1. Rong Fan, hereby submit this original work as part of the requirements for the degree of Master of Arts in Geography.

It is entitled:
Evaluation of the efficacy of different best management practices under current and future climate regimes in Ludlow watershed

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Evaluation of the efficacy of different best management practices under current and future climate regimes in Ludlow watershed

A thesis submitted to the
Graduation School
of the University of Cincinnati
in partial fulfillment of the
requirements for the degree of

Master of Arts

in the Department of Geography
of the College of Arts and Sciences by

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B.S. China University of Geosciences, China, 2008

July 2015
Abstract

As watersheds are urbanized, most of their surfaces will be paved. The impervious surfaces will reduce water infiltration, thereby, increasing the volume of surface runoff. Best Management Practices (BMPs) are used to mitigate these effects of urban land use by retaining large volumes of stormwater runoff.

With continued urban development and the impending changes in our climate, it is essential to have a better knowledge of the effectiveness of BMPs in reducing surface runoff under different climate conditions. As construction and implementation of BMPs is often very expensive, this information will be especially useful in planning long-term development projects and in devising appropriate mitigation strategies to combat future changes in our environment.

In this study, the main objective was to explore the most cost-effective arrangement of BMPs in reducing stormwater quantity under current and future climate regimes. The Ludlow watershed in Kenton County, northern Kentucky, was selected as a case study. A decision-support system, System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) (US EPA 2009b), developed by U.S. Environmental Protection Agency, was used as an assessment tool. A SUSTAIN model for the study area was first developed, calibrated, and validated. It was then used to identify the most cost-effective BMPs arrangement under the current land use and climate conditions. To ensure that these
BMPs will still be appropriate in alleviating future water resources problems, this study also simulated the hydrologic conditions under future climate conditions. The future climate scenarios were developed based on the Intergovernmental Panel on Climate Change (IPCC) Annual Report 4 (AR4) B1 climate scenario (IPCC AR4 2007).

The results of this study reveal the most cost-effective configuration of BMPs in the Ludlow watershed. By simulating the effectiveness of the BMPs in 2030 and 2050 under future climate change scenarios, the findings shed lights on the most appropriate BMPs design. This information may be useful to resource managers and planners in deriving sound water management policies.
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Acknowledgements

This research was partially funded by the U.S. Environmental Protection Agency and the University of Cincinnati. The author gratefully acknowledges the financial support of the agency and the University.

I would like to express my gratitude to my adviser, Dr. Susanna Tong, for accepting me into her group, engaging me in new ideas, and demanding a high quality of work in all my endeavors. Her expertise, understanding, and patience, added considerably to my graduate experience.

I would like to thank the members of my committee, Dr. Joong Lee and Dr. Richard Beck, for the assistance they provided at all levels of the research project. I greatly benefited from their keen scientific insight and ability to put complex problem into simple term.

Last but not the least, I would also like to thank my parents for the support they provided through my entire life and in particular during the course of my study.
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1 Introduction

Advances in industry and technology in the 20th century have resulted in the rapid industrialization and urbanization of what once was a predominantly rural country. One of the many consequences of this rapid growth has been the alteration of the natural waterways and soil profiles. Water, which used to be detained in wetlands and estuaries, or slowly permeate into the groundwater, has been redirected and channelized with paved surface construction. This disruption of the natural drainage system has increased stormwater runoff and deteriorated water quality (Livingston 2001).

In the past decades, the growth of urbanized areas in the United States has been dramatic and even exceeded the population growth. For example, from 1982 to 2007, the population has increased from 231 million to 301 million (30%) while the urbanized areas have increased from 0.29 million km² to 0.45 million km² (55%). This trend is expected to continue in the 21st century, and some studies indicate that the urbanized area will increase by an additional 65 million acres in the first quarter of the 21st century in the United States (Beach 2003; USDA 2006).

With land becoming more urbanized, the pervious surfaces, such as open spaces or forests, that provided temporary storage for stormwater flow or enabled groundwater recharge are covered or altered. In their places are roadways, parking lots, and buildings. As a result, the amount of stormwater runoff generated from a typical storm increases
significantly. In addition, pollutants from vehicles and other atmospheric sources are accumulated on impervious areas and are washed off by stormwater and carried into rivers, lakes, streams and coastal waters (Sample et al. 2003). Figure 1 shows the impacts of urbanization on increasing stormwater runoff. To reduce the impacts of stormwater runoff in urban areas, it is imperative to develop plans to manage stormwater runoff more effectively. The traditional stormwater management schemes often utilize storm drains and other conveyance means to transport the water rapidly off-site. "Green" stormwater management strategies, however, concentrate on allowing the water to permeate into the ground before reaching the piped networks in order to reduce the risk of sewer overflow and the amount of water entering the treatment plants. Methods used for such strategies include strategic site and landscape planning, reducing impervious areas, and treatment of runoff water near the source. These approaches differ from traditional stormwater systems that are designed to detain surface flow, but still convey the stormwater through the water treatment plant (Roy et al. 2008; US EPA 2009b). As such, the implementation of green infrastructure Best Management Practices (BMPs) is a more effective way to manage stormwater runoff with respect to both flow quantity and flow quality. BMPs consist of systems designed to prevent or reduce the volume of water runoff from entering the stormwater collection system. The primary purposes of BMPs are to store, permeate, evapotranspire, and filter the stormwater on site to reduce the volume and peak flow discharges and control water quality.

The main objective of this research was to create a stormwater management model for the Ludlow watershed in Kenton County, northern Kentucky. The SUSTAIN modeling
software was used to guide future BMP installation decisions, such as the types and locations of BMPs, by simulating the efficiencies of different arrangements of BMPs in reducing surface runoff.

The use of hydrologic models and methods to help in identifying the optimal locations of BMPs started in the early 80s. These early studies were mostly focused on water quantity but not water quality. But the desire for sustainable development had necessitated the integration of different components of stormwater and sewer systems (Delleur 2003). As such, stormwater management plans and BMP implementation strategies started to consider not only water quantity but also water quality (Arnold et al. 1998).

