1-1-2012

Hydraulic design model of underground bioretention system: a source control measure for wet weather urban stormwater management

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HYDRAULIC DESIGN MODEL OF UNDERGROUND BIORETENTION SYSTEM:

A SOURCE CONTROL MEASURE FOR WET WEATHER

URBAN STORMWATER MANAGEMENT

by

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Ph. D. in Hydraulic Engineering, Iwate University, JAPAN, 2001

A thesis

presented to Ryerson University

in partial fulfilment of

the requirement for the degree of

Master of Applied Science

in the Program of

Civil Engineering

Toronto, Ontario, Canada, 2012

ABSTRACT

Title: Hydraulic Design Model of Underground Bioretention System: A Source Control Measure for Wet Weather Urban Stormwater Management

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The conventional practices of urbanization, land use strategies and stormwater management are considerably increasing the risk of wet weather flooding, downstream erosion and water pollution. To minimize the water pollution problem associated with the urban development various concepts of low impact development are being implemented. The city of Toronto has installed an underground bioretention system at Queensway Avenue. The hydraulic design criteria and specification of the underground bioretention system are not yet well developed.

Hydraulic design model is developed using five mass balance equations of the five components of bioretention system. All design water depth variables of the bioretention system are solved simultaneously using Matlab program. An application of the model in Toronto is included to illustrate the design of the underground bioretention system.

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ACKNOWLEDGEMENTS

Thanks to Allah Who is the Almighty, Compassionate, Merciful and Owner of this Universe.

The author would like to thank Dr. James Li & Dr. Darko Joksimovic of Ryerson University for providing continuous valuable expert guidance, support, encouragement, and inspiration throughout the thesis.

The author would like to thank Dr. Arnold Yuan for his well-organized approach to develop Matlab program and thesis write up; and Dr Ahmed El-Rabbani of Ryerson University for his invaluable suggestion and encouragement for improvement of the thesis.

Thanks are extended to Dr. Jinyuan Liu of Ryerson University for advice in conducting experiments.

The author would like to thank Mr Patrick Cheung of City of Toronto for collaborating at project site and providing supporting documents.

Thanks are also extended to Yunus Ali of Ryerson Graduate student for technical support in numerical model. Endless love and thanks to my family member (Mina, Arnab, and Jannat) for their support and encouragement.

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Chapter I

INTRODUCTION

1.1 Background

The conventional practices of urbanization, land use strategies and stormwater management are considerably increasing the risk of wet weather flooding, downstream erosion and water pollution. It is well recognized that urbanization impacts the rainfall runoff process in a variety of ways. Infiltration is reduced due to the addition of impervious surfaces, resulting in increasing runoff quantity. Tree removal, surface levelling, soil flipping and surface compaction are also likely to boost up the quantity of runoff. Moreover, stormwater runoff rate is intensified due to the extensive network of pipes and channel of urban environment. Inclusion of gutters and pipes in drainage system has shortened the long surface travel time. As a result, time of concentration gets shorter. The increase in runoff quantities and rates can produce downstream flooding and accelerate channel erosion.

Stormwater quantity isn’t the only problem associated with urbanization; receiving water quality is impaired as well. Urban land surfaces are subject to the build up of pollutants during dry weather, many of which are related to human activities. When precipitation occurs, these pollutants are washed off the land surface and contribute to diminish the receiving water quality. These non-point sources of pollution include eroded soil from construction sites, oil and grease from cars, nitrogen and phosphorous from fertilizers, pesticides from lawn and shrub care products, fecal dropping from pets and other animals, dust and dirt from dry fall and various pollutions from illegal dumping and spills (Akan et. al., 2003).

A study of the biophysical and public health damages and associated economic costs of stormwater runoff were estimated by Booth et al (2006). These costs include flood-related property damage and financial losses, capital costs of new stormwater infrastructure, cleaning up stormwater polluted water resources, and habitat restoration and protection efforts. The Natural Resources