-R-99-012. United States Environmental Protection Agency, Washington DC.

U.S. Environmental Protection Agency (USEPA) (2000). *Low impact development (LID) A literature review*. EPA 841-B-00-005. United States Environmental Protection Agency, Washington DC.

U.S. Environmental Protection Agency (USEPA) (2005). *National management measures to control nonpoint source pollution from urban areas*. EPA-841-B-05-004. United States Environmental Protection Agency, Washington DC.

Van Buren, M. A., Watt, W. E., Marsalek, J., and Anderson, B. C. (2000a). "Thermal balance of on-stream stormwater management pond." *J. Environ. Engg.,* 126 (6), 509-517.

Van Buren, M. A., Watt, W. E., Marsalek, J., and Anderson, B. C. (2000b). "Thermal enhancement of stormwater runoff by paved surfaces." *Water Res.,* 34 (4), 1359-1371.

Walsh, C. J., Leonard, A. W., Ladson, A. R., and Fletcher, T. D. (2004). *Urban stormwater and the ecology of streams.* Cooperative Research Centre for Freshwater Ecology and Cooperative Research Centre for Catchment Hydrology, Canberra, Australia.

Walsh, C. J., Roy, A. H, Feminella, J. W., Conttingham, P. D., Groffman, P. M., and Morgan II, R. P. (2005). "The urban stream syndrome: Current knowledge and the search for a cure." *J. N. Am. Benthol. Soc.,* 24 (3), 706-723.

Wang, L., Lyons, J., and Kanehl, P. (2003). "Impacts of urban cover on trout streams in Wisconsin and Minnesota." *Trans. Am. Fish. Soc.,* 132 (4), 825-839.

Weatherbe, D. G. (1995). "A simplified stream temperature model for evaluating urban drainage inputs." *Modern methods for modeling the management of stormwater impacts*, W. James, ed., 1st Ed., Computational Hydraulics International, Ontario, Canada, 259-273.

Wehrly, E. K., Wiley, M. J., and Seelbach, P. W. (1998). *Landscape-based models that predict July thermal characteristics of Lower Michigan rivers*. Michigan Department of Natural Resources Fisheries, Ann Arbor, MI., Report No. 2037.

Xie, D. M., and James, W. (1994). "Modelling solar thermal enrichment of urban stormwater." *Current practices in modeling the management of stormwater impacts*, W. James, ed., 1st Ed., Lewis, Florida, 205-219.