1-1-2013

Investigation of Appropriate Model Structures for Modelling Small Urban Catchments

Naglaa Ahmed
Ryerson University

INVESTIGATION OF APPROPRIATE MODEL STRUCTURES FOR MODELLING SMALL URBAN CATCHMENTS

by

NAGLAA AHMED

B.Sc. Cairo University, Egypt

A thesis
presented to Ryerson University

in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in the Program of
Civil Engineering

Toronto, Ontario, Canada, 2013

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

Although the hydrologic modelling of small urban catchments has been practised for several decades, guidance on the development of models is still needed. This research evaluates and compares several modelling structures of small residential areas with and without low impact development implementation using distributed and lumped models. Hypothetical small areas were modelled to examine several grid based models with different grid sizes. The results were used to test the ability of uncalibrated models to predict runoff using three model configurations: 1) single catchment, 2) grid, and 3) homogenous areas, where every building, backyard, and street was modelled separately as a single catchment. The results of the models were compared and evaluated based on the total runoff volume, peak flow rate, and infiltration volume. The results of a real case study show that the grid model is an appropriate model structure for modelling small urban catchments.

ACKNOWLEDGEMENTS

I would like to thank the Department of Civil Engineering for providing me with an excellent learning environment in which to complete my graduate studies, which included: high quality labs, advanced software, and amazing staff and teachers. Special thanks to my supervisors Dr. James Li and Dr. Darko Joksimovic for their support, guidance, patience, and friendship. I am also grateful to my examiners, Dr. Grace Luck and Dr. Arnold Yuan for their constructive comments and guidance. My research colleagues also provided me with a great deal of support. Thanks to Dr. Cilia Fan for explaining SWMM operations and Dr. Wai Yeung Yan for his advice and support during the GIS data analysis.

In addition to academic research support, I also owe thanks to many government bodies, such as, the Credit Valley Conservation Authority and the Lake Simcoe Conservation Authority for providing me with data and advice. I am also grateful to the City of Mississauga for providing digital maps of Mississauga's sewer system.

Finally, and most importantly, I would like to thank my husband, my parents, and my friends for their love and support over the years.

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

1.1. Problem Statement

Urban and suburban developments have a large impact on the hydrologic cycle due to the increase in the imperviousness and the change of the drainage efficiency. The increase of impervious surfaces prevents water from infiltrating to the ground which in turn decreases the volume of ground water recharge, lowers the water tables, increases surface runoff volumes and peak discharges, and decreases base flow of receiving systems during dry periods. Currently, Low Impact Development (LID) techniques and best management practices (BMPs) are used to reduce the negative effects of urbanization, increase the pervious area, and treat the runoff; however, the effectiveness of these measurements has not been extensively examined due to the lack of the available models for the simulation of the hydrologic processes.

It becomes essential to interpret hydrologic spatial data which become available with the development of remote sensing technology and geographic information systems (GIS). Modelling small catchments using a grid-based distributed model method has not been explored extensively, although significant experience exists using gridded models on a large (i.e. watershed) scale (Vieux, 2004).

The need for small scale simulations of catchments may be a viable way to predict systems' response at different locations with potentially minimal model calibration. Models are frequently applied to evaluate potential benefits of LIDs, in both the new developments and retrofit situations, without the ability to calibrate them based on measured data. Developing a grid distributed model with finer resolutions would allow modellers to better evaluate runoff and the flow rate at any location in the catchment as well as the LID quantity performance in any urbanized areas. Distributed models are more compatible with flow direction algorithms than lumped models. Distributed models can calculate the runoff volume and the infiltration volume per grid cell, allowing more direct simulation of the processes and more realistic representation of drainage areas.

For a long time, the modelling of hydrologic processes was based on gross simplifications and lumping parameters in the catchment, such as the slope and the hydraulic roughness. These assumptions are acceptable when the computer resources are limited and there is a lack of spatial data. Currently, detailed mathematical modeling can be supported by accurate spatial data, digital maps, and spatial data management using state-of-the-art remote sensing and GIS techniques. New generations of high performance computers offer an efficient platform to transform the hydrologic simulation from lumped representations to distributed representations. The lack of approaches that utilize these developments in data and computer resources lead to a need for this research.

1.2. Research Objectives

The hydrologic representation of an urban catchment using an appropriate model, which can simulate all hydrological processes and flow directions, is important for the evaluation of the potential benefits that can be gained from implementing LIDs. The objectives of this research are:

- to investigate the sensitivity of grid size and time steps for grid models with and without LIDs in several levels of disaggregation (Lumped, Regular grid, and Homogeneous areas)
- to evaluate the effect of the flow path direction on runoff volume and peak flow at the outlets of catchments.

- to provide modelling guidance regarding the appropriate hydrological model structure for modelling small urban catchments

1.3. Task Description

The thesis objectives are achieved by conducting the following tasks:

1. Review the available modelling tools and their applicability for modelling LIDs. The following models were selected for the review: a) TOPMODEL, b) ANSWERS, c) SWMM, d) QUALHYMO, e) GSSHA, f) LISEM. The review criteria of the models are based on the following: 1) Minimum time step, 2) Overland/groundwater flow routing methods, 3) Hydrologic losses, 4) Grid / subcatchment size, and 5) Drainage network.
2. Review main flow path algorithms used to define the flow direction in grid models. The flow routing algorithms reviewed are: a) the deterministic eight node (D8), b) The random eight node (Rho8), c) FD8, d) The Digital Elevation Model Network (DEMON), and e) D∞.
3. Test different levels of aggregation (grid size) and the flow directions using the selected model based on the previous review and hypothetical data.
4. Examine different levels of aggregation and time steps using the SWMM model and the D8 algorithm for residential single lots with hypothetical data.
5. Select models structures and time steps for examination of a real case study site.
6. Evaluate appropriate model structures based on the closest agreement between the predicted runoff volume and peak flow and field measurements.

1.4. Contribution

This research examines different levels of aggregation to guide modellers to define appropriate model structures and suitable grid size and time steps for grid models. The research studies and compares the flow path algorithms and describes the possibility of adopting these algorithms to a distributed model. The research helps to develop guidelines for modellers to evaluate the effects of retrofitting options for developed areas and implementing source controls in new developments. Distributed models up to that small level of disaggregation (2x2m grid size) on small catchments have not been examined before. The research helps to develop guidelines to predict the behavior of grid models and lumped models for small developed areas.

1.5. Thesis Organization

Chapter One describes the motivation of the research, introduces the objectives of the thesis, and identifies the tasks to be conducted in the research work. Chapter Two reviews the existing literature with respect to distributed and lumped models, and provides a review of some of the distributed models and flow routing algorithms available. It also includes an in-depth discussion on the use of these routing algorithms in hydrologic modelling and how they are carried out. Chapter Three presents the overall research methodology. Chapter Four describes the experimental work using a small hypothetical residential lot. Chapter Five summarizes the results of the small hypothetical residential lot by examining grid sizes and different time steps with distributed models. Chapter Six introduces the case study and provides the results of applying different models and comparing them with the measured data. The last chapter concludes this research and suggests possible future research directions.

2 LITERATURE REVIEW

2.1 Background

Evaluating appropriate distributed models for small urban catchments requires understanding of hydrologic modelling approaches to solve overland flow. A catchment model is a set of mathematical modules describing hydrologic processes aimed at converting precipitation into runoff. Ponce (1989) argues that models can be classified mathematically in three ways: (1) theoretical, (2) conceptual, or (3) empirical. In another classification of mathematical models, he describes them as four types: (1) deterministic (given input will always produce the same output); (2) probabilistic (estimate based on past data which forecasts the probability of event happening again); (3) conceptual (each subcatchment is treated as non-linear reservoir); and, (4) parametric (using a finite number of parameters).

Hydrologic models try to simulate processes in a watershed or catchment. Hydrologic model are either lumped or distributed models. Lumped models describe temporal variations, but not spatial variations. Distributed models describe both spatial and temporal variation but require more intensive computation compared to lumped models.

Different approaches can be used to describe the flow of water over a land surface; defining these approaches will help to understand and compare models. The approaches to solve overland flow problems are: 1) storage concept, 2) kinematic wave technique, 3) diffusion wave technique, and 4) dynamic wave technique. The storage concept is based on mass balance concepts used in reservoir routing. The simplest approach is the kinematic wave technique, which neglects the local acceleration term, convective acceleration term, pressure term in the momentum equation, as well as assumes that the friction and gravity forces balance each other out.

The diffusion wave technique neglects the local and convective acceleration terms, but incorporates the pressure term. The dynamic wave technique considers all terms in the momentum equation (Chow, 1988). Kinematic wave technique was formulated by simplifying the momentum principle into a steady uniform flow, while the diffusion wave technique is based on simplifying the momentum principle into a steady non-uniform flow. The fourth type of overland flow approach, the dynamic wave technique, considers the complete momentum principle (Ponce, 1989).

Physically based distributed model solutions are based on solving momentum, mass, and energy equations. Most physically based models make simplifications to the governing equations because some of the parameters, initial conditions, or boundary conditions may be unknown (Vieux, 2004). These simplifications could cause mathematical discontinuities or errors in the physical representations, which is the case with the kinematic wave solution.

Vieux (2004) developed a model called r.water.fea for the U.S. Army Corps of Engineers, Construction Engineering Research Laboratory in Champaign, Illinois (CERL) to solve this issue. Vieux extended the solution to a network of elements representing the watershed in the GIS environment. Using nodal values of parameters in a finite element solution and interpolating the values across the finite elements, the kinematic wave solution can be applied to spatially variable surface without numerical difficulties.

The kinematic wave technique can be solved using a network of finite elements connecting grid cells together. Solving the resulting system of equations defined by the connectivity of finite elements provides the possibility of hydrograph simulation, cumulative infiltration, and runoff depth in each grid cell. The solution represents the roughness and slope as nodal; rather than, elemental parameters. This approach simulates a spatially variable watershed surface without breaking the surface into equivalent planes or subareas. Channel routing, Green and Ampt infiltration routing, and distributed radar rainfall were also added to the model capabilities (Vieux, 2004).

Since the non-linear reservoir routing method does not count for time lag, it can simulate the rainfall- runoff process reasonably well when the storm duration is longer than the watershed time of concentration, but obtains poor results when the rainfall duration is shorter than the time of concentration. The kinematic wave method simulates both cases very well because it considers the actual physical processes related to surface flow generation (Xiong & Melching, 2005).

The growth of geospatial data, remote sensing and radar technology can improve simulating hydrologic processes using distributed models. Most of the existing models, used to simulate stormwater catchments quantity and quality, can be used to model the low impact development practices (LID). However, these models failed to capture all LID features needed to model comprehensive design scenarios (Shamsi, 2010).

Zoppou (1999) reviewed twelve stormwater models and found that many of the models are capable of simulating urban water quantity and quality. However, numbers of deficiencies were found in most of these models. These deficiencies can be summarized as:

- spatial distribution of rainfall is not considered in many of these models and assumed to be uniformly distributed in sub-catchments;
- shallow water wave equations in these models are seldom employed;

- simple storage is the most common approach to routing flows; and,
- lumped models ignore spatial variability.

Elliot (2007) reviewed ten models which employ conventional methods of runoff generation and routing for modelling LID devices. Elliot found that only half of the models include the groundwater base flow component. Despite this progress, it was found that there are many areas for further model development (treating base flow components and runoff from pervious surfaces more thoroughly, up-scaling for representations of on-site devices at catchment level, and catchment scale testing of model prediction).

Raster data is a potentially source for catchment characteristics in distributed models. Quinn et al. (1991) derived flow pathways from raster digital terrain data and proved that the flow direction and flow path algorithms may have an important effect on model predictions. Although GIS have been used as a tool to calculate the required geometric or kinematic properties, there is a significant uncertainty associated with the extraction of those properties (Gironas et al., 2010).

Elliot (2009) showed the effect of different level of aggregation on stormwater control devices such as detention tanks and bioretention in an urban catchment model. The research showed that aggregation had a small effect on mean flow, base flow, and water quality. The aggregation from 810 catchments to a single source increased peak flow by approximately 38.1% for bioretention using a single design event. The author also concluded that the variability in relation between device size and the source area increased the effect of aggregation.

Jain et al. (2004) developed a grid based process oriented distributed rainfall-runoff model capable of handling catchment heterogeneity and modeling catchment response to isolated storm events. The model would generate slope, flow direction, and drainage depth for each cell from a digital elevation model. Information about land use, soil, etc., were derived through analysis of digital satellite data and the input variables to the model were derived using GIS. This model simulated the runoff hydrograph at the outlet reasonably well and realistically predicted the temporal variation of spatial distribution of flow depth and runoff over the catchment.

Jourdan (2003) combined a ground water model and a distributed hydrologic model to develop a detailed two dimensional hydrologic model capable of predicting discharge, depth, and velocity in rivers. The same concept can be used to predict the runoff and the peak flow in urban watersheds. Rossman (2010) described a research done by Huber (2006) and concluded that the model's capability to model LID alternatives is limited and the model's representation of evapotranspiration should be refined.

Bosley (2008) indicated that LID models should have a physical basis in order to be capable of continuous simulation, applicable at a fine spatial scale, and capable of transferring water from one surface to another. The small spatial scale of LID would need a small model time step to accurately compute runoff response.

Some researches focused on the effect of catchment aggregation on runoff and peak flow, while others studied the importance of using spatial data to simulate urban catchments more accurately. The need for distributed models to simulate the catchment runoff using the metrological data emerged in the last decade. Although some temporally and spatially distributed models are available, (e.g. GSSHA), the effects of modeling using distributed models on the runoff depth and on the peak flow at an outlet of an urban catchment are not well investigated. The relation between the time step and the grid size should also be investigated. There is a need to investigate the effect of distributed models, grid size, and time step on runoff volume and peak flow at the outlet of a catchment, especially when modeling catchments with LID controls.

The previous reviews provide an idea on some of the routing methods, methods of presenting hydrologic processes, and model's capabilities to simulate catchments in a distributed way. In the previous research, LIDs have been modelled as a single catchment. The effect of modelling small watershed and LIDs with distributed models has not been investigated fully. The following section describes the hydrological models used for calculating the storm water runoff and peak flow.

2.2 Hydrological Models Review

The following review is focused on assessing the capabilities of available distributed hydrologic models for modeling urban drainage systems, as well as the capability of these models to model LIDs.

2.2.1 GSSHA- Gridded Surface Subsurface Hydrologic Analysis

The GSSHA model (Byrd, 2005) is a grid based and distributed parameter hydrologic model. GSSHA is able to identify runoff mechanisms and simulate surface water flows in watersheds with both Hortonian and non-Hortonian runoff. GSSHA is a modification and a reformulation of the CASC2D model. The CASC2D model (Byrd, 2005) was developed to predict surface runoff in arid and semi-arid basins. The GSSHA model adds the ability to simulate saturated and unsaturated groundwater and forecast discharge in both Hortonian and non-Hortonian basins.

GSSHA distributes precipitation between gages using either Thiessen polygons or an inverse distance square weighted method. For precipitation interception, GSSHA uses an empirical two-parameter model. Infiltration is simulated either by the Green and Ampt method or Richards' equation. There are three different solutions available in the model: the point explicit, alternating direction explicit (ADE), and ADE with prediction-correction (ADE-PC). Evapotranspiration can be modeled using two different techniques: Deardorff and Monteith. The soil moisture in the unsaturated zone can be simulated with one of two methods: a simple fixed soil volume accounting method, bucket method, or simulation of soil moisture movement and hydrologic fluxes using Richards' equation.

Saturated groundwater flow may be simulated with a finite difference representation of 2-D, lateral, saturated, groundwater flow equations. Exfiltration is the flux of water from the saturated zone onto the overland flow plane. Fluxes on the land surface are computed using Darcy's law. GSSHA presents the watershed as grids. Each grid cell has uniform topographic, soil, and landuse properties. GSSHA routes the flow in two principal directions while adapting to cascade routing using the full Saint Vienant Equation (Kalin & Hantush, 2006).

2.2.2 TOPMODEL

TOPMODEL (Bosley, 2008) was initially developed by the School of Geography, University of Leeds in UK in 1974. TOPMODEL was originally designed to simulate the hydrological responses of single or multiple subcatchments in humid areas: a) with shallow soils and moderate topography, b) in a semi-distributed way, and c) using gridded elevation data. It is considered a physically based model, as its parameters can theoretically be measured. The model includes two mechanisms to estimate the surface runoff production: the infiltration excess and the saturation excess.

The model predicts surface runoff and soil moisture based on precipitation, an evapotranspiration time series, infiltration, and a high quality (DEM) digital elevation model. A correct estimation of evaporation is critical for model performance. Evaporation is estimated by using the Penman-Monteith method. The major factors affecting runoff generation are the catchment topography and the soil's ability to transmit water. The model uses a topographic index as an index of hydrological similarity. This index is derived from basin topography. The topographic index derivation was obtained by manual analysis in the early version, but the present version provides a program to derive its distribution from a regular raster grid of elevations. The model assumes all points with the same value of the topographic index will respond in a hydrological similar way.

The soil profile is defined by a set of stores. When the field capacity is exceeded, a second store starts filling until the soil reaches saturation. An alternative approach based on the Darcian flux at the base of the unsaturated zone can also be considered. TOPMODEL intends to compute the water table depth at any location for every time step. When the water table depth equals 0, the saturation condition is reached and the rainfall produces direct surface runoff.

TOPMODEL uses the Green-Ampt model for computing infiltration excess. Runoff is routed to the catchment outlet using a linear routing algorithm and the time step is given in hours. TOPMODEL parameters required are: the mean soil surface transmissivity, a transmissivity profile decay coefficient, a root zone storage capacity, an unsaturated zone time delay, a main channel routing velocity, and an internal subcatchment routing velocity. The lack of adequate field measurement for parameter estimations makes it necessary to use calibration techniques.

The time step and the grid size have also been shown to influence TOPMODEL simulations. One of the model's advantages is its capability to visualize the simulation results in a spatial context.

2.2.3 Limburg Soil Erosion Model (LISEM)

The (Limburg Soil Erosion Model, 2010) model was originally made for Limburg province in the Netherlands. It is a grid based model, which simulates the hydrology and sediment transport during and immediately after a single rainfall event in a small catchment (between 10 and approximately 300 ha). The main hydrologic processes simulated are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, and channel flow in man-made ditches.

LISEM is a physically based model that is completely integrated in a raster GIS. All input and output maps are raster maps that can easily be displayed and treated with the PCRaster software. The model can be used for planning purposes and as a research tool because of its complexity. At each grid cell, the model calculates the following processes: rainfall, interception, infiltration, surface storage, and overland flow. The canopy storage capacity is estimated by Von Hoyningen-Huene in 1981.

Infiltration is calculated with various sub-models like Holtan, Green and Ampt, subtraction of soil saturated hydraulic conductivity (K_sat), or using the SWATRE model which is a finite difference solution of the Richard equation. This option includes vertical soil water transport during a rainfall event; re-calibration is advisable when a different infiltration model is used. The model inputs are maps with soil hydrological properties. LISEM enables the simulation of several types of soil surfaces in a grid cell. These types are normal soil surface (tilled), crusted, compacted road (impermeable), and grass strips. Surface storage is calculated using Maximum Depression Storage (MDS).

Runoff is calculated based on the MDS value and the fraction of ponded area before the water level reaches the MDS height. The grid cell can have more than one type of surface; and thus, the infiltration is calculated for each different type. The model uses a four-point finite-difference solution of the kinematic wave combined with Manning's equation for distributed overland and channel flow routing.

2.2.4 QUALHYMO

The QUALHYMO model (The Partenership for Water Sustainability in British Columbia, 2008) was originally developed for Ontario Ministry of Environment in the early 1980s to be used for watershed scale. The model targeted designing and evaluating BMPs long term quantity and quality behavior. The model can simulate surface hydrology and pollutant loads and can route flow through stream channels and management facilities. The model applies mass balance at each times step and surface runoff generated when liquid input exceeds the infiltration capacity varying with soil moisture. Soil moisture is depleted by evapotranspiration, which is defined by the user as a factor or monthly value. When soil moisture is higher than field capacity, excess is available for percolation.

Each surface is presented by slope, length, and surface roughness. The flow rate from each surface is computed using Manning’s equation. The impervious area is treated separately from the pervious area of the catchment. The runoff generation uses a Hortonian mechanism where the catchment contributes to runoff when the rainfall intensity exceeds the infiltration rate. The model overestimates the high peak flow and underestimates the smaller peak flow due to its high contribution of flow (Valeo & Moin, 2001). The runoff volume is determined from the pervious area based on the soil conservation service method and from the impervious area based on the volumetric coefficient approach. The runoff rate is calculated by determining two unit hydrographs of the pervious and impervious areas (Zheng & Baetz, 1999).

2.2.5 Storm Water Management Model (SWMM)

SWMM was developed in 1971 by the United States Environmental Protection Agency to simulate runoff quantity and quality for single event and continuous simulation (Rossman, 2009). SWMM is a physically based model that uses principals, such as the conservation of mass, energy, and momentum. SWMM can simulate hydrologic processes like evaporation of standing water, snow accumulation and melting, rainfall interception, infiltration of rainfall, percolation of infiltrated water to the groundwater, and routing of overland flow through LID measures.

To calculate surface runoff, SWMM uses a nonlinear reservoir method where inflow is the precipitation and infiltration, and evaporation and surface runoff are outflows. When the depth of water in the reservoir exceeds the maximum depression storage, runoff occurs and outflow is calculated by Manning's equation. The depth of the water is continuously updated and calculated by solving the water balance equation over the subcatchment numerically. Infiltration can be described by different models such as Horton, Green-Ampt, and Curve Number. Evaporation rates can be added to the model as a single constant value, a set of monthly average values, user-defined time series of daily values, values computed from daily temperature, or daily values.

Groundwater is presented in two zones: an unsaturated zone and a saturated zone. The groundwater model in SWMM applies the mass balance for the water volume stored in each zone and calculates the new water table depth and the moisture content in unsaturated zone for the next time step. SWMM uses an integrated form of the equation that compensates for the reduced loss of soil infiltration capacity when a light rainfall occurs (Viessman et. al., 1989; and Huber & Dickinson, 1988).

There are two different approaches for placing LID in a subcatchment: 1) placing LID in an existing subcatchment, where the LIDs act in parallel, and 2) placing LID as a separate subcatchment, allowing the modeling of LIDs acting in series (outflow from one LID can be inflow to another LID). SWMM has three different methods to route the flow into the drainage system. The steady flow routing assumes that the flow is steady and uniform, where the model uses Manning's equation to relate flow rate to flow area or depth with no sensitivity to the time step employed.

The second routing method is kinematic wave routing, where the flow and area vary spatially and temporally and the model uses a continuity equation coupled with a momentum equation. This method is stable with time steps from 5 to 15 minutes. The third method is dynamic wave routing. The method uses Saint Venant's flow equation and the time step has to be as small as 1 minute or less.

2.2.6 Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS)

ANSWERS (Bosley, 2008) was developed in technical cooperation with Purdue University, as a grid based distributed model. The model is intended for simulation of watersheds with mainly agricultural land use, as well as for relating water flow rates and hydrologic parameters at every catchment. Its primary application is to plan and evaluate different strategies for controlling nonpoint source pollution. ANSWERS represents a watershed with a matrix of small and equal grid cells, ranging in size from 1 to 4 ha. The overland flow of each element that flows into neighboring elements is based on the direction of element's slope. Each element's hydrologic response is calculated as a function of time using an explicit backward difference solution of the continuity equation.

For overland flow and flow routing, the continuity equation is solved using Manning's equation with appropriate coefficients. The infiltration method used by ANSWERS was developed by Holtan in 1961. This method uses soil water content instead of time as an independent variable. Holtan's equation requires six parameters for each soil type: total porosity, field capacity, depth of the control zone (depth to impeding soil), steady state infiltration rate, and the two unsteady state coefficients. BMP's are presented in ANSWERS by using appropriate parameter values, which result in reducing the overland flow rate. Tables 2.1 and 2.2 are descriptions of reviewed distributed models and summary of their main characteristics.

Table 2-1 Features of reviewed grid based models to fine scale LID simulation

Model Name	Min. Time Step	Overland Flow Routing			Groundwater Routing		Evapo-transpiration	Channel Routing	Infiltration Routine	Min.Grid Size
		Method	Coupled	Cascade	Unsaturated	Saturated				
TOPMODEL	1HR	Linear routing algorithm	Yes	No	GA	GA	Yes	-	GA	-
GSSHA	20s	DW	Yes		RE, GAR	RE, GAR	Yes	1-D longitudinal, explicit, up-gradient, diffusive wave	RE, GA	10-250m
ANSWERS	30s/24hr	KW	Yes	Yes	Brooks-Corey	Crude	Ritchie	KW	GA	
SWMM	Less than 1 min	Nonlinear reservoir	Yes		Horton, GA, CN	Horton, GA, CN	Yes	KW, DV	Horton, GA, CN	-

DW= Diffusive wave

RE= Rechards' equation, GA = Green and Ampt, GAR = Green and Ampt redistribution, CN= Curve Number

KW= Kinematic wave, DV= Dynamic Wave.

Table 2-2 Features of reviewed grid based models to fine scale LID simulation

Model Name	Stream/groundwater interaction	Routing to drainage network	Routing through devices	Hydrologic routing in drainage network	Exfiltration	Lateral saturated groundwater flow
TOPMODEL	-	-	No	Yes	-	-
GSSHA	Darcy's Law	Yes	No	Yes	Darcy's Law	2D vertically averaged
SWMM	Yes	Yes	Yes	Yes	Yes	-

The above review demonstrates that TOPMODEL does not calculate the lateral flow or consider run-on. It also requires single soil layer with transmissivity distributed with depth. The review also showed that the TOPMODEL unable to simulate flow from land-use type to another (cascade). The previous TOPMODEL characteristics indicated that the model cannot be considered as evaluation tool for LIDs. In similar manner, although ANSWERS is a grid based model intended for planning best management practices (BMP), its original development to simulate agriculture areas does not represent the impervious of urban areas.

GSSHA is grid based model that divides the watershed into homogeneous cells and routes the flow in two principal directions. In other words, the flow is allowed to move in four principal directions. Diagonal cells cannot receive flow, which does not represent reality. QUALHYMO is a conventional hydrologic model that uses the infiltration excess overland flow to generate runoff. QUALHYMO treats impervious areas separate from pervious areas, which results in an over predicted flow.

LISEM is a grid based model which simulates rainfall- runoff processes and sediment transport in small catchments for single events only. LISEM uses a four-point finite-difference solution based on the kinematic wave using the Manning's equation to calculate the overland flow. The LISEM model can calculate infiltration using the Holtan or Green-Ampt approach.

SWMM was originally designed for modeling urban storm sewers and describing the watershed as a system of overland flow plans, links and nodes. SWMM averages the flow depth between the end of the previous time interval and the midpoint of the current one, which leads to a slow hydrograph peaking response, especially for narrow and long flow plans. That problem can usually be solved by adjusting the width and impervious area depression storage during calibrations.

SWMM was selected in this study based on the followings: a) it is a popular, well-established model, b) available as open source, c) SWMM can be used as distributed model, since the model considers the run-on from contributing catchments, and d) it allows different subrouting options inside the subcatchment where the runoff can be diverted from a pervious to an impervious area, from an impervious to a pervious, or a pervious and an impervious area to an outlet. The previous options can change the predicted runoff and peak flow and can mimic the catchment more accurately.

2.3 Review of Flow Direction Algorithms

Flow routing algorithms are used in hydrologic models to simulate the transfer of water, sediments, and/or nutrients from one point to another point in a landscape (Lam, 2004). A flow routing algorithm determines the way in which the outflow will be distributed from one grid cell to one or more down-slope cells. The solution of a flow routing algorithm is a very important issue because it affects the calculation of the upslope contribution area. The following is a review of the most commonly used algorithms focused on assessing and evaluating these routing methods. The review evaluates the difference between algorithms and assesses the possibility of adapting these algorithms to SWMM.

2.3.1 The Deterministic Eight-node (D8) Algorithm

The deterministic eight-node (D8) algorithm is a single flow directional approach which directs flow from one cell to one of the eight neighboring cells based on the steepest slope or the slope gradient. The D8 algorithm has been used to mimic the flow of rivers and streams and flow convergence in valleys. In this algorithm, the aspect (measured degree clockwise from north) is used to mark the direction of steepest slope of each grid cell and the direction the water will follow. The algorithm calculates the gradient of each of the eight neighbor cells and directs the flow to the steepest cell.

One of D8 algorithm limitations is that it limits the possible flow direction to one cell only; therefore, the algorithm is unable to simulate divergent flows. This limitation is expressed when simulating parallel flow paths. In this algorithm, the upslope contributing area is calculated simply by multiplying the number of cells contributing to the cell of interest by the cell area. (Lam, 2004).

2.3.2 The Random Eight-node (Rho8) Algorithm

The random eight-node (Rho8) algorithm uses randomness to calculate the flow direction to break parallel flow paths developed by D8 algorithm. The algorithm starts by identifying all neighboring cells in the downslope, then calculating the slope gradient of each of these cells and choosing a number from a table of random numbers to direct the flow to one of these cells. These numbers are developed based on slope weight bases, so that the flow path with the steepest gradient has the greatest probability of being selected.

The Rho8 algorithm develops unrealistic flow direction because it relies on a table of random numbers. This algorithm also alters the flow directions by 15% compared to those developed by D8 algorithm. One of the Rho8 algorithm's problems is that different flow networks can be developed each time the algorithm is used. The changes of the flow direction are relying on a table of randomness to direct the flow to downslope cells. The previous problem can sometimes cause overestimation or underestimations in attributes (Lam, 2004).

2.3.3 The (FD8) Algorithm

The FD8 multiple flow direction algorithm directs flow to more than one cell based on slope weighted bases, as illustrated in Figure 2.1. The algorithm uses two weights for cardinal and diagonal directions (0.5 and 0.35) in addition to slope gradients that are utilized to calculate the proportion of flow directed to three cells from the center cell. A fraction of the flow is allocated to a cell in the down-slope then the algorithm assigns the flow to each cell in a three by three moving window to all cells. This algorithm means that each cell receives only a proportion of the upslope flow. The upslope contributing area for the cell of interest is composed of contributions from different cells. The specific catchment area is the sum of the contributed area divided by the length of the cell of interest receiving the flow (Lam, 2004).

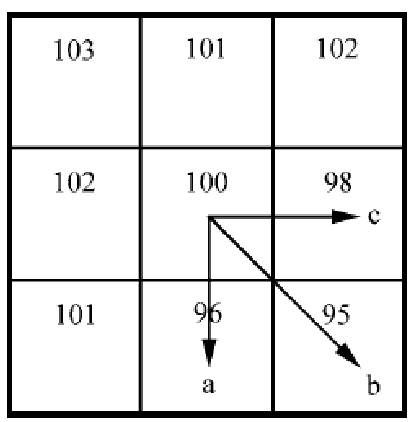


Figure 2-1 Allocation of flow among down-slope cells using FD8 multiple flow direction apportioning algorithm (Quinn et al. 1995).

2.3.4 The Digital Elevation Model Network (DEMON) Algorithm

This algorithm is based on stream tube where the algorithm traces flow through each pixel. In this algorithm, the flow direction is determined from the local aspect angle. It describes the flow as a rolling ball released from the center of the grid cell to the steepest grade. If two opposite pixels have the same elevation, the algorithm applies the three by three moving window to identify the lowest cell.

This approach transforms the catchment into irregular shapes that are defined by orthogonal and equipotential lines. The width of the stream tube increases over divergent topography, decreases over convergent topography, and remains constant over planar surfaces. The amount of flow at each cell is the amount of flow generated from the cell itself plus the flow entering the cell. When the direction of flow entering the grid cell is 90 degrees or its multiples, the flow is directed to the neighbor cell; and if the flow direction is not 90 degrees, the flow splits to the cardinal cells (Lam, 2004).

2.3.5 The (D∞) Algorithm

The (D∞) algorithm incorporates several ideas from the DEMON algorithm. The flow direction is calculated using eight triangular faces. Each down-slope vector may be drawn from the center cell with an angle that lies within or outside 45°. Different cases of flow are defined based on the slope vector angle. If the slope vector angle falls within the facet, it represents the steepest flow direction. In case the slope falls out of the facet, the steepest flow occurs along the steepest edge.

The flow is forced to flow toward a neighbor of equal elevation. The upslope area of a cell is the area of the cell, plus the fractional area of upslope neighbors which drain into this cell. The flow is directed to single cell, if the flow angle falls on a diagonal direction. Finally, if the flow angle falls between the direct angles, the flow is split into the two neighbor cells (Lam, 2004).

2.4 Description of Low Impact Development (LID) Practices

The Low Impact Development (LID) stormwater management approach was introduced by Prince George's County, Maryland in the early 1990s. The main goal of LID is to control stormwater runoff at the source by mimicking the watershed predevelopment conditions to increase infiltration and reduce runoff impact. Another LID goal is to protect environmentally sensitive sites such as wetlands, steep slopes, valuable (mature) trees, flood plains, woodlands, and highly permeable soils.

The design techniques of the LID are based on distributing small scale control units throughout the watershed at the source of the stormwater, which reduces the impervious surface and lengthens the flow path. These units act as stormwater detention and retention areas where stormwater can infiltrate through them (Rossman, 2009). LID's can increase the amount of rainfall that infiltrates into the groundwater if properly sited and correctly located (Gilory & McCuen, 2009). Using LID techniques reduce both the volume of stormwater entering the combined sewer system and the peak flows during wet weather events (Kennedy et al., 2007).

TRCA guide manual for design low impact development (2010) states that LID is a stormwater management technique that mitigates the influence of increased runoff and pollution by controlling the runoff close to the source. LIDs mimic the natural or the predevelopment hydrologic process such as infiltration, evapotranspiration, harvesting, and detention of stormwater. These practices can remove nutrients and metals effectively from the runoff, as well as reduce the runoff volume and flow rate. The following is an overview of LIDs practices for stormmwater management.

2.4.1 Rainwater Harvesting

The strategy of rainwater harvesting is to intercept and store the rainfall for future use. The collection of rainwater for domestic purposes has been practiced in rural Ontario for over a century. There's been an increasing interest in adapting these practices in urban settings. Rainwater harvesting helps to conserve potable water and reduce stormwater runoff. The rain that falls on a roof in a catchment is collected and conveyed into storage. The size of the storage ranges from rain barrels for residential land use to cisterns for commercial or industrial land use.

2.4.2 Green Roof

A green roof consists of a thin layer of vegetation that grows on top of a conventional flat or sloped roof. Green roof has many benefits to cities as it reduces urban heat, increases energy efficiency, and controls peak flow. Green roof can store rainwater in its medium and pond areas much like a lawn while the excess rainfall enters underdrain and is conveyed into the building drainage system.

2.4.3 Roof Downspout Disconnections

Downspout disconnection directs the flow from the roof to a pervious area that drains away from the building. Downspout disconnection reduces stormwater from entering the storm sewer directly or flowing over the driveway into the storm sewer.

2.4.4 Soakaways

Soakaways and infiltration trenches are used in sites suitable for underground stormwater infiltration practices. Soakaways are rectangular or circular excavations lined with geotextile fabric and filled with clean stones. Soakaways receive runoff through a pipe inlet and allow it to infiltrate through into the native soil. Typically, they receive roof runoff in individual lots and can be designed to receive overflow from rainwater harvesting. Soakaways are suitable for sites where available space for infiltration is limited.

2.4.5 Bioretention

Bioretention is a stormwater infiltration practice that can store, treat, and infiltrate runoff. A bioretention system is designed to capture small storm events and improve the storage water quality. Bioretention can include underdrain for partial infiltration when the soil infiltration rate is less than15mm/hr. Bioretention system design can go without underdrain for full infiltration or with an impermeable liner and underdrain for filtration only. The main part of a bioretention system is the filter bed, which contains sand, and organic material. The other elements of the system are mulch ground cover and plants. Generally, bioretntion fits into different development areas.

2.4.6 Vegetated Filter Strips

The function of vegetated filter strips is to slow runoff velocity and filter suspended sediment and pollutants. Vegetated filter strips have gentle slopes and dense vegetated areas that treat runoff from impervious areas. Vegetation may include a variety of trees, shrubs, and native plants. Vegetated filter strips are suitable for snow storage and treatment.

2.4.7 Permeable Pavement

Permeable pavement is a good alternative for pavement areas which allow stormwater to drain through it into a stone reservoir. It is useful in areas with low traffic roads, parking lots, driveways, and walkways. The design of the permeable pavement systems depends on the native soil. The system can include underdrain for partial infiltration, underdrain with impermeable liner for filtration only, or no underdrain for full infiltration.

2.4.8 Grass Swales

Grass swales are vegetated open channels that can receive and treat stormwater runoff. They are used for roadway drainage to allow sedimentation, filtration through the root zone, evapotranspiration, and infiltration into the native soil. Enhanced grass swales include design features such as check dams, which improve contaminate removal and slow the water flow.

2.5 Model Characteristics of LID

Models used to evaluate the change in land use need to represent hydrologic processes accurately, as well as to represent the land conditions before and after development. The model required to evaluates or design LIDs has to be able to represent different hydrological conditions of undeveloped land and urban areas as well. Since model calibration is important for analysis of future conditions, physically-based models, where parameters can be estimated, are required. The model should be capable of continuous simulation at a fine spatial scale to improve estimates of moisture conditions and successfully transform runoff from one surface to another.

Disconnected impervious areas and distributed bioretention also require spatially distributed modeling at a fine scale. The small spatial scale demands models with small time steps to accurately compute runoff responses. The following hydrologic model requirements are necessary for LID modelling:

- Long – term continuous simulation
- Ability to predict flow from small sub-catchments
- Associated sub-catchment with a node of the drainage network
- Ability to divide the catchment to pervious and impervious areas
- Include soil moisture stores in each sub-catchment element
- Large number of catchments available in the model
- Account for the effect of vegetation on soil moisture and interception
- Ability to route between sub-areas within sub-catchment

2.6 Chapter Summary

The models reviewed are categorized into lumped and grid based models. Most of the lumped models can simulate the catchment in a semi-distributed way (e.g. SWMM, QUALHYMO). Grid based models can divide the catchment into small cells, distribute the flow from one cell to another cell, and simulate some of the hydrologic processes at each cell or catchment, like infiltration and overland flow.