Since the early 1980s, the use of computer simulation models has resulted in significant changes in the field of stormwater management. Application of hydraulic and hydrologic computer models facilitated the simulation of hydrologic impacts of stormwater runoff and the performance of BMPs in urban and rural areas (Delleur 2003). In 1982, a study was conducted to optimize the size and location of BMPs in a stormwater catch basin. The methodology used in that project involved combining dynamic programming algorithms and traditional methods to simulate the performance of BMPs in the study area (Mays and Bedient 1982). While new methods were developed in simulating BMPs performance, only the size and location of BMPs were the factors taken into consideration. In 1997, Kao utilized multi-objective linear programming to determine the most cost effective BMPs in reducing phosphorus downstream of a watershed (Kao and Tsai 1997).
It was a big progress to determine the cost-effectiveness of BMPs instead of only location and size. However, their study only evaluated water quality factors. Newer methods have been utilized in recent BMP implementation projects. These methods, including the genetic algorithm (GA), have been used in computer modeling to identify mathematically the most effective BMP implementation strategies. GAs are search algorithms that mimic the process of natural genetics used for some types of optimization on mixed or combinational problems. The processes in these algorithms include evaluating potential solutions with regard to the obtained information in order to define the solutions with higher effectiveness (Li et al. 2002). Utilizing GAs in BMP optimization results has many advantages. First, the output would include not only one solution but many near optimal solutions for the problem. Also, different assessment points could be taken into account using these algorithms. A study in 2002 indicated that genetic algorithm could be utilized together with pollution model in order to optimize BMPs implementation (Srivastava et al. 2002). There are multiple examples of utilizing GA and integrating it with other hydrologic techniques for optimizing BMP implementation. For example, Perez-Pedini et al. (2005) combined a rainfall-runoff model with a genetic algorithm to identify the best BMPs implementation strategy to reduce peak flow discharge in an area in the northeast United States. In 2010, Kaini et al. (2012) integrated a genetic algorithm with a semi-distribution hydrologic model, Soil and Water assessment Tool (SWAT), to identify the best strategy for implementing BMPs in order to achieve the treatment goals in an area. Their project was based on reducing sediment and nutrients from runoff. However, they neglect the factors, such as environment and construction costs and feasibilities, in their analyses.
In some of the BMP implementation reports, the performance of BMPs was assumed to be constant during the entire life of the facility. However, since different environmental impacts, such as clogging, could affect the performance of BMPs, it is critical to estimate the long-term performance of the BMPs. In 2008, a study in New England utilized EPA's Stormwater Management Model (SWMM) and the BMP Decision Support System (BMPDSS) to examine the long-term effectiveness of eight types of BMPs under different land uses based on a variety of water quality goals. The results were used to evaluate the cumulative performance of BMPs over a long period of time (Tetra Tech 2013). Despite new algorithms and hydrologic models were used in these studies, the cost-effectiveness of BMPs was not considered. As such the information derived from these studies was still inadequate to be utilized in BMPs construction and in deriving future management plans.

2 Methodology

2.1 Study area

The Middle Ohio-Laughery watershed, with the 8-digit HUC number 05090203, is located in Indiana-Kentucky-Ohio Tri-State region (Figure 2). The Dry Creek – Ohio River (DCOR) watershed, with the 12-digit HUC number 050902030202, lies in the east of the Middle Ohio-Laughery watershed. The DCOR watershed encompasses an area of approximately 141.02 km², and it lies within the Cincinnati-Northern Kentucky Metropolitan Area (Figure 3). The Ludlow watershed, which is within the DCOR watershed, is selected as the study area in this research.
Located in Kenton County in northern Kentucky and on the south side of the Ohio River, the Ludlow watershed has an area of 1.24 km$^2$ and a perimeter of about 6357.84 m. A small watershed was chosen in this study because detailed BMP analyses often require a fine resolution scale. This small area include most of urbanized land use types. From the 2006 National Land Cover Database (NLCD) land use data (Figure 4 & Table 1), the dominant land use category in the watershed is deciduous forest at 47.08%, while the medium intensity developed area is about 27.27% of the whole watershed. Impervious land, which is mainly the developed area, such as buildings, roads, and parking lot, occupies about 46.64% of the watershed, while vegetation-covered land is over 53.36% of the watershed. Table 2 shows the general land use types in the watershed.

The watershed is sloping gently to the north. Pleasant Run Creek rises between South Fort Mitchell and Lakeside Park, Kentucky, and flows generally northeast through lightly urbanized development before entering the Ohio River between Ludlow and Bromley. Historically, Ludlow was the site of the regionally significant Ludlow Lagoon Amusement Park. But as it locates minutes from downtown Cincinnati, the population in the watershed has grown substantially, and its land use has been changed rapidly.

The Northern Kentucky and Cincinnati region spreads over a number of hills, bluffs, and low ridges overlooking the Ohio River in the Bluegrass region of the country (Brockman 1998). It is a populous and urbanized area in mid-west. Cincinnati is the third largest city in Ohio and the 28th largest Metropolitan Statistical Area (MSA) in the United
States. Its metropolitan population was 2,114,580 in 2010 (U.S. Census Bureau 2013). The population of the metropolitan area has grown 8.1 percent between 2000 and 2009 (U.S. Census Bureau 2013). Lying at the heart of the tristate area, the Ludlow watershed is experiencing increasing problems in terms of water resources because of the recent urban developments.

The climate of the Ludlow watershed is cool and wet; its average daily temperature varies from -5°C to 12°C in mid-winter and from 17°C to 31°C in mid-summer. In Winter and Spring, rains generally come in low intensity but last over a longer period of time, while high-intensity and short-duration rain events occur in Summer. The average annual precipitation is 1694.5 mm; its total rainfall is 1084.6 mm, while that for the United States is 927.1 mm, and its total snowfall is 469.9 mm comparing to 635.0 mm in United States (NCDC 2012). The average number of precipitation days per year in the watershed is 120, while that for the United States is 100.

Located within a climatic transition zone, the Ludlow watershed is at the extreme northern limit of the humid subtropical climate. Evidence of both humid subtropical climate and humid continental climate can be found, and plants indicative of each climatic region are present in the watershed. Other factors, including the presence of the Ohio River, the hilly terrain, and the urban heat island due to the proximity of the Cincinnati/Northern Kentucky metropolitan area, also affect the overall climate of the study area.
There are several reasons for choosing the Ludlow watershed as the study area. First, the research area is composed of both developed (constructed and paved) and undeveloped (vegetation-covered) areas, which is typical in urban areas, and research on this type of land is instrumental to shed light on flood control (Criss and Shock 2001; Konrad 2003). Second, there are major flooding within the flood plain along the Ohio River. Hundreds of homes, businesses, and many low-lying roads near the river are frequently flooded. Located on the southern bank of the Ohio River, the study area is often flooded during intense rainfall (Neff 2006). Stream gradient is extremely steep upstream from the flood plain of the Ohio River. As the valley is narrow with very little flood plain, extreme stream velocities are the rule rather than the exception. Hence, there is a need to install BMPs to control flooding (Federal Insurance Administration 1979). Third, while there is a relatively large amount of literature addressing the optimal network of detention pond storm water control structures on a watershed, to my knowledge, there are only a few attempts to determine the optimal number and locations of BMPs in this area (Horn and Grayman 1993; Snead 2000). With the impending changes in climate and land use, the threats of flooding may be heightened; it is therefore essential to determine the optimal number and locations of BMPs to mitigate future flash floods in this area.

2.2 Hydrologic modelling using SUSTAIN

2.2.1 Data

To evaluate the cost-effectiveness of BMPs in the Ludlow watershed, several GIS data layers are needed. The National Oceanic and Atmospheric Administration (NOAA)
provides a Global Historic Climatology Network Daily Summaries (GHCND) database (NOAA 2012), which contains station-based climate records. The daily maximum and minimum air temperature time series data for this study were obtained from the Cheviot, OH (GHCND: USC00331515) National Climatic Data Center (NCDC) station at 39.15°N and 84.62°W, and hourly precipitation were obtained from the Cincinnati Northern Kentucky Airport (COOP:151855) NCDC station at 84.67°W and 39.04°N. Both data sets were abstracted from the NOAA website (NOAA 2012). Data required to generate the future climate scenarios were derived from the Intergovernmental Panel on Climate Change (IPCC) World Climate Change Projections-SRES B1 scenario final data for 2030 and 2050 periods (IPCC 2007). These future time periods were chosen because BMPs generally have a life span of 20 to 40 years. Besides, watershed planning often entails such a time frame. The 2001 and 2006 land cover data were obtained from the NLCD database (Fry et al. 2011; Homer et al. 2007). Soil data for the Ludlow watershed (including soil types, textures and other features) were retrieved from the USDA STATSGO database published in 1995 (Schwarz and Alexander 1995). Soils are categorized in four hydrological groups: A, B, C and D with high permeability in group A and very low permeability in group D. The map of the Ludlow watershed was derived from the National Hydrography Dataset Plus (NHDPlus). It is an integrated suite of application-ready geospatial data sets that incorporate many of the best features of the National Hydrography Dataset (NHD) and the National Elevation Dataset (NED) published by U.S. Environment Protection Agency, USEPA (US EPA 2005). The observed water discharge data (m³/s, from September 2007 to November 2008) for model development, calibration, and validation were collected from the U.S. Geological Survey (USGS) gage station (USGS
03260015 PLEASANT RUN CREEK AT OAK STREET NEAR LUDLOW, KY) at 39.09°N and 84.56°W NAD27 in Kenton County, Kentucky. The available discharge data from this gage station were from August 1, 2007. To be consistent with the available NOAA climate data and land use data, the hydrologic year from October 2007 to September 2008 was selected to determine the current optimal number and locations of BMPs.

### 2.2.2 Stormwater management and SUSTAIN

Stormwater management starts with analyzing the area and defining the issues, the aim, and scope of the plan according to the problems in current or future conditions. BMPs are often used in stormwater management to reduce storm water runoff and peak flow. As such, they can help to ameliorate the hydrologic conditions in a watershed. Studies show that the effectiveness of various BMPs is based on different characteristics of the area, such as land use, climate, and hydrologic conditions (Park et al. 1994; Strecker et al. 2001; Zomorrodian 2013). To estimate the effectiveness of BMPs, it is more accurate to use dynamic models rather than traditional techniques that rely either on field measurements or merely on the calculation of evaporation and transpiration as a residual of a water balance (Ackerman and Stein 2008).

There are several software programs available to model BMPs. Storm Water Management Model (SWMM) (Rossman 2010) is one of the public domain models for simulation of sewer systems hydraulics, but it considers only settling and first-order decay in in-stream pollutant routing and transformation (Rossman 2010). Hydrological
Simulation Program--Fortran (HSPF) (Bicknell et al. 2001) is another watershed model, and it can comprehensively simulate watershed hydrology and associated water quality processes on pervious and impervious land surfaces. It performs land-to-land routing, and it offers base flow and interflow simulation. It, however, does not perform dynamic hydraulic flow routing in the simulation. Loading Simulation Program in C++ (LSPC) (Tech and Center 2009) includes a streamlined set of HSPF subroutines and algorithms. Thus, it also does not fully perform dynamic hydraulic flow routing.

In this study, to optimize and evaluate the implementation and cost-effectiveness of BMPs, System for Urban Stormwater Treatment and analysis Integration (SUSTAIN) (US EPA 2009b) was chosen to simulate the current hydrologic condition and the future condition based on the proposed BMP development in the study area.

SUSTAIN is an ArcGIS based decision-making support tool to assist in selecting, designing, and placement of BMPs in both urban and rural watersheds in order to control the quantity of stormwater and to alleviate water quality problems. It consists of hydraulic and water quality models for identifying optimal stormwater management strategies so as to achieve multiple objectives at the least cost. SUSTAIN uses a graphical platform by which users can have the ability to visualize the area, allocate the BMPs, and identify the linkages (US EPA 2009b). It also has the ability to integrate with other stormwater management models, such as SWMM and InfoWorks (Liew and Ghani 2009), by accepting other modeled information of the watershed as input. SUSTAIN adapts SWMM and HSPF, as well as LSPC, which is a C++ version of HSPF. While the others are analytical models,
SUSTAIN is a design and planning tool, so it is the best choice for this study to evaluate the performances of the selected BMP ensembles and their associated costs.

In this study, a BMP model was developed using SUSTAIN. Suitable places in the study area for installing different types of BMPs were first identified. Then, the performance of the installed BMPs under the historical and future climate conditions was evaluated. The results of the performance and cost of various BMP options and their placement scenarios were compared, and the best strategy identified based on the total implementation costs and the environmental benefits.

In this research, SUSTAIN's BMP siting tool was used to identify suitable areas to install different types of BMPs. Based on the suitability criteria on appropriate soil type, road, building and parking buffer, drainage slope, imperviousness, water table depth, and drainage area for each type of BMP, GIS analysis was performed on different types of datasets. The suitability criteria were derived from two USEPA reports (US EPA 2004a; US EPA 2004b). They are detailed in Table 3.

2.2.3 BMP selection and implementation

The evaluation of the performance of BMPs and their costs involved analyzing an assortment of BMP arrangements. After collecting the required information and inputting the needed data in SUSTAIN, different BMPs would be chosen for simulation. BMP simulation included defining their placement scenarios, configuration, and cost. In SUSTAIN, each BMP was installed in one single subwatershed for simulation. In this study,
three subwatersheds were delineated based on different hydrologic information of the area, such as surface flow direction and land use type. The characteristics of these three subwatersheds are detailed in Table 4.

SUSTAIN estimates the performance of BMPs in a user defined time period. Figure 5 represents the annual precipitation recorded in station COOP: 151855, the Cincinnati Northern Kentucky Airport, from 1980 to 2010. After analyzing the precipitation patterns in recent years and taking into account of the availability of other climatic data, the hydrologic year 2008 was selected as the simulation period for the development of the base model. The annual precipitation in 2008 was 75.18mm, which is very close to the 30-year average (76.24mm) between 1980 and 2010. This simulation period therefore represents the average climatic conditions in Ludlow, Kenton County. Moreover, there was no big storm event occurred in that year. Data on temperature, land use, and BMP costs, close to this period are also available.

To identify the most cost-effective BMPs configuration and arrangement in terms of numbers and locations, the watershed was divided into three subwatersheds based on terrain, land use, and geological characteristics. The performance of BMPs changes according to the hydrologic characteristics and the rain events in the study area. Furthermore, it depends on the tradeoff between the environmental benefits, such as flow reduction and the cost of installing and implementing the BMPs. The consideration of these
factors would assist in selecting the number and the locations of BMPs to achieve the best results under a specific budget (Damodaram et al. 2010).

The evaluation of the performance of BMPs and the identification of the most cost effective scenarios involve analyzing an assortment of BMP practices. The BMP siting tool in SUSTAIN is developed to assist users in selecting suitable locations for different types of BMPs. The tool is implemented using ESRI's ArcView and the Spatial Analyst extension. Site suitability is used as the dominant factor in identifying potential site locations (US EPA 2004b). The siting tool uses GIS analysis to help users identify suitable sites for placement of structural BMPs on the basis of a series of suitability criteria, including elevation, slope, soil type, urban land use, stream location, and drainage area. The output of the siting tool is a suitability index map of the watershed, which illustrates the areas that meet the defined criteria for installing each type of BMPs (Figure 6). Hence, the results can serve as a guide for determining the types and locations of the BMPs.

The results of the BMP siting tool analysis show that bioretention and infiltration trench are the most appropriate stormwater management tools for the Ludlow watershed. There are three suitable locations and arrangements of BMPs (Figure 7). Arrangement 1 shown on the first map shows that infiltration trenches can be installed in Subwatershed 1 and Subwatershed 3, while bioretention can be installed in Subwatershed 2. In Arrangement 2, the infiltration trench in Subwatershed 1 and bioretention in Subwatershed 2 can be remained in the same locations, while the infiltration trench in Subwatershed 3 is replaced by bioretention in a different location. In Arrangement 3, the locations of the
infiltration trench in Subwatershed 1 and bioretention in Subwatershed 3 can be kept the same, while an infiltration trench replaces the bioretention in Subwatershed 2 but in the same location.

After collecting the required information and inputting the needed data in SUSTAIN, specific BMPs should be defined and their placement scenarios, configuration, and cost should be evaluated. The cost for each type of BMP was derived from SUSTAIN BMP cost database. Table 5 shows the cost information for these two types of BMPs as abstracted from SUSTAIN BMP database. The dimension of BMPs can be set as a decision parameter, and SUSTAIN would create different scenarios based upon different dimensions during the simulation.

In addition to defining BMP types and locations, SUSTAIN requires the specification of the virtual outlet in each subwatershed. According to the direction of the stream flow and surface runoff, the outlet was put near the discharge station COOP: 151855. Table 6 shows the information of different types of BMPs selected for the simulation.

2.2.4 BMP simulation

There are two options for simulating the performance of BMPs by SUSTAIN: internal and external simulations. In internal simulation, the land module computes the hydrograph using algorithms adapted from the SWMM (version 5) land surface compartment and sediment algorithms adapted from the HSPF model. Conversely, external simulation utilizes externally generated time series to represent hydrology and water
quality at the landscape level, which allows importation of the hydrograph and pollutograph for each land use category from a pre-calibrated external watershed model. In this study, since most of the parameters, including land use and rain gauge, were chosen in SUSTAIN, and the weather data were processed by converting the precipitation values to snow or rain according to temperature and imported into the system, the internal simulation method was selected to compute the hydrograph using algorithms adapted from version 5 of the land surface compartment in SWMM.

SUSTAIN requires runoff time series data in order to drive the simulation. In internal simulation, the time series data are created by the land module of SUSTAIN. The land simulation module computes the hydrograph based on information about climate and subwatershed characteristics. It estimates the amount of runoff during rain events based upon precipitation, evapotranspiration, infiltration, groundwater outflow, and groundwater recharge (US EPA 2009b).

BMPs in SUSTAIN are simulated using a combination of fundamental algorithms to represent the processes of storage, routing, infiltration, evapotranspiration, underdrain infiltration, and pollutant routing and removal (US EPA 2004a). SUSTAIN supports two options for the simulation of infiltration in BMPs: (1) the Holtan-Lopez equation adopted from the Prince George’s County BMP module (Tetra Tech 2001) and (2) the Green-Ampt equation as is applied in the SWMM (Rossman 2010). In this study, the Holtan-Lopez equation was selected to simulation the infiltration of BMPs as the Green-Ampt method.
does not include a parameter to explicitly reflect the effects of the vegetation root zone on the infiltration rate.

An assessment point is the location where the amount of runoff is evaluated. In this study, the assessment point was located at the gage station of the watershed (Figure 4). At this assessment point, the average annual flow volume was selected as the evaluation factor to compare with that monitored under the existing condition, and the results were expressed as percentage values (from 0-100%). After defining the evaluation point and evaluation factor, an input file for the simulation period would be created. Then the model would be run to obtain the simulation results.

2.3 Model calibration and validation

After the Ludlow watershed SUSTAIN model has been developed, it has to be calibrated and validated to ascertain its reliability. Without measured discharge data for the Ludlow watershed, the water balance and stream flow in the Ludlow watershed was assumed to be similar to that derived from the Licking Basin (Figure 8). The Licking Basin is the drainage area of a USGS gage station near Ludlow (gauging station: USGS 03260015 Pleasant Run Creek at Oak Street near Ludlow, KY), and its land cover type is similar with that of the Ludlow watershed. The model was calibrated by comparing the simulated flow results from SUSTAIN with the observed daily discharge records from the gage station and iteratively adjusting the values of the model parameters to match the local conditions of the river basin by trial-and-error until the error rate between simulated and observed streamflow was acceptable. Following Bicknell et al. (2001) and Tong et al. (2012), the
error rate was calculated as \[ \sum (\text{simulated value} - \text{observed value})/\sum \text{observed value} \]. By showing the differences between the simulated results and the monitored values as a percentage of the monitored value, the percentage error can reveal how close the simulated values are to the actual monitored values.

After calibration, the Ludlow watershed SUSTAIN model was validated to ensure that the model could fairly accurately simulate the real world conditions even under different climate regimes. In this study, the validation was performed by using the same parameters of the calibrated model, the same 2006 land use data, but different historic climate data, from October 2008 to September 2009. Similar to that of the calibration, the validation involved the comparison between the estimated and observed values of each month by the error rate.

2.4 Simulation under future climate change scenarios

Climate change poses a variety of challenges for water management, and there is a need to develop methods to enhance our understanding of the impending hydrologic impacts and to manage the potential risks. The Fourth Assessment of the Intergovernmental Panel on Climate Change states that an increasing concentration of greenhouse gases in the atmosphere is likely to cause an increase in global average temperature of between 1.1°C and 2.9°C degrees over the 21st century even under the global environmental sustainability scenario (IPCC AR4 2007). Freshwater resources are highly sensitive to variations in weather and climate. The changes in global climate that are occurring as a result of the accumulation of greenhouse gases in the atmosphere will affect freshwater availability and
will alter the frequencies and magnitudes of floods and droughts. Total surface flows, probabilities of extreme high or low flow conditions, seasonal runoff regimes, groundwater–surface water interactions and water quality characteristics could all be significantly affected by climate change over the course of the coming decades.

In this study, the seasonal precipitation and temperature data from the IPCC B1 scenario were employed to generate the future climate scenarios. The B1 scenario storyline describes a convergent world with global population that peaks in mid-century and declines thereafter. There will be a rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives (IPCC AR4 2007). The assumption under the IPCC B1 scenario is that people desire for a clean environment and a gradual depletion of the conventional fossil fuels. The governments, businesses, the media, and the public pay increased attention to the environmental and social aspects of development (Nakicenovic and Swart 2000). As people are becoming more knowledgeable of their impacts on the environment and are now more responsive to mitigation strategies that would enable developments that are more economically, socially, and environmentally sustainable, B1 seems to be the most appropriate development scenario for our future. Because of this reason, B1 scenario was chosen in this study.
To simulate the future precipitation and temperature in 2030 and 2050, many scientists averaged the values of climate variable over the 20 years of the General Circulation Model (GCM) simulation from 2000 through 2099. Using the simple anomaly method by modifying a historical baseline with differences or ratios projected by the GCMs, scientists from the California Academy of Sciences downscaled monthly average temperature and monthly total precipitation from 16 different GCMs. The disaggregated future climate data were applied to the Community Climate System Model (CCSM 3.0). CCSM 3.0 is one of the GCMs used by IPCC. It is a coupled climate model for simulating the earth's climate system (Collins et al. 2006) and has been widely used in many research of climate change (Back et al. 2013; Perkins et al. 2007; Ren and Karoly 2006). The climate data of 2020-2039 were used in this study to predict the 2030 hydrologic conditions, while the climate data for 2040-2059 were used to predict the 2050 hydrologic conditions. The amount of the total surface runoff and river discharge in the Ludlow watershed were then simulated from the model.

3 Results and Discussions

3.1 Calibration and validation results

The calibration process is a long and tedious adjustment of parameters. It is a time-consuming task to find a suitable value for each parameter. After numerous trials adjusting various parameters, including the Zero Impervious Percentage (% Zero Imp), Depth of depression storage in pervious area (Dstore Perv), Maximum Infiltration Rate (Max Infil
Rate), Minimum Infiltration Rate (Min Infil Rate), Drying Time, and Maximum Infiltration Volume (Max Infil Vol), the Ludlow watershed SUSTAIN model finally provided an acceptable performance with an percentage error of approximately 1.98% (Table 7). The calibration results also show a correlation coefficient of 0.76 between simulated and observed flows (Table 7). Based on historic climate data, precipitation in Ludlow watershed occurs mostly as irregular, high-intensity, and short-duration storms in Summer (June to August) and low-intensity but long-duration rainfall events in Winter (December to February). The calibration results also show that the percentage error from Dec 2007 to Feb 2008 is 7.14%, while the percentage error from Jun 2008 to Aug 2008 is 9.43%. The correlation coefficient values are 0.92 and 0.99, respectively.

In the validation, the 2006 land use, 2008-2009 weather data, and the parameter values used in the calibration were used. The validation results show a small difference (3.55%) between simulated and observed values, and the correlation coefficient between simulated and observed flows is 0.85 (Table 7). The percentage error and correlation coefficient values in Winter and Summer are 5.49%/0.93 and 4.83%/0.99, respectively (Table 7).

According to literature (Bicknell et al. 1996), a percentage error below 10% in flow simulation is considered as very good, and a range from 10 to 15% is regarded acceptable. As both the calibration and validation results are within acceptable limits (Table 8) (Tetra Tech 2013), the developed Ludlow watershed SUSTAIN model is deemed to be accurate enough to simulate the hydrologic conditions in the study area.
3.2 Predictions of hydrologic conditions in 2030 and 2050

Among the climatic community, the general consensus is that the future climate will be warmer. However, the predictions of precipitation from different GCMs and different development scenarios are inconsistent. Some of the predicted results indicate an increase in precipitation, whereas others depict a decrease.

In this study, the future hydrologic conditions in 2030 and 2050 were simulated using the data from the IPCC AR4 B1 climate scenario Table 9 lists the temperature change at the end of the 21st century under the IPCC B1 scenario as compared to the situation of the end of 20th century. Table 10 and Table 11 show the temperature and precipitation changes under the B1 scenario as compared to the 2008 climate conditions. They show that, generally, the climate of the study area will be drier. Notwithstanding the precipitation in Fall has an increasing trend, especially from 2008 to 2030, this trend will not be as prominent for 2030 to 2050 as that for 2008 to 2030.

To analyze how climate change would affect the hydrologic conditions in the Ludlow watershed, two simulations using the future climate data in 2030 and 2050 were performed. The land-use data and other data remain the same as those in current scenario. When compared to the current scenario, where the climate and land use conditions were kept at the 2008 level, future climate change would alter the flow regime. Table 12 shows that when climate change is considered, the amount of river discharge will decrease in Winter, Spring, and Summer, implying that the area will become drier in these seasons. There will
be a decrease of 31.5% flow under the 2030 scenario and a decrease of 27.4% under the 2050 scenario. These results show that under the IPCC AR4 B1 scenario, in 2030, with a 13.09% increase in temperature and a 21.71% decrease in precipitation, the daily flow will be reduced by 0.23 m$^3$/s, which is a 31.5% reduction. Similarly, in 2050, a 15.87% increase in temperature and a 19.99% decrease in precipitation will induce a reduction of 0.20 m$^3$/s, or 27.4%, in daily flow.

Although under these future climate scenarios, there will be a decrease in flow in the watershed, BMPs may still be beneficial to control flash floods, especially during and after intense rainstorms.

3.3 Modelling results from SUSTAIN under current climate conditions

The effectiveness of a BMP is better analyzed from a long-term continuous simulation. The BMP design optimization problem of this study can be formulated as follows:

$$\text{Minimize } \sum_{i=1}^{23} [\text{Cost (Bioretention)} + \text{Cost (Infiltration Trench)}]$$

where $i =$ each subwatershed, Reduction (%) = ($P_{\text{Current}} - P_{\text{BMP}}$)/$P_{\text{Current}}$, $P_{\text{Current}} =$ flow volume from the current existing condition, and $P_{\text{BMP}} =$ flow volume with BMPs. In order to present a wide range of BMP implementation scenarios, a cost-effectiveness curve based on annual flow volume reduction was developed in this study as presented in Figure 9 for Arrangement 1. Each data point in the figure represents the removal effectiveness and the
associated cost of a BMP implementation scenario. The dotted line in Figure 9 represents optimal (i.e., least-cost) or near-optimal solutions for a wide range of removal effectiveness on annual flow volume reductions. If distributed BMPs are installed to accomplish about 40% of annual flow volume reduction, the least-cost option for the BMP implementation requires about $1,500,000.

To evaluate the most cost-effective combination of BMPs in the Ludlow watershed, three arrangements of BMPs were simulated and evaluated in SUSTAIN (Table 11). From the cost-effectiveness curves, it can be concluded that when the flow reduction is 40%, the cost of the BMPs under Arrangement 2 is approximately $2,000,000, a 33.33% more expensive than that under Arrangement 1. The cost under Arrangement 3 is 46.67% more expensive than that under Arrangement 1, which is about $2,200,000. Similar situation is found when the flow reduction is 50% reduction. Arrangement 2 is 30.00% more expensive than Arrangement 1, which is $2,600,000 comparing with $2,000,000, and Arrangement 3 is 45% more expensive than Arrangement 1 as the cost of BMPs under Arrangement 3 is $2,900,000. Another similar case is found under a 60% flow reduction. The cost of Arrangement 1 is $3,200,000, while the cost of Arrangement 2 and Arrangement 3 are $4,100,000 and $4,800,000, respectively. The Arrangement 2 and Arrangement 3 scenarios have 28.13% and 50.00% higher cost comparing with that of Arrangement 1.

These results demonstrate that in order to reduce 40%, 50%, or 60% of the flow in the outlet of the Ludlow watershed, Arrangement 1 will cost less when compared with Arrangement 2 and Arrangement 3. It implies that Arrangement 1, with two infiltration
trenches and one bioretention (Figure 7a) is the most cost-effective configuration of BMPs in the Ludlow watershed under the current climate condition, comparing with other BMP configurations.

3.4 Modelling results from SUSTAIN under future climate conditions

After applying the future climate conditions from IPCC AR4 B1 scenario to SUSTAIN, the 2030 and 2050 hydrologic conditions as well as the cost-effectiveness of BMPs under Arrangement 1 were simulated. The cost-effectiveness curves were generated based on the 2030 and 2050 climate scenarios (Figure 10 and Figure 11).

In 2030, if the average temperature increases while the precipitation decreases, the BMPs which cost $1,500,000 can reduce about 36% flow (Table 14). The BMPs with the same cost can cause 40% flow reduction in 2008. Similarly, the flow reduction of BMPs which cost $2,000,000 will decrease from 50% in 2008 to 43% in 2030. The BMPs which cost about $3,200,000 can reduce about 60% of flow, but they can only reduce 50% in 2030. Judging from these results, it is evident that in 2030, the installed BMPs in Arrangement 1 have significant impacts on flood reduction. In 2050, however, the BMPs which cost $1,500,000 can reduce about 40% of flow, which is similar to the reduction in 2008. For BMPs which cost $2,000,000, the flow reduction in 2050 is about 48%, quite close to the 50% reduction in 2008. BMPs which cost $3,200,000 can reduce about 57% flow in 2050, which is also close to 60% in 2008.
The results of this study show that the flow reduction by the BMPs will be less than that under the current (2008) condition. This is mainly because, according to the IPCC AR4 B1 scenario, there will be a lesser amount of precipitation in 2030 and 2050. As the simulation of flow reduction by BMPs in SUSTAIN is dependent on the precipitation input, a lower amount of future precipitation in the study area will therefore instigate a lower percentage of flow reduction by the BMPs in the future. However, the results from this simulation exercise show that the installation of BMPs with configurations such as Arrangement 1 can still contribute to flow reduction in 2030 and 2050 as in 2008 despite the precipitation may be decreased in the next 20 and 40 years. It implies that this BMP configuration would be appropriate not only under the current but also the future climate scenarios in controlling stormwater runoff in the Ludlow watershed and reducing potential flood risks.

It has to be noted that aside from B1 scenario, other development scenarios or other GCMs provide a different prediction for the amount of future precipitation; many modeling results postulate that there will be an increase in precipitation. Most importantly, the simulation exercises reported in the study only examine the average climatic conditions. But future climate change may entail more extreme weather events, and intense storms can cause more flash floods. Under these conditions, BMPs will be particularly instrumental in stormwater management and in mitigating flood events.

Conclusions
This research attempts to explore the most cost-effective BMPs in the Ludlow watershed under the current climate condition and future climate scenarios. By developing a SUSTAIN model for the study area, the research successfully identifies the best combination of BMPs to reduce flow and ascertains the efficacy of BMPs under the impacts of climate change in the years 2030 and 2050.

To determine suitable locations for installing BMPs, SUSTAIN's BMP siting tool generates the potential locations for installing different types of BMPs. The output of this tool, a BMP suitability map, provides useful information about different potential locations for implementing BMPs. This information can be used in future stormwater management plans. In addition, by utilizing the BMP simulation module of SUSTAIN, different BMP options are identified based on different budgets. The simulation results can be used for estimating the current hydrologic condition of the Ludlow watershed and determining the most cost-effective scenarios for future watershed stormwater management plans.

The simulation model of this research was created based on the geographical and climatic information of the Ludlow watershed. This model can further be utilized to evaluate the efficiency and performance of BMP plans other than the ones that have used in this study.

From the results of the present research, it is obvious that BMPs can help in stormwater management by reducing the stormwater runoff volume and peak flow discharge in the Ludlow watershed. Hence, efforts to resolve these problems should be included in any
future water management plans in the Ludlow watershed. In general, under the current climate condition, Arrangement 1, which includes two infiltration trenches, one in Subwatershed 1 and the other in Subwatershed 3, and one bioretention in Subwatershed 2, is the most cost-effective arrangement in the Ludlow watershed to reduce surface runoff. This research also provides some recommendations on the most cost-effective combination of BMPs to reduce urban surface runoff in the Ludlow watershed. This information can be of value to decision-makers as they devise their adaptation and mitigation strategies to minimize the adverse impacts of flow and non-point source pollution in the face of the impending changes in climate and land use.

While this study reveal some useful information, the results should be used with care. One of the issues that may change the reliability of the results is the accuracy of the precipitation data used in the simulation. In this research, the hourly precipitation data collected from the climate station located near Cincinnati Northern Kentucky Airport have some missing values, which may affect the model results. Another limitation is that SUSTAIN does not consider the sewer system network in the simulations, which can affect the direction of stormwater runoff. In simulating the future scenarios, the future temperature and precipitation data generated using the IPCC AR4 B1 scenario are roughly linear amplified, and there are no climate data under extreme storm events. Because of this reason, in this study, when the future flow reductions by the BMPs were simulated, future storm events were not considered. Hence, the results reported in this paper only reflect the average climate conditions. However, weather phenomena, including intense convective thunderstorms, torrential storms and hurricanes, extratropical cyclones and frontal
passages, can cause flash flood, which usually deliver more precipitation to a drainage basin. BMPs are more important in stormwater management under these conditions.

Nonetheless, this research shows that SUSTAIN is a reliable and convenient tool for predicting the future hydrologic impacts of climate changes and estimating the efficacy of BMPs in flow reduction under such conditions. It may be useful to environmental scientists, state and local agencies, watershed managers, and regional planners.
References


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Figures

Figure 1 Urban runoff under different ground cover

Figure 2 Location of Ludlow watershed

Legend

- Major Streams
- State Boundary
- Middle Ohio-Laughery Watershed
- DCOR Watershed
- Ludlow Watershed

Source: USDA Data, ESRI Data
Figure 3 The Dry Creek – Ohio River watershed within Cincinnati-Northern Kentucky metropolitan area
Figure 4 A land use map of the Ludlow watershed

Source: Wickham et al., 2013
Figure 5 Annual precipitation collected at station COOP 151855 from 1981 to 2010
Figure 6 A map showing the BMP siting tool results
Figure 7 Possible BMP locations in the Ludlow watershed

a. Arrangement 1

b. Arrangement 2

c. Arrangement 3
Figure 8 The Ludlow watershed in the Licking basin
Figure 9 Cost-effectiveness curves for a wide range of BMP implementation scenarios under current climate condition.
Figure 10 Cost-effectiveness curves for a wide range of BMP implementation scenarios under 2030 climate scenario
Figure 11 Cost-effectiveness curves for a wide range of BMP implementation scenarios under 2050 climate scenario
**Tables**

Table 1 Percentages of different land use types in the Ludlow watershed

<table>
<thead>
<tr>
<th>Land use ID</th>
<th>Land use type</th>
<th>Land use percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Developed, Open Space</td>
<td>11.04%</td>
</tr>
<tr>
<td>22</td>
<td>Developed, Low Intensity</td>
<td>5.63%</td>
</tr>
<tr>
<td>23</td>
<td>Developed, Medium Intensity</td>
<td>27.27%</td>
</tr>
<tr>
<td>24</td>
<td>Developed, High Intensity</td>
<td>2.70%</td>
</tr>
<tr>
<td>41</td>
<td>Deciduous Forest</td>
<td>47.08%</td>
</tr>
<tr>
<td>71</td>
<td>Grassland/Herbaceous</td>
<td>0.44%</td>
</tr>
<tr>
<td>81</td>
<td>Pasture/Hay</td>
<td>5.84%</td>
</tr>
</tbody>
</table>

Source: (Wickham et al. 2013)

Table 2 General land use categories in the Ludlow watershed

<table>
<thead>
<tr>
<th>General land use type</th>
<th>General land use percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impervious land</td>
<td>46.64%</td>
</tr>
<tr>
<td>Pervious land</td>
<td>53.36%</td>
</tr>
</tbody>
</table>

Table 3 BMP suitability criteria used in SUSTAIN modeling

<table>
<thead>
<tr>
<th>BMP</th>
<th>Drainage Area (acre)</th>
<th>Drainage Slope (%)</th>
<th>Imperviousness (%)</th>
<th>Hydrological Soil Group</th>
<th>Water Table Depth (m)</th>
<th>Road Buffer (m)</th>
<th>Stream Buffer (m)</th>
<th>Building Buffer (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioretention</td>
<td>&lt;2</td>
<td>&lt;5</td>
<td>&gt;0</td>
<td>A-D</td>
<td>&gt;0.3</td>
<td>&lt;30</td>
<td>&gt;30</td>
<td>--</td>
</tr>
<tr>
<td>Cistern</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt;9</td>
</tr>
<tr>
<td>Constructed Wetland</td>
<td>&gt;25</td>
<td>&lt;15</td>
<td>&gt;0</td>
<td>A-D</td>
<td>&gt;0.6</td>
<td>--</td>
<td>&gt;30</td>
<td>--</td>
</tr>
<tr>
<td>Dry Pond</td>
<td>&gt;10</td>
<td>&lt;15</td>
<td>&gt;0</td>
<td>A-D</td>
<td>&gt;0.6</td>
<td>--</td>
<td>&gt;30</td>
<td>--</td>
</tr>
<tr>
<td>Grassed Swale</td>
<td>&lt;5</td>
<td>&lt;4</td>
<td>&gt;0</td>
<td>A-D</td>
<td>&gt;0.3</td>
<td>&lt;30</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Green Roof</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Infiltration Basin</td>
<td>&lt;10</td>
<td>&lt;15</td>
<td>&gt;0</td>
<td>A-B</td>
<td>&gt;0.6</td>
<td>--</td>
<td>&gt;30</td>
<td>--</td>
</tr>
<tr>
<td>Infiltration Trench Porous</td>
<td>&lt;5</td>
<td>&lt;15</td>
<td>&gt;0</td>
<td>A-B</td>
<td>&gt;0.6</td>
<td>--</td>
<td>&gt;30</td>
<td>--</td>
</tr>
<tr>
<td>Pavement Rain Barrel</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt;9</td>
</tr>
<tr>
<td>Vegetated Filterstrip Wet pond</td>
<td>--</td>
<td>&lt;10</td>
<td>&gt;0</td>
<td>A-D</td>
<td>&gt;0.3</td>
<td>&lt;30</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Source: (US EPA 2009b)
Table 4 Information about the three subwatersheds in study area

<table>
<thead>
<tr>
<th></th>
<th>Subwatershed 1</th>
<th>Subwatershed 2</th>
<th>Subwatershed 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (m²)</td>
<td>4.78*10⁵</td>
<td>4.06*10⁵</td>
<td>3.47*10⁵</td>
</tr>
<tr>
<td>Width (m)</td>
<td>691.18</td>
<td>636.99</td>
<td>586.30</td>
</tr>
<tr>
<td>Impervious land percentage</td>
<td>29.19%</td>
<td>92.24%</td>
<td>17.36%</td>
</tr>
<tr>
<td>Pervious land percentage</td>
<td>70.81%</td>
<td>7.76%</td>
<td>82.64%</td>
</tr>
</tbody>
</table>

Table 5 Functional components and unit cost of BMP in SUSTAIN BMP cost database

<table>
<thead>
<tr>
<th>Functional Components</th>
<th>Unit cost</th>
<th>Source Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation</td>
<td>4.20*10⁻³/ m³</td>
<td>2005</td>
</tr>
<tr>
<td>Grading/finishing</td>
<td>2.62*10⁻³/ m³</td>
<td>2005</td>
</tr>
<tr>
<td>Grass</td>
<td>8.50*10⁻³/ m³</td>
<td>2007</td>
</tr>
<tr>
<td>Gravel2</td>
<td>3.38*10⁻²/ m³</td>
<td>2007</td>
</tr>
<tr>
<td>Soil/planting media</td>
<td>3.28*10⁻²/ m³</td>
<td>2007</td>
</tr>
<tr>
<td>Excavation &amp; removal</td>
<td>4.47*10⁻³/ m³</td>
<td>2007</td>
</tr>
</tbody>
</table>

Table 6 The length and area of each of the three BMPs in study area

<table>
<thead>
<tr>
<th>Locations in Subwatershed</th>
<th>BMP ID</th>
<th>Type</th>
<th>Length (m)ᵃ</th>
<th>Width(m)</th>
<th>BMP area ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrangement 1</td>
<td>1</td>
<td>I1</td>
<td>Infiltration Trench</td>
<td>80</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>B1</td>
<td>Bioretention</td>
<td>91</td>
<td>30.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>I2</td>
<td>Infiltration Trench</td>
<td>76</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>I1</td>
<td>Infiltration Trench</td>
<td>80</td>
<td>39</td>
</tr>
<tr>
<td>Arrangement 2</td>
<td>2</td>
<td>B1</td>
<td>Bioretention</td>
<td>91</td>
<td>30.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>B2</td>
<td>Bioretention</td>
<td>53</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>I1</td>
<td>Infiltration Trench</td>
<td>80</td>
<td>39</td>
</tr>
<tr>
<td>Arrangement 3</td>
<td>2</td>
<td>I2</td>
<td>Infiltration Trench</td>
<td>88</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>B2</td>
<td>Bioretention</td>
<td>53</td>
<td>32</td>
</tr>
</tbody>
</table>

ᵃ Length is defined as a decision parameter for BMPs
Table 7 Calibration and validation results for the SUSTAIN model

<table>
<thead>
<tr>
<th>Data Climate</th>
<th>Period</th>
<th>Mean Observed Daily Flow (m³/s)</th>
<th>Mean Simulated Daily Flow (m³/s)</th>
<th>% Error between simulated and observed flow⁴</th>
<th>Average Daily correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>Oct 2007 – Apr 2008</td>
<td>0.2627</td>
<td>0.2679</td>
<td>1.98%</td>
<td>0.76</td>
</tr>
<tr>
<td>Winter</td>
<td>Dec 2007 – Feb 2008</td>
<td>0.8679</td>
<td>0.9299</td>
<td>7.14%</td>
<td>0.92</td>
</tr>
<tr>
<td>Summer</td>
<td>Jun 2008 – Aug 2008</td>
<td>0.3795</td>
<td>0.4153</td>
<td>9.43%</td>
<td>0.99</td>
</tr>
<tr>
<td>Validation</td>
<td>Oct 2007 – Apr 2008</td>
<td>0.2454</td>
<td>0.2541</td>
<td>3.55%</td>
<td>0.85</td>
</tr>
<tr>
<td>Period 2009 Winter</td>
<td>Dec 2007 – Feb 2008</td>
<td>0.8134</td>
<td>0.8581</td>
<td>5.49%</td>
<td>0.93</td>
</tr>
<tr>
<td>Summer</td>
<td>Jun 2008 – Aug 2008</td>
<td>0.3419</td>
<td>0.3584</td>
<td>4.83%</td>
<td>0.99</td>
</tr>
</tbody>
</table>

⁴% error = [(simulated – observed)/observed] ×100%.

Source: (Bicknell et al. 1996)

Table 8 Calibration targets

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error in total volume</td>
<td>≤ 10%</td>
</tr>
<tr>
<td>Error in storm volumes</td>
<td>≤ 20%</td>
</tr>
<tr>
<td>Error in summer storm volumes</td>
<td>≤ 50%</td>
</tr>
</tbody>
</table>

Source: (Tetra Tech 2013)

Table 9 Projected global average surface warming at the end of the 21st century

<table>
<thead>
<tr>
<th>Case</th>
<th>Temperature Change (°C at 2090-2099 relative to 1980-1999)⁵</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Year 2000</td>
<td>Best estimate 0.6 Likely range 0.3-0.9</td>
</tr>
<tr>
<td>Concentrations</td>
<td></td>
</tr>
<tr>
<td>B1 scenario</td>
<td>1.8 1.1-2.9</td>
</tr>
</tbody>
</table>

⁵These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth System Model of Intermediate Complexity and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs).

Source: (Solomon 2007)
Table 10 Predicted temperature under the B1 scenario as compared to 2008 climatic condition

<table>
<thead>
<tr>
<th></th>
<th>Winter Average</th>
<th>Winter Change ratio</th>
<th>Spring Average</th>
<th>Spring Change ratio</th>
<th>Summer Average</th>
<th>Summer Change ratio</th>
<th>Fall Average</th>
<th>Fall Change ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>-0.143</td>
<td>0.00</td>
<td>10.471</td>
<td>0.00</td>
<td>23.297</td>
<td>0.00</td>
<td>13.150</td>
<td>0.00</td>
</tr>
<tr>
<td>2050</td>
<td>1.400</td>
<td>-1079.02</td>
<td>13.3</td>
<td>27.02</td>
<td>24.800</td>
<td>6.45</td>
<td>14.700</td>
<td>11.79</td>
</tr>
</tbody>
</table>

Source: (IPCC 2007; NOAA 2012)

Table 11 Predicted precipitation under the B1 scenario as compared to 2008 climatic condition

<table>
<thead>
<tr>
<th></th>
<th>Winter Average</th>
<th>Winter Change ratio</th>
<th>Spring Average</th>
<th>Spring Change ratio</th>
<th>Summer Average</th>
<th>Summer Change ratio</th>
<th>Fall Average</th>
<th>Fall Change ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>110.236</td>
<td>0.00</td>
<td>157.396</td>
<td>0.00</td>
<td>85.852</td>
<td>0.00</td>
<td>43.011</td>
<td>0.00</td>
</tr>
<tr>
<td>2050</td>
<td>65.816</td>
<td>-40.30</td>
<td>98.361</td>
<td>-37.51</td>
<td>83.820</td>
<td>-2.36</td>
<td>69.209</td>
<td>60.91</td>
</tr>
</tbody>
</table>

Source: (IPCC 2007; NOAA 2012)

Table 12 The impacts of future climate change on river discharge

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Year</td>
<td>2007.12 – 2008.11</td>
<td>0.73</td>
<td>-31.5</td>
</tr>
<tr>
<td>Winter</td>
<td>2007.12 – 2008.02</td>
<td>0.88</td>
<td>-28.4</td>
</tr>
<tr>
<td>Spring</td>
<td>2008.03 – 2008.05</td>
<td>1.57</td>
<td>-35.7</td>
</tr>
<tr>
<td>Summer</td>
<td>2008.06 – 2008.08</td>
<td>0.38</td>
<td>-36.8</td>
</tr>
<tr>
<td>Fall</td>
<td>2008.09 – 2008.11</td>
<td>0.09</td>
<td>22.2</td>
</tr>
</tbody>
</table>
### Table 13 Costs of different BMPs arrangement

<table>
<thead>
<tr>
<th>Reduction Percentage</th>
<th>Arrangement No.</th>
<th>Cost to reduce ($million)</th>
<th>% difference from Arrangement 1&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>1</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>33.33%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.2</td>
<td>46.67%</td>
</tr>
<tr>
<td>50%</td>
<td>1</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.6</td>
<td>30.00%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.9</td>
<td>45.00%</td>
</tr>
<tr>
<td>60%</td>
<td>1</td>
<td>3.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.1</td>
<td>28.13%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.8</td>
<td>50.00%</td>
</tr>
</tbody>
</table>

<sup>a</sup> % Difference = (current arrangement – Arrangement 1)/ Arrangement 1

### Table 14 Flow reduction under current and future climate scenarios

<table>
<thead>
<tr>
<th>BMPs cost</th>
<th>Climate scenario</th>
<th>Flow reduction %</th>
<th>difference from current scenario&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1,500,000</td>
<td>2008</td>
<td>40%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>36%</td>
<td>-4%</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>40%</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>50%</td>
<td>-</td>
</tr>
<tr>
<td>$2,000,000</td>
<td>2030</td>
<td>43%</td>
<td>-7%</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>48%</td>
<td>-2%</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>60%</td>
<td>-</td>
</tr>
<tr>
<td>$3,200,000</td>
<td>2030</td>
<td>50%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>57%</td>
<td>3%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Difference = selected scenario – 2008 scenario