Lumped models aggregate many characteristics in each catchment and simulate the catchment runoff up to a certain level of accuracy. Some lumped models cannot simulate all processes in the LID measures which reduce the model efficiency and possibility of simulating catchments with LIDs. TOPMODEL is an example of lumped models where it can simulate hydrologic responses in catchments with LIDs.

Distributed models can get metrological data from very detailed sources up to a very small scale, such as digital maps, GIS or satellite images. Some of the distributed models can route the flow more accurately using this data while not all distributed models can simulate LIDs in catchments. Flow direction is an important issue when designing or analyzing catchments. The flow direction can change the catchment's response to the storm event, the runoff volume calculated, and the peak flow rate. Most of the available distributed grid based models adopt only one flow direction algorithm.

There are five main flow directions algorithms: 1) the deterministic eight-node (D8) which direct the flow from one cell to one of the eight neighboring cells, 2) the random eight-node (Rh08) introduce degree of randomness into the flow direction computations and direct the flow to only one cell, 3) FD8 direct the flow to more than one cell, 4) the Digital Elevation Model Network (DEMON) direct the flow to only two cells and does not allow flow to be directed to the diagonal cell, 5) D∞ direct the flow to one or two cells maximum based on the calculated slope.

In this research, the SWMM model, as an open source model, was selected to be used as a tool to investigate small scale hydrological models with several levels of disaggregation. The suitable flow direction algorithm for SWMM model is D8 algorithm and it is used in the research.

3 METHODOLOGY

3.1 Introduction

This chapter describes the research methodology to investigate the appropriate model structures for modelling small urban catchments. Figure 3.1 shows the methodology of the research work followed by a detailed description of each step in order to achieve the research objectives.

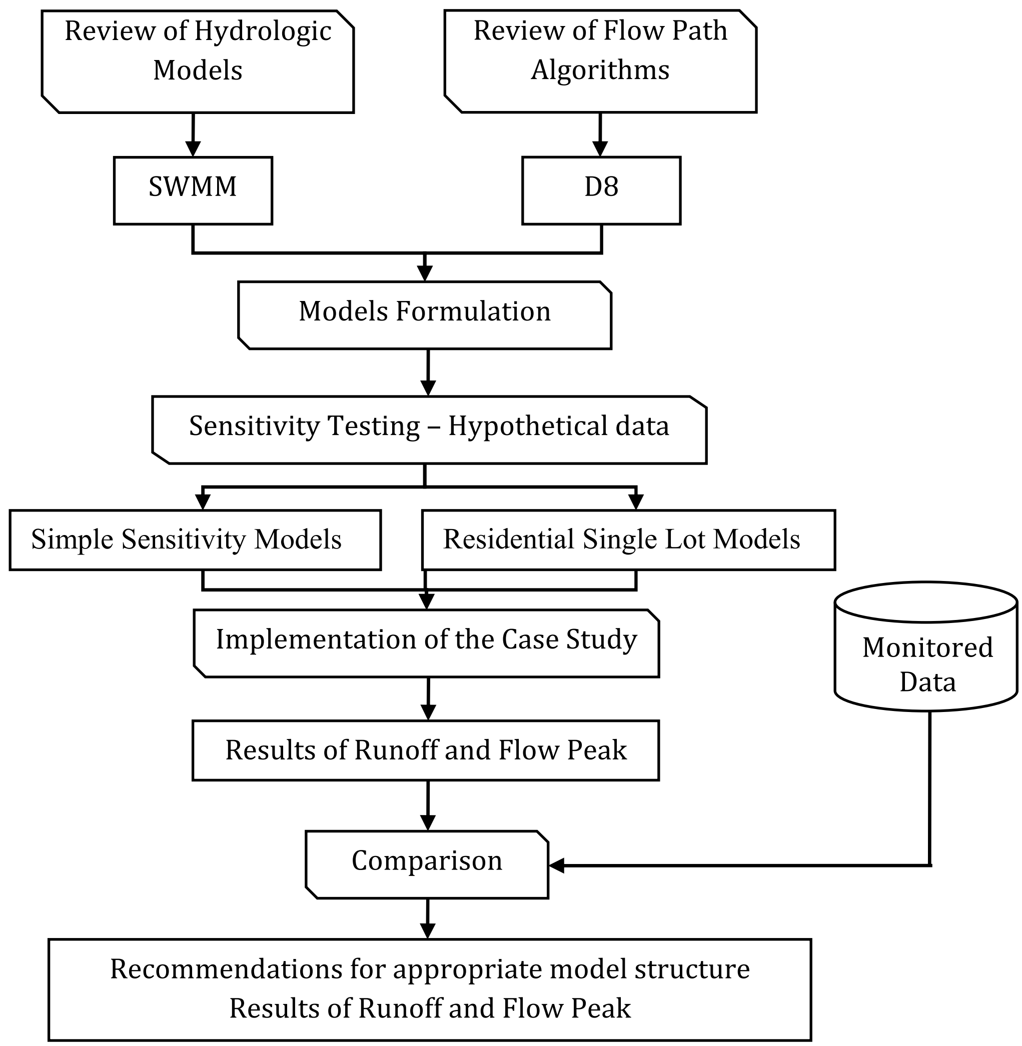


Figure 3-1 Flow chart of the research methodology

3.2 Review of Hydrologic Models

The following hydrological models were selected to be reviewed due to the availability of their detailed manual description in the literature:

- Gridded Surface Subsurface Hydrologic Analysis (GSSHA)
- TOPMODEL
- LImburg Soil Erosion Model (LISEM)
- QUALHYMO
- Storm Water Management Model (SWMM)
- Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS)

The models were reviewed and assessed based on their capability to model urban drainage systems and simulate LIDs. The reviewing and assessing criteria are based upon:

- Minimum time steps
- Overland flow routing (method, cascade, coupled)
- Groundwater routing (saturated zone, unsaturated zone)
- Evapotranspiration
- Channel routing
- Infiltration methods
- Catchment/grid size
- Routing to drainage network
- Routing through LIDs
- Exfiltration

- Lateral saturated groundwater flow

Based on the review in Chapter Two, the SWMM model was selected and applied to hypothetical data and a real case study.

3.3 Review of Flow Path Algorithms

There are five main algorithms used to generate flow directions in grid models. These flow path algorithms are:

- The deterministic eight-node (D8)
- The random eight-node (Rho8)
- The (FD8)
- The Digital Elevation Model Network (DEMON)
- The (D∞)

The review of algorithms includes: a) how the flow direction is calculated; b) the algorithm's limitations; c) the calculation of the upslope contributing area; and, d) the number of catchments receiving the flow. From the flow path algorithms reviewed in Chapter Two, the D8 algorithm was selected to be used with the selected modelling tool.

3.4 Models Formulations and Post-Processing

Different model structures, such as grid, homogenous, and lumped are developed to test the effects of disaggregation on modelling stormwater at small urban catchments. SWMM assumes each subcatchment is homogeneous and has the same area, the same width, and it receives the same amount of precipitation. The slope in each subcatchment is assumed to match the slope of the land cover (roof, lawn, and driveway) which occupies more than fifty percent of the subcatchment. The following is a description of SWMM subcatchment parameters:

- WIDTH is the subcatchment width. The subcatchment width is defined as the area of the subcatchment divided by the flow path length. In this research, the subcatchments (grids) are square shapes and the width is the grid length.
- AREA is the area of each subcatchment (grid).
- %IMP is the percent of the impervious area inside the catchment. This parameter is set to 100% if the whole subcatchment is roof, drive way, or street and is set to 0% if the whole subcatchment is lawn or bioretention.
- S is the slope of the subcatchment.
- N-IMPERV and N-PERV are the Manning's roughness coefficients of the impervious and pervious areas, respectively. The values of these coefficients were taken based on the type of the land covers in accordance with SWMM guide values.
- Dstore-Imperv and Dstore-Perv are the depression storage values for impervious and pervious areas. Depression storages were taken as described in SWMM manual. Other values for LID's were taken based on the literature.
- Max. Infil. Rate is the rate used in Horton's infiltration equation. This parameter is the initial infiltration rate at the beginning of the storm max infiltration rate change based on the soil type. The values are used in the study according to the SWMM guide table for loamy soil.
- Min. Infil. Rate is the minimum infiltration rate that the soil attains when the soil is fully saturated. It is usually set to the soil's hydraulic conductivity. The values are used in the study according to the SWMM guide table for loamy soil.

- Decay Constant parameter indicates how quickly the soil infiltration rate will decay from the initial value to the minimum value.

The deterministic eight-node (D8) algorithm is selected to route the flow to the steepest cell of eight neighboring cells. The flow direction is defined manually based on the steepest downslope where the outlet of each subcatchment is defined by the modeller. The rainfall rate is assumed to be uniformly distributed over the study area. The hydrologic processes taken into consideration in this research are the infiltration process and evapotranspiration. Horton's equation is used to calculate the infiltrated volume as an empirical equation with only three parameters: minimum infiltration capacity, maximum infiltration capacity, and decay coefficient.

Horton's is a simple equation since it has no soil parameter, such as hydraulic conductivity (Anderson, 1998). Horton's equation was also chosen for the infiltration calculations due to its suitability for small watersheds that respond quickly to storms (Verma, 1982). After selecting the modelling tool and the flow path algorithm, two tests were conducted to achieve the research objectives. The following is a description of the models formulation for both tests.

3.4.1 Simple Sensitivity Models

The test was conducted to investigate the effect of different flow paths on the total runoff volume at the outlet of a square area using the hypothetical data. The test examined a $256m^2$lot which was twenty five percent impervious. The lot was simulated using four models: Single catchment, an 8x8m grid, a 4x4m grid and a 2x2m grid. For this test, the runoff from more than one subcatchment was directed to a single subcatchment to examine the catchment response to different flow directions. The test also examined the effect of different levels of disaggregation on runoff volume at the outlet. All model scenarios were examined using loamy and sandy soils to investigate the models' behaviors under different infiltration rates.

The rainfall data used for the models' calculations was based on records of the Barrie Water Pollution Control Centre's (Barrie WPCC) rain gauge station, the Ontario Climate Centre, Environment Canada. The rainfall data of 1985 was the average rainfall per year for the City of Barrie and there were no missing records for that particular year. The test was run based on continuous simulation from April to November 1985.

3.4.2 Residential Single Lot Models

The test was aimed at examining a residential single lot using hypothetical data. The test was conducted to investigate the effect of different levels of disaggregation on runoff volume and peak flow at the outlet without LID, with bioretention, and with porous pavement. The test also examined the effect of different time steps on runoff volume and peak flow at the outlet in the previous three cases. The rainfall data used was the average rainfall per year for the City of Barrie and was the same data used for the previous test. A continuous simulation and a single event were examined over the lot area to evaluate the effects of different temporal scales on runoff volume and peak flow rates at the outlet. The residential single lot ($600m^2$) was tested using five models; one catchment, a 2x2m grid, a 4x4m grid, a 5x5m grid and a 10x10m grid.

After running the different scenarios using the SWMM model, the results were exported to a Microsoft Excel program. The analyses of the model results were based on comparing the total infiltration volume, the total runoff volume, and the peak flow rate at the outlet of each model.

3.5 Implementation of the Case Study

The previous two tests were helpful to choose the model structures for the case study with monitored runoff. The area of the real case study used in this research is located in the south part of the City of Mississauga. The rainfall data examined was for continuous simulation and single events. The case study used lumped, grid and homogenous models. Based on the evaluation of the hypothetical data results, the time step and the grid size of the grid model were selected for the case study.

The flow routing options in each subcatchment were based on the model structure. The one catchment and the grid model used a pervious option, allowing the runoff to be routed from impervious to pervious area. The homogenous model, which included only one type of land cover in each subcatchment, used outlet option (both impervious and pervious routed to the outlet). Horton's equation was used to describe the soil infiltration parameters. The models of the case study examined continuous simulation from July to December 2011. Five events with the highest peak flow were selected for the model evaluation based on the runoff volume, time to peak, and the peak flow value.

The models also examined two single events and were evaluated based on comparisons between the models hydrographs to the observed hydrographs considering the shape, the peak value, and the time to peak. ArcGIS was used to create layers with different land cover to calculate the percentage of imperviousness in each grid, the total area of each catchment in the homogenous model, and the total area of roofs. The appropriate model was determined based on comparing the three models predicted runoff and peak flow values to the observed values without calibration. If model predicted values were within ± 20% of the observed values, the model was considered appropriate.

4 SENSITIVITY TESTING MODELS

4.1 Description of Simple Sensitivity Models

A small square lot of 256 m^2 was used as a simple model for the sensitivity test to investigate the effect of different grid sizes and different flow directions on the modelled runoff. Four models were built: single catchment (Case (A), Figure 4-1); four subcatchments in 8x8m grid – (Case (B), Figure 4-2); sixteen subcatchments in 4x4m grid (Case (C1), Figure 4-3 and Case (C2), Figure 4-4); and, sixty-four subcatchments in 2x2m grid (Case (D1), Figure 4-5 through Case (D3), Figure 4-7). No smaller subcatchments are tested due to the stability of the results obtained from the sixteen and the sixty-four subcatchments (4x4m and 2x2m grids).

The sensitivity models were tested at 25% imperviousness. In each model, the area was divided into regular grid cells with homogeneous hydrologic characteristics. The models ran for continuous simulation and a single event. The continuous simulation was conducted using the City of Barrie's average yearly rainfall data in 1985. The continuous simulation was run from April to November, with a total rainfall of 544.2mm and 26.9 mm/hr maximum rainfall intensity (Figure 4-9). The single event of July 15th had one of the highest rainfall intensity (Figure 4-8).

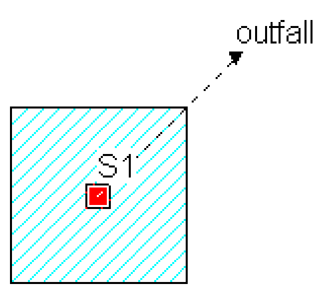


Figure 4-1 Case (A) - Single catchment with 25% impervious area

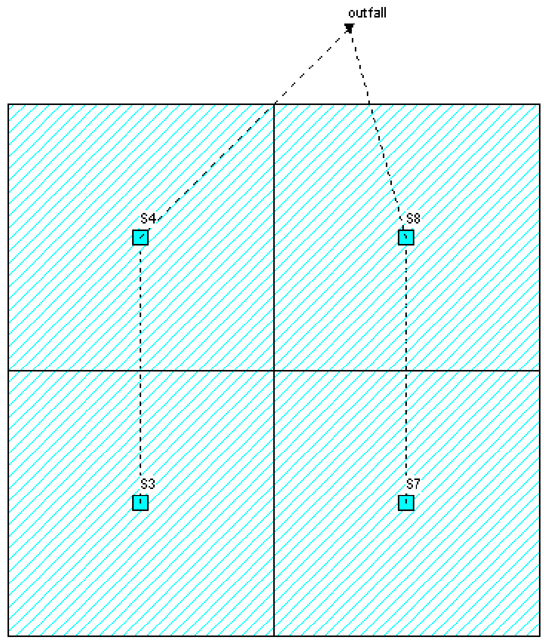


Figure 4-2 Case (B) - 8x8m grid model showing the flow direction

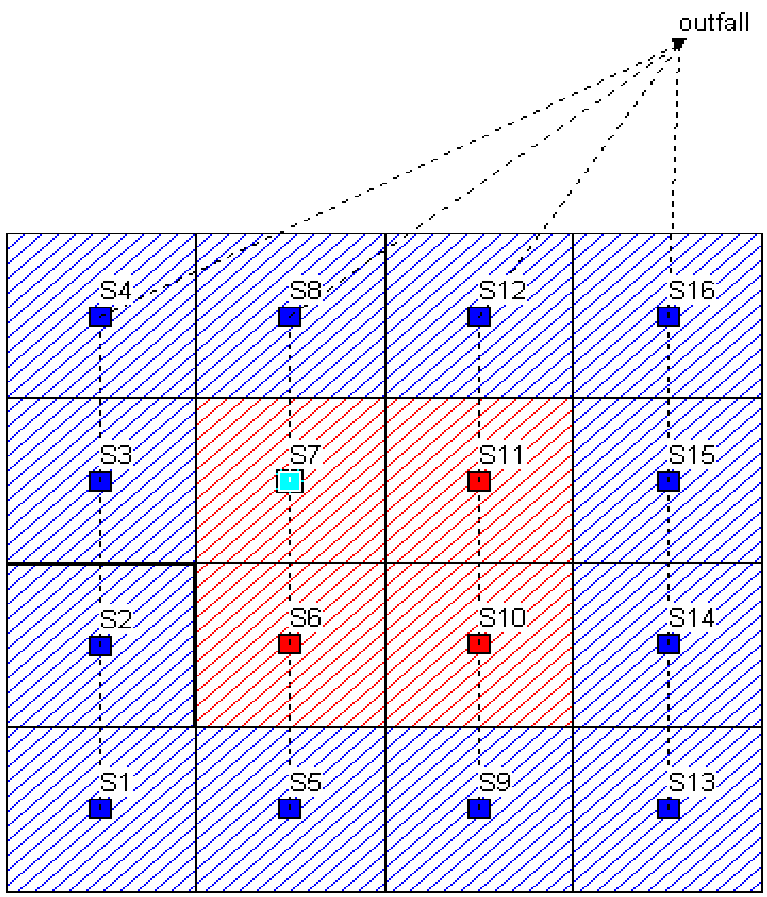


Figure 4-3 Case (C1) - 4x4m grid model showing the flow direction

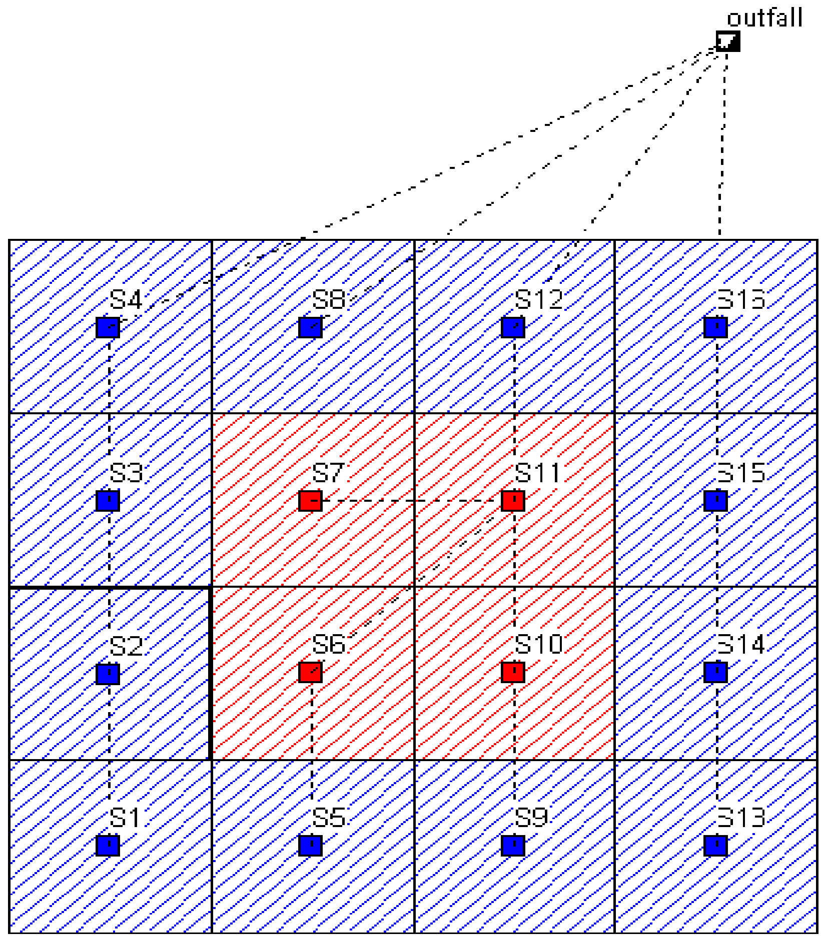


Figure 4-4 Case (C2) - 4x4m grid model showing the flow directions from subcatchments S7, S6, S10 to subcatchment S11

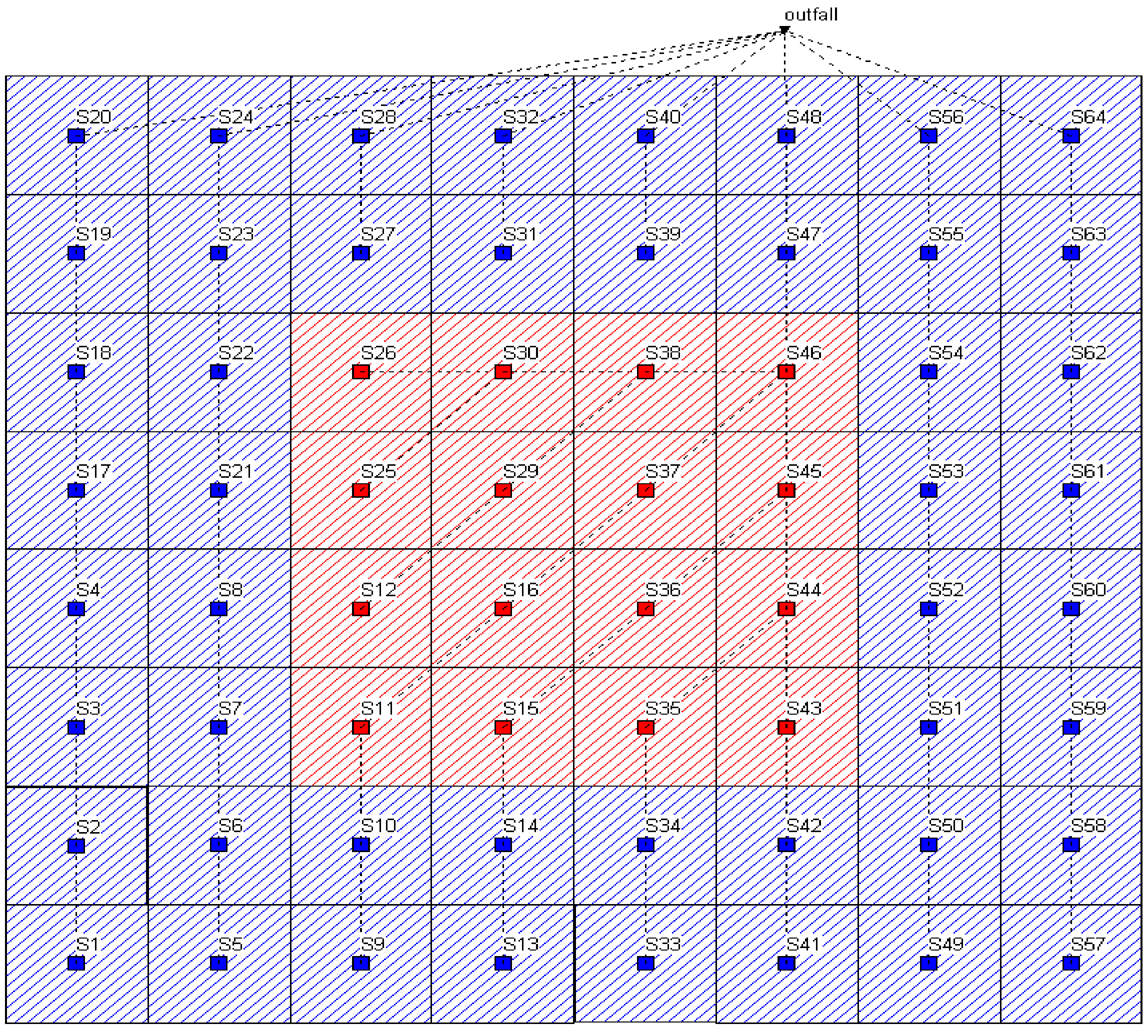


Figure 4-5 Case (D1) - 2x2m grid model showing the flow directions from the impervious area directed diagonally and horizontally to subcatchment S46

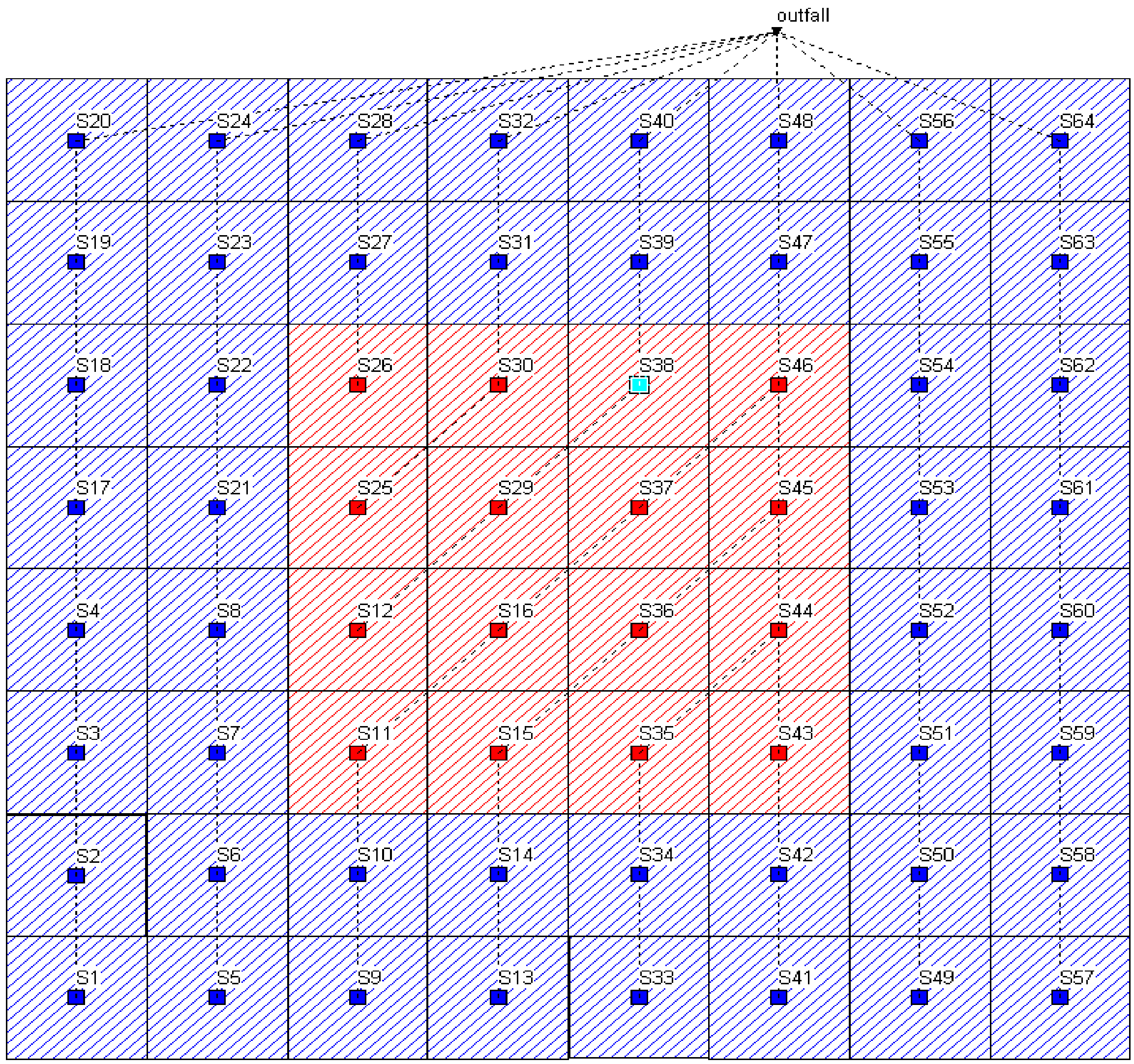


Figure 4-6 Case (D2) - 2x2m grid model showing the flow directions from the impervious area directed diagonally without directing the flow from subcatchments S26, S30 and S38 to the subcatchment S46

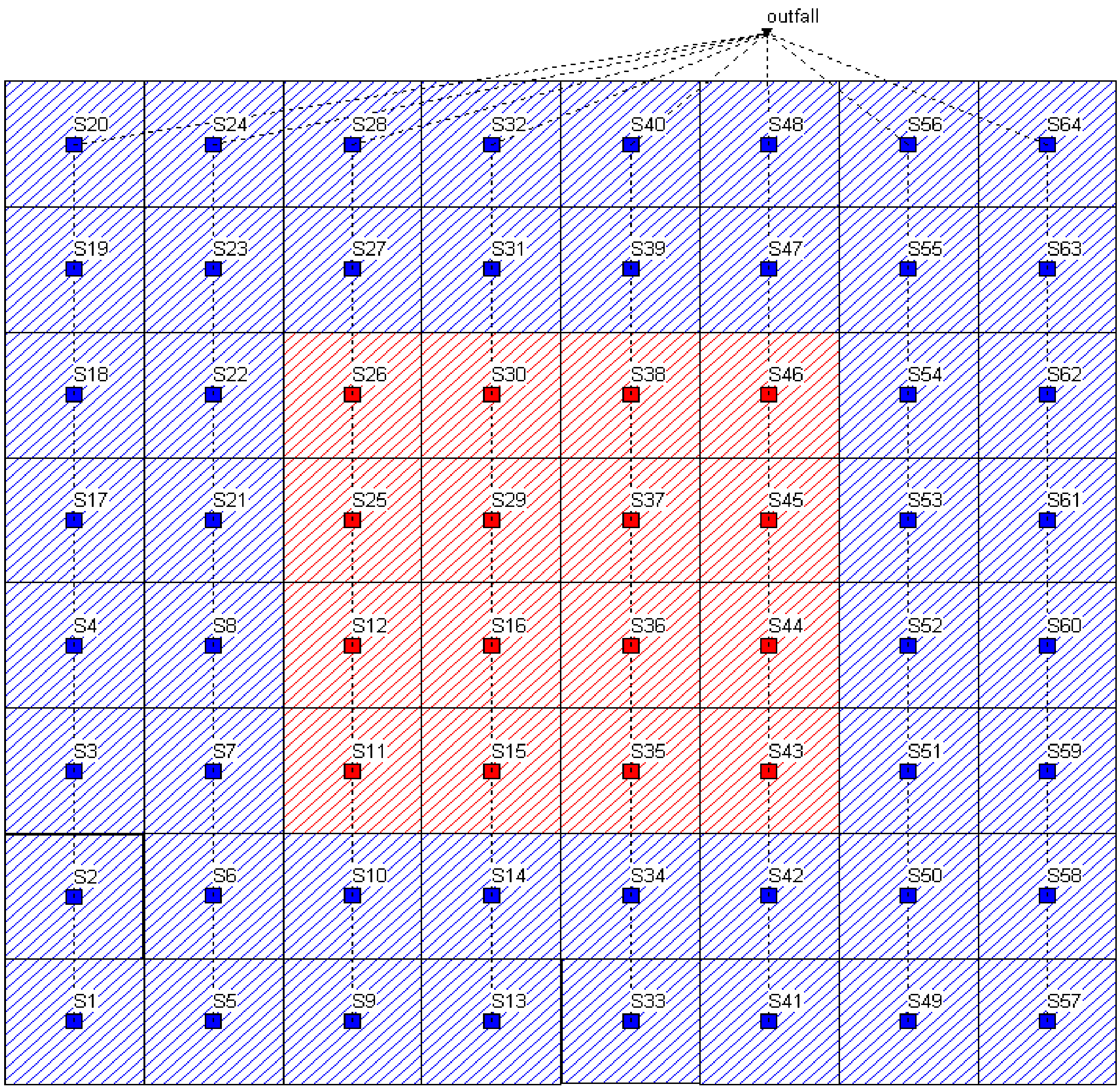


Figure 4-7 Case (D3) - 2x2m grid model showing the flow direction in vertical direction.

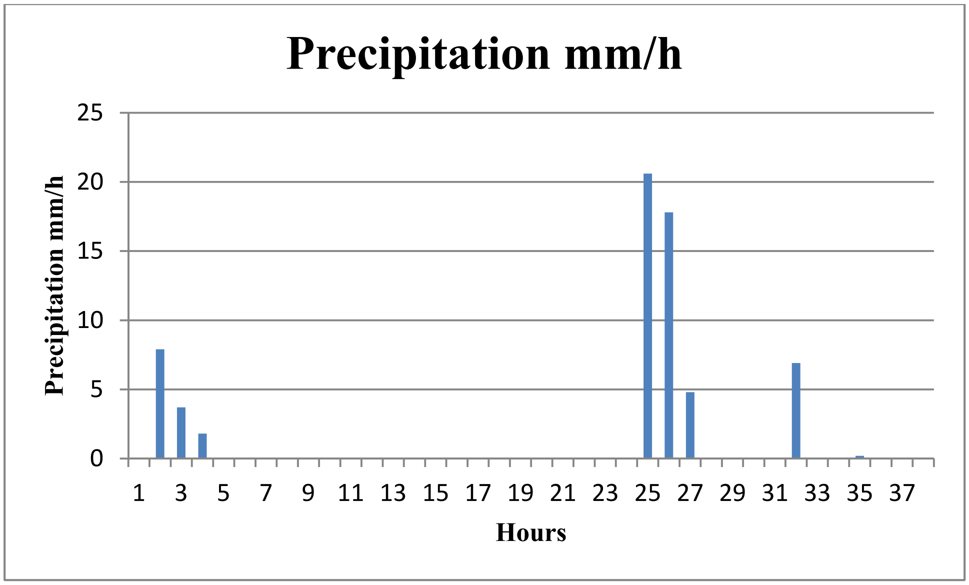


Figure 4-8 The distribution of the rainfall event (July 14th to July 16th, 1985)

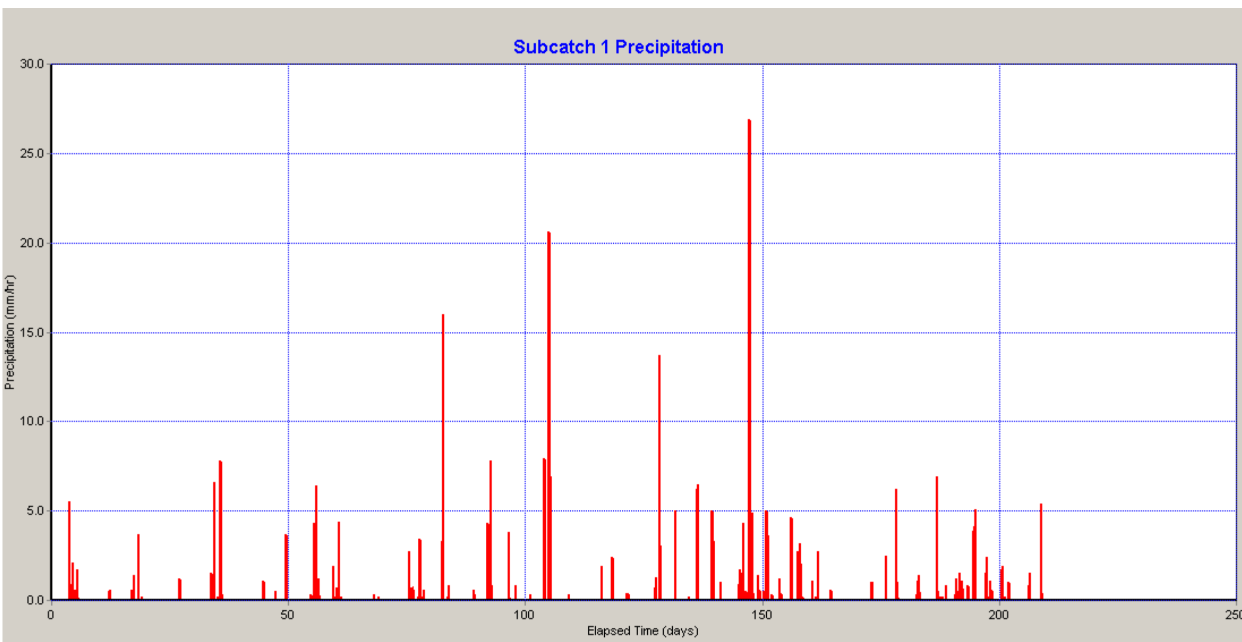


Figure 4-9 The distribution of the rainfall event (April to November 1985)

The soil types considered were sandy and loamy soils. Horton's equation was used in SWMM to calculate the infiltration rate. Table (4-1) describes the soil parameters for Horton's equation while other parameters such as the Manning's roughness coefficient and depression storage values were taken from the tables published in the SWMM user's manual (Rossman, 2009). The flow path method was assumed to drain to one of the eight surrounding grids with the lowest elevation.

The Climatology editor in SWMM provides many ways in which to add evaporation data. For this sensitivity test, the monthly average method was chosen. Table (4-2) shows the monthly average evaporation data based on the 1985 City of Barrie evaporation data. The width of the catchment was assumed to be the grid width, the slope of all catchments was assumed to be 2%, and the rest of the parameters were default values from SWMM.

Table 4-1 Horton's equation parameters for different soil types, ((Rossman, 2009)

Soil texture class	Max Infiltration rate (mm/hr)	Min Infiltration rate (mm/hr)	Decay coefficient (mm/hr)
Loamy	75	12.5	4
Sandy	125	46	4

Table 4-2 Monthly average evaporation (mm/day), (City of Barrie, 1985)

Jan	February	March	April	May	Jun
0	0	0.019	0.943	2.519	3.766
July	August	September	October	November	December
4.129	3.684	2.580	1.223	0.315	0

4.2 Simple Sensitivity Model Scenarios

The simple sensitivity models were created to understand the behavior of distributed models under different grid size assumptions and to explain the behavior of complex distributed models. The sensitivity test also investigated the effect of different flow routing directions on the total runoff volume at the outlet of the catchment. In all models, the depression storage values of the pervious and impervious areas were set to 3.75 mm and 1.75mm, respectively, based on the recommendation of the SWMM manual. The percentage of imperviousness with zero depression storage was assumed to be zero. The color coding in all figures showed the 100% pervious area in blue and the 100% impervious area in red except Case (B) in Figure 4-2, where each subcatchment includes 25% imperviousness.

The single catchment model was referred to it as Case (A) (Figure 4-1). The 8x8m grid model was referred to it as Case (B). It was examined using one flow direction, which allowed the flow from one subcatchment to another; in addition, each subcatchment received flow from a single subcatchment (Figure 4-2). The 4x4 grid model (Case (C1) and Case (C2)) examined two flow directions with the rest of the parameters being the same as previously mentioned (see Figure 4-3 and Figure 4-4). In Case (C1), the flow was directed from one subcatchment to another allowing the subcatchment to receive the flow from a single subcatchment (Figure 4-3). In Case (C2), the flow was directed from one subcatchment to another subcatchment similar to Case (C1) for the 100% pervious areas. On the other hand, one subcatchment (S11) received the flow from other subcatchments (S6, S10 and S7) in the 100% impervious (Figure 4-4).

The 2x2m grid model examined three Cases (D1, D2 and D3) with three different flow directions. Case (D1) is similar to Case (C2), except for the smaller grid size (Figure 4-5). In Case (D2), the flow was directed from one subcatchment to another and the subcatchment with 100% impervious directed the flow diagonally up to subcatchments S30, S38, and S46. Then subcatchments S30, S38, and S46 directed the flow to the next subcatchment (Figure 4-6). In Case (D3), the flow was directed from one catchment to another, where each subcatchment received flow from only a single subcatchment (Figure 4.7).

4.3 Residential Single Lot Sensitivity Models

Figure 4-10 shows a 600 m² hypothetical residential lot that includes a building with an area of 140 m², a driveway with an area of 15 m², and a large lawn. The percentage of imperviousness in the lot was assumed to be 25%. The soil type was assumed to be loamy (associated Horton's parameters are shown in Table 4-1). The SWMM model was used as a distributed model tool to investigate the runoff volume, the peak flow, and the infiltration volume. The residential single lot was modeled using single catchment model and models with different grid sizes (2x2m, 4x4m, 5x5m and 10x10m). The time steps were selected as 15 minutes, 10 minutes, 5 minutes, 1 minute and 30 seconds, based on the SWMM recommendation (i.e., all time steps less than the rainfall interval of 1 hour). The following modelling cases were investigated:

- Without applying any LID to the site.
- With the addition of a bioretention area next to the building before diverting the flow to the outlet, as well as collecting the flow from the roof.
- With the application of porous pavement on the driveway.

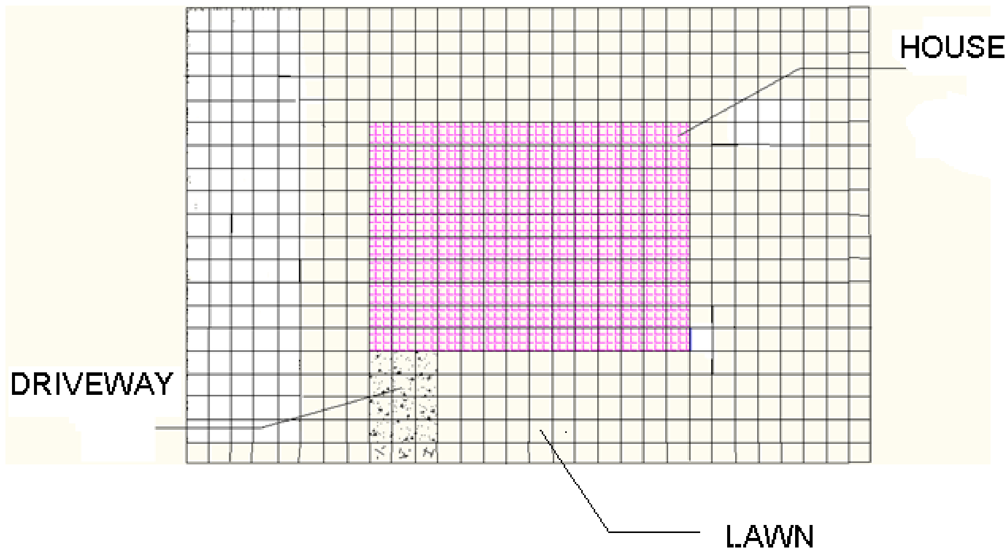


Figure 4-10 Plan of the single lot study area

4.4 Climate and Rainfall Data for the Sensitivity Testing

Continuous SWMM modelling requires a continuous rainfall time series. Barrie's hourly rainfall data, based on the Ontario Climate Centre of Environment Canada, was used for all sensitivity scenario testing. The rainfall data was measured between April and November 1985, previously determined as a typical rainfall year for the City of Barrie. The total rainfall depth was 544.1 mm. The monthly evaporation data were also recorded by Environment Canada for the City of Barrie.

4.5 Residential Single Lot Sensitivity Scenarios

4.5.1 Models without LIDs

The residential single lot was first simulated without applying any LIDs. The area was divided into 2x2m, 4x4m, 5x5m and 10x10m grid cells. The same rainfall and evaporation data used in the simple sensitivity models was used in the residential single lot sensitivity models. In each trial, the runoff depth, the evaporation losses, the infiltration losses, and the peak flow values were calculated at different time steps of 15 minutes, 10 minutes, 5 minutes, 1 minute, and 30 seconds.

Figures 4-11 to 4-14 show the study area in different grid sizes, as well as the direction of the flow from each grid cell. For these models, loamy soil characteristics were applied to the Horton Infiltration equation. The slope of all grid cells was assumed to be 0.5%. The catchment width was assumed to be the grid length. The subareas were routed to a single outlet. The percentage of imperviousness was calculated at each grid cell. Other SWMM parameters were taken as default values based on the SWMM user's guide. The color coding in Figures 4-11 to 4-14 represents the percentage of imperviousness of each catchment.

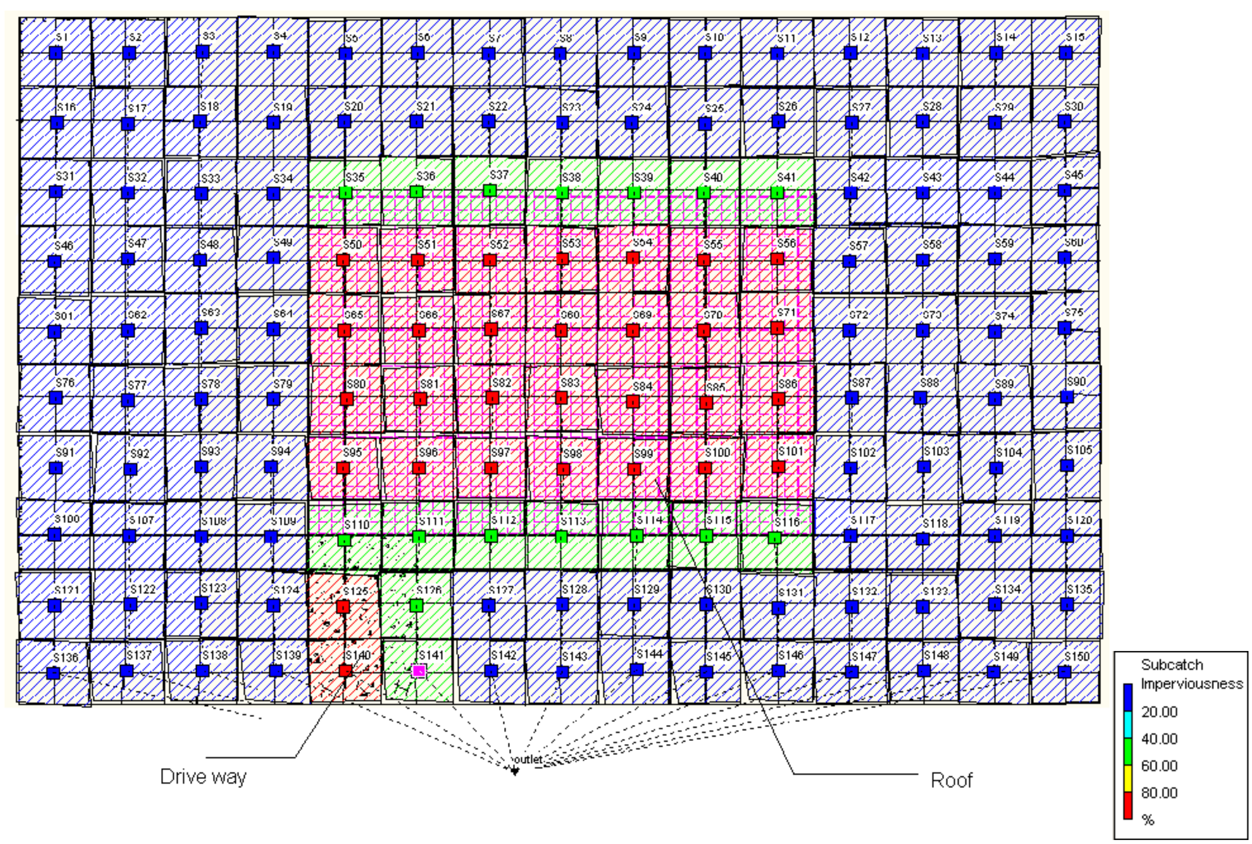


Figure 4-11 The study area with flow directions using regular 2x2m grids

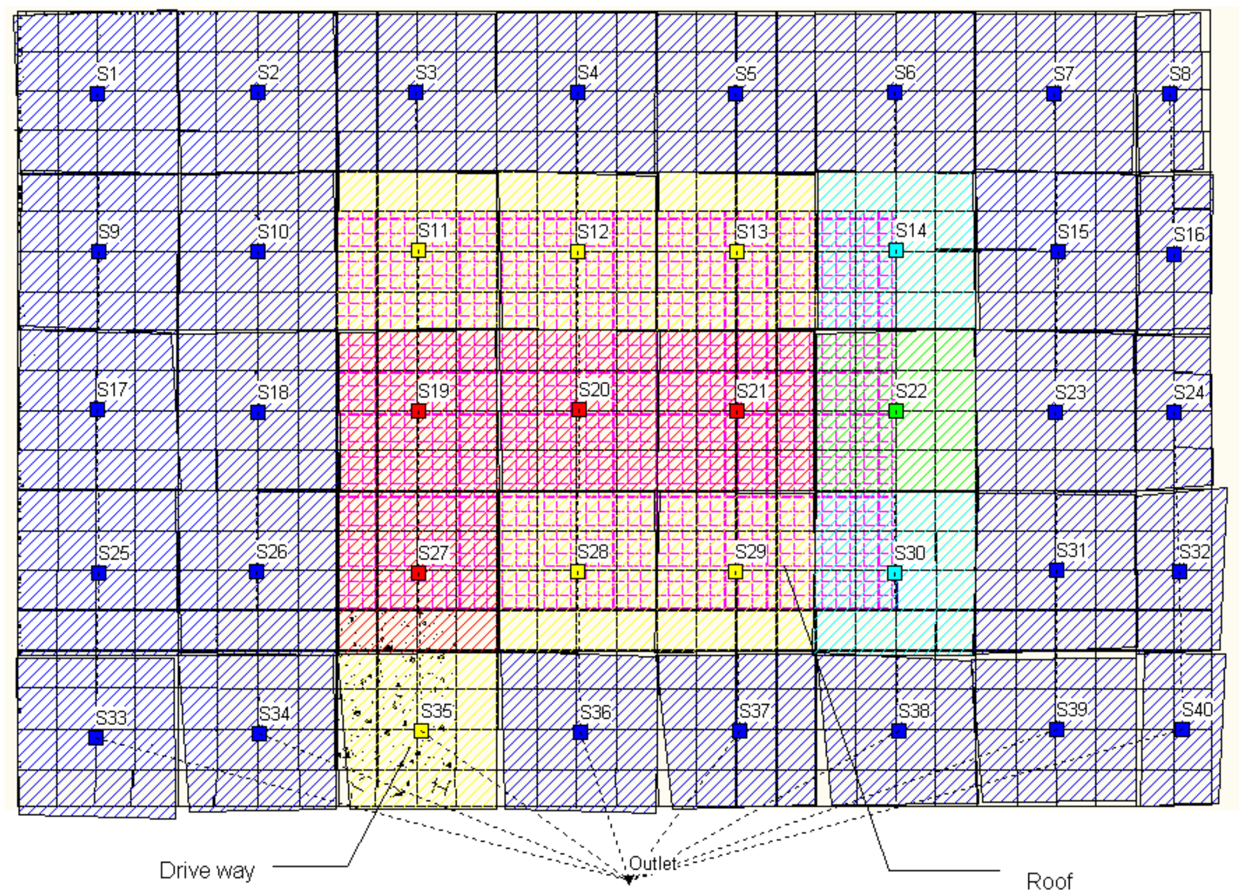


Figure 4-12 The study area with flow direction using regular 4x4 m grids.

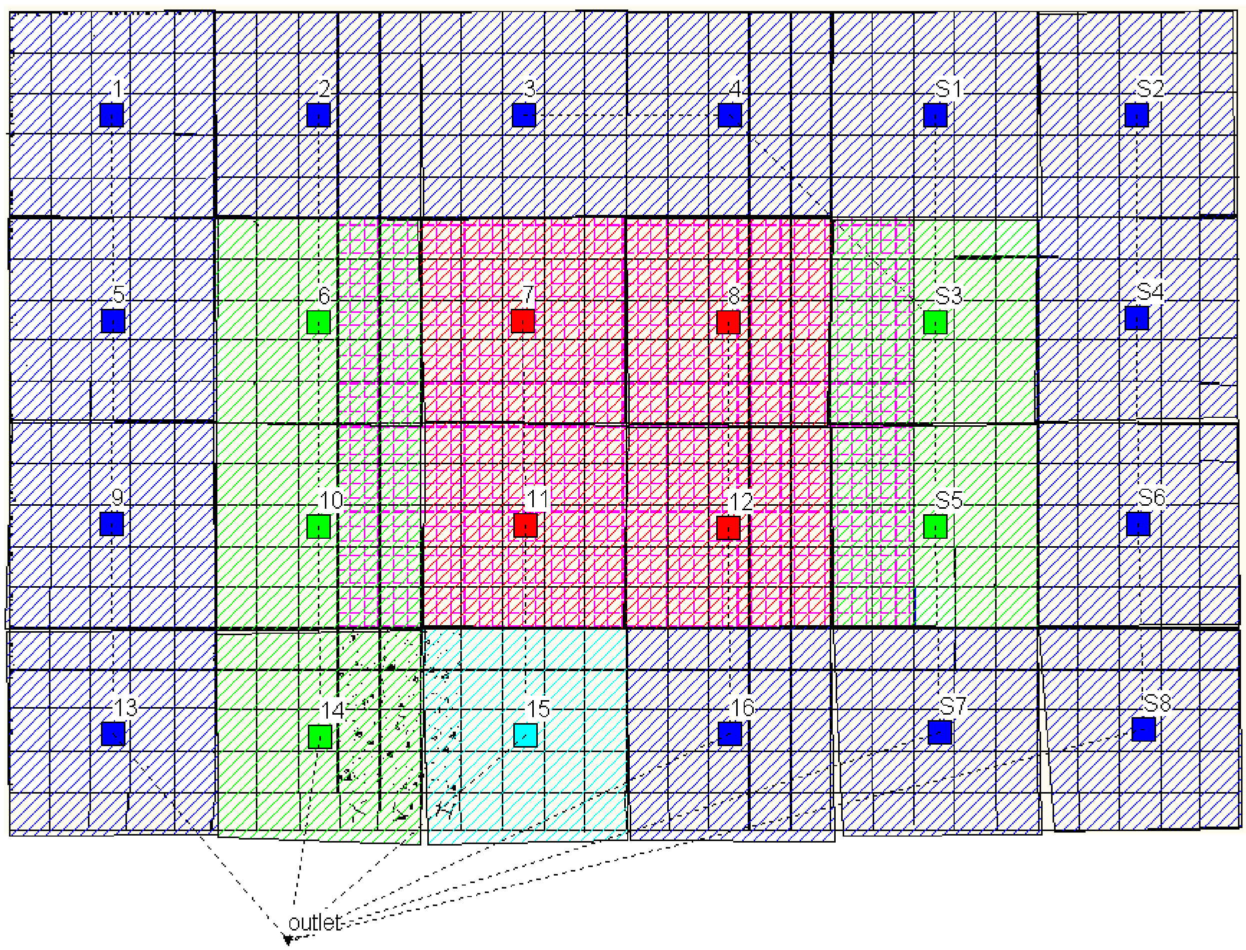


Figure 4-13 The study area with flow direction using regular 5x5 m grids.

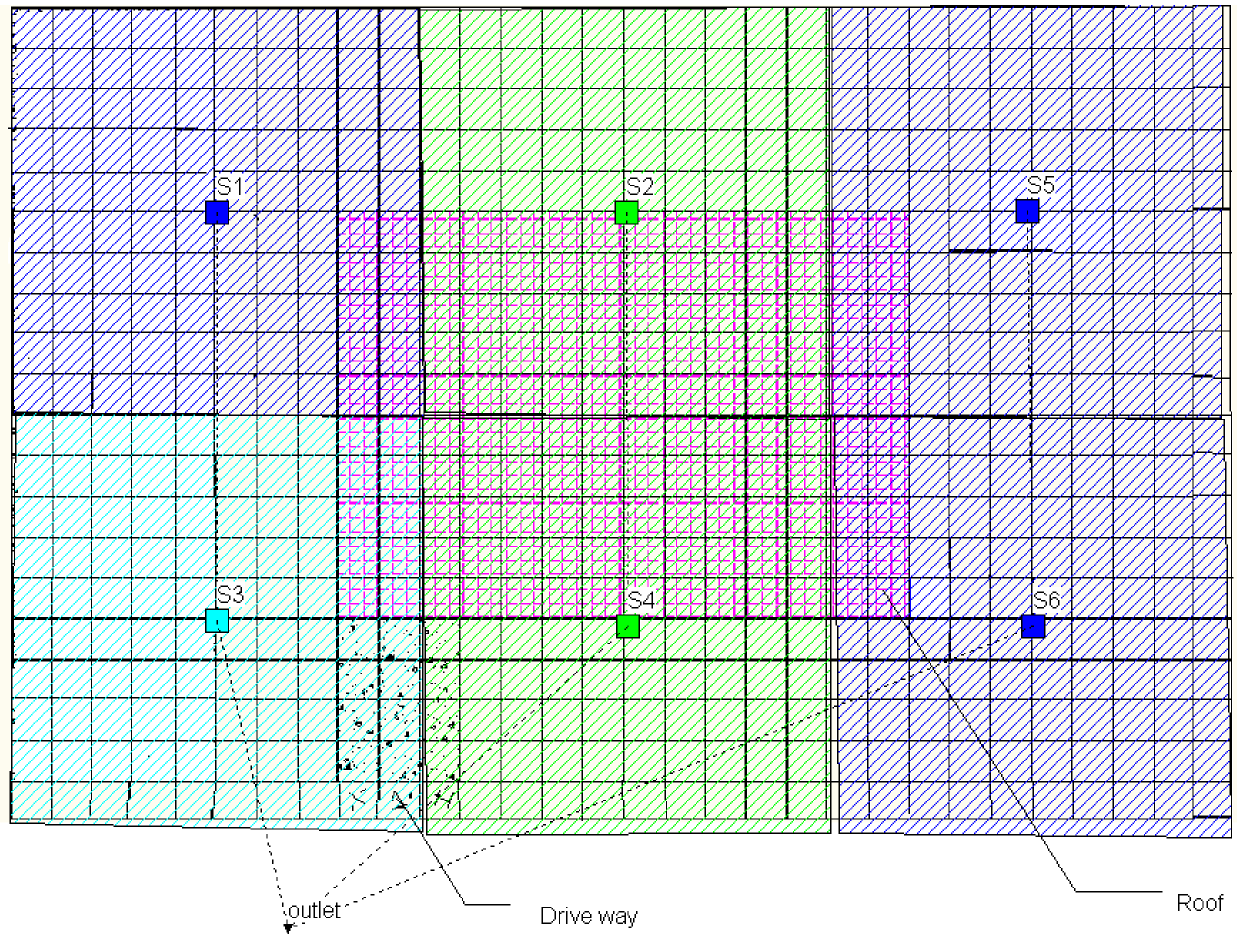


Figure 4-14 The study area with flow direction using regular 10x10 m grids.

4.5.2 LID Model with On-site Bioretention

Bioretention is a system to store, treat, and infiltrate runoff from a pervious or impervious area. A bioretention system captures runoff from small storm events. It is designed with or without underdrain based on the native soil infiltration rate. An underdrain is a pipe embedded in the coarse gravel storage layer of the system. The primary component of a bioretention system is a filter bed of sand, fines, and organic materials. The system contains other elements, including: a mulch ground cover and plants which can be adapted to different development areas. A bioretention system was implemented in the sensitivity models next to a building, with an area of about $14m^2$ based on the TRCA (Toronto and Region Conservation Authority) and CVC (Credit Valley Conservation Authority) LID design guidelines (TRCA, 2010), as shown in Figures 4-15 to 4-17. The total runoff volume, the peak flow, the infiltration volume, and evaporation were compared with and without the application of bioretention, as well as with models featuring different grid sizes.

There are some key constrains and physical suitability that have to be considered when designing bioretention systems (TRCA, 2010):

- Available space: About 10% to 20% of the contributing drainage area has to be reserved for the open areas.
- Site topography: Bioretention is best applied when the contributing slope is 1% to 5% and usually located at a natural depression to minimize excavation. For this research, the bioretention cells were assumed to be located along the road. Thus, road longitudinal slope was assumed to be applied to the filter bed to allow flow to spread out.
- Available head: For a bioretention cell with an underdrain, an elevation difference of 1 to 1.5 metres should be applied between the inflow point and the downstream storm drain invert, which in turn will enable large flows to move out of the system. If a bioretention cell is without an underdrain, enough elevation difference should be designed to move the flow without generating backflow. The bioretention cell in the research was assumed to be without underdrain due to the native soil infiltration rate which is higher than 15 mm/hr as recommended by the TRCA guidelines.

- Soils: Bioretention cells should be located on the highest native soil infiltration rate. When the infiltration rate of the native soil is less than 15mm/hr, bioretention cells with underdrain is recommended.
- Drainage Area and Runoff Volume: Bioretention cells are very effective for runoff control over small drainage areas. A typical drainage area is between 100m^2 to 0.5 hectare. Ideally, bioretention cells are used as a source control, not as an end of pipe control. The typical ratio between impervious areas to bioretention areas is 5:1 to 15:1. In the sensitivity models, the ratio was assumed to be 10:1.

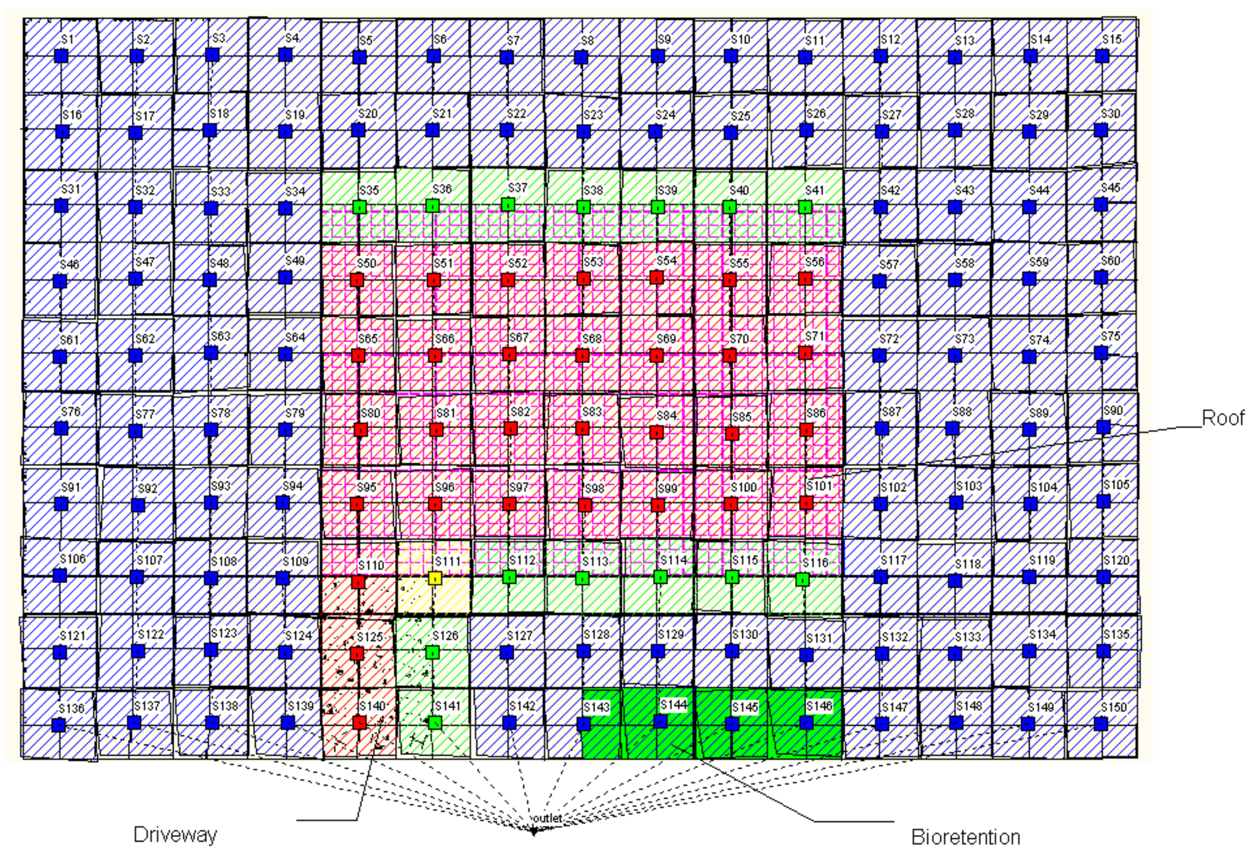


Figure 4-15 The location of the bioretention cell in the study area of 2x2m grids

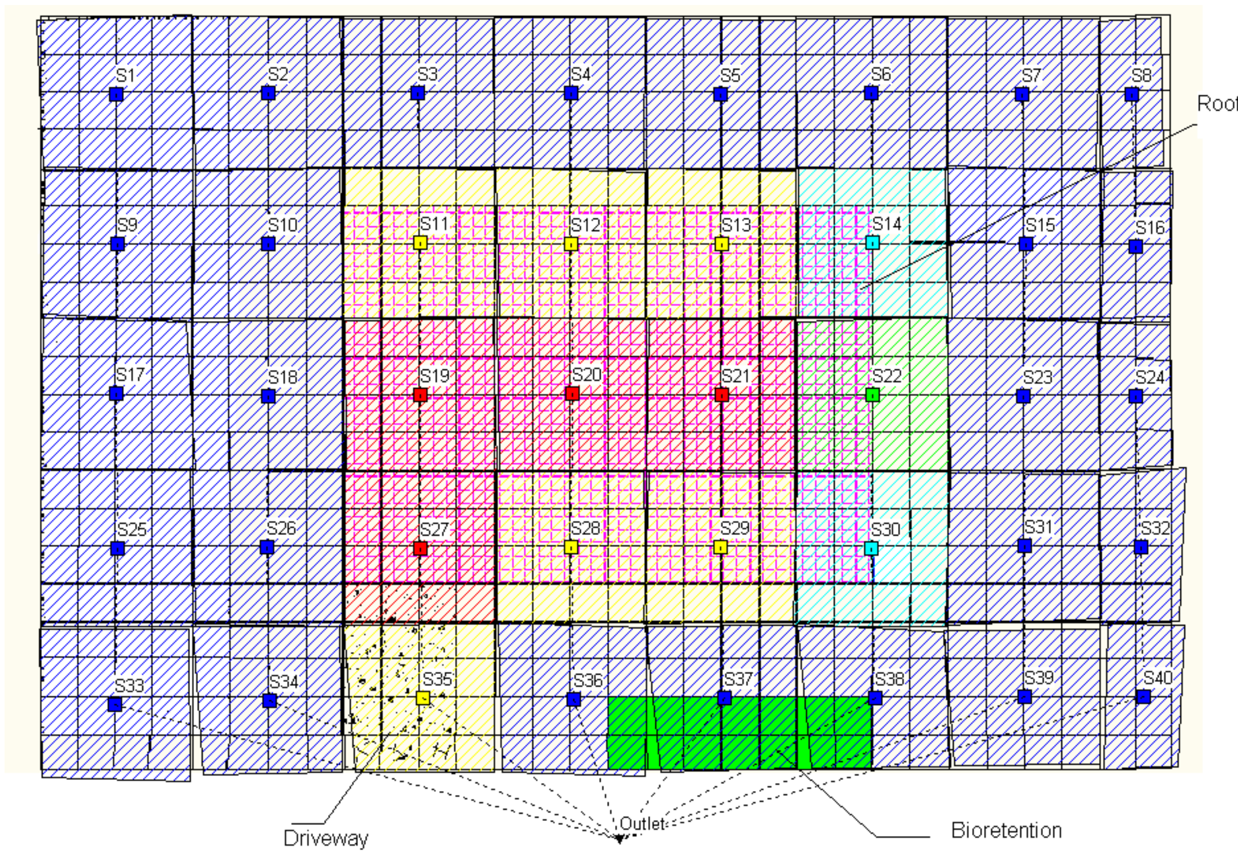


Figure 4-16 The location of the bioretention cell in the study area of 4x4m grids

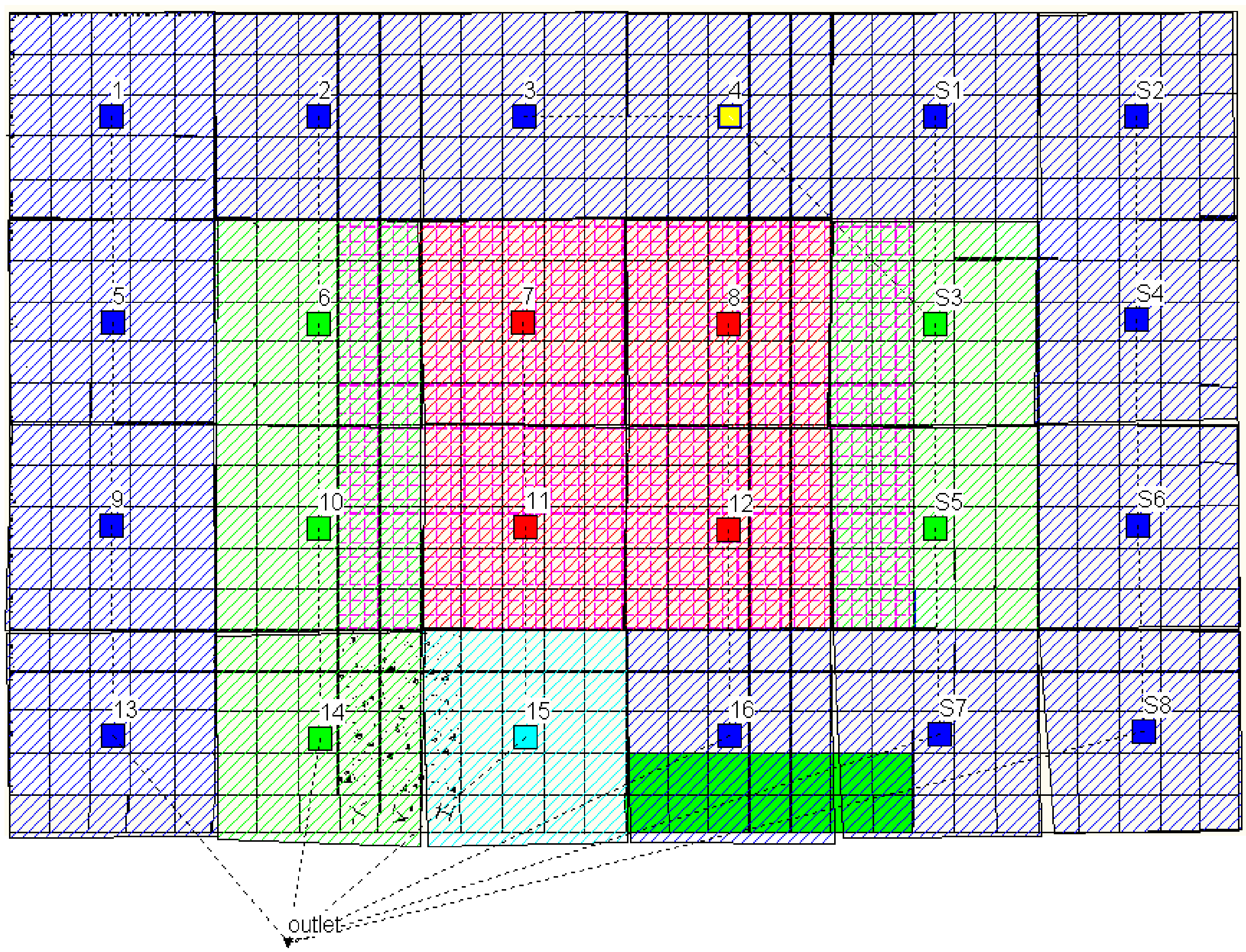


Figure 4-17 The location of the bioretention cell in the study area of 5x5 m grids

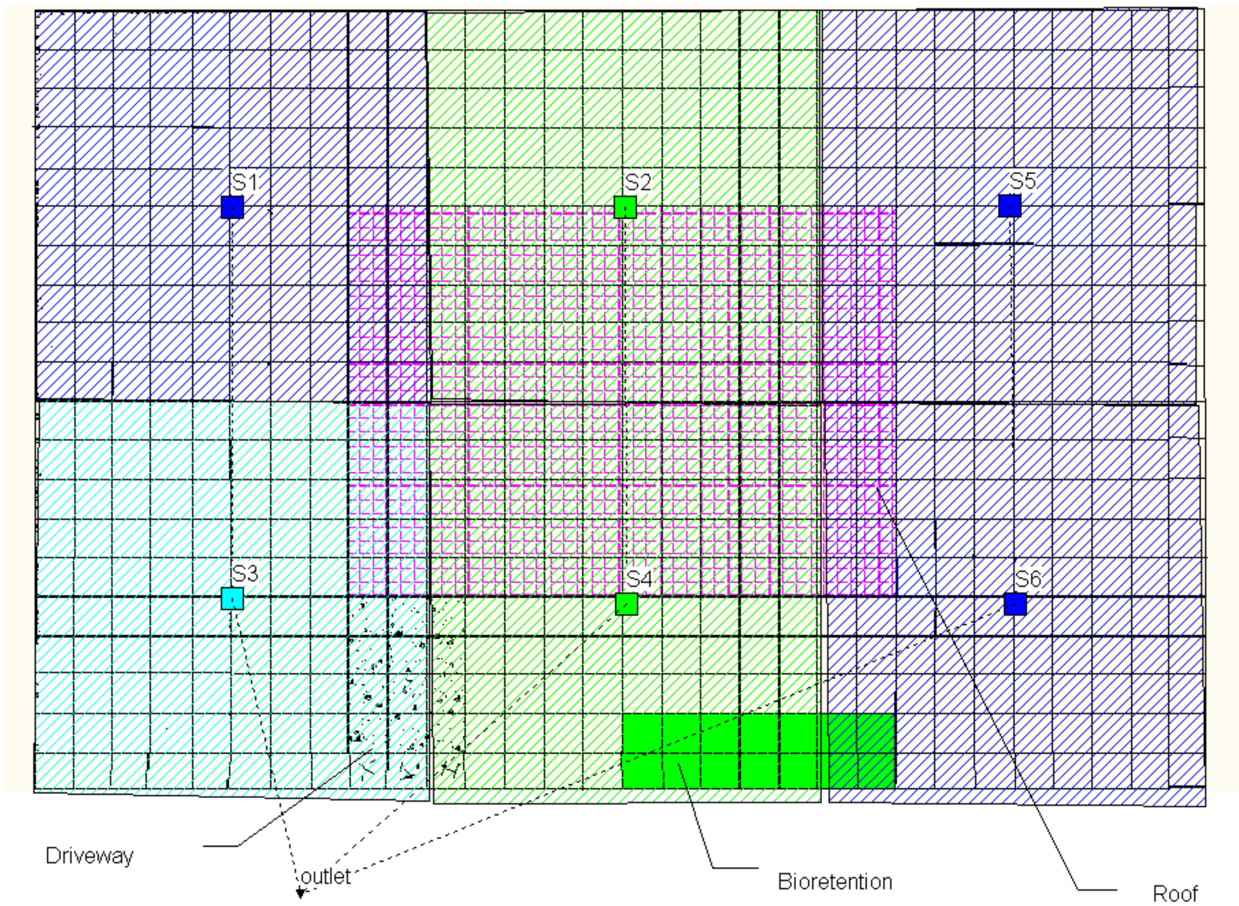


Figure 4-18 The location of the bioretention cell in the study area of 10x10 m grids.

4.5.3 LID Model with Permeable Pavement

Permeable pavement is a stormwater management alternative to regular pavement, which allows stormwater to drain through native soil and reduce the overall stormwater runoff. Permeable pavement is ideal for small sites where there is not enough space for other stormwater management techniques. It can be used for parking lots, driveways, and pedestrian areas.

The effect of distributed models using regular grids on permeable pavement was studied by applying the permeable pavement in the driveway of the tested catchment. A permeable pavement system can be designed without an underdrain for full infiltration, with an underdrain for partial infiltration, or with an impermeable liner and an underdrain for no infiltration (TRCA, 2010). The following are some key constraints and physical suitability when designing a permeable pavement system (TRCA, 2010):

- Site topography: The slope of a permeable pavement surface should be 1% to 5% maximum. The slope of the surrounding impervious area should not exceed 20% and any pervious area should not drain onto the pavement. In this research, the permeable pavement surface slope was assumed to be 5%.
- Soils: When a permeable system is located in low permeability soil with an infiltration rate less than 15mm/hr, an underdrain should be used. In this research, the soil infiltration rate was assumed to be 24mm/hr; therefore, an underdrain was not used. The permeable pavement parameters used in this research are shown in Table 4-3. Figures 4-19 to 4-22 show the location of the porous pavement using different grid sizes.

Table 4-3 SWMM parameters for modelling permeable pavement (Rossman, 2009)

Control Name	PP
BMP type	Porous Pavement
Process Layers: Surface	
Storage Depth, in mm	0
Surface Slope, in %	5
Surface Roughness (Mannings n)	0.024
Process Layers: Pavement	
Thickness, in mm	125
Void Ratio	0.165
Effective Particle Size, in mm	15.5
Process Layers: Storage	
Height or Thickness, in mm	900
Void Ratio	0.4
Drain Height, in mm	0
Drain Coefficient, in mm/hr	0

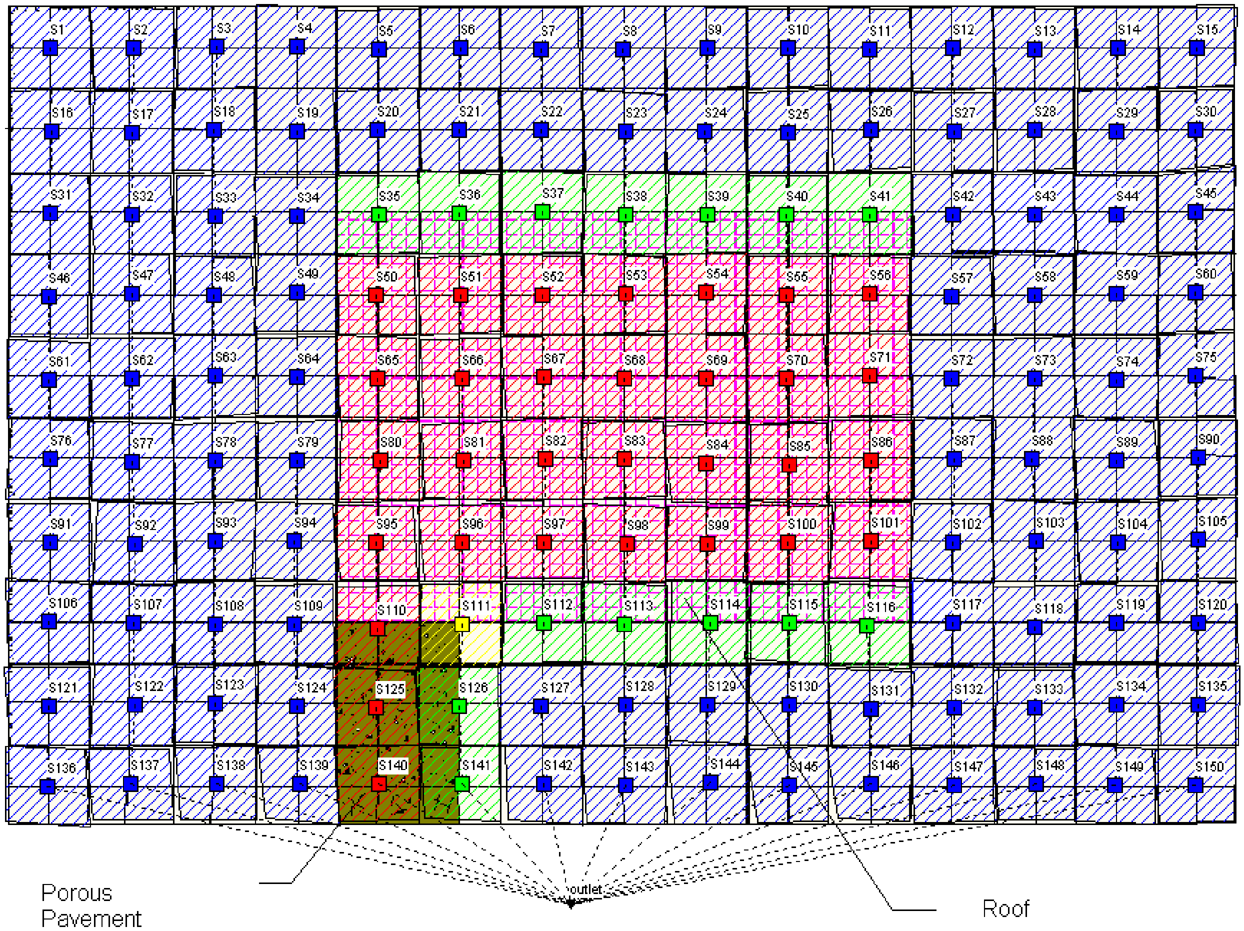


Figure 4-19 The porous pavement located on the driveway in the study area of 2x2 m grids

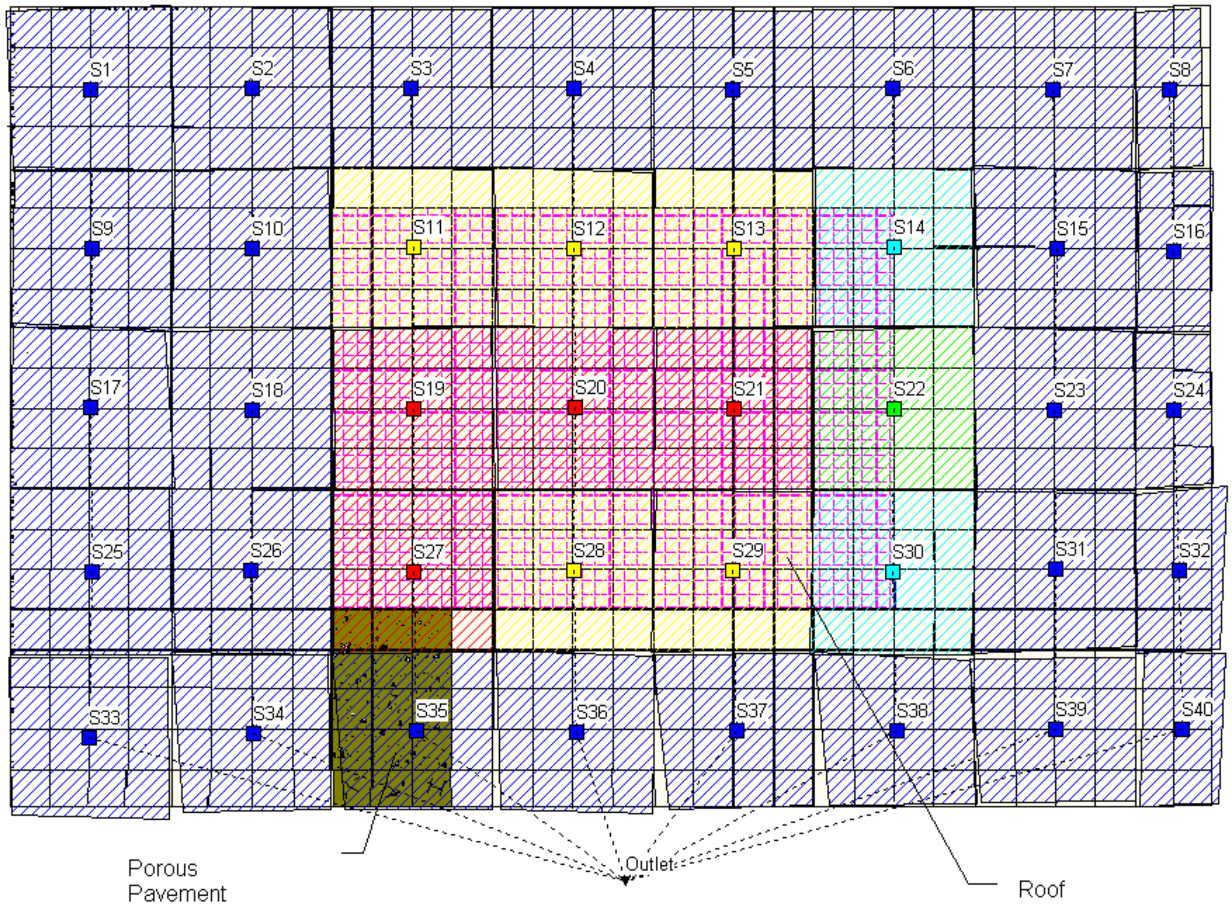


Figure 4-20 The porous pavement located on the driveway in the study area of 4x4 m grids

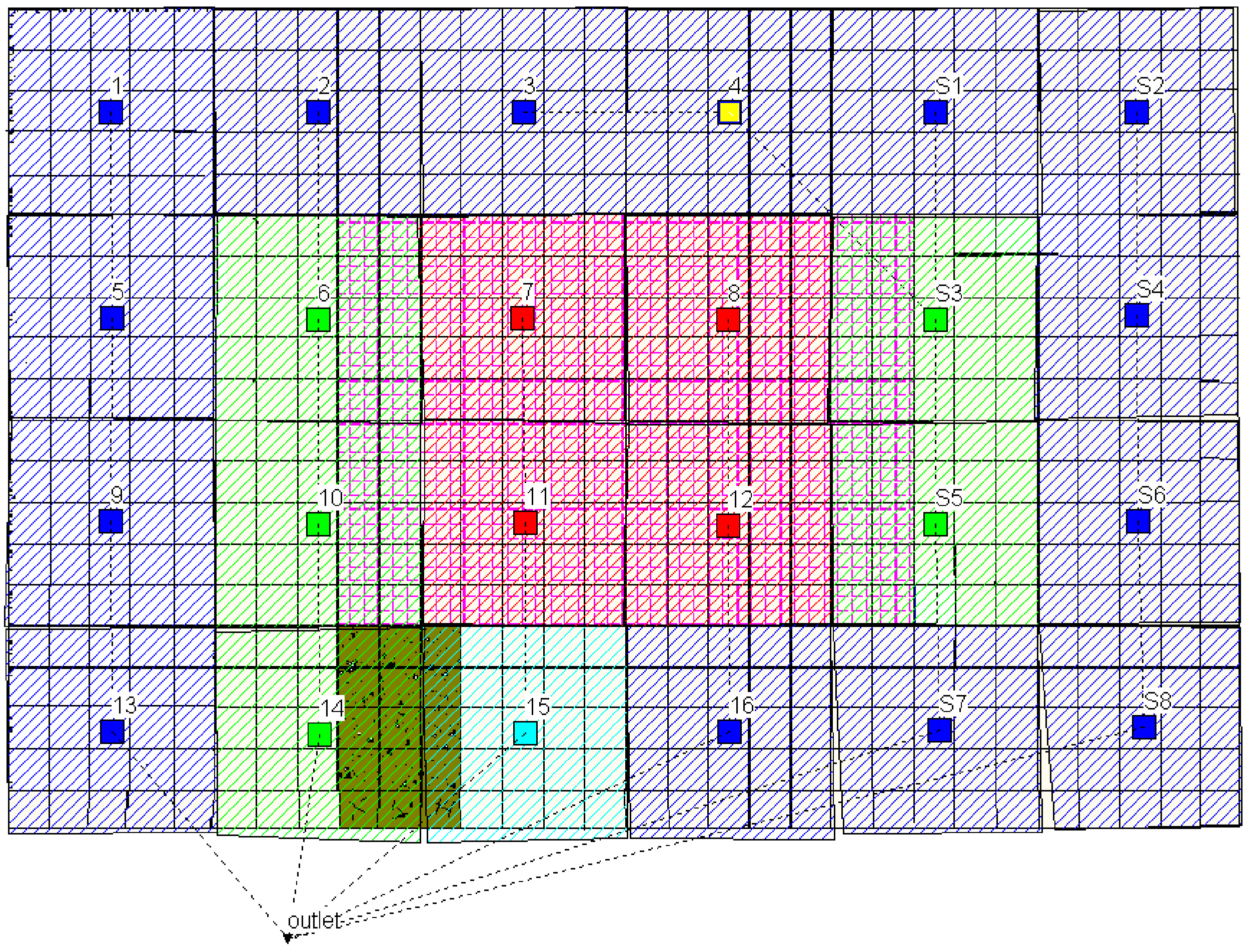


Figure 4-21 The porous pavement located on the driveway in the study area of 5x5 m grids

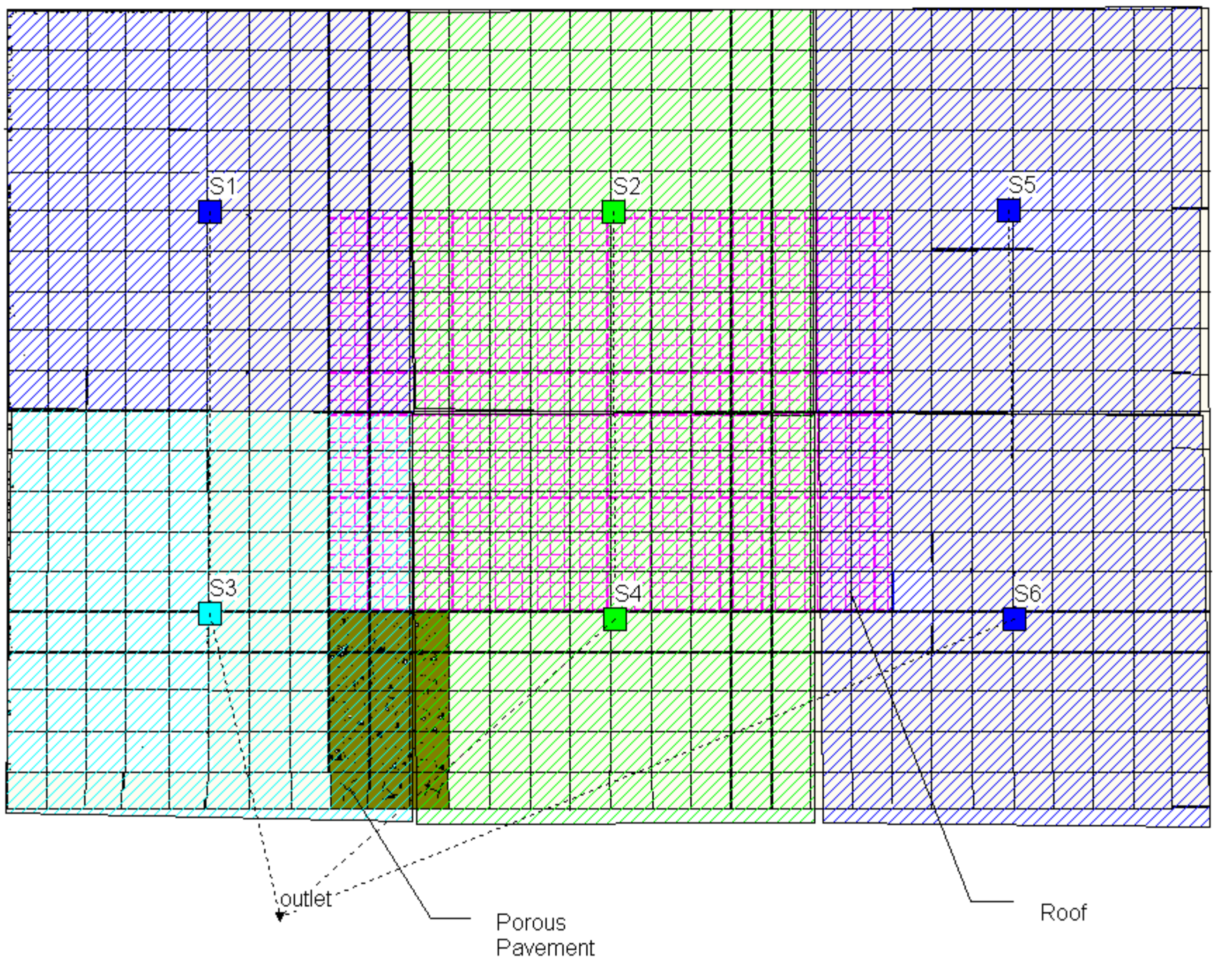


Figure 4-22 The porous pavement located on the driveway in the study area of 10x10 m grids

5 RESULTS AND ANALYSIS

5.1 A Simple Sensitivity Model

The runoff of a small lot was modeled based on a short event that occurred July 14 and 15, 1985 (Tables 5-1) and the continuous rainfall record between April and November, 1985 (Table 5-2). The results show the effect of different grid size on the infiltration, evaporation, and runoff volume assuming loamy and sandy soil types. It is should be noted that Case (A), the single catchment model, shows the highest runoff and the smallest infiltration. There is no routing allowed in this catchment model, which could be the reason behind the decrease in infiltration volume.

The results of the continuous simulation and July event show more reduction in the total runoff volume when reviewing a 4x4m grid compared to a 8x8m grid. The 4x4m grid model was tested using two different flow directions (Case (C1) and Case (C2)). The results of this grid model show different runoff volumes generated depending on the flow direction. The runoff volume of Case (C2) was slightly higher than that of Case (C1), where the flow was directed from three subcatchments to one subcatchment. It is evident through the results of Case (C2) and Case (C1) that the direction of the flow and the size of the subcatchment are very sensitive parameters. When the flow was directed from three subcatchments to one, the infiltration rate in the receiving subcatchment increased and reached its maximum infiltration rate in short time.

During the experiment using the 2x2m grid model, three different flow directions were tested as shown in Figure 4-5 to Figure 4-7. It is noted that the runoff of Case (D1) is larger than those of Case (D2) and Case (D3) for both continuous simulation and July event, which may be attributed to the routing of flow from all subcatchments with 100% impervious to one subcatchment (S46).

Subcatchment S47 received the runoff from S46 and reached its maximum infiltration rate in short time; hence, leading to a higher total runoff volumes. Although the size of the grid in Case (D1) is smaller than the grid size of Case (C1) and Case (C2), the runoff volume generated from Case (D1) is higher than the runoff volume generated in Case (C1) and Case (C2). The size of the grid of Cases (D1), (D2), and (D3) are expected to be too small to handle the amount of the runoff received. The results show that runoff volume is sensitive to grid size; and thus, decreasing the grid size reduces the total runoff volume of Case (A) (single catchment).

Table 5-1 The runoff depth and losses based on the July event and the parameters of loamy soil

Case Name	Precipitation mm	Evaporation mm	Infiltration mm	Runoff mm
Case (A)	63.7	0.62	46.18	16.90
Case (B)	63.7	0.64	48.51	14.56
Case (C1)	63.7	1.51	51.03	11.20
Case (C2)	63.7	1.49	49.51	12.72
Case (D1)	63.7	1.46	47.93	14.34
Case (D2)	63.7	1.5	49.9	12.34
Case (D3)	63.7	1.53	50.94	11.28

Table 5-2 The runoff depth and losses using continuous simulation in loamy soil.

Case Name	Precipitation mm	Evaporation mm	Infiltration mm	Runoff mm
Case (A)	544.1	10.11	403.63	130.37
Case (B)	544.1	10.05	444.4	89.72
Case (C1)	544.1	31.79	483.61	28.78
Case (C2)	544.1	31.86	472.04	40.31
Case (D1)	544.1	31.81	453.37	59.07
Case (D2)	544.1	31.87	474.38	38
Case (D3)	544.1	31.98	483.68	28.62

Table 5-3 and Table 5-4 illustrate the results of the models tested on sandy soil for the same short event and the continuous rainfall record presented previously. The results indicate that the runoff volume of the single catchment model, Case (A) is higher than those of other models. More specifically, the runoff volume generated by the 8x8m grid is lower than the runoff volume generated by the one catchment.

In a same manner, the 4x4m grid generated runoff volume less than the runoff volume of the 8x8m grid. It should also be noted that the 4x4m grid model, Case (C1) and Case (C2), generated zero runoff using the July event due to the small amount of rainfall and the high permeability of the sandy soil. The continuous simulation using the 4x4m grid showed that Case (C1) generated runoff while Case (C2) generated zero runoff due to different flow directions.

The 2x2m grid model, Case (D1), Case (D2), and Case (D3), generated runoff volume more than the 4x4m grid models in July event and the continuous rainfall due to the loamy soil. Figure 5-1 shows that the total flow to outlet from Case (D1) using a 2x2m grid model was higher than that of Case (C1) using a 4x4m grid model.

Table 5-3 The runoff depth and losses using July event on the sandy soil.

Case Name	Precipitation mm	Evaporation mm	Infiltration mm	Runoff mm
Case (A)	63.7	0.366	47.775	15.563
Case (B)	63.7	0.359	53.615	9.732
Case (C1)	63.7	1.164	62.542	0
Case (C2)	63.7	1.164	62.541	0
Case (D1)	63.7	1.173	59.593	2.946
Case (D2)	63.7	1.168	62.529	0.013
Case (D3)	63.7	1.161	62.547	0

Table 5-4 The runoff depth and losses using continuous simulation on the sandy soil.

Case Name	Precipitation mm	Evaporation mm	Infiltration mm	Runoff mm
Case (A)	544.1	9.636	408.075	126.41
Case (B)	544.1	9.467	455.555	79.108
Case (C1)	544.1	30.957	512.6	0.572
Case (C2)	544.1	30.952	513.173	0
Case (D1)	544.1	30.94	506.1	7.117
Case (D2)	544.1	30.919	512.098	1.13
Case (D3)	544.1	30.927	513.215	0

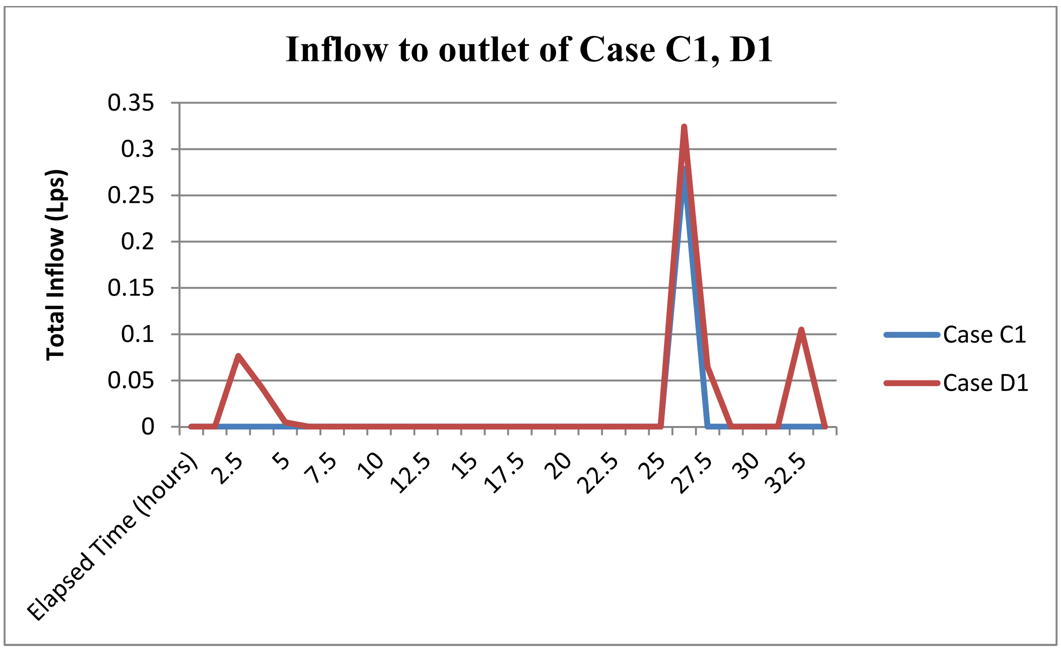


Figure 5-1 The total inflow to outlets in Case (D1) and (C1)

A comparison between losses from subcatchment S47 and subcatchment S12 on Case (C1) and Case (D1) is shown in Figure 5-2. The two subcatchments received the highest runoff volume due to the flow direction. The losses from subcatchment S47 in Case (D1) are less than those from subcatchment S12 in Case (C1). Regardless of the difference in losses, both subcatchments received the same amount of the runoff. Figure 5-3 shows the location of S47 on the 2x2m grid model and S12 on the 4x4m grid model. The results reflect the effect of subcatchment size on the infiltration volume of a subcatchmnet. Samples of the status reports of all models are presented in Appendix A for all catchment data and results.

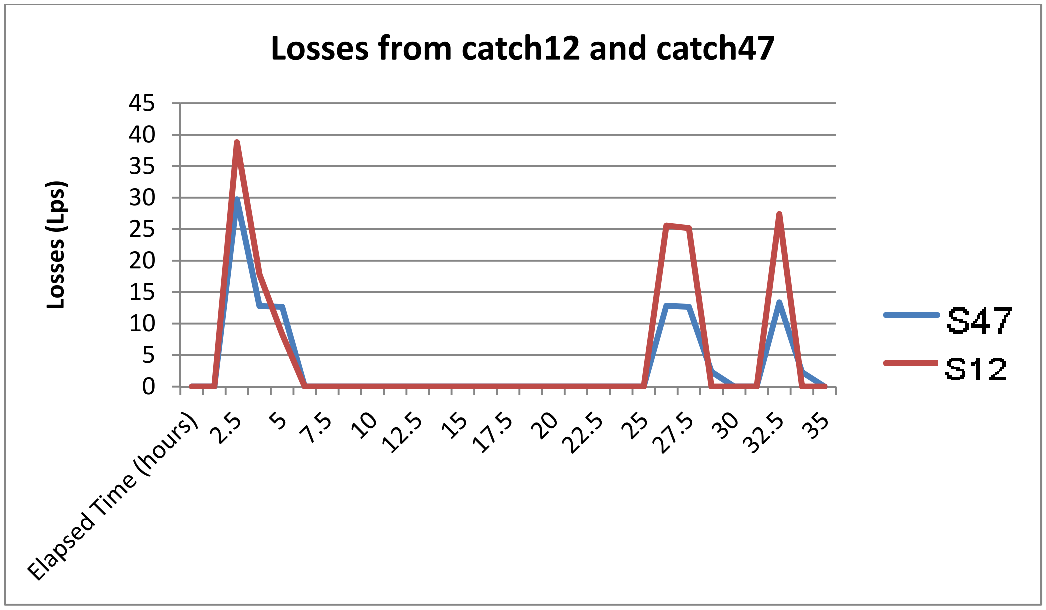


Figure 5-2 Hydrologic losses in subcatchments S47 and S12 Case (C1) and (D1) for the July 14 to July 15, 1985 event.

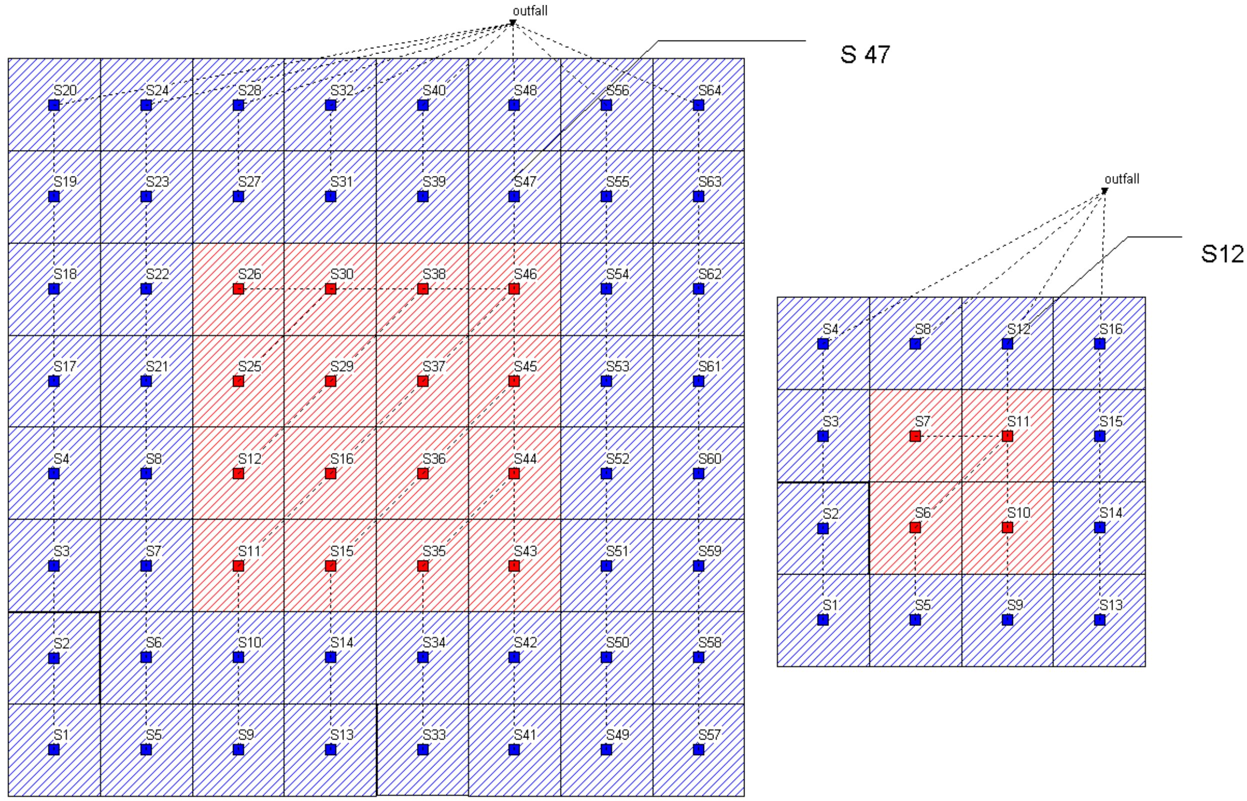


Figure 5-3 Cases (D1) and (C1) and the location of the two subcatchments S47 and S12.

5.2 Results of Single Lot Sensitivity Model

5.2.1 Results without LID

Tables (5-5), (5-6) and (5-7) show the evaporation, infiltration, runoff volume, and peak flow rate of the models using different grid sizes and different time steps (5 minutes, 1 minute, and 30 seconds). The single catchment model generated the highest runoff volume compared to those of other models. Lumping catchment properties such as slope, soil type, and flow direction to a single catchment did not simulate the runoff flow inside the catchment properly despite using one of the subcatchment routing options in SWMM. SWMM allows for different routing options when modelling the flow within the subcatchment. These options are: (1) Directing the runoff from both the pervious and impervious part of the subcatchment to the outlet; (2) directing the runoff from the pervious area to impervious area; and, (3) directing the flow from the impervious to pervious area.

By directing the flow from the impervious to pervious area, the model allows more infiltration if the saturation has not yet been reached during the event. Using the drain to pervious option will result in a smaller runoff depth for all grid cells, excluding the cells that contain only impervious areas. The results shown in this research are based on the modelling option where the flow in the sub-catchments drains to the outlet only. In other words, no internal routing of impervious/pervious combinations was allowed.

The results also show that the total runoff volume decreases when the grid size decreases. When the model simulates the runoff from one grid cell to an adjacent cell, the cumulative infiltration increases until the catchment reaches its maximum infiltration capacity. The runoff volume generated from the upstream grid is considered a run-on to the downstream grid. If the catchment can handle the run-on and the precipitation, the runoff volume continues to decrease until the soil reaches its maximum capacity resulting in more runoff subsequently.

The results illustrate that there is a small difference in the evaporation volume when using different grid sizes. The single catchment model produced less evaporation volume than those of the grid models. In addition, there was almost no change in the evaporation volume after reducing the time step in all models. The SWMM calculation of evaporation volume is based on the soil moisture, the infiltration rate, and the depression storage.

Table 5-5 The runoff, evaporation, infiltration, and peak flow using regular grids at 5 minute time steps

No LID	5min time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	32.5	423.2	89.4	2.5
5x5m	32.73	468.9	43.7	2.24
4x4m	32.8	461.3	51.3	2.03
2x2m	32.4	471.4	42.3	1.8
Single catchment	27	400.2	117.8	2.4

Table 5-6 The runoff, evaporation, infiltration, and peak flow using regular grids at 1 minute time steps

No LID	1min time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	32.6	422.9	88.7	2.59
5x5m	32.8	467.9	43.5	2.6
4x4m	32.8	460.2	51.2	2.6
2x2m	32.3	468.9	43.1	2.52
Single catchment	27.1	400.2	116.9	2.38

Table 5-7 The runoff, evaporation, infiltration, and peak flow using regular grids at 30 second time steps

No LID	30sec time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	32.6	422.9	88.6	2.6
5x5m	32.8	467.9	43.5	2.6
4x4m	32.8	460.1	51.2	2.57
2x2m	32.3	468.6	43.2	2.6
Single catchment	27.13	400.2	116.8	2.38

Table 5-8 summaries the effect of different time steps on the total runoff volume. The results show that models using larger time steps produce larger total runoff volume. By comparing the results of different time steps (the 10x10m grid, the single catchment, and the 5x5m grid), it is clearly demonstrated that the total runoff volume increases when the time step increases. The 4x4m grid model shows very small reduction when the time steps are reduced. The 2x2m grid model generates higher runoff when the time step is decreased. The 2x2m grid model cannot capture the exact amount of runoff volume at longer time steps.

Table 5-8 The runoff volume using different time steps and grid sizes

No LID	15min time step	10min time step	5min time step	1min time step	30sec time step
Trial Name	Runoff Depth				
10x10m	92.57	91	89.4	88.7	88.6
5x5m	44.63	44.2	43.7	43.5	43.5
4x4m	51.8	51.65	51.3	51.2	51.2
2x2m	39.74	41.1	42.3	43.1	43.2
Single catchment	121.18	119.45	117.8	116.9	116.8

Table 5-9 summarizes the calculated peak flow using different grid sizes and time steps. As it was previously demonstrated, the peak flow values were affected by the size of the grid and time steps. When modelling with a finer grid, the peak flow value decreases. It can also be noted that the peak flow decreases with time step increase. The single catchment model has almost no change in the peak flow with different time steps. The changes in the peak flow values with different time steps depend on the grid size. Small grid sizes and time steps result in a significant increase in the peak flow.

Table 5-9 The peak flow values using different time steps and grid sizes

No LID	15min time step	10min time step	5min time step	1min time step	30sec time step
Trial Name	Peak flow				
10x10m	2.13	2.37	2.5	2.59	2.6
5x5m	1.82	1.9	2.24	2.6	2.6
4x4m	1.72	1.83	2.03	2.6	2.57
2x2m	1	1.29	1.8	2.52	2.6
Single catchment	2.37	2.38	2.4	2.38	2.38

5.2.2 Results of Single Lot Model with LIDs

Tables (5-10), (5-11) and (5-12) present the evaporation, infiltration, runoff volume, and peak flow rate of different grid sizes when a bioretention system was included in the model next to the building to treat the runoff from the roof using different time steps. The bioretention system had an area of $12m^2$ and was built into the model to control the runoff from the roof based on the TRCA and CVC design guidelines for low impact development. The model results show that the runoff volume decreases when the grid size decreases in a manner similar to the model results without LIDs. The reduction in the runoff volume leads to a reduction in peak flow. The influence of grid size and time step on peak flow and runoff volume is same as that without LID.

Table 5-10 The change in runoff depth using regular grids and a bioretention cells with 5 minute time steps

Bioretention LID	5min time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	40.5	421.7	82.9	2.4
5x5m	42.5	462.8	39.9	1.99
4x4m	42.7	456.2	46.4	1.75
2x2m	42.5	466.1	37.4	1.16
Single catchment	34.9	394.6	115	2.3

Table 5-11 The change in the runoff depth using regular grids and a bioretention cells with 1 minute time steps

Bioretention LID	1min time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	40	421.4	82.18	2.5
5x5m	42.6	461.8	39.7	2.3
4x4m	42.7	455.1	46.3	2.2
2x2m	42.3	463.7	37.9	1.7
Single catchment	35.1	394.6	114.2	2.3

Table 5-12 The change in the runoff depth using regular grid and a bioreterntion cell with 30 second time steps

Bioretention LID	30sec time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	40.6	421.4	82.1	2.46
5x5m	42.6	461.8	39.7	2.3
4x4m	42.7	455.1	46.3	2.2
2x2m	42.4	463.5	37.9	1.85
Single catchment	35.1	394.6	114.1	2.34

Table (5-13) and (5-14) demonstrate the effect of different time steps (15 minutes, 10 minutes, 5 minutes, 1 minutes, and 30 seconds) on the total runoff volume and peak flow rate with bioretention. The total runoff volume increases when the time steps are increased. In addition, the effect of time steps on the runoff volume is not significant for small grid models; however, there is still a reduction in the total runoff volume. The 2x2m grid model generated higher runoff volume when using smaller time steps. The 2x2m grid size was likely too small since the grid size could not handle the amount of flow and the grid reached the maximum infiltration capacity quickly. Table 5-14 shows the peak flow value changes when modeled using different time steps and grid sizes. The peak flow increases when the time steps are decreased. Moreover, the effect of time steps becomes more apparent when using small grid size.

Table 5-13 The runoff values at different time steps (15 minute, 10 minute, 5 minute, 1 minute and 30 seconds) with bioretention adopted to the models

Bioretention LID	15min time step	10min time step	5min time step	1min time step	30sec time step
Trial Name	Runoff				
10x10m	85.8	84.4	82.9	82.18	82.1
5x5m	40.8	40.35	39.9	39.7	39.7
4x4m	46.9	46.7	46.4	46.3	46.3
2x2m	36.4	36.7	37.4	37.9	37.9
Single catchment	118.2	116.5	115	114.2	114.1

Table 5-14 The peak flow values at different time steps (15 minute, 10 minute, 5 minute, 1minute and 30 second) with bioretention adopted to the models

Bioretention LID	15min time step	10min time step	5min time step	1min time step	30sec time step
Trial Name	Peak flow				
10x10m	2	2.2	2.4	2.5	2.46
5x5m	1.6	1.66	1.99	2.3	2.3
4x4m	1.4	1.5	1.75	2.2	2.2
2x2m	0.57	0.8	1.16	1.7	1.85
Single catchment	2.3	2.3	2.3	2.3	2.34

Tables (5-15), (5-16) and (5-17) also show the results of the runoff, evaporation, infiltration, and peak flow using different grid sizes and time steps with porous pavement on the drive way. The results show a reduction in the runoff volume when modelling with small grid sizes similar to the model results without LID and those with bioretention. The Single catchment predicted the highest runoff volume compared to the grid models. The reduction in the runoff volume when modelling using grid models is expected since the grid models allow more routing of the runoff resulting in more infiltration. The results also demonstrate that grid size has a significant effect on the peak flow rate. Generally, the peak flow decreases when using small grid sizes.

Table 5-15 The change in the runoff, evaporation, infiltration, and peak flow using regular grids with permeable pavement on the driveway of the building using 5 minute time steps

Porous pavement LID	5min time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	32.6	428.1	84.7	3.7
5x5m	32.8	477.1	35.4	1.99
4x4m	32.8	477.1	35.4	1.99
2x2m	31.4	490	22.1	1.4
Single catchment	27.3	402.9	114.9	2.3

Table 5-16 The change in the runoff, evaporation, infiltration, and peak flow using regular grids with permeable pavement on the driveway of the building using 1 minute time steps

Porous pavement LID	1min time step			
Trial Name	Evaporation	Infiltration	Runoff	Peak flow
10x10m	32.6	427.6	83.9	2.46
5x5m	32.8	476	35.2	2.4
4x4m	32.8	476	35.2	2.47
2x2m	31.4	487	22.9	2.2
Single catchment	27.3	402.7	114	2.3

Table 5-17 The change in the runoff, evaporation, infiltration and peak flow using regular grids with permeable pavement on the driveway of the building using 30 second time steps

Porous pavement LID	30sec time step			
Trial Name	Precipitation	Evaporation	Infiltration	Runoff
10x10m	544.1	32.6	427.5	83.8
5x5m	544.1	32.8	475.9	35.2
4x4m	544.1	32.7	475.9	35.2
2x2m	544.1	33.1	487.2	23
Single catchment	544.1	27.4	402.7	113.9

Table 5-18 shows the runoff volume calculated by the models using different time steps. The results show a reduction in the runoff volume when modelling with small time steps, which is the same as those without LID and those with bioretention, respectively. Table 5-19 shows the peak flow value calculated by the models using different time steps. The effect of smaller time steps is still significant on the peak flow as observed in results without LID and those with bioretention, respectively. Tables 5-1 to 5-19 are presented as bar graph figures of percentage of losses and runoff in Appendix B.

Table 5-18 The runoff values using (15 minute, 10 minute, 5 minute, 1 minute and 30 second) time steps with porous pavement adopted to the models

Porous pavement LID	15min time step	10min time step	5min time step	1min time step	30sec time step
Trial Name	Runoff				
10x10m	87.6	86.1	84.7	83.9	83.8
5x5m	36.48	35.8	35.4	35.2	35.2
4x4m	21.8	21.8	21.8	35.2	35.2
2x2m	19.5	20.8	22.1	22.9	23
Single catchment	118	116.5	114.9	114	113.9

Table 5-19 The peak flow values using (15 minute, 10 minute, 5 minute, 1 minute and 30 second) time steps with porous pavement adopted to the models

Porous pavement LID	15min time step	10min time step	5min time step	1min time step	30sec time step
Trial Name	Peak flow				
10x10m	2	2.3	2.4	2.46	2.47
5x5m	1.64	1.7	2	2.4	2.44
4x4m	1.4	1.6	1.8	2.47	2.54
2x2m	0.78	1	1.4	2.24	2.36
Single catchment	2.32	2.34	2.34	2.34	2.34

5.3 Conclusions

The simple sensitivity tests examined the effects of different flow directions on the runoff volume calculated at the outlet of the catchment. It also examined different levels of disaggregation using 2x2m, 4x4m, 8x8m grids and one catchment models. The results obtained using different flow directions show significant changes in the runoff volume. The same model structure (size) calculates different runoff volumes for different flow direction scenarios. It is also evident that runoff volume is sensitive to grid size. The test shows that the smaller the grid size, the lower the runoff volume generated. The total runoff volume decreases when the model simulates the runoff from one grid cell to an adjacent cell that; thus, leading to more infiltration in each grid. The runoff volume can reach a stable value at a certain grid size based on the model structure and subcatchment parameters (width, slope, depression storage, and soil type).

The single lot sensitivity model examined the effects of different levels of disaggregation on the total runoff volume and peak flow rate at the outlet of the catchment. The test also examined the influence of different time steps on the runoff volume and the peak flow. All models were tested using the following scenarios: 1) without any LID practices, 2) with bioretention; and, 3) using porous pavement.

The results show a reduction in the total runoff volume and peak flow when using small grid sizes in all model scenarios. The reduction in the runoff volume leads to a reduction in the peak flow rate calculated. The one catchment model calculated the highest runoff volume for all model scenarios. Examining different time steps demonstrates an increase in the peak flow when using smaller time steps. The peak flow rate calculation is dependent upon different parameters, such as the model structure and the catchment parameters (slope, depression storage, and grid width). The one catchment model has no significant change in the peak flows when reducing the time steps for all model scenarios.

The single lot sensitivity model demonstrates that the calculated runoff volume of a 2x2m grid and a 5x5m grid is almost the same. This observation reveals that the appropriate grid size is between these two grid sizes. The 2x2m grid and the 5x5m grid are 1% and 4% of the total area of the lot. The two models show no difference in runoff volume at 5 minutes and 1 minute. In order to draw conclusions, the results from the hypothetical data need to be verified by real (monitored) data. The following chapter describes a case study with a grid size ranging between 1% to 4% of the total area and 5 minute time steps.

6 CASE STUDY

6.1 Introduction

The purpose of this research is to investigate the effectiveness of distributed models for modelling small urban areas. Chapters Four and Five present the modelling results of a single residential lot with hypothetical data using different modelling approaches. The findings from previous chapters were used to test a case study area with monitored data in this chapter. The routing method for the case study is the D8 method which directs the flow from one catchment to only other single catchment. The grid size chosen in the grid model is about 1% to 4% of the total area based on the findings of the hypothetical tests. The effect of grid size is verified in this chapter by comparing the grid model results of the case study with the actual monitored data at the site.

6.2 Site Description

The subject site for the study, shown in Figure 6.1, is located within the Lakeview District Neighborhood in the City of Mississauga. The site is outside of the Cooksville Creek Watershed and drains directly into Lake Ontario. The Credit Valley Conservation Authority (CVC) and the City of Mississauga have been monitoring four sites (shown in Figure 6.2) by installing flow and water quality monitoring equipment at manholes. The data collected from site LV1 was used in this research.

The manhole, where the equipment was installed, is located on Northmount Avenue north of 4th street, which has curbed and gutter drainage (Figure 6.3). The manhole has a flow meter to measure the flow and water level at ten minutes intervals. The drainage area that contributes the flow into the manhole is not specified by either the Conservation Authority or the City of

Mississauga. Based on the existing DEM, Google maps, the City of Mississauga's catch basins digital maps and site visits, the drainage area was delineated to be about 1.64 hectares.

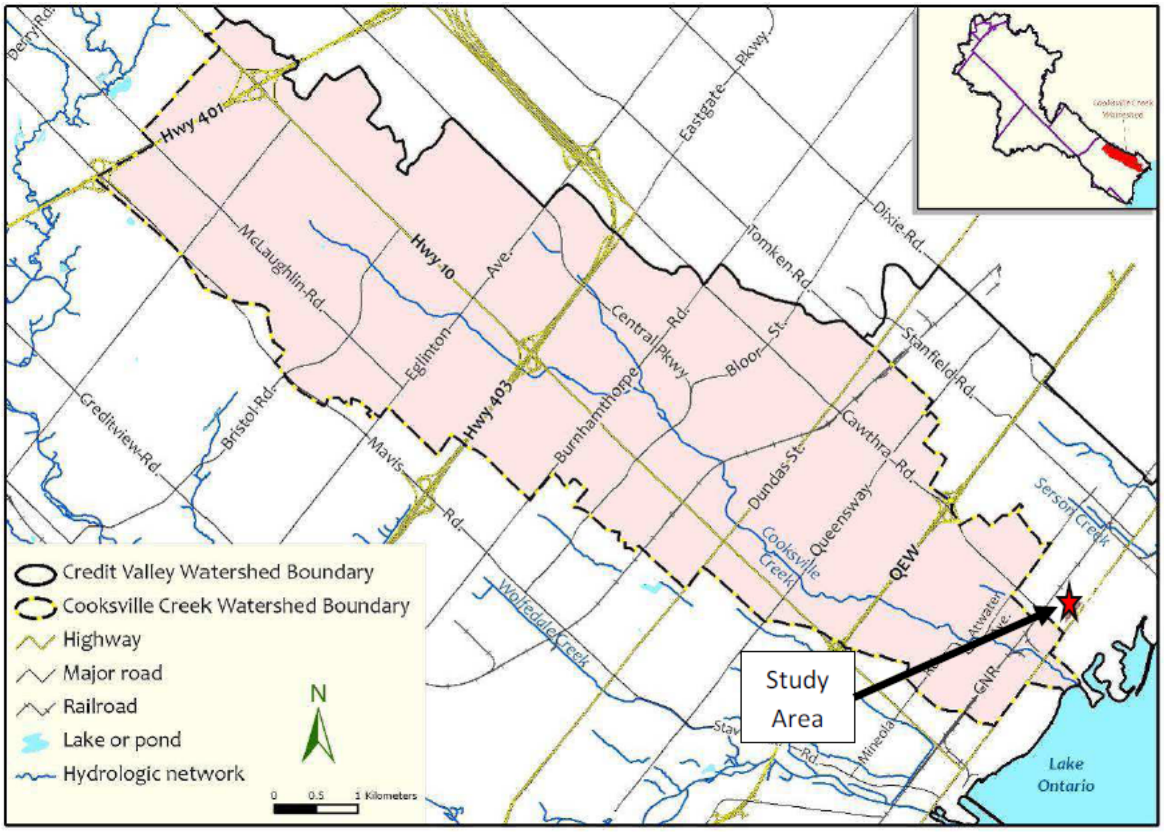


Figure 6-1 Location of the study area out of Cooksville Creek Watershed (Credit Valley Conservation Authority, 2012)

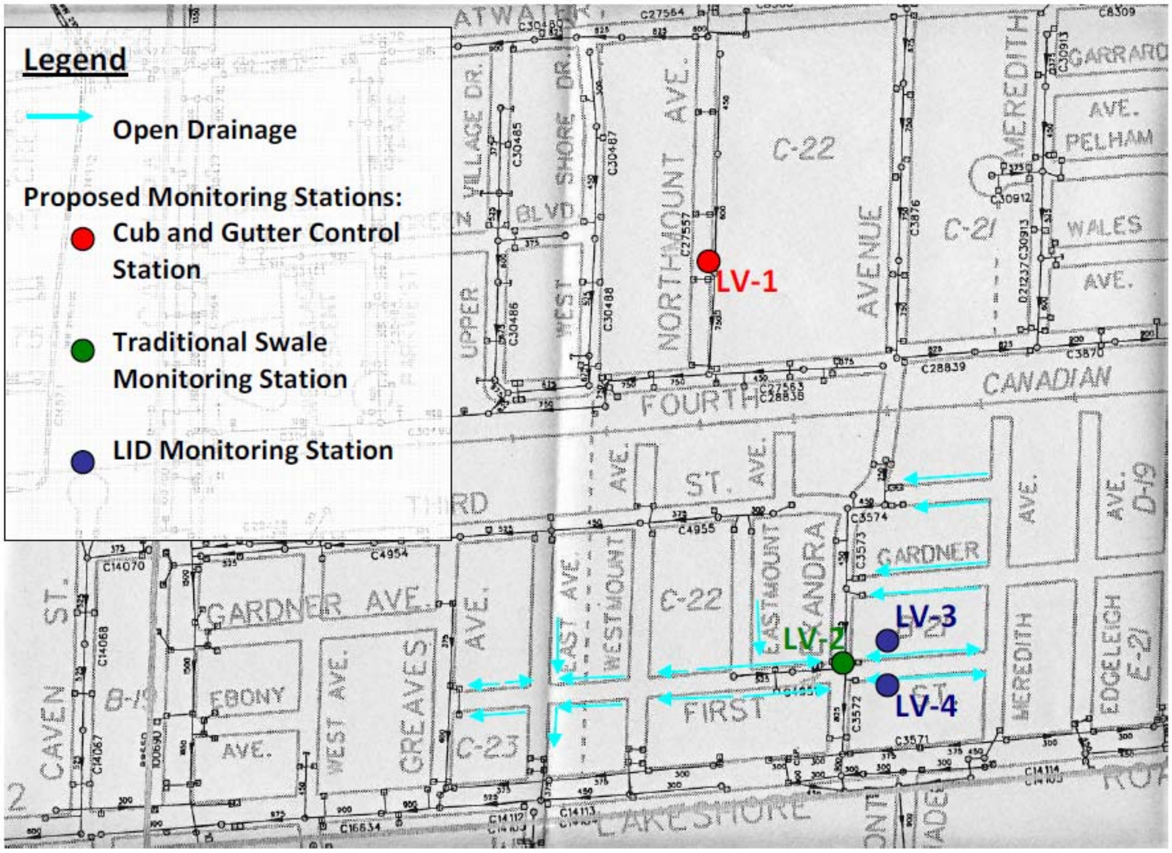


Figure 6-2 Location of monitoring manhole LV-1 (Credit Valley Conservation Authority, 2012)

Figure 6-3 Location of the manhole on Northmount Avenue and the delineated drainage area.

6.3 Rainfall Runoff Data

A water quality and quantity monitoring program at four different residential areas in Lake View District neighborhood in City of Mississauga was established in 2010 for the purpose of calibrating models used in designing LID's applications and will ended by 2015. The rainfall data used in the case study was for the year 2011. The monitoring program aimed to compare the stormwater quantity and quality before and after applying LIDs. The rainfall data collected from January 1st to October 25th by CVC climate station located on the roof of the Cawthra Community Centre. In addition, the City of Mississauga has a rainfall gauge at 920 East Avenue as a backup. The rainfall data from October 26th to Decemeber 31st is collected by Mississauga gauge. Both of the CVC climate station and the City of Mississauga rainfall gauge are located about 1km from the study area.

The rainfall data were collected from January 1st to December 31st, 2011 with a total rainfall of 491.4 mm, highest rainfall of 10 mm. The rainfall was measured in five minute intervals. A flow meter was installed at the downstream manhole. It recorded water levels at 10 minute intervals, which were subsequently converted into a flow rate using a rating curve. The events that occurred between July and December were selected to be used in this research because these six months had the greatest number of events and the most of flow rates recorded. Any rain without runoff measured and followed by big event was eliminated from the selection of the storms to ensure that the soil was dry before simulating the event runoff. Any rain event with only flow measured, or with only rainfall recorded was also eliminated.

The models were run continuously from July to December, 2011, including two storms which had the highest recorded flow rates (August 24th and September 30th). In order to evaluate the results of the continuous simulation models, two important tasks need to be undertaken. First, the total runoff volume and peak flow rates of the observed data need to be compared to those calculated by the three models. Second, the measured runoff volume and peak flow rate of five events are compared to the recorded runoff volume and peak flow.

6.4 Models Description

The study area was examined using the SWMM model based on three different model structures, which are described below:

- Single catchment model

- 10x10 m grid model
- Homogenous model

6.4.1 Single Catchment Model

The single catchment model simulates the study area as one catchment with an area of 1.65 ha. The parameters of the model were specified as follows:

- The width of the catchment was assumed to be double the length of the catchment since the flow is moving laterally along the houses to the gutter which is part of the street.
- The percentage of the imperviousness was the total impervious area divided by the total area.
- The slope of the catchment was the average slope based on the Digital Elevation Model provided by the CVC.
- The depression storage for impervious areas, such as smooth asphalt pavements, was assumed to be 1.25 mm while the depression storage for pervious areas such as lawns was assumed to be 3.75 mm.
- The subarea routing parameter was adjusted to the pervious option to allow flow from impervious to pervious areas. The percentage of runoff routed parameter was calculated as the percentage of roofs to the total area since roofs were assumed to be disconnected.
- Horton infiltration method was used and the infiltration parameters were defined for top soil with high maximum infiltration rate.
- The model was run with five minute time steps.
- The DEM data was derived from the orthophotos, 2009. The resolution of the DEM is 5m, and was derived from the 10m grid-points. The vertical accuracy of the DEM is ±50 cm. The data is provided in NAD 83 Zone 17 format (CVC, 2010).

6.4.2 Grid Model

The study area was divided into small sub-catchments (or grid cells) with area of 100 m^2 each (10x10m) (Figure 6.4). The outlet of each grid was defined based on the assumption that the runoff from the lawn and roof drains to the front yard following the slope calculated from the DEM. The flow from each grid cell was assumed to be diverted to the lowest level of the neighboring eight grid cells. The slope parameter of each sub-catchment (i.e. grid cell) was calculated using the DEM. The depression storage of pervious (lawn) and impervious (smooth asphalt) areas were assumed to be 1.25mm and 3.75mm, respectively.

The subarea routing parameter was adjusted to the pervious option to allow flow from impervious areas to pervious areas. SWMM includes another parameter called percent routed. This parameter allows the modeller to define the percent of the impervious to be routed to the pervious area. The roof area in each grid is calculated and defined in the percent routed parameter. Horton's method was used to calculate the infiltration volume. The sewer system included in the area had two inlets to collect the runoff into the storm sewer and into the manhole, where the flow measurement equipment was installed (Figure 6.3). The model was run using five minute time steps.

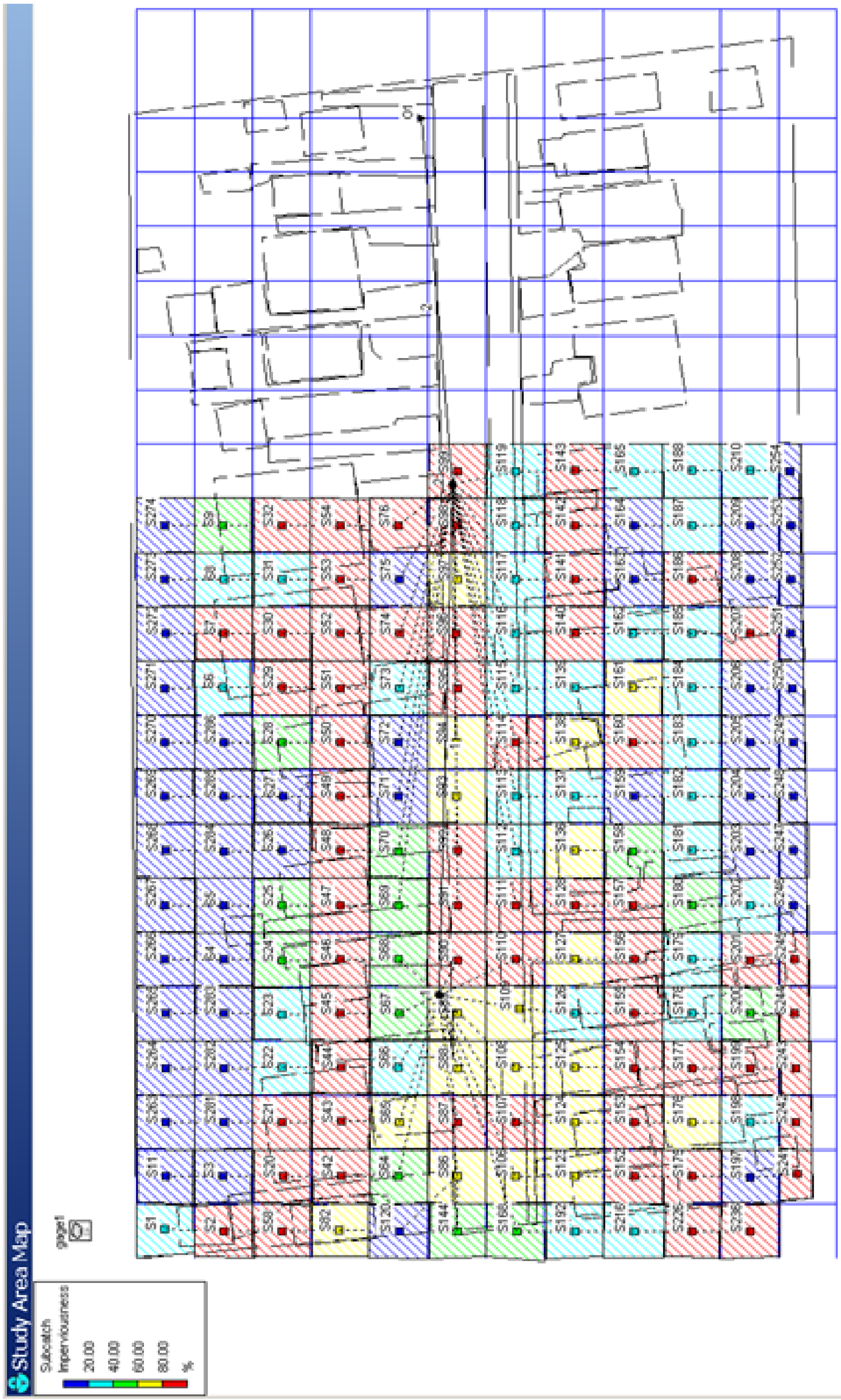


Figure 6-4 10x10 metre grid model

The grid model was created based on the use of existing geospatial data (including digital elevation model (DEM) and orthophoto). Figure 6-5 shows the overall workflow for creating the grid model dataset. Firstly, the geospatial boundaries of all topographic features were manually digitized in ArcGIS and ArcMap in order to determine the percentage of imperviousness and percentage of roof area. The slope value of the study area was derived by using a GIS function together with the DEM. Finally, 10×10 m grid cells were created in AutoCAD and then imported in ArcMap for intersection. The resulting grid cells; thus, contained the imperviousness area as well as the slope value.

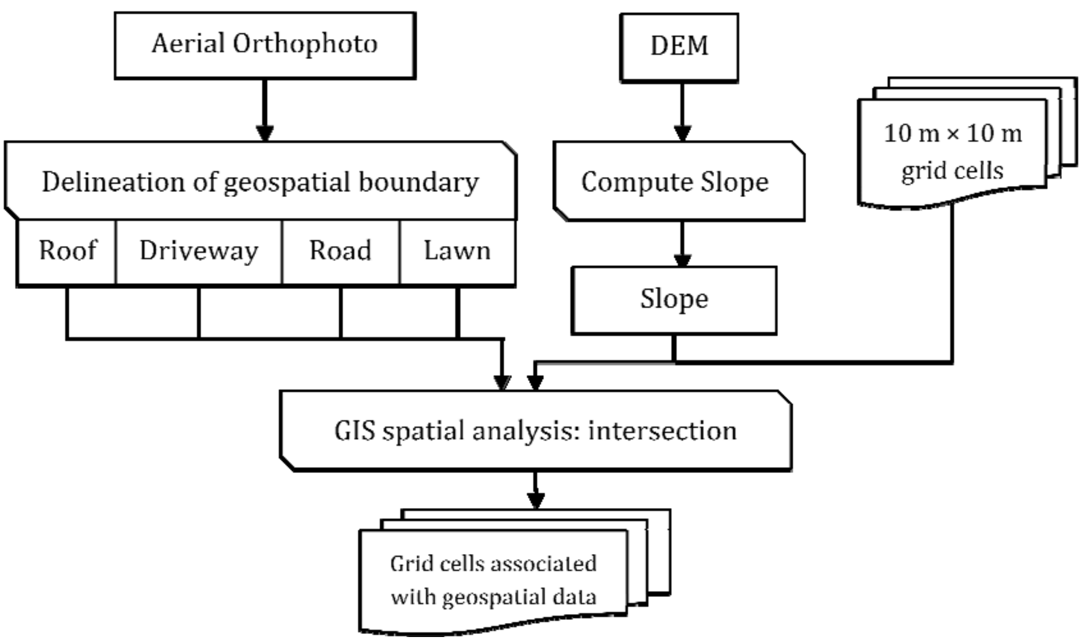


Figure 6-5 Overall workflow for creating grid model dataset

By using ArcGIS and ArcMap, four new feature datasets (roof, driveway, road and lawn) were created in the personal geodatabase and then exported as a shapefile (*.shp) in the same projection system as the DEM. Under the ArcMap platform, manual digitization was conducted to delineate the geospatial boundary of each feature dataset. The empty feature GIS layer was first imported to the ArcMap platform. By “start editing” the feature layer, the boundary of the roof was delineated with reference to the aerial orthophoto. Once the digitization was finished, the feature layer was saved by "stop editing". The area of each feature was computed by launching the attribute table, and performing the "Calculate Geometry" function as shown in Figure 6-6. Figure 6-7 shows an example for delineated boundary of rooftops, driveways, road and lawns. After delineating all the boundaries for the aforementioned features, the GIS layer was saved. With the provided DEM, the slope was computed by using the 3D Analyst function (Figure 6-8).

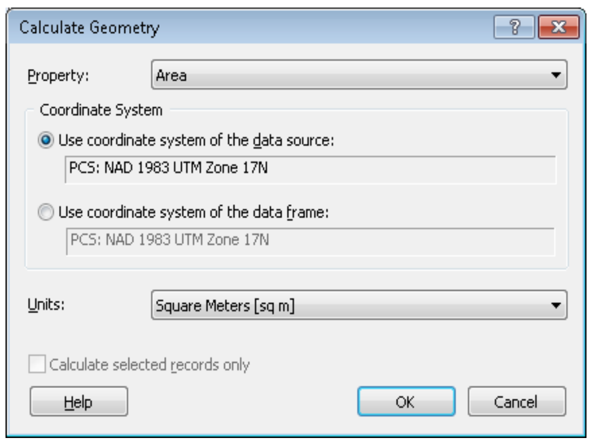
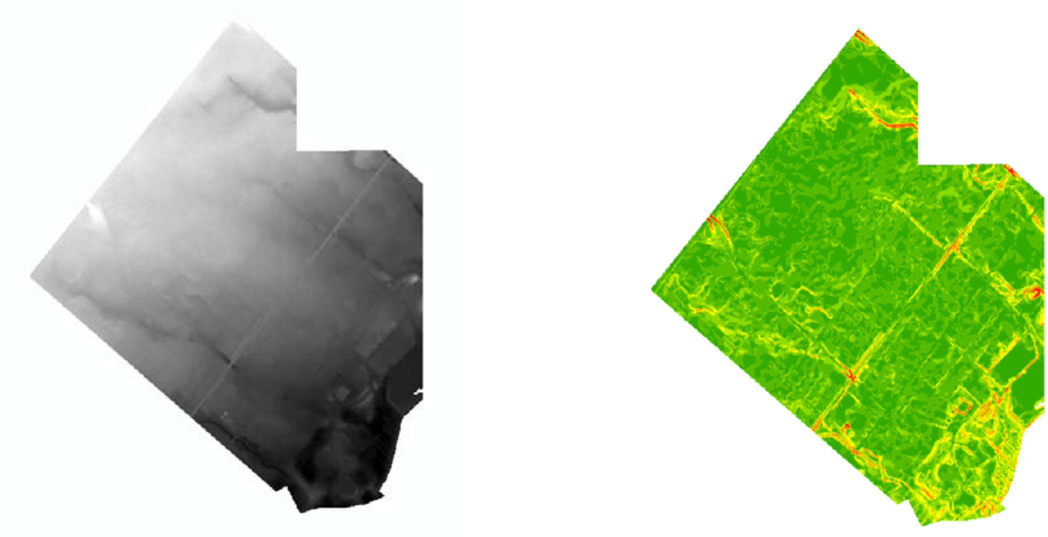


Figure 6-6 Area l computation using "Calculate Geometry"

Figure 6-7 The delineated geospatial boundaries



(a) (b)

Figure 6-8 (a) DEM and (b) Computed slope layer

The study area was separated into small sub-catchments or grid cells with an area of 100 m^2 (10x10m) each using AutoCAD. The AutoCAD file was then imported into ArcGIS and ArcMap and saved as a shapefile for further manipulation. Figure 6-9 shows the grid cell with the grid size 10×10m.

Figure 6-9 The 10×10m grid cells for the study area.

The slope in each of the cells was determined by using the "zonal statistics" function. The function can compute the mean of slope value with each grid cell and associate the slope value to the grid cell. Fig. 6-10 shows the "zonal statistics" under the "Spatial Analyst" function.

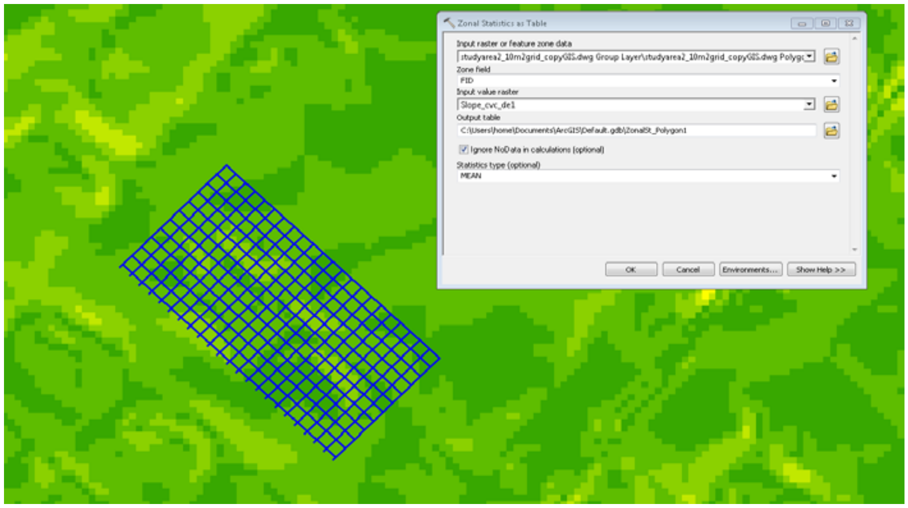


Figure 6-10 Zonal statistics function for assigning the slope value to each grid

After assigning the slope value to the grid cell, the delineated topographic features (red polygon in Figure 6-11) and grid cells (blue polygon in Figure 6-11) were intersected so that each grid cell was associated with the topographic features. Fig. 6-12 shows the intersected grid cell layers.

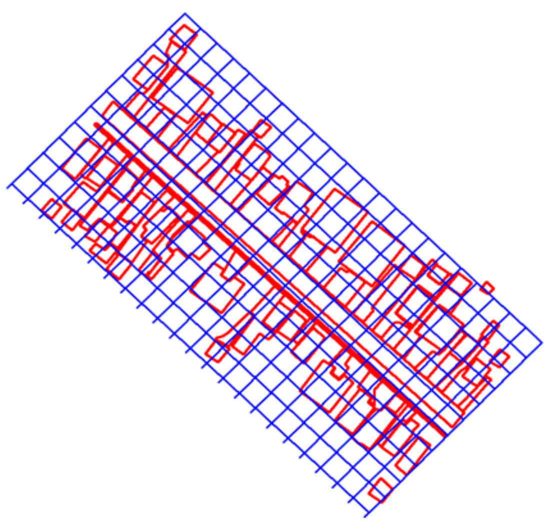


Figure 6-11 Spatial intersection of grid cell and delineated topographic features

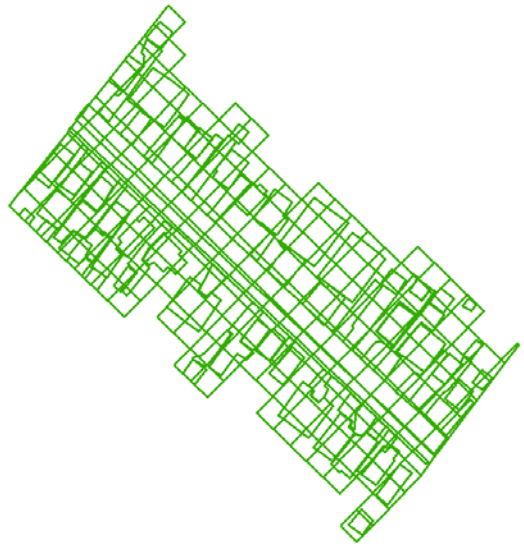


Figure 6-12 The resulting layer of intersected grid cells

Since SWMM does not support the import of geospatial data except those directly from AutoCad files, the grid model was created by using the resulting layer of intersected grid cells as shown in Figure 6-12 as a background to create the individual subcatchemnts manually. Precise areas of pervious and impervious areas in each grid were defined based on the ArcGIS measurements. The outlet of each grid was defined based on the assumption that the runoff from the lawn and the roof drain to the front yard follows the slope calculated from the DEM.

6.4.3 The Homogenous Model

Every homogenous area with the same land use and soil characteristics was considered as a separate sub-catchment in the case study area. Each part of the lot, such as roof, lawn, front yard, and driveway, was represented as a separate sub-catchment (Figure 6.13). The sub-catchments were therefore assumed to be either 100 percent impervious (e.g. roof, driveway) or zero percent impervious (e.g. lawn). The outlet of each sub-catchment was defined based on the following assumptions:

- the runoff from the lawn drains into the front yard
- the driveway drains into the street
- the roof drains into the front yard based on the assumption that all roofs are disconnected.

There are two inlets which collect runoff from the street into the sewer system. They were modelled as two separate subcatchments. The first street subcatchment was assumed to collect runoff from the houses that drained into the first inlet. The second street sub-catchment was assumed to collect runoff from the remaining houses that drained into the second inlet. The area of each subcatchment was calculated using ArcGIS (version 10.0) after digitizing all sub-catchments.

The dataset was prepared by manual digitization of the topographic features with reference to the orthophoto, similar to the steps in section 6.4.2. The homogeneous areas were represented using different polygons in a shapefile, and the area of each polygon was determined using the function “Calculate Geometry” in ArcMap. The flow path of each subcatchment was measured approximately using ArcGIS to calculate the subcatchment width. After creating the homogeneous model dataset in ArcGIS, the model was built manually as described in section 6.4.2. Horton’s equation was used as the infiltration method and the other parameters like depression storage for pervious and impervious area were selected similar to those of the previous two sensitivity models.

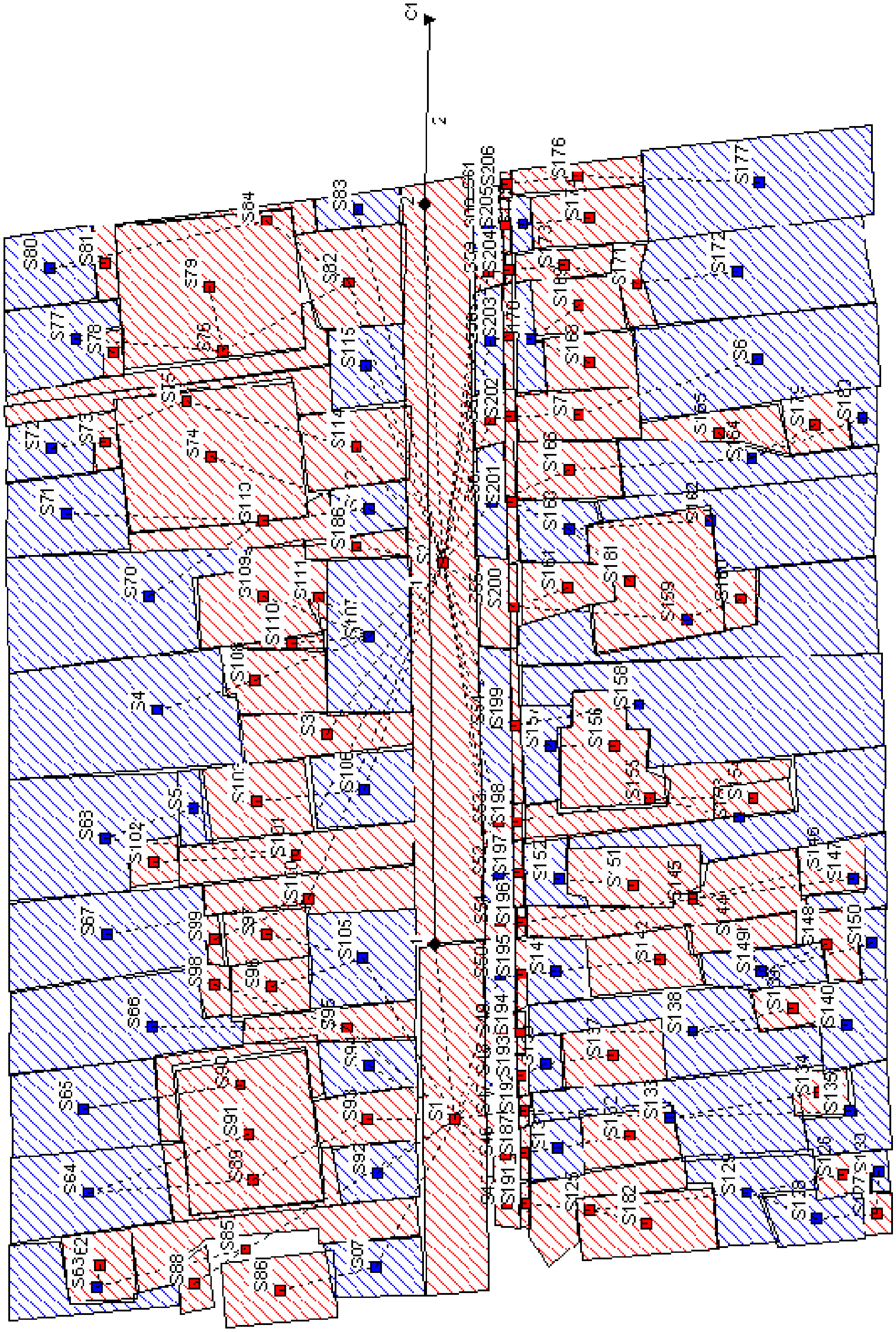


Figure 6-13 The homogenous model defined in SWMM

6.5 Results and Analysis

6.5.1 August 24th Event

The three models' (single catchment, grid model, and homogenous model) results were evaluated and compared to the measured data based on the total runoff volume, the infiltration volume, and the peak flow rate. Figures 6.14 and 6.15 show the runoff hydrographs and the rainfall hyetograph of August 24th, 2011. The single catchment model calculated two very high peak flows compared to the measured peak flows and the time to peak was almost at the same. Modelling using a single catchment without any distribution to the runoff within the catchment may be the cause of the very high peak flow value.

The grid model for the August event followed the same shape of the measured outflow hydrograph with peak flow occurring at the same time as the measured hydrograph. The first peak flow predicted by the grid model was lower than the measured hydrograph (68%) and the second peak flow was higher than the measured hydrograph (90%). The first peak flow predicted by the homogenous model was lower than the measured hydrograph (22%) and the second peak flow was higher than the measured hydrograph (400%). Figure 6-16 shows the peak flow of the three models compared to the field measurements. From Figure 6-16, it is clear that the single catchment model runoff volume for the August event was the highest compared to the measured values.

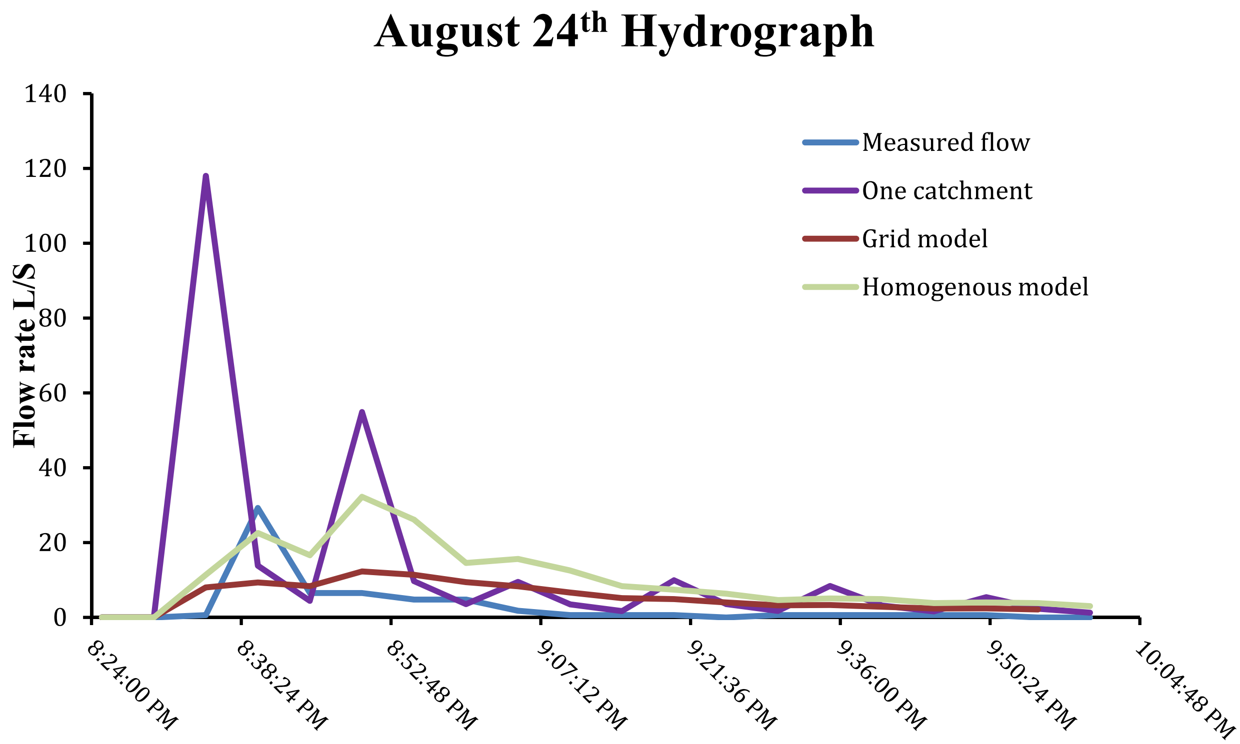


Figure 6-14 The hydrograph of the three models comparing to the measured during August 24th storm

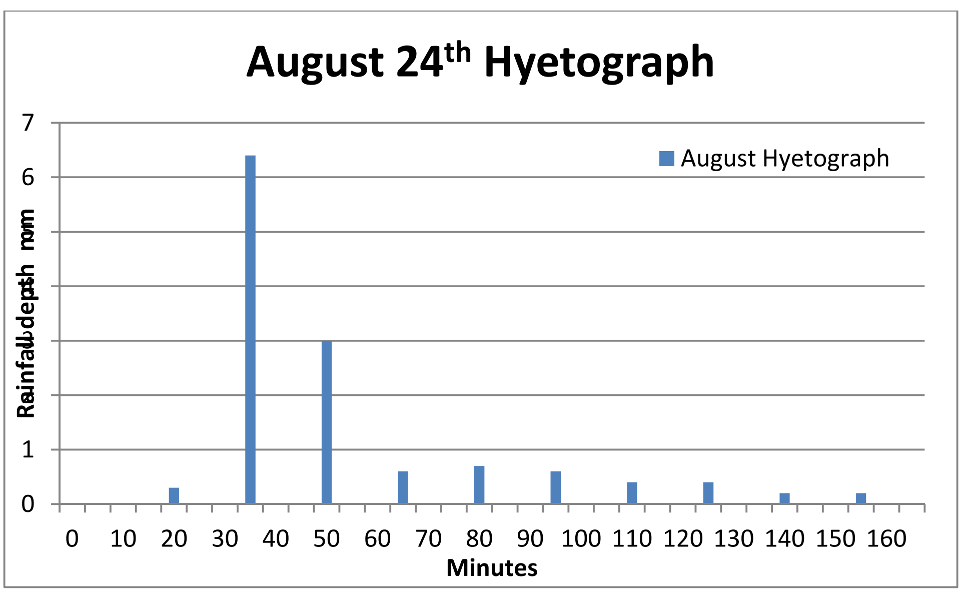


Figure 6-15 The rainfall hyetograph of August 24th event

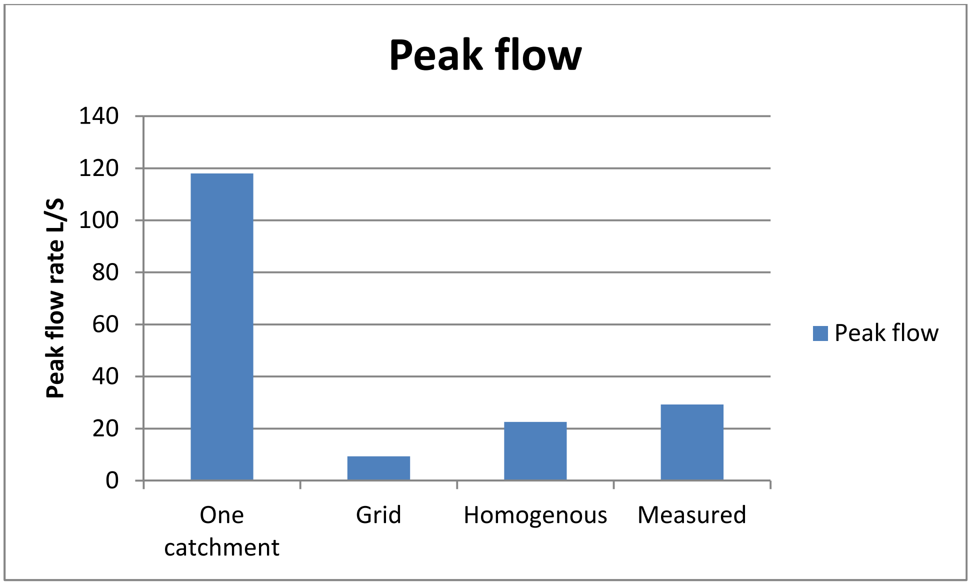


Figure 6-16 The peak flow value in the three models compared to the field measured values during August 24th storm.

Figure 6-17 presents the runoff volume of the three models compared to the field runoff volume measurements. It is noted that the grid model runoff volume is 70% greater than the measured values. However, the grid model predicted the closest runoff volume to the field measured values compared to those of the homogenous and the single catchment models. Figure 6-18 shows that the three models' infiltration volume supports the results of the runoff volume in Figure 6-17.

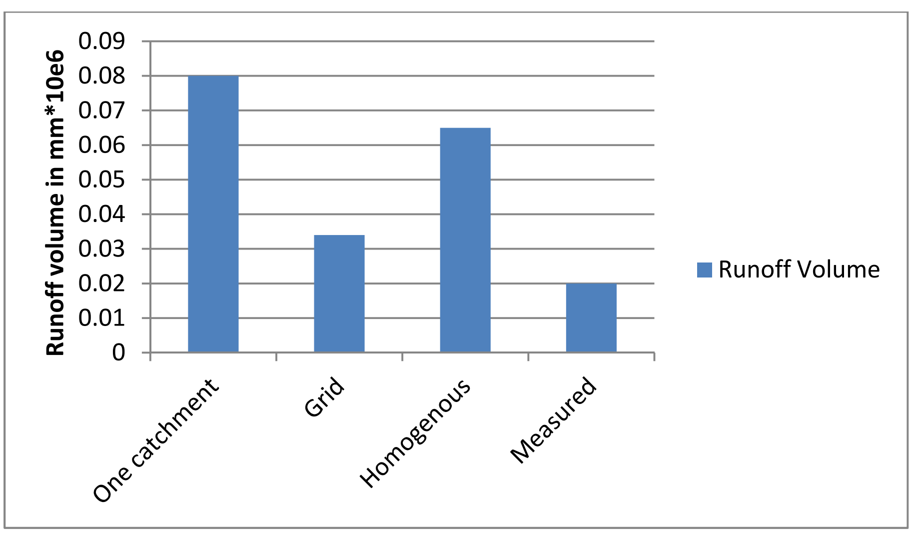


Figure 6-17 The runoff volume of the three models as compared to the filed measured volume during the August 24th storm.

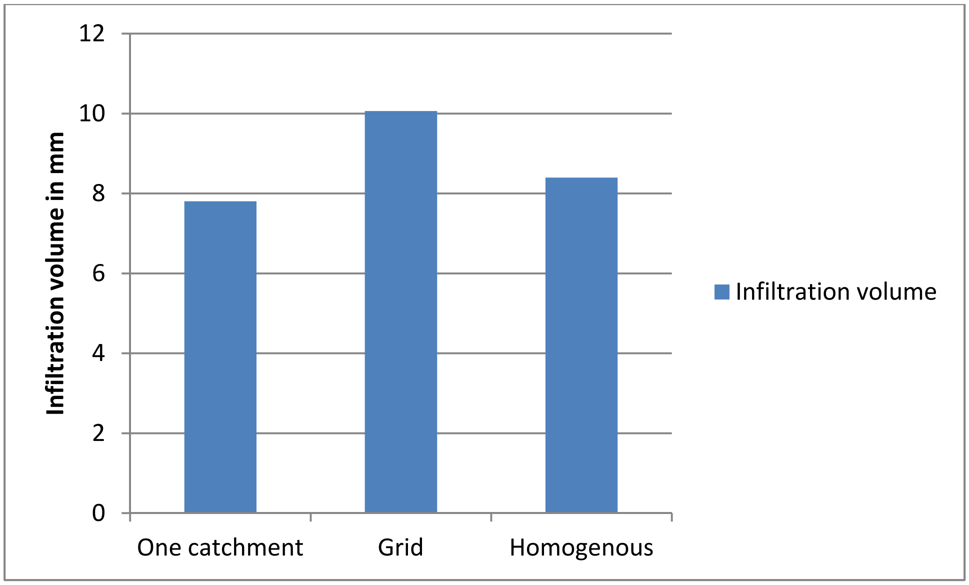


Figure 6-18 The infiltration volume of the three models during the August 24th storm.

6.5.2 September 30th Event

Figures 6-19 and 6-20 show the runoff hydrographs and the rainfall hyetograph of the September 30th, 2011 event. Similar to the August 24th event, the single catchment model calculated a very high runoff volume compared to the measured value. The homogenous model predicted runoff volume 87% greater than the measured value while the grid model calculated almost the same runoff volume (Figure 6-21). The one catchment model's peak flow was the highest compared to the measured value. The homogenous model's peak flow was 21% greater than the measured value. The grid model peak flow was 39% less than the measured value (Figure 6-22). The infiltration loses of the one catchment model was the lowest compared to those of the homogeneous and grid models (Figure 6-23).

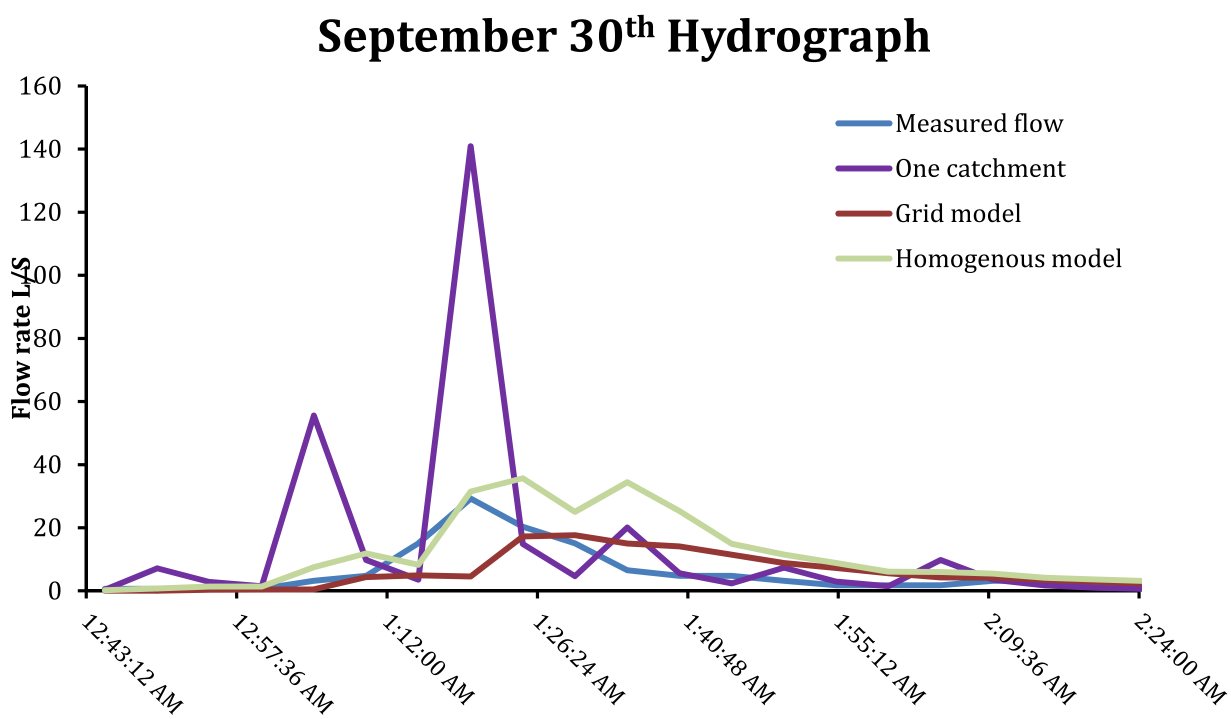


Figure 6-19 The hydrograph of the three models compared to the measured value during the September 30th storm.

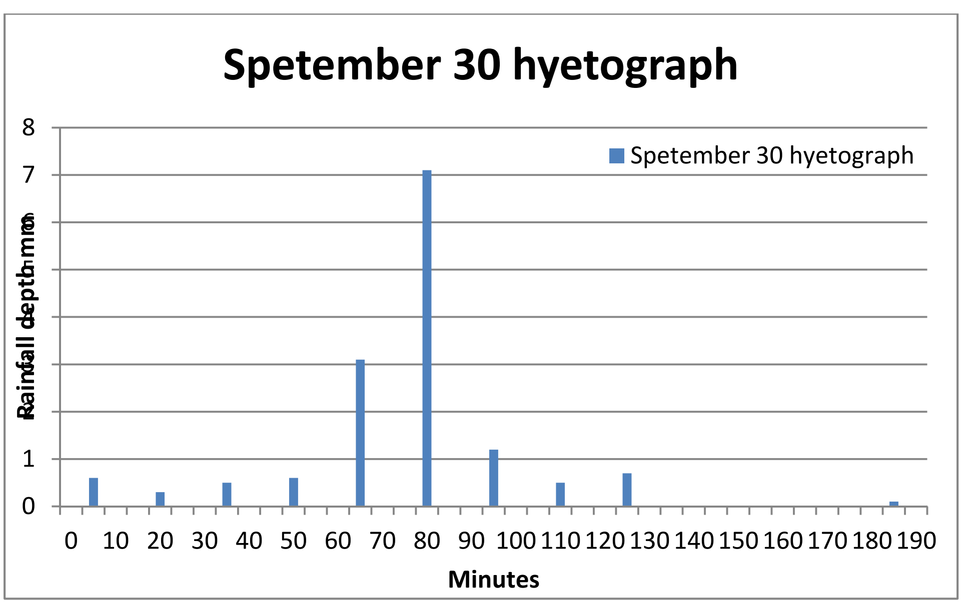


Figure 6-20 Rainfall hyetograph for September 30th event

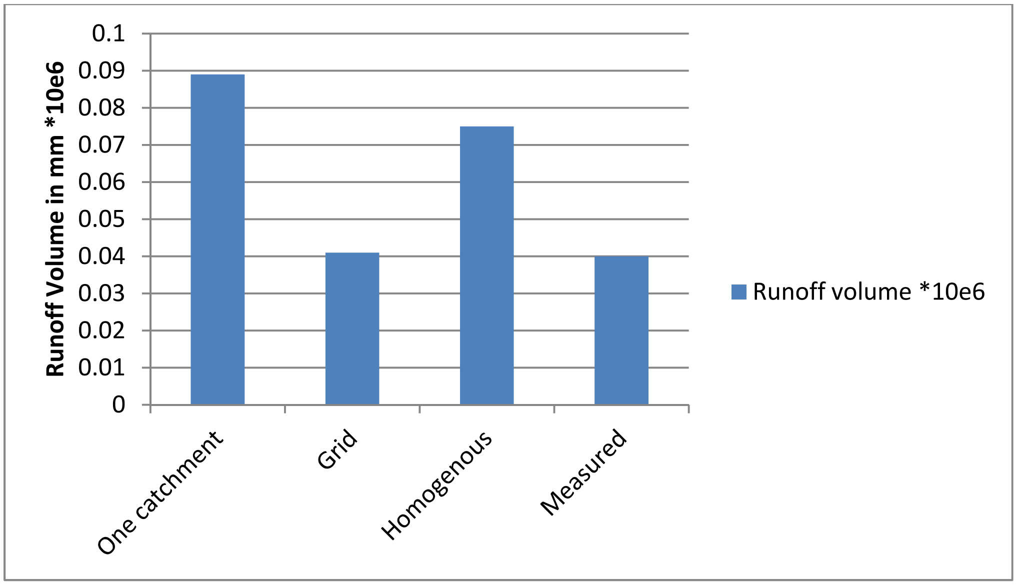


Figure 6-21 The runoff volume of the three models compared to the measured value during the September 30th storm.

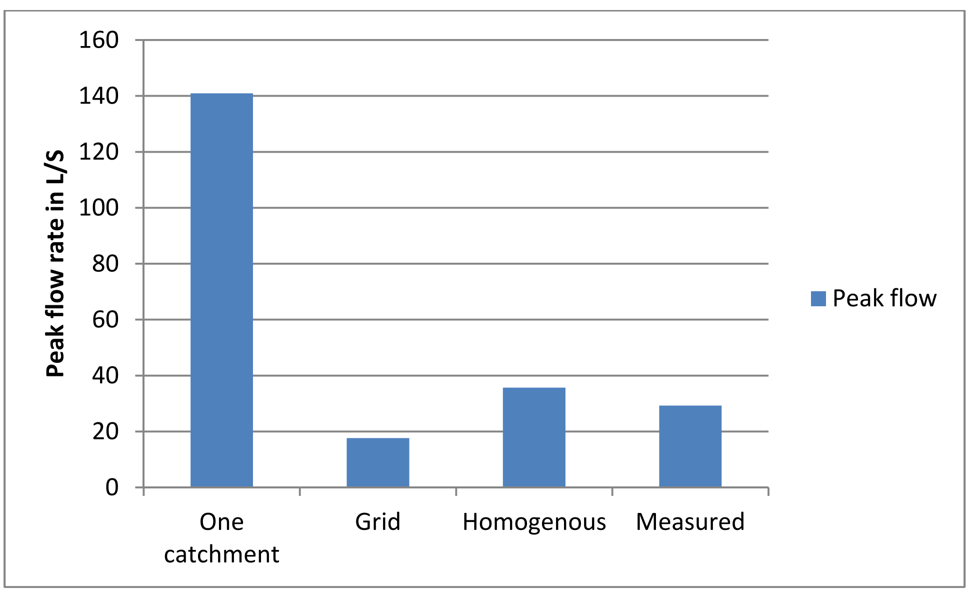


Figure 6-22 The peak flow value in the three models compared to the measured value during the September 30th storm.

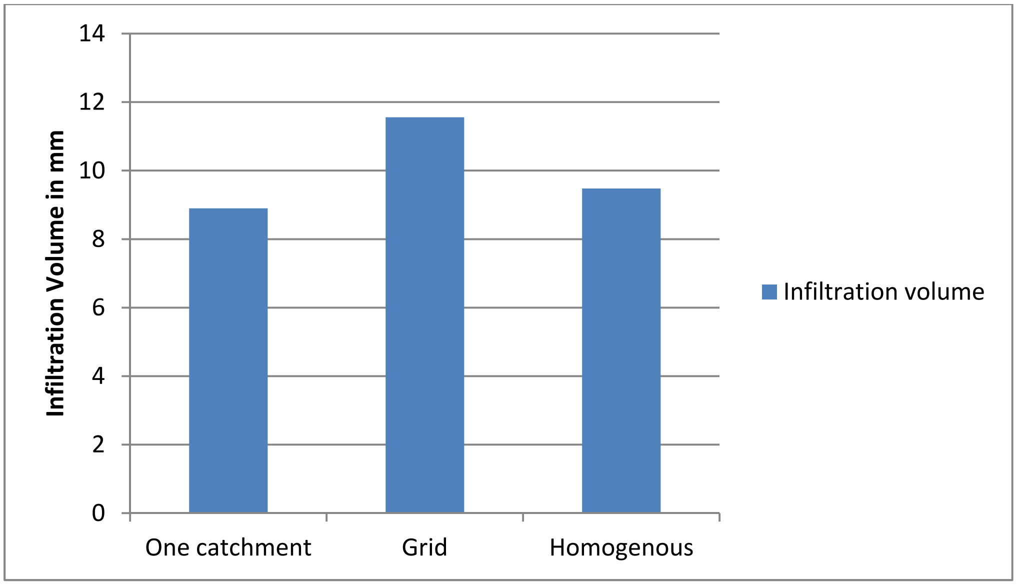


Figure 6-23 The infiltration volume of the three models compared to the measured value during the September 30th storm.

6.5.3 Continuous Simulation

Figures 6-24 to 6-27 show the measured flow values and the three models' hydrographs from July to December. The single catchment model, in general, showed very high flow rates compared to the measured values. Many lumped parameters of the single catchment model (e.g., the width, the slope, and the percentage of runoff diverted from impervious to pervious) were very sensitive resulting in large changes of runoff volume. The single catchment model's flow rates were smaller than the measured values and the time was delayed by five to ten minutes. The homogenous model's flow rates were higher than the measured flow values, but the time is delayed by five to ten minutes. In the homogenous model, the width of each catchment was calculated by dividing the area of the catchment by the longest flow path. The sensitivity of the width may be the cause of large discrepancy in runoff volume and peak flow between the homogenous model and the measured values.

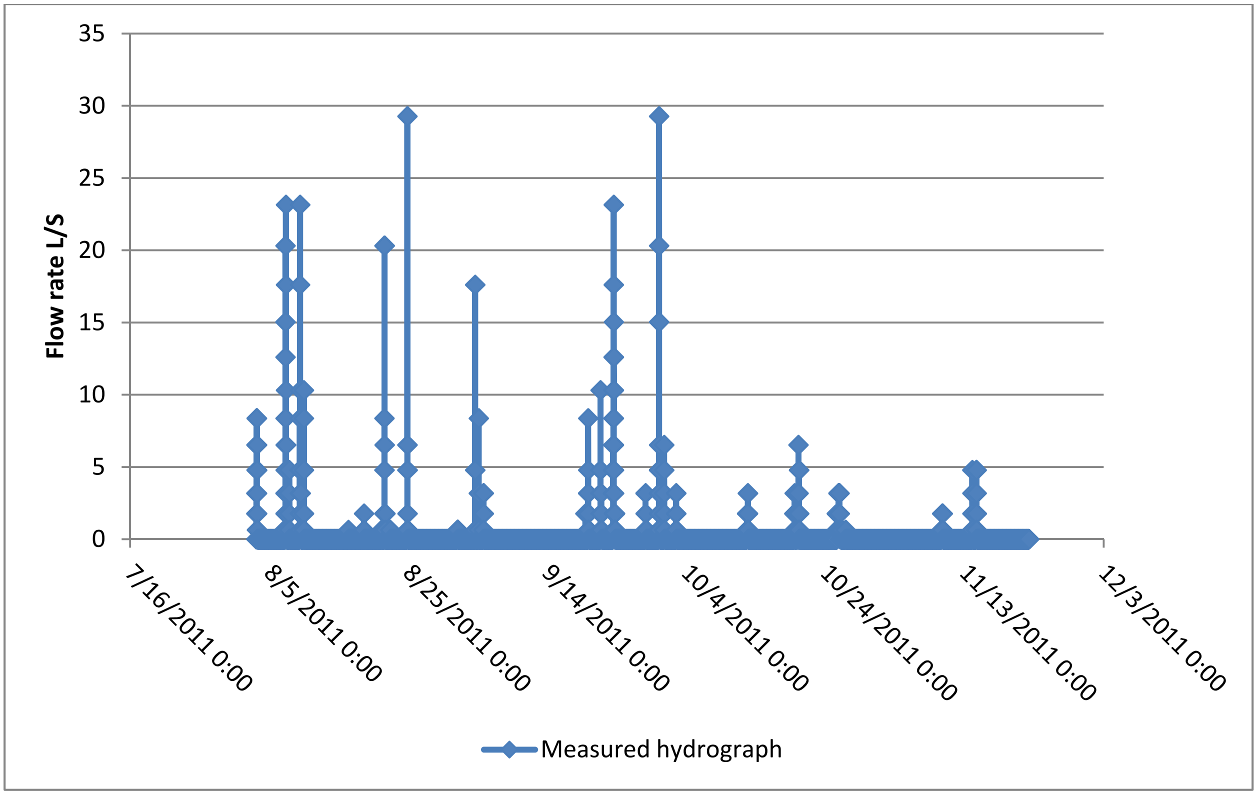


Figure 6-24 The measured hydrograph from July to December

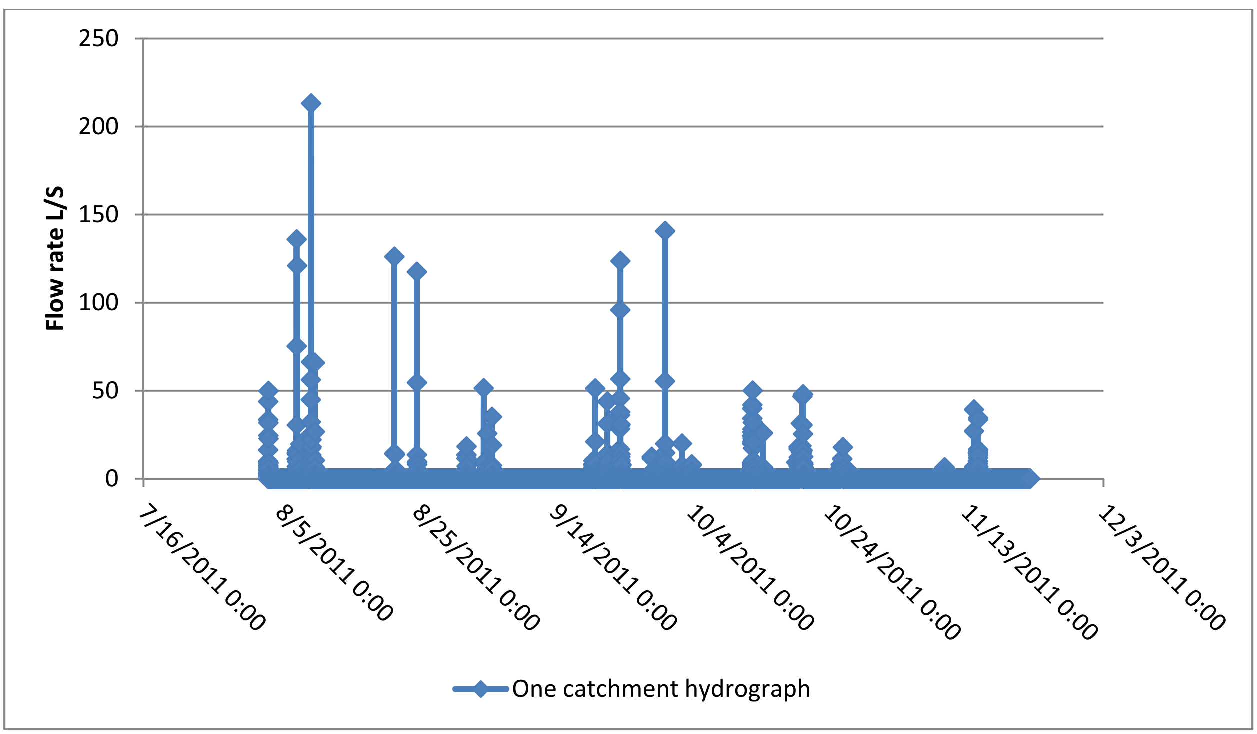


Figure 6-25 The single catchment model hydrograph from July to December.

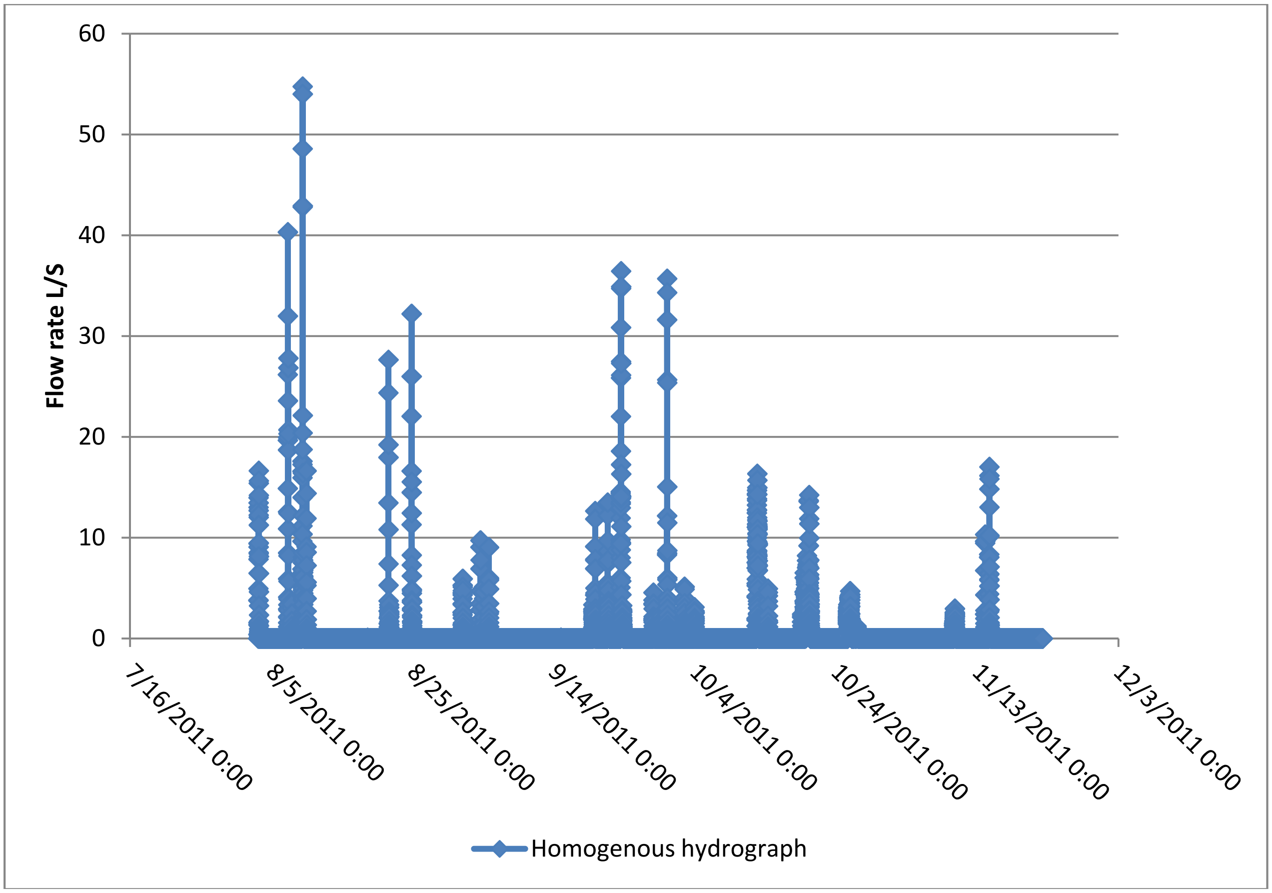


Figure 6-26 The hydrograph of the homogenous model for continuous simulation from July to December

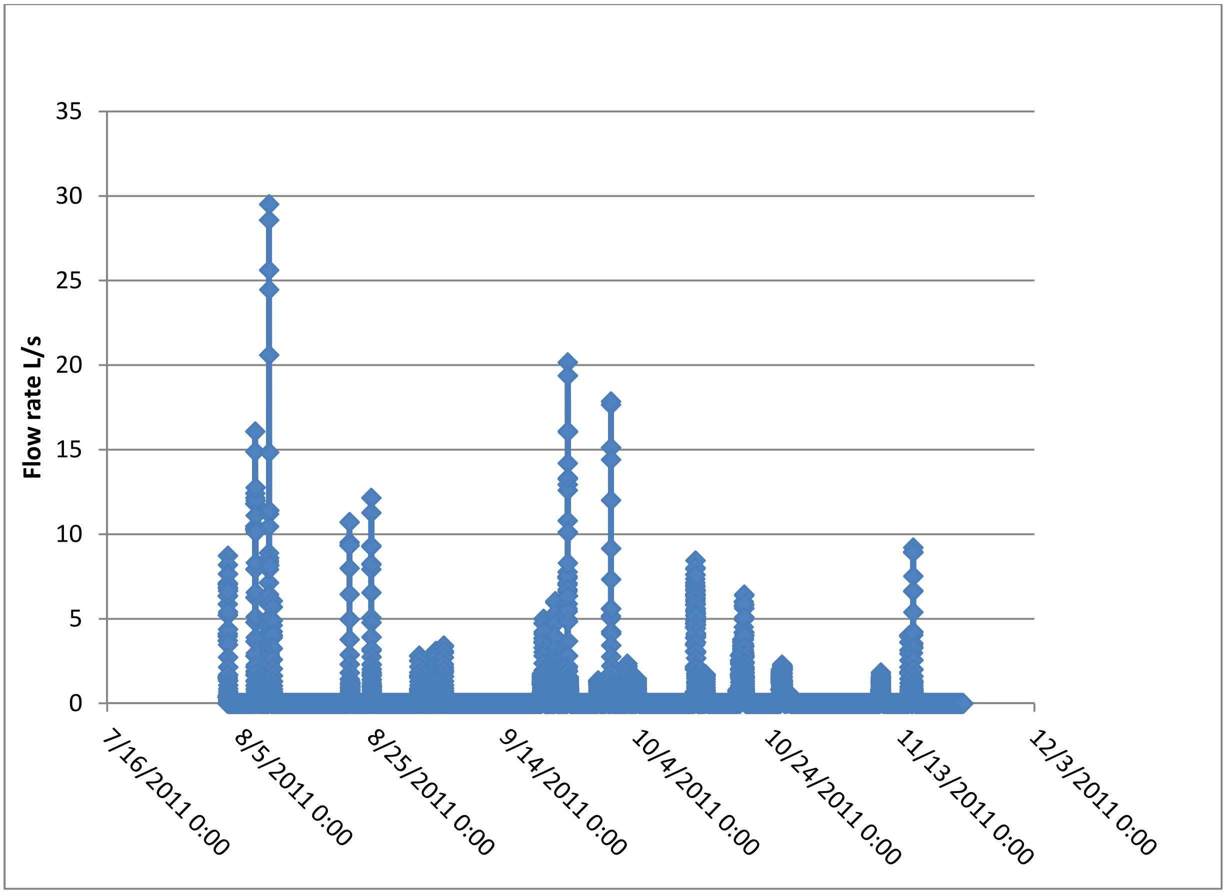


Figure 6-27 The hydrograph of the grid model for continuous simulation from July to December

The total infiltrated volume and the total runoff volume of the three models are compared to the observed value in Figures 6-28 and 6-29, respectively. By comparing the infiltration volume of the three models, the grid model generated the largest infiltration volume. This observation could be attributed to the routing of the flow in the grid model from one catchment to another which allows more infiltration. In addition, the width parameter is less sensitive to the catchment shape. The total runoff volume of the grid model is 80% greater than the measured value. Meanwhile, the single catchment model is three times greater than the observed runoff. The homogenous model was two times greater than the observed runoff.

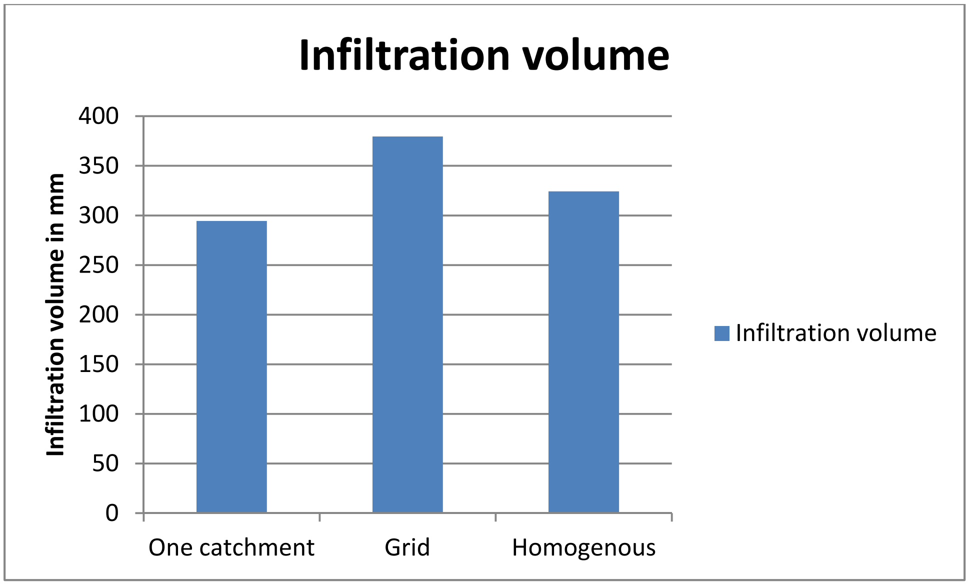


Figure 6-28 The infiltration volume of the three models for continuous simulation from July to December.

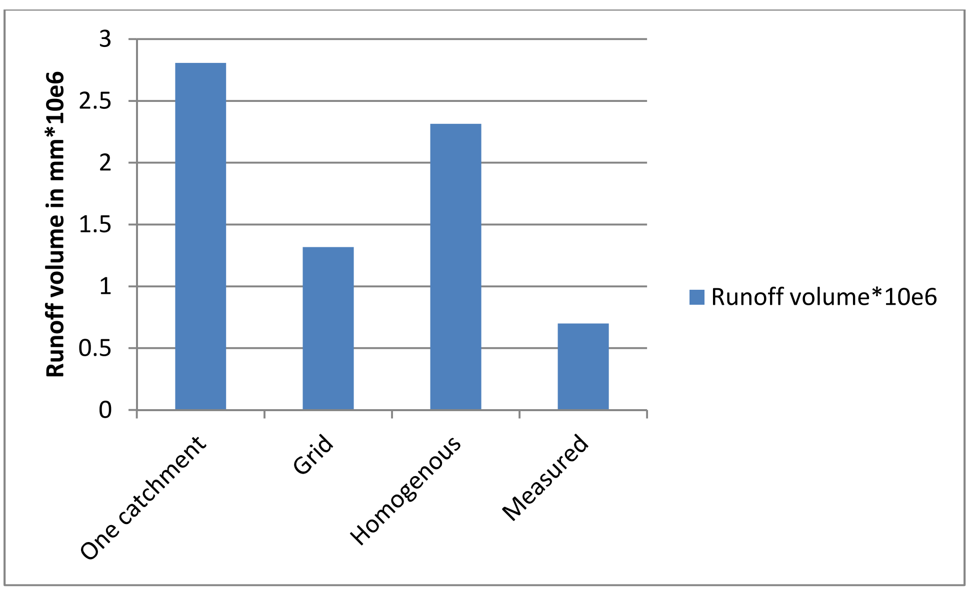


Figure 6-29 The runoff volume of the three models for continuous simulation from July to December.

Table 6-1 shows a comparison of the runoff volumes and peak flows of five events between the model predictions and the measured values. The single catchment model calculated the highest peak flow rate compared to those of the homogenous and the grid models. The homogenous model predicted larger peak flow than the measured peak flow in most events. The single catchment model and the homogenous model predicted high runoff volumes compared to the measured values. The grid model predicted the lowest peak flow compared to the other models and the measured data in most events. The results give an indication that regardless of whether or not the grid model structure allows more flow routing, it generates a low peak flow compared to the measured value.

The case study results indicate that the homogeneous model and the single catchment model predict runoff volumes greater than the measured runoff volumes. The grid model runoff volume predicted is also greater than the measured runoff volume. However, the runoff predicted by the grid model is the closest to the measured runoff compared to those predicted by the homogenous and the single catchment models.

Table 6-1 The highest five peak flow and the runoff volumes

		Measured Data	Homogeneous Model	Grid Model	Single Catchment
Peak1 Aug 7	Runoff	0.022	0.123	0.066	0.054
	Peak flow	23.151	31.990	16.080	121.020
Peak2 Aug 9	Runoff	0.034	0.183	0.102	0.206
	Peak flow	23.151	54.760	29.510	213.150
Peak 3 Aug 24	Runoff	0.018	0.067	0.036	0.080
	Peak flow	29.278	32.210	12.150	117.510
Peak 4 Sep 23	Runoff	0.080	0.191	0.105	0.221
	Peak flow	23.151	36.440	20.160	123.650
Peak 5 Sep 30	Runoff	0.038	0.080	0.045	0.093
	Peak flow	29.278	35.700	17.850	140.690

7 SUMMARY AND CONCLUSIONS

7.1 Summary

The increase in urban development and its direct impact to hydrology, water quality, and ecology increases the need to better predict storm runoff volumes and peak flows. Modelling small urban watersheds can be done either using lumped models, where many parameters are lumped and represented by a single value; or by using distributed models where parameters are varied with finer spatial resolution. With the current development in computing power and the availability of GIS and remote sensing data, there is a need to investigate the modelling of small urban watersheds using lumped and distributed models. Uncalibrated models are typically used, regardless of configuration, to investigate stormwater management retrofit options or design source control for new developments. The evaluation of retrofit options is done assuming that models can correctly predict the catchment runoff response. For new developments, models have not been calibrated against measured data since calibrated data are simply not available.

The primary goal of this research is to investigate the effect of using distributed models to model small urban watersheds compared to those of lumped models. The first objective is to investigate the modelling of small urban catchments using different levels of disaggregation. This objective was achieved by testing a residential single lot with four different grid size models. By comparing the runoff volume and peak flow of the residential single lot model to the one catchment model, it is observed that smaller grids reduce runoff and smaller time steps increase in peak flow rate.

The second objective is to investigate the effect of the flow path direction on runoff volumes. This objective was achieved by the development of grid models with different sizes and flow paths. The flow path has a significant effect on the predicted runoff volume and that effect becomes more significant when the grid is smaller. The last objective was to evaluate the appropriate model structure for small urban catchments. This objective provides modellers with guidance regarding the appropriate hydrological model structure for modelling small urban catchments. To achieve this objective, the results from hypothetical catchments were verified by a real case study with field measured data. The case study was tested by one catchment model, a homogenous model, and a grid model to evaluate the appropriate model structure. The grid model size and the appropriate time step of the case study was selected based on the results of hypothetical tests.

Initially, six modelling tools and five flow path algorithms were reviewed and compared to select the appropriate modelling tool and the flow path algorithm for the hypothetical catchment tests and the case study. From the models reviewed, the US EPA SWMM was selected as a modelling tool and the deterministic eight-node (D8) flow path algorithm was used for defining the flow direction from one cell to another in grid models. SWMM was selected due its availability as an open source; in addition to, it's allowing different subrouting options inside the subcatchment which help to illustrate the subcatchment's behaviour more accurately. The D8 flow path algorithm was selected because it is the only algorithm that can be adapted to SWMM.

The first sensitivity tests were conducted on a 256 m^2 catchment with 25% imperviousness. The study area was tested by four models: 1x1m, 2x2m, 4x4m grids, and one catchment. The tests examined different flow directions, soil types, and grid sizes. The results were evaluated based on the total runoff volume compared to one catchment model's results. The results showed a decrease in the runoff volume with smaller grid size and significant changes with different flow directions. The test was performed using continuous simulation rainfall data with loamy and sandy soils. The soil with high permeability has no significant influence on the smaller grid size due to its high infiltration rate. Based on the previous test, the flow direction has a significant effect on the calculated runoff volume at the outlet.

The second test examined a 600 m^2 residential single lot with 25% imperviousness. The residential single lot was modeled using: 2x2m, 4x4m, 5x5m, 10x10m grids, and one catchment. The test examined the previous models without LID, with bioretention, and with porous pavement using different time steps (15min, 10min, 5 min, 1 min, 30 sec). The results showed a reduction in total runoff volume given a smaller grid size and a reduction in total runoff volume when provided with bigger time steps. The peak flow rate was reduced when both smaller grid size and bigger time steps were used. The same influence on the total runoff volume and peak flow was shown when LIDs was adapted.

The sensitivity test on the 256 m^2 lot also showed that the runoff volume predicted by a 4x4m grid and 2x2m grid were almost the same. That means that the 4x4m grid is appropriate since there is no difference in the runoff calculated with a smaller grid. The appropriate grid size is found to be between 2% and 6% of the catchment area. The runoff volume (37.4mm and 39.9mm) in the sensitivity test of a 600 m^2 catchment showed almost no difference between the 2x2m or5x5m grid models. As a result, the appropriate grid size is between 1% and 4% of the catchment area.

The results from the sensitivity tests with hypothetical catchment were verified by a real case study site with measured flow data. The case study was a 1.65 hectare sub-division located in the Lakeview District Neighborhood on the west of the City of Mississauga. The site was simulated using three models: a) single catchment, b) grid model, and c) homogenous model.

The single catchment model represented the drainage area as one catchment with one value of slope, depression storage, percentage of imperviousness, width, and outlet. The grid model divided the drainage area into 10x10m grids, with each grid having its own parameters. The grid model size and five minute time steps were chosen for the case study based on the previous tests on the hypothetical catchment.

The homogenous model represented each roof, back yard, front yard, drive way, and street as one catchment. The models diverted the runoff from one catchment to another based on the slope and the assumption that all roofs drained into the front yards. All models were tested using continuous simulation and single events. Outputs of models simulation were analyzed using SWMM graphs and the outputs were then imported into Excel to develop hydrographs and charts for comparison. The comparison included the runoff volume, the peak flow rate, the infiltration volume, and the hydrograph shape of the observed data.

The continuous simulation was evaluated based on comparing five events with the highest peak flow. The comparison showed that the runoff volume of grid models were the closest to the observed values. However, the grid models runoff volume was greater than the observed runoff volume in most events. The homogenous and the single catchment models produced runoff volume and peak flow double-to-triple the observed values during the continuous simulation and the single events. The homogenous model behaves similar to Case (C2) and Case (D1) of the hypothetical catchment test. In the homogenous model the flow from backyards subcatchments and roofs subcatchments directed to the front yards subcatchments. The front yards subcatchments received large amount of flow and reached the maximum infiltration rate in short time that could cause the high runoff volume calculated by the homogenous model.

The difference between the grid model predictions and the observed values may also be attributed to different sources of uncertainty. The sources of uncertainty are due to the uncertainty of: 1) accuracy of the digital elevation model to extract slopes, 2) delineation of the drainage area, 3) accuracy of the rainfall and the flow measuring equipment, 4) calculations of the catchment width, 5) determination of the flow direction, 6) the drainage area delineation, and 7) the assumption that all roofs were connected to the front lawn.

The peak flow performance in the sensitivity test increases with larger grid cell sizes. In the case study, the grid model generated the lowest peak flow in all events tested. The highest peak flow value of all single events and continuous simulation was calculated using single catchment model. The peak flow calculated by the homogenous models was higher than the observed peak flow by 10% to 20%. Gird models in most events predicted smaller peak flow than the observed one. The grid models calculated more infiltration volumes compared to single catchment model in both the sensitivity tests using hypothetical catchment and with the real data case study.

7.2 Conclusions & Recommendations

Based on the results and the analysis, the following conclusions can be drawn:

1. Based on the results of the hypothetical catchment and the case study, distributed models (grid models) produced less runoff volume and peak flow than lumped models.
2. Grid size is a sensitive parameter to the runoff volume. Generally, the runoff volume predicted by grid models increases as the grid size increases.
3. Peak flow is sensitive to grid size and time step. It decreases with smaller grid size and bigger time steps. The same influence on the total runoff volume and peak flow has been detected when LIDs is adapted.

4. One catchment model is a lumped model which produces very high runoff volumes, peak flows, and small infiltration volumes.
5. The homogenous models peak flow rate is 10 % to 20 % greater than the observed flow in single events.
6. The predicted runoff volume of the homogenous model was 75% to 200% greater than the observed runoff volume. The homogeneous model sometimes has catchments with irregular shapes, which makes the calculation of the catchment width difficult.
7. The flow path direction is a sensitive parameter which affects the calculation of runoff from small urban areas; an accurate DEM is recommended (5x5m or better).
8. Run-on has to be considered in modelling small urban catchments.
9. Runoff volume from soils with high permeability is insensitive to small grid size due to its high infiltration rate. There is no need to use small grid size when modelling sites with high permeability soil.
10. Modelling urban catchments with grid models may result in smaller LIDs comparing to lumped models, since grid models calculate smaller runoff volume than lumped.

7.3 Further Research

There are a number of unanswered questions related to modelling small urban catchments with distributed and grid models. The following areas require further investigation:

- Grid size is a sensitive parameter of grid models and more investigation is needed to verify the suitable size for each model.
- Methods to delineate drainage area from GIS data should be further investigated with the focus on fine resolution grid model development.

- Effects of using distributed models on total runoff volume and peak flow after using LIDs needs to be evaluated using more real data and case studies.
- Application of grid models for sitting LIDs in a lot or in a sub-division needs further investigation.
- Uncertainty of measured data and models calculations are important issues in modelling without calibration need further investigation. There are different sources of uncertainty:
    - Delineation of the drainage area
    - Accuracy of the digital elevation model to extract slopes
    - Accuracy of rainfall and flow measuring equipment
    - Calculation of the catchment width
    - Flow direction calculations

Appendix A: SWMM Output Status Report

Case (A) - Sandy Soil_July14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units.....................	LPS
Process Models:	
Rainfall/Runoff............	YES
Snowmelt.....................	NO
Groundwater................	NO
Flow Routing................	NO
Water Quality................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date...................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

************************** Runoff Quantity Continuity **************************	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.700
Evaporation Loss............	0.000	0.366
Infiltration Loss…...........	0.001	47.775
Surface Runoff…..........	0.000	15.563
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

************************** Flow Routing Continuity **************************	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.004
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.000	0.004
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	0.00	0.37	47.78	15.56	0.00	0.36	0.244

Analysis begun on: Thu Dec 15 15:54:42 2011
Analysis ended on: Thu Dec 15 15:54:42 2011
Total elapsed time: < 1 sec

Case (A) – Loamy Soil Continuous Simulation

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff.............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality.................	NO
Infiltration Method.........	HORTON
Starting Date..................	APR-01-1985 00:00:00
Ending Date...................	NOV-01-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

************************** Runoff Quantity Continuity **************************	Volume hectare-m ---------	Depth mm -------
Total Precipitation..........	0.014	544.10
Evaporation Loss............	0.000	10.114
Infiltration Loss…...........	0.010	403.633
Surface Runoff…............	0.003	130.377
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

************************** Flow Routing Continuity **************************	Volume hectare-m ---------	Volume 10^6 ltr ---------
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.033
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.003	0.033
Internal Outflow…..........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	544.10	0.00	10.11	403.63	130.38	0.03	1.15	0.240

Analysis begun on: Mon Dec 12 10:08:11 2011
Analysis ended on: Mon Dec 12 10:08:12 2011
Total elapsed time: 00:00:01

Case (C1) – Loamy Soil July 14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units.....................	LPS
Process Models:	
Rainfall/Runoff............	YES
Snowmelt.....................	NO
Groundwater................	NO
Flow Routing...............	NO
Water Quality................	NO
Infiltration Method.........	HORTON
Starting Date.................	JUL-14-1985 00:00:00
Ending Date..................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step..............	00:00:30
Dry Time Step..............	01:00:00

****
Runoff Quantity Continuity
****

Runoff Quantity Continuity	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.70
Evaporation Loss...........	0.000	1.513
Infiltration Loss….........	0.001	51.032
Surface Runoff…...........	0.000	11.206
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

****
Flow Routing Continuity
****

Flow Routing Continuity	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.003
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow...........	0.000	0.003
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	5.98	0.35	61.72	7.61	0.00	0.09	0.109
3	63.70	120.33	1.09	101.26	82.04	0.00	0.21	0.446
4	63.70	4.18	0.34	61.56	5.98	0.00	0.07	0.088
5	63.70	61.27	4.67	0.00	120.33	0.00	0.18	0.963
6	63.70	120.33	1.09	101.26	82.04	0.00	0.21	0.446
7	63.70	5.98	0.35	61.72	7.61	0.00	0.09	0.109
8	63.70	61.27	4.67	0.00	120.33	0.00	0.18	0.963
9	63.70	4.18	0.34	61.56	5.98	0.00	0.07	0.088

10	63.70	2.20	0.34	61.38	4.18	0.00	0.05	0.063
11	63.70	2.20	4.65	0.00	61.27	0.00	0.10	0.930
12	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035
13	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035
14	63.70	2.20	4.65	0.00	61.27	0.00	0.10	0.930
15	63.70	2.20	0.34	61.38	4.18	0.00	0.05	0.063
16	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035
17	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035

Analysis begun on: Mon Dec 12 11:19:18 2011
Analysis ended on: Mon Dec 12 11:19:18 2011
Total elapsed time: < 1 sec

Case (C2) – Loamy Soil July 14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff.............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality.................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date...................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

Runoff Quantity Continuity	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.700
Evaporation Loss............	0.000	1.494
Infiltration Loss…...........	0.001	49.516
Surface Runoff…............	0.000	12.721
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

Flow Routing Continuity	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.003
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.000	0.003
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	5.98	0.35	61.72	7.61	0.00	0.09	0.109
3	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035
4	63.70	4.18	0.34	61.56	5.98	0.00	0.07	0.088
5	63.70	0.00	4.65	0.00	59.07	0.00	0.09	0.927
6	63.70	236.27	1.52	116.09	182.74	0.00	0.40	0.609
7	63.70	9.62	0.35	61.99	10.99	0.00	0.13	0.150
8	63.70	177.21	4.68	0.00	236.27	0.00	0.36	0.981

9	63.70	8.10	0.35	61.83	9.62	0.00	0.11	0.134
10	63.70	2.20	0.34	61.38	4.18	0.00	0.05	0.063
11	63.70	0.00	4.65	0.00	59.07	0.00	0.09	0.927
12	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035
13	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035
14	63.70	0.00	4.65	0.00	59.07	0.00	0.09	0.927
15	63.70	6.38	0.35	61.64	8.10	0.00	0.09	0.116
16	63.70	2.20	0.34	61.38	4.18	0.00	0.05	0.063
17	63.70	0.00	0.34	61.17	2.20	0.00	0.02	0.035

Analysis begun on: Thu Dec 12 11:23:21 2011
Analysis ended on: Thu Dec 12 11:23:21 2011
Total elapsed time: < 1 sec

Case (C2) – Loamy Soil Continuous Simulation

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

```
*********************************************************
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
*********************************************************

****************
Analysis Options
****************
Flow Units...................... LPS
Process Models:
  Rainfall/Runoff............. YES
  Snowmelt..................... NO
  Groundwater................. NO
  Flow Routing................ NO
Water Quality................. NO
Infiltration Method......... HORTON
Starting Date.................. APR-14-1985 00:00:00
Ending Date................... NOV-16-1985 00:00:00
Antecedent Dry Days..... 0.0
Report Time Step........... 01:00:00
Wet Time Step............... 00:00:30
Dry Time Step............... 01:00:00

**************************        Volume        Depth
Runoff Quantity Continuity        hectare-m     mm
**************************        ---------     -------
Total Precipitation..........     0.014         544.100
Evaporation Loss............      0.001         31.860
Infiltration Loss…..........      0.012         472.040
Surface Runoff…............       0.001         40.316
Final Surface Storage.....        0.000         0.000
Continuity Error (%)......        -0.021

**************************        Volume        Volume
Flow Routing Continuity           hectare-m     10^6 ltr
**************************        ---------     ---------
Dry Weather Inflow.......         0.000         0.000
Wet Weather Inflow.......         0.001         0.010
Groundwater Inflow.......         0.000         0.000
RDII Inflow……............        0.000         0.000
External Inflow…............      0.000         0.000
External Outflow............      0.001         0.010
Internal Outflow…..........       0.000         0.000
Storage Losses…...........        0.000         0.000
Initial Stored Volume.....        0.000         0.000
Final Stored Volume......         0.000         0.000
Continuity Error (%).....         0.000

***************************
Subcatchment Runoff Summary
***************************
```

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	544.10	17.44	0.64	538.35	22.56	0.00	0.24	0.040
3	544.10	0.00	0.62	537.27	6.22	0.00	0.06	0.011
4	544.10	12.01	0.64	538.04	17.44	0.00	0.18	0.031
5	544.10	0.00	123.68	0.00	420.50	0.01	0.12	0.773
6	544.10	1681.70	7.66	1636.34	583.13	0.01	0.54	0.262
7	544.10	28.50	0.65	538.81	33.15	0.00	0.35	0.058
8	544.10	1261.50	124.09	0.00	1681.7	00.03	0.48	0.931
9	544.10	23.54	0.64	538.51	28.50	0.00	0.30	0.050

10	544.10	6.22	0.63	537.69	12.01	0.00	0.12	0.022
11	544.10	0.00	123.68	0.00	420.50	0.01	0.12	0.773
12	544.10	0.00	0.62	537.27	6.22	0.00	0.06	0.011
13	544.10	0.00	0.62	537.27	6.22	0.00	0.06	0.011
14	544.10	0.00	123.68	0.00	420.50	0.01	0.12	0.773
15	544.10	18.23	0.64	538.15	23.54	0.00	0.24	0.042
16	544.10	6.22	0.63	537.69	12.01	0.00	0.12	0.022
17	544.10	0.00	0.62	537.27	6.22	0.00	0.06	0.011

Analysis begun on: Thu Dec 12 11:23:21 2011
Analysis ended on: Thu Dec 12 11:23:21 2011
Total elapsed time: < 1 sec

Case (C2) – Sandy Soil July 14-17

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff.............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality.................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date...................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

Runoff Quantity Continuity	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.70
Evaporation Loss............	0.000	1.164
Infiltration Loss…...........	0.002	62.541
Surface Runoff…............	0.000	0.000
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

Flow Routing Continuity	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.000
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.000	0.000
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
3	63.70	118.13	0.00	181.83	0.00	0.00	0.00	0.000
4	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
5	63.70	59.07	4.67	0.00	118.13	0.00	0.18	0.962
6	63.70	118.13	0.00	181.83	0.00	0.00	0.00	0.000
7	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
8	63.70	59.07	4.67	0.00	118.13	0.00	0.18	0.962
9	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000

10	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
11	63.70	0.00	4.65	0.00	59.07	0.00	0.09	0.927
12	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
13	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
14	63.70	0.00	4.65	0.00	59.07	0.00	0.09	0.927
15	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
16	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
17	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000

Analysis begun on: Thu Dec 15 20:36:58 2011
Analysis ended on: Thu Dec 15 20:36:58 2011
Total elapsed time: < 1 sec

Case (D1) – Loamy Soil July14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality.................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date...................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:15:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

************************** Runoff Quantity Continuity **************************	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.70
Evaporation Loss...........	0.000	1.460
Infiltration Loss…........	0.001	47.931
Surface Runoff….........	0.000	14.343
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

************************** Flow Routing Continuity **************************	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.004
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…........	0.000	0.000
External Outflow...........	0.000	0.004
Internal Outflow…........	0.000	0.000
Storage Losses….........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
3	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
4	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
5	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
6	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
7	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
8	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037

9	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
10	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
11	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
12	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
13	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
14	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
15	63.70	118.20	4.64	0.00	177.29	0.00	0.07	0.975
16	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
17	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
18	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
19	63.70	885.64	1.74	120.34	827.97	0.00	0.38	0.872
20	63.70	28.60	0.36	62.31	29.64	0.00	0.09	0.321
21	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
22	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
23	63.70	945.48	1.78	122.47	885.64	0.00	0.37	0.878
24	63.70	27.47	0.36	62.22	28.60	0.00	0.08	0.314
25	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
26	63.70	295.48	4.66	0.00	354.58	0.00	0.14	0.987
27	63.70	886.43	4.67	0.00	945.48	0.00	0.36	0.995
28	63.70	26.23	0.36	62.11	27.47	0.00	0.08	0.305
29	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
30	63.70	236.38	4.66	0.00	295.47	0.00	0.11	0.985
31	63.70	177.29	4.65	0.00	236.38	0.00	0.09	0.981
32	63.70	24.88	0.35	62.00	26.23	0.00	0.07	0.296
33	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
34	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
35	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
36	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
37	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
38	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
39	63.70	118.20	4.64	0.00	177.29	0.00	0.07	0.975
40	63.70	23.41	0.35	61.88	24.88	0.00	0.07	0.286
41	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
42	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
43	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
44	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
45	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
46	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
47	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
48	63.70	21.79	0.35	61.74	23.41	0.00	0.06	0.274
49	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
50	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
51	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
52	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
53	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
54	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
55	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
56	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
57	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
58	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
59	63.70	17.66	0.34	61.59	19.43	0.00	0.05	0.239
60	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
61	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
62	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
63	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
64	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
65	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069

Analysis begun on: Mon Dec 12 16:14:03 2011
Analysis ended on: Mon Dec 12 16:14:03 2011
Total elapsed time: < 1 sec

Case (D1) - Sandy Soil July 14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date...................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:15:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

****
Runoff Quantity Continuity
****

Runoff Quantity Continuity	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.70
Evaporation Loss...........	0.000	1.173
Infiltration Loss….........	0.002	59.593
Surface Runoff…...........	0.000	2.946
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

****
Flow Routing Continuity
****

Flow Routing Continuity	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.001
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.000	0.001
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
3	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
4	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
5	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
6	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
7	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
8	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000

9	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
10	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
11	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
12	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
13	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
14	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
15	63.70	118.20	4.64	0.00	177.29	0.00	0.07	0.975
16	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
17	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
18	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
19	63.70	391.07	0.34	266.01	188.53	0.00	0.14	0.415
20	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
21	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
22	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
23	63.70	945.48	0.51	617.74	391.07	0.00	0.25	0.388
24	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
25	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
26	63.70	295.48	4.66	0.00	354.58	0.00	0.14	0.987
27	63.70	886.43	4.67	0.00	945.48	0.00	0.36	0.995
28	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
29	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
30	63.70	236.38	4.66	0.00	295.47	0.00	0.11	0.985
31	63.70	177.29	4.65	0.00	236.38	0.00	0.09	0.981
32	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
33	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
34	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
35	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
36	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
37	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
38	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
39	63.70	118.20	4.64	0.00	177.29	0.00	0.07	0.975
40	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
41	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
42	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
43	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
44	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
45	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
46	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
47	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
48	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
49	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
50	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
51	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
52	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
53	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
54	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
55	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
56	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
57	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
58	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
59	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
60	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
61	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
62	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
63	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
64	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
65	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000

Analysis begun on: Thu Dec 15 21:12:14 2011
Analysis ended on: Thu Dec 15 21:12:14 2011
Total elapsed time: < 1 sec

Case (D2) - Loamy Soil July 14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

```
*********************************************************
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
*********************************************************

****************
Analysis Options
****************
Flow Units.....................     LPS
Process Models:
  Rainfall/Runoff............       YES
  Snowmelt.....................     NO
  Groundwater.................      NO
  Flow Routing................      NO
Water Quality................       NO
Infiltration Method.........        HORTON
Starting Date..................     JUL-14-1985 00:00:00
Ending Date...................      JUL-16-1985 00:00:00
Antecedent Dry Days.....            0.0
Report Time Step...........         01:15:00
Wet Time Step...............        00:00:30
Dry Time Step...............        01:00:00

**************************          Volume        Depth
Runoff Quantity Continuity          hectare-m     mm
**************************          ---------     -------
Total Precipitation..........       0.002         63.700
Evaporation Loss...........         0.000         1.499
Infiltration Loss…..........        0.001         49.900
Surface Runoff…...........          0.000         12.344
Final Surface Storage.....          0.000         0.000
Continuity Error (%)......          0.000

**************************          Volume        Volume
Flow Routing Continuity             hectare-m     10^6 ltr
**************************          ---------     ---------
Dry Weather Inflow.......           0.000         0.000
Wet Weather Inflow.......           0.000         0.003
Groundwater Inflow.......           0.000         0.000
RDII Inflow……............           0.000         0.000
External Inflow…...........         0.000         0.000
External Outflow...........         0.000         0.003
Internal Outflow…..........         0.000         0.000
Storage Losses…...........          0.000         0.000
Initial Stored Volume.....          0.000         0.000
Final Stored Volume......           0.000         0.000
Continuity Error (%).....           0.000

***************************
Subcatchment Runoff Summary
***************************
```

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
3	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
4	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
5	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
6	63.70	39.81	0.38	62.03	41.10	0.00	0.04	0.397
7	63.70	80.29	0.46	66.08	77.46	0.00	0.06	0.538
8	63.70	59.10	0.60	82.39	39.81	0.00	0.03	0.324

9	63.70	118.19	1.10	100.86	80.29	0.00	0.05	0.441
10	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
11	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
12	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
13	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
14	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
15	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
16	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
17	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
18	63.70	127.61	0.82	76.36	114.32	0.00	0.08	0.598
19	63.70	531.81	1.47	113.62	480.86	0.00	0.24	0.807
20	63.70	28.60	0.36	62.31	29.64	0.00	0.09	0.321
21	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
22	63.70	177.27	1.43	112.30	127.61	0.00	0.08	0.530
23	63.70	590.95	1.77	121.70	531.81	0.00	0.24	0.812
24	63.70	27.47	0.36	62.22	28.60	0.00	0.08	0.314
25	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
26	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
27	63.70	531.85	4.67	0.00	590.95	0.00	0.23	0.992
28	63.70	26.23	0.36	62.11	27.47	0.00	0.08	0.305
29	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
30	63.70	295.48	4.66	0.00	354.58	0.00	0.14	0.987
31	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
32	63.70	24.88	0.35	62.00	26.23	0.00	0.07	0.296
33	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
34	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
35	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
36	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
37	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
38	63.70	118.20	4.64	0.00	177.29	0.00	0.07	0.975
39	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
40	63.70	23.41	0.35	61.88	24.88	0.00	0.07	0.286
41	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
42	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
43	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
44	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
45	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
46	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
47	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
48	63.70	21.79	0.35	61.74	23.41	0.00	0.06	0.274
49	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
50	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
51	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
52	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
53	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
54	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
55	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
56	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
57	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
58	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
59	63.70	17.66	0.34	61.59	19.43	0.00	0.05	0.239
60	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
61	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
62	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
63	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
64	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
65	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069

Analysis begun on: Mon Dec 12 16:16:27 2011
Analysis ended on: Mon Dec 12 16:16:27 2011
Total elapsed time: < 1 sec

Case (D2) - Sandy Soil July 14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date...................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:15:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

****
Runoff Quantity Continuity
****

	Volume hectare-m	Depth mm
	---------	-------
Total Precipitation..........	0.002	63.700
Evaporation Loss...........	0.000	1.168
Infiltration Loss….........	0.002	62.529
Surface Runoff…...........	0.000	0.013
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

****
Flow Routing Continuity
****

	Volume hectare-m	Volume 10^6 ltr
	---------	---------
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.000
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.000	0.000
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
3	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
4	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
5	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
6	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
7	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
8	63.70	59.10	0.00	122.80	0.00	0.00	0.00	0.000

9	63.70	118.19	0.00	181.89	0.00	0.00	0.00	0.000
10	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
11	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
12	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
13	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
14	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
15	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
16	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
17	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
18	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
19	63.70	166.83	0.17	229.55	0.81	0.00	0.01	0.004
20	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
21	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
22	63.70	177.27	0.00	240.97	0.00	0.00	0.00	0.000
23	63.70	590.95	0.35	487.53	166.83	0.00	0.12	0.255
24	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
25	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
26	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
27	63.70	531.85	4.67	0.00	590.95	0.00	0.23	0.992
28	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
29	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
30	63.70	295.48	4.66	0.00	354.58	0.00	0.14	0.987
31	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
32	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
33	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
34	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
35	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
36	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
37	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
38	63.70	118.20	4.64	0.00	177.29	0.00	0.07	0.975
39	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
40	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
41	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
42	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
43	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
44	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
45	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
46	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
47	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
48	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
49	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
50	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
51	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
52	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
53	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
54	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
55	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
56	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
57	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
58	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
59	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
60	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
61	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
62	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
63	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
64	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
65	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000

Analysis begun on: Thu Dec 15 21:22:09 2011
Analysis ended on: Thu Dec 15 21:22:09 2011
Total elapsed time: < 1 sec

Case (D3) – Loamy Soil July 14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff.............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality.................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date....................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

************************** Runoff Quantity Continuity **************************	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.700
Evaporation Loss...........	0.000	1.530
Infiltration Loss….........	0.001	50.943
Surface Runoff…...........	0.000	11.285
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

************************** Flow Routing Continuity **************************	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.003
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.000	0.003
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
3	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
4	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
5	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
6	63.70	188.04	1.01	86.08	165.01	0.00	0.11	0.656
7	63.70	188.04	1.01	86.08	165.01	0.00	0.11	0.656

8	63.70	240.92	1.50	115.47	188.04	0.00	0.10	0.617
9	63.70	240.92	1.50	115.47	188.04	0.00	0.10	0.617
10	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
11	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
12	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
13	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
14	63.70	181.85	4.66	0.00	240.92	0.00	0.09	0.981
15	63.70	181.85	4.66	0.00	240.92	0.00	0.09	0.981
16	63.70	122.76	4.65	0.00	181.85	0.00	0.07	0.975
17	63.70	122.76	4.65	0.00	181.85	0.00	0.07	0.975
18	63.70	188.04	1.01	86.08	165.01	0.00	0.11	0.656
19	63.70	188.04	1.01	86.08	165.01	0.00	0.11	0.656
20	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
21	63.70	13.95	0.35	61.77	15.54	0.00	0.05	0.200
22	63.70	240.92	1.50	115.47	188.04	0.00	0.10	0.617
23	63.70	240.92	1.50	115.47	188.04	0.00	0.10	0.617
24	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
25	63.70	12.27	0.35	61.68	13.95	0.00	0.04	0.184
26	63.70	181.85	4.66	0.00	240.92	0.00	0.09	0.981
27	63.70	181.85	4.66	0.00	240.92	0.00	0.09	0.981
28	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
29	63.70	10.50	0.34	61.59	12.27	0.00	0.03	0.165
30	63.70	122.76	4.65	0.00	181.85	0.00	0.07	0.975
31	63.70	122.76	4.65	0.00	181.85	0.00	0.07	0.975
32	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
33	63.70	8.63	0.34	61.49	10.50	0.00	0.03	0.145
34	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
35	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
36	63.70	63.67	4.64	0.00	122.76	0.00	0.05	0.964
37	63.70	63.67	4.64	0.00	122.76	0.00	0.05	0.964
38	63.70	63.67	4.64	0.00	122.76	0.00	0.05	0.964
39	63.70	63.67	4.64	0.00	122.76	0.00	0.05	0.964
40	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
41	63.70	6.66	0.34	61.39	8.63	0.00	0.02	0.123
42	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
43	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
44	63.70	4.58	4.63	0.00	63.67	0.00	0.03	0.933
45	63.70	4.58	4.63	0.00	63.67	0.00	0.03	0.933
46	63.70	4.58	4.63	0.00	63.67	0.00	0.03	0.933
47	63.70	4.58	4.63	0.00	63.67	0.00	0.03	0.933
48	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
49	63.70	4.58	0.34	61.28	6.66	0.00	0.02	0.098
50	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
51	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
52	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
53	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
54	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
55	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
56	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
57	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
58	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
59	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
60	63.70	2.36	0.34	61.16	4.58	0.00	0.01	0.069
61	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
62	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
63	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
64	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037
65	63.70	0.00	0.33	61.01	2.36	0.00	0.01	0.037

Analysis begun on: Mon Dec 12 16:20:13 2011
Analysis ended on: Mon Dec 12 16:20:13 2011
Total elapsed time: < 1 sec

Case (D3) – Loamy Soil Continues Simulation

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff.............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality.................	NO
Infiltration Method.........	HORTON
Starting Date..................	APR-01-1985 00:00:00
Ending Date...................	NOV-01-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

**************************	Volume	Depth
Runoff Quantity Continuity	hectare-m	mm
**************************	---------	-------
Total Precipitation..........	0.014	544.100
Evaporation Loss............	0.001	31.980
Infiltration Loss…...........	0.012	483.683
Surface Runoff…............	0.001	28.625
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	-0.035	

**************************	Volume	Volume
Flow Routing Continuity	hectare-m	10^6 ltr
**************************	---------	---------
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.001	0.007
Groundwater Inflow.......	0.000	0.000
RDII Inflow……............	0.000	0.000
External Inflow…............	0.000	0.000
External Outflow............	0.001	0.007
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	544.10	40.97	0.64	538.40	46.04	0.00	0.12	0.079
3	544.10	40.97	0.64	538.40	46.04	0.00	0.12	0.079
4	544.10	35.73	0.64	538.23	40.97	0.00	0.10	0.071
5	544.10	35.73	0.64	538.23	40.97	0.00	0.10	0.071
6	544.10	600.74	2.89	730.59	411.97	0.00	0.18	0.360
7	544.10	600.74	2.89	730.59	411.97	0.00	0.18	0.360

8	544.10	1695.22	7.82	1632.39	600.74	0.00	0.16	0.268
9	544.10	1695.22	7.82	1632.39	600.74	0.00	0.16	0.268
10	544.10	30.31	0.64	538.06	35.73	0.00	0.09	0.062
11	544.10	30.31	0.64	538.06	35.73	0.00	0.09	0.062
12	544.10	24.70	0.63	537.87	30.31	0.00	0.08	0.053
13	544.10	24.70	0.63	537.87	30.31	0.00	0.08	0.053
14	544.10	1274.81	123.88	0.00	1695.22	0.01	0.15	0.932
15	544.10	1274.81	123.88	0.00	1695.22	0.01	0.15	0.932
16	544.10	854.28	123.75	0.00	1274.81	0.01	0.12	0.912
17	544.10	854.28	123.75	0.00	1274.81	0.01	0.12	0.912
18	544.10	600.74	2.89	730.59	411.97	0.00	0.18	0.360
19	544.10	600.74	2.89	730.59	411.97	0.00	0.18	0.360
20	544.10	40.97	0.64	538.40	46.04	0.00	0.12	0.079
21	544.10	40.97	0.64	538.40	46.04	0.00	0.12	0.079
22	544.10	1695.22	7.82	1632.39	600.74	0.00	0.16	0.268
23	544.10	1695.22	7.82	1632.39	600.74	0.00	0.16	0.268
24	544.10	35.73	0.64	538.23	40.97	0.00	0.10	0.071
25	544.10	35.73	0.64	538.23	40.97	0.00	0.10	0.071
26	544.10	1274.81	123.88	0.00	1695.22	0.01	0.15	0.932
27	544.10	1274.81	123.88	0.00	1695.22	0.01	0.15	0.932
28	544.10	30.31	0.64	538.06	35.73	0.00	0.09	0.062
29	544.10	30.31	0.64	538.06	35.73	0.00	0.09	0.062
30	544.10	854.28	123.75	0.00	1274.81	0.01	0.12	0.912
31	544.10	854.28	123.75	0.00	1274.81	0.01	0.12	0.912
32	544.10	24.70	0.63	537.87	30.31	0.00	0.08	0.053
33	544.10	24.70	0.63	537.87	30.31	0.00	0.08	0.053
34	544.10	18.88	0.63	537.67	24.70	0.00	0.06	0.044
35	544.10	18.88	0.63	537.67	24.70	0.00	0.06	0.044
36	544.10	433.63	123.61	0.00	854.28	0.00	0.09	0.874
37	544.10	433.63	123.61	0.00	854.28	0.00	0.09	0.874
38	544.10	433.63	123.61	0.00	854.28	0.00	0.09	0.874
39	544.10	433.63	123.61	0.00	854.28	0.00	0.09	0.874
40	544.10	18.88	0.63	537.67	24.70	0.00	0.06	0.044
41	544.10	18.88	0.63	537.67	24.70	0.00	0.06	0.044
42	544.10	12.85	0.63	537.45	18.88	0.00	0.05	0.034
43	544.10	12.85	0.63	537.45	18.88	0.00	0.05	0.034
44	544.10	12.85	123.44	0.00	433.63	0.00	0.06	0.779
45	544.10	12.85	123.44	0.00	433.63	0.00	0.06	0.779
46	544.10	12.85	123.44	0.00	433.63	0.00	0.06	0.779
47	544.10	12.85	123.44	0.00	433.63	0.00	0.06	0.779
48	544.10	12.85	0.63	537.45	18.88	0.00	0.05	0.034
49	544.10	12.85	0.63	537.45	18.88	0.00	0.05	0.034
50	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
51	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
52	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012
53	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012
54	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
55	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012
56	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
57	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
58	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
59	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
60	544.10	6.57	0.62	537.21	12.85	0.00	0.03	0.023
61	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012
62	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012
63	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012
64	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012
65	544.10	0.00	0.62	536.92	6.57	0.00	0.02	0.012

Analysis begun on: Mon Dec 12 16:18:57 2011
Analysis ended on: Mon Dec 12 16:19:00 2011
Total elapsed time: 00:00:03

Case (D3) - Sandy Soil July 14-16

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.0 (Build 5.0.022)

****
NOTE: The summary statistics displayed in this report are
based on results found at every computational time step,
not just on results from each reporting time step.
****

****
Analysis Options
****

Flow Units......................	LPS
Process Models:	
Rainfall/Runoff.............	YES
Snowmelt......................	NO
Groundwater.................	NO
Flow Routing................	NO
Water Quality.................	NO
Infiltration Method.........	HORTON
Starting Date..................	JUL-14-1985 00:00:00
Ending Date....................	JUL-16-1985 00:00:00
Antecedent Dry Days.....	0.0
Report Time Step...........	01:00:00
Wet Time Step...............	00:00:30
Dry Time Step...............	01:00:00

Runoff Quantity Continuity	Volume hectare-m	Depth mm
Total Precipitation..........	0.002	63.700
Evaporation Loss...........	0.001	1.161
Infiltration Loss….........	0.002	62.547
Surface Runoff…...........	0.000	0.000
Final Surface Storage.....	0.000	0.000
Continuity Error (%)......	0.000	

Flow Routing Continuity	Volume hectare-m	Volume 10^6 ltr
Dry Weather Inflow.......	0.000	0.000
Wet Weather Inflow.......	0.000	0.000
Groundwater Inflow.......	0.000	0.000
RDII Inflow……...........	0.000	0.000
External Inflow…...........	0.000	0.000
External Outflow............	0.000	0.000
Internal Outflow….........	0.000	0.000
Storage Losses…...........	0.000	0.000
Initial Stored Volume.....	0.000	0.000
Final Stored Volume......	0.000	0.000
Continuity Error (%).....	0.000	

****
Subcatchment Runoff Summary
****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
1	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
3	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
4	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
5	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
6	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
7	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
8	63.70	236.35	0.00	300.05	0.00	0.00	0.00	0.000

9	63.70	236.35	0.00	300.05	0.00	0.00	0.00	0.000
10	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
11	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
12	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
13	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
14	63.70	177.27	4.66	0.00	236.35	0.00	0.09	0.981
15	63.70	177.27	4.66	0.00	236.35	0.00	0.09	0.981
16	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
17	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
18	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
19	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
20	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
21	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
22	63.70	236.35	0.00	300.05	0.00	0.00	0.00	0.000
23	63.70	236.35	0.00	300.05	0.00	0.00	0.00	0.000
24	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
25	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
26	63.70	177.27	4.66	0.00	236.35	0.00	0.09	0.981
27	63.70	177.27	4.66	0.00	236.35	0.00	0.09	0.981
28	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
29	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
30	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
31	63.70	118.19	4.65	0.00	177.27	0.00	0.07	0.975
32	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
33	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
34	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
35	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
36	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
37	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
38	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
39	63.70	59.10	4.64	0.00	118.19	0.00	0.05	0.962
40	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
41	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
42	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
43	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
44	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
45	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
46	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
47	63.70	0.00	4.63	0.00	59.10	0.00	0.02	0.928
48	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
49	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
50	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
51	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
52	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
53	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
54	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
55	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
56	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
57	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
58	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
59	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
60	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
61	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
62	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
63	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
64	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000
65	63.70	0.00	0.00	63.70	0.00	0.00	0.00	0.000

Analysis begun on: Thu Dec 15 21:24:06 2011
Analysis ended on: Thu Dec 15 21:24:07 2011
Total elapsed time: 00:00:01

Appendix B: Percentage of Losses and Runoff for Hypothetical Data

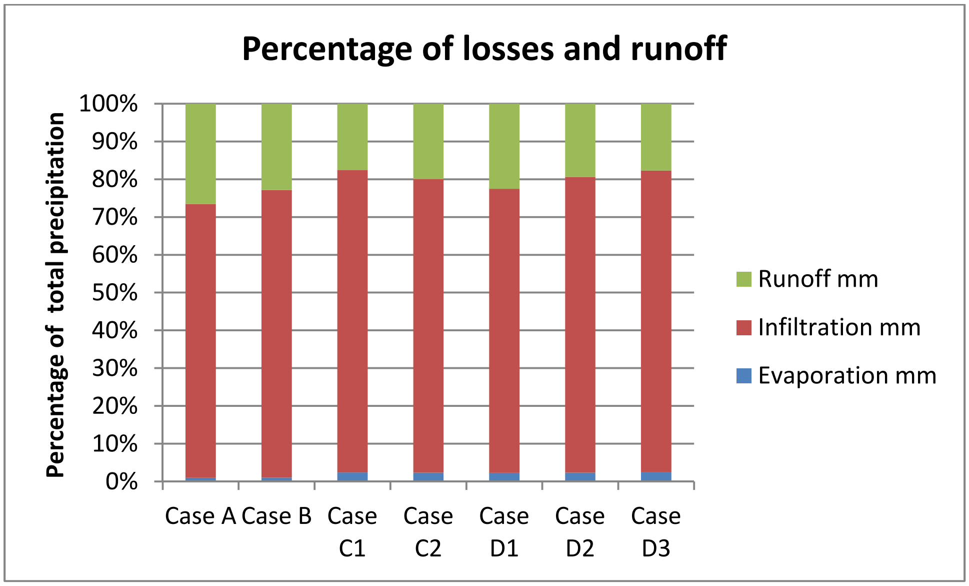


Figure B-1 Percentage of runoff depth, infiltration and evaporation losses using July event on loamy soil

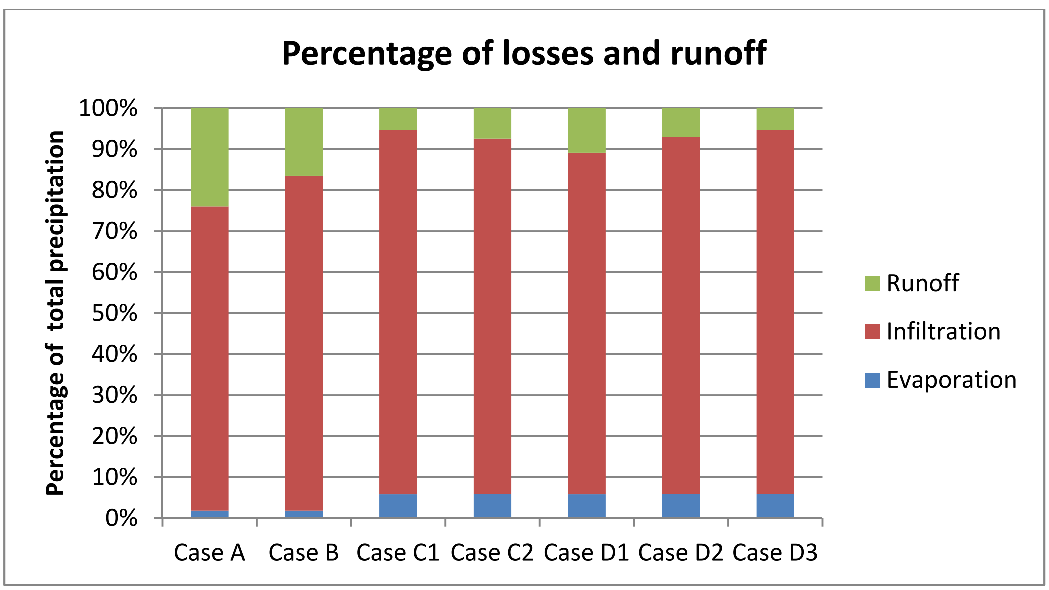


Figure B-2 Percentage of runoff depth, infiltration and evaporation losses using continuous simulation on the loamy soil.

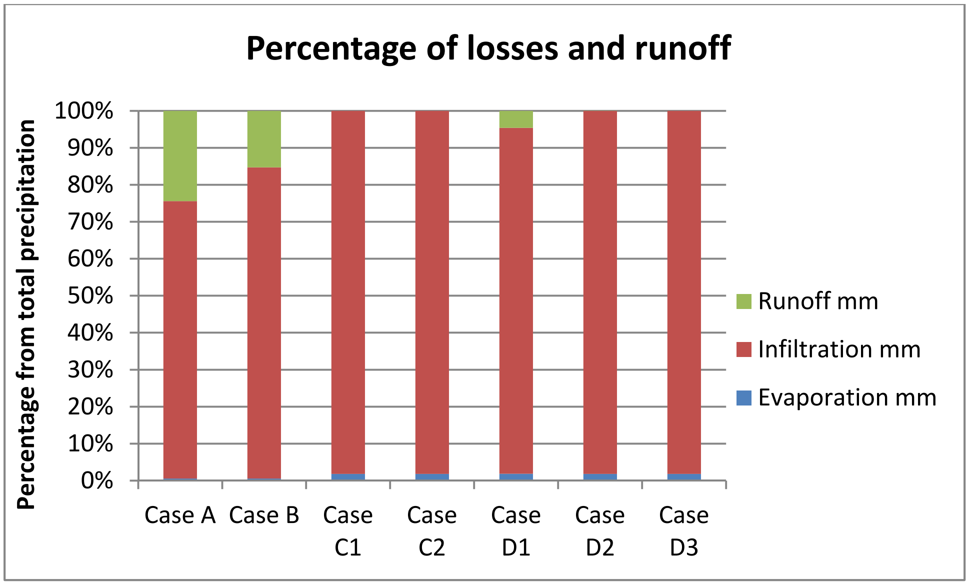


Figure B-3 Percentage of runoff depth, infiltration and evaporation losses July event on the sandy soil

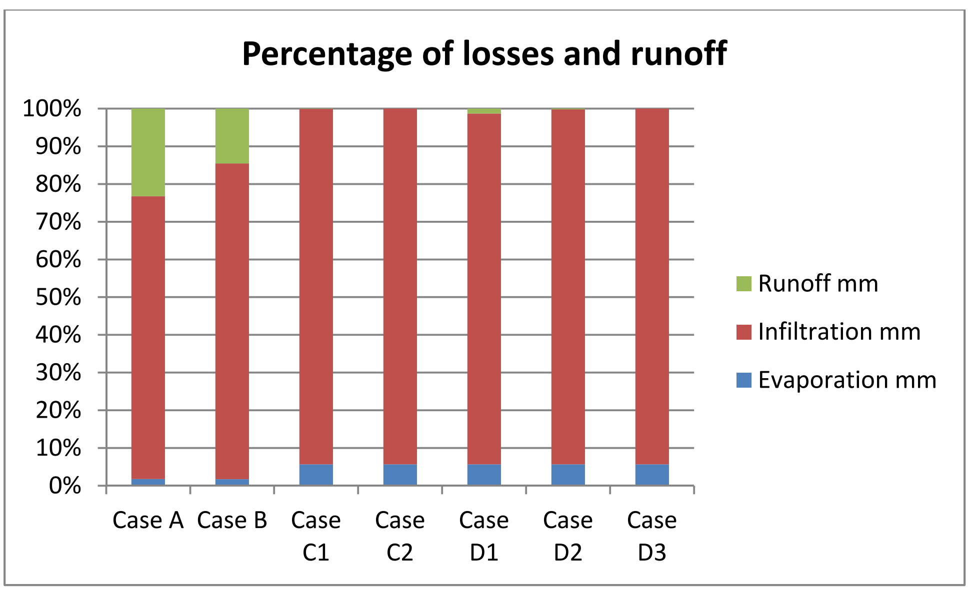


Figure B-4 The runoff depth, infiltration and evaporation losses for continuous simulation of the sandy soil condition

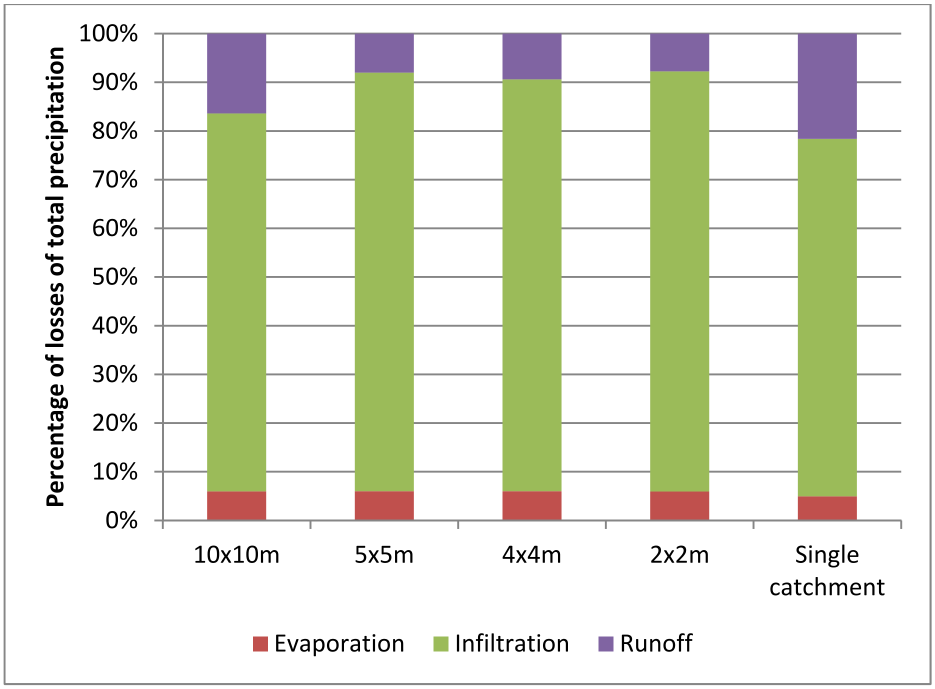


Figure B-5 The runoff values and losses using regular grids with 5min time step

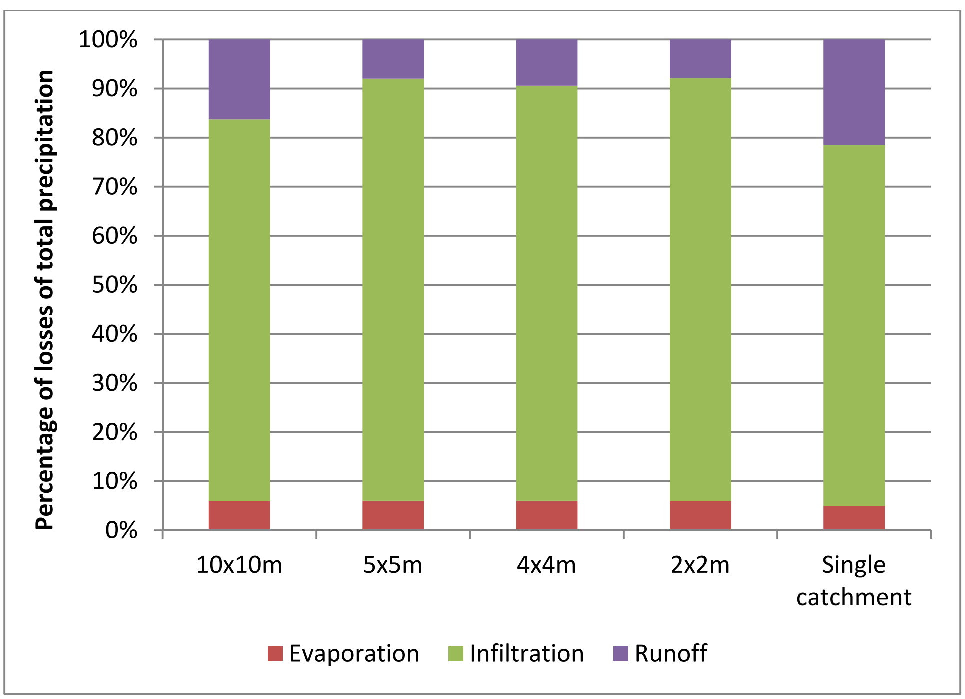


Figure B-6 The runoff values and losses using regular grids with 1min time step

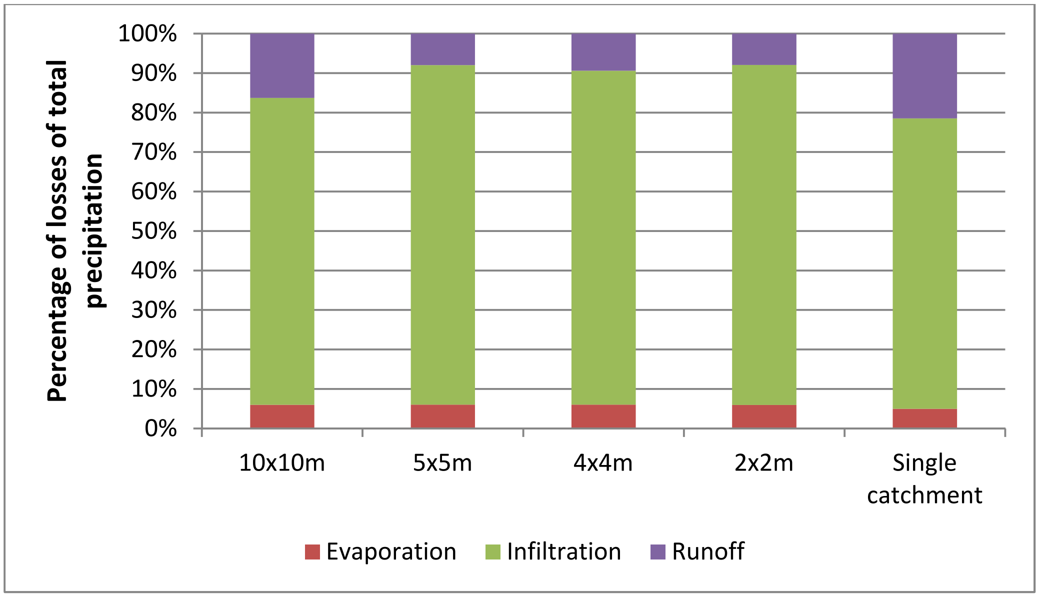


Figure B-7 The runoff values and losses using regular grids with 30sec time step

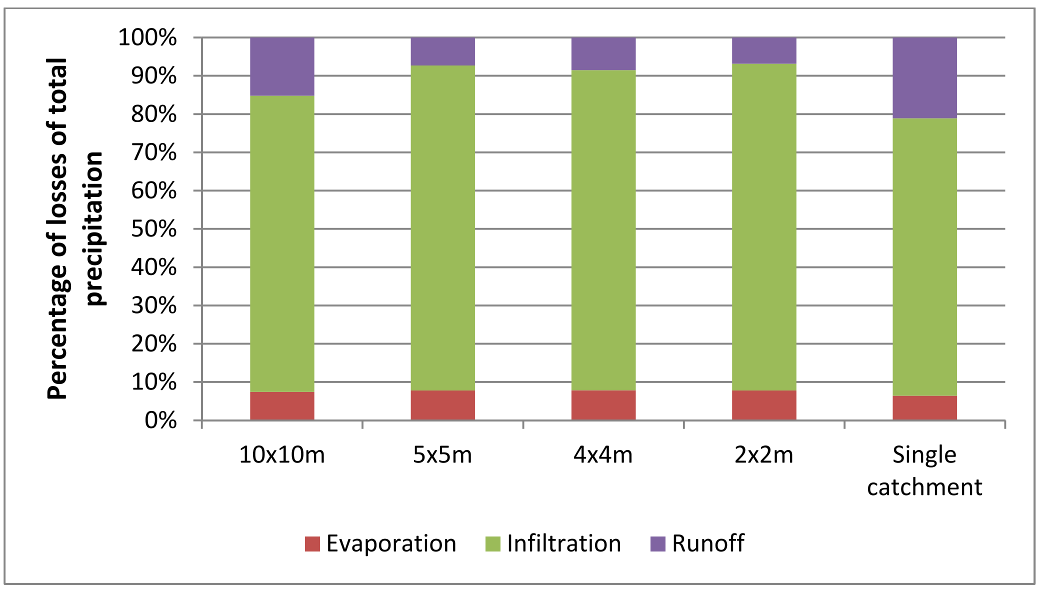


Figure B-8 The runoff depth and infiltration using bioretention with 5 min time step

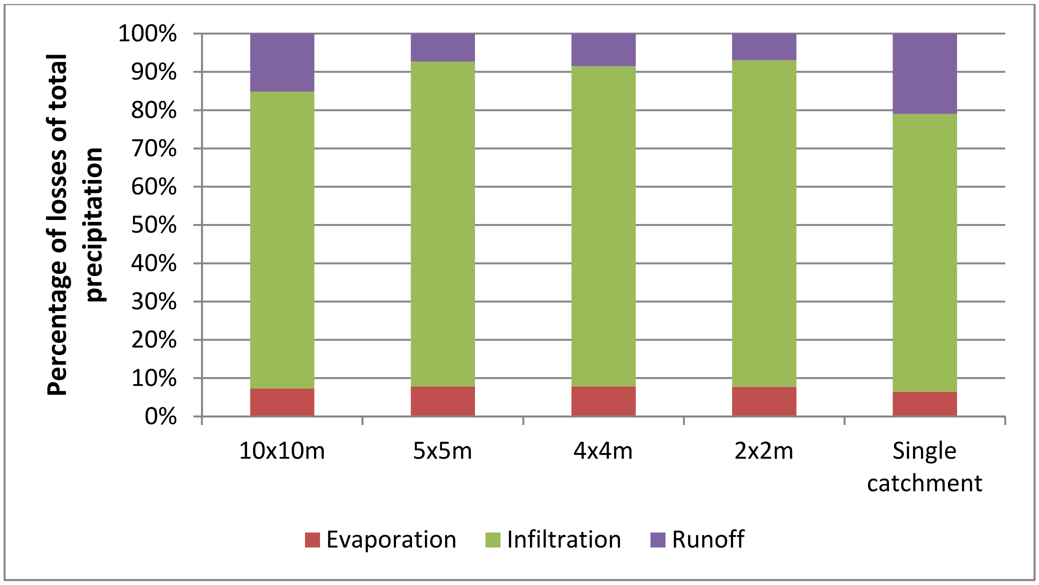


Figure B-9 The runoff depth and infiltration using bioretention with 1 min time step

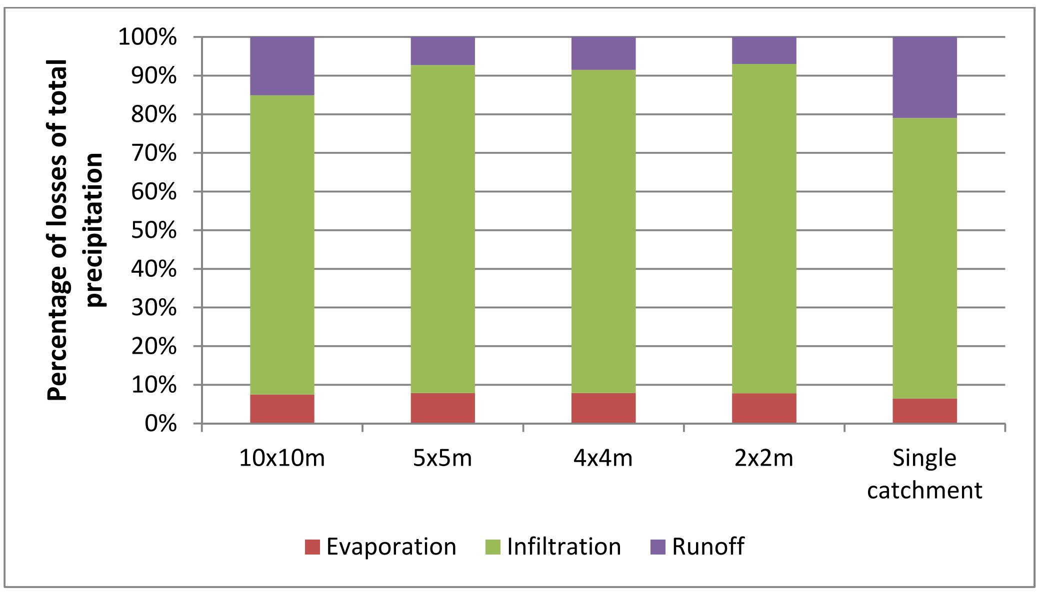


Figure B-10 The runoff depth and infiltration using bioretention with 30 sec time step

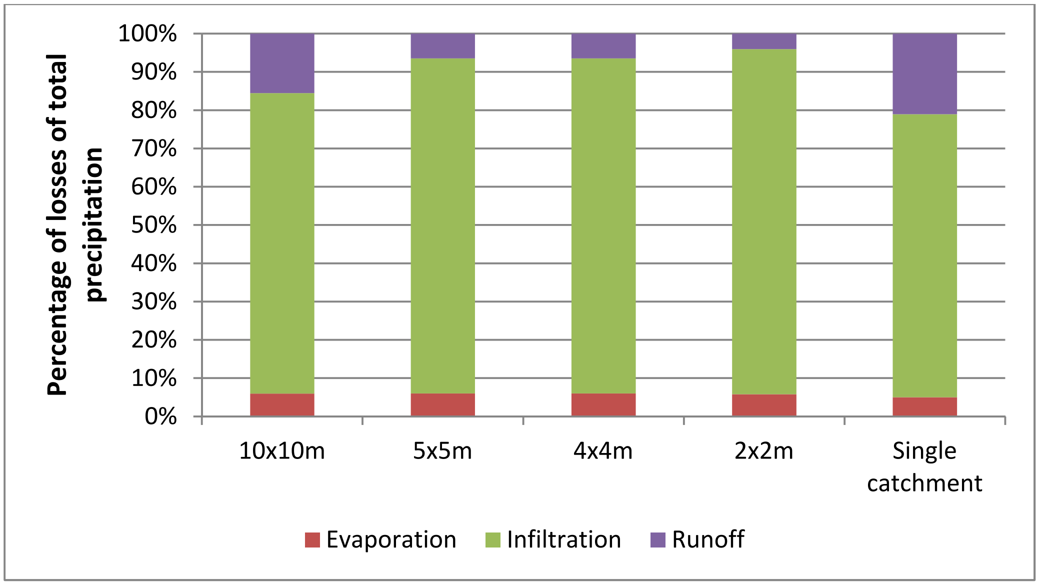


Figure B-11 The runoff depth and losses with porous pavement and 5min time step

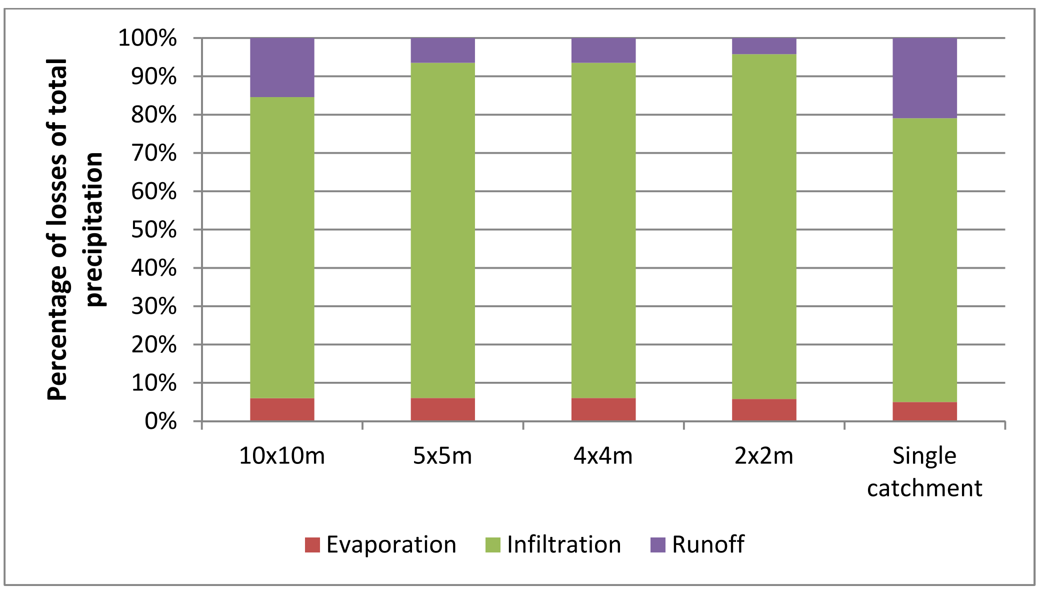


Figure B-12 The runoff depth and losses with porous pavement and 1 min time step

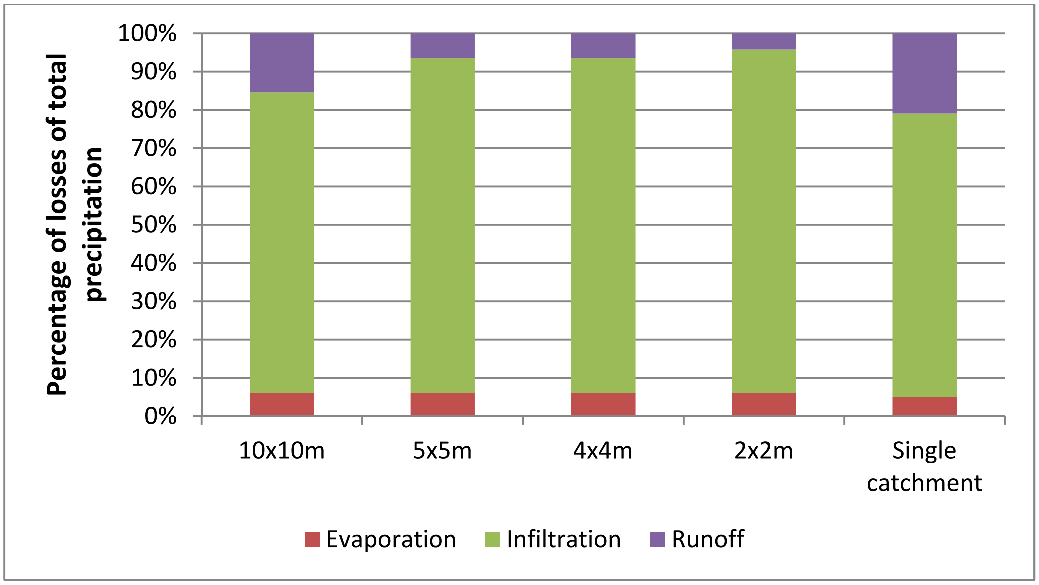


Figure B-13 The runoff depth and losses with porous pavement and 30 sec time step

REFERENCES

Anderson, M. (1998). Comparison of Horton's, Smith's, And Green- Ampt's Infiltration Equations Using Flooding Infiltrometer Data in Engineering Applications (Master's thesis). Retrieved April 25, 2013, from. http://hdl.handle.net/2346/22649

Bosely, E. (2008). Hydrologic Evaluation of Low Impact Development Using a Continuous, Spatially-Distributed Model (Master's thesis). Retrieved May5, 2010, from http://scholar.lib.vt.edu/theses/available/etd-07302008-220841/unrestricted/Bosley_MS_Thesis.pdf

Byrd, A. (2005). Gridded Surface Subsurface Hydrologic Analysis (GSSHA). Retrieved May, 2010 from http://chl.erdc.usace.army.mil/gssha

Chow, V., Maidment, D. & Mays, L. (1988). Applied Hydrology. McGraw-Hill Book co. ISBN 0-07-010810-2

Credit Valley Conservation Authority (CVC). (2010). Credit Valley Conservation Proposal: Monitoring of innovative multi-functional green infrastructure project.

Elliott, A. & Trowsdale, S. (2007). A review of models for Low impact Urban stormwater drainage. Environmental Modelling & Software, 22(3), 394-405.

Elliot, A., Trowsdale, S. & Wadhwa, S. (2009). Effect of Aggregation of on- site Storm-Water Control Devices in Urban Catchment Model. Journal of Hydrologic Engineering ASCE, 14(9), 975-983.

Gilory, K. & McCuen, R. (2009). Spatio- temporal effect of low impact development practices. Journal of Hydrology, 367(3-4), 228-236.

Gironas, J., Niemann, J., Roesner, P., Rodriguez, F., & Andrieu, H. (2010). Evaluation of Methods for Representing Urban Terrain in Storm-Water Modeling. Journal of Hydrologic Engineering. 15(1), 1–14

Huber, W. & Dickinson, R. (1988). Storm Water Management Model Version 4: User's Manual. Georgia: U.S. Environmental Protection Agency.

Jain, M., Kothyari, U., Ranga, R., & Kittur, G. (2004). A GIS Based Distributed Rainfall-Runoff Model. Journal of Hydrology, 299(1-2), 107-135.

Jourdan, M. & Ogden, F. (2003). Hybrid Hydrologic Modeling: Conceptual Groundwater Model Coupled to a Distributed Hydrologic Model. ASCE conference proceeding, 1-9, doi: 10.1061/40685(2003)210

Kennedy, L., Holmes, L., & McDonald, S. (2007). Low Impact Development San Francisco's Green Approach to Stormwater Management. Proceeding of the Water Environment Federation, 723-737

Kalin, L. & Hantush, M. (2006). Comparative Assessment of Two Distributed Watershed Models with Application to a Small Watershed. Journal of Hydrological Processes. 20(11), 2285-2307.

Lam, C. (2004). Comparison of Flow Routing Algorithms Used in Geographic Information System (Master's thesis). Retrieved April 25, 2013, from

ftp://www.lwr.kth.se/Common/UllaM/For_Imran/[2004]%20lam%20-%20comparison%20of%20flow%20routing%20algorithms%20used%20in%20geographic%20information%20systems.pdf

Limburg Soil Erosion Model. (2010). Retrieved May, 2010, from http://www.itc.nl/lisem/

Ponce, V. (1989). Engineering Hydrology Principles and Practices. Prentice Hall College Div., ISBN-13: 978-0132778312

Quinn, P., Beven, K., Chevallier, P., & Planchon, O. (1991). The Prediction of Hillslope Flow Paths for Distributed Hydrological Modeling Using Digital Terrain Models. Journal of Hydrological Processes, 5(1), 59-79.

Rossman, L. (2009). Stormwater Management Model User's Manual, Version 5.0., U.S. Environmental Protection Agency (USEPA).

Rossman, L. (2010). Modeling Low Impact Development Alternatives with SWMM. Dynamic Modeling of Urban Water Systems, Monograph 18. ISBN 978-0-9808853-3-0.

Shamsi, U. (2010). Low Impact Development for Stormwater Quantity and Quality. Dynamic Modeling of Urban Water Systems, Monograph 18, ISBN 978-0-9808853-3-0.

The Partenership for Water Sustainability in British Columbia. (2008). An Overview of QUALHYMO Engine. Retrieved June, 2010, from http://bc.waterbalance.ca/water-balance-model/about-the-model-2/an-overview-of-the-qualhymo-engine/

Toronto and Region Conservation Authority (TRCA). (2010). Low Impact Development Stormwater Management Planning and Design Guide. Retrieved April 25, 2013, from http://www.sustainabletechnologies.ca/Portals/_Rainbow/Documents/LID%20SWM%20Guide%20-%20v1.0_2010_1_no%20appendices.pdf

Valeo, C. & Moin, S. (2001). Hortonian and Variable Source Area Modelling in Urbanizing Basins. Journal of Hydrologic Engineering, 6(4), 328-335.

Verma, S. (1982). Modified Horton's Infiltration Equation. Journal of Hydrology, 58(3-4), 383-388

Viessman, J., Gary L., & John W. (1989). Introduction to Hydrology - 3rd edition. New York : Harper Collins Publishers, ISBN 13: 9780060468224

Vieux, B. (2004). Distributed Hydrologic Modeling Using GIS. Dordrecht: Kluwer Academic Publishers, ISBN 978-1-4020-2459-7

Xiong,Y. & Melching, C. (2005). Comparison of Kinematic-Wave and Nonlinear Reservoir Routing of Urban Watershed Runoff. Journal of Hydrologic Engineering, 10(1), 39-49.

Zheng, P. & Baetz, B. (1999). GIS Based Analysis of Development Options from Hydrology Perspective. Journal of Planning and Development, 125(4), 164-180.

Zoppou, C. (1999). Review of Storm Water Models. CSIRO Land and Water, Technical Report, Canberra, Retrieved April 10, 2012 from http://forum.cjk3d.net/bbs/images/upfile/2006-1/200616105011.pdf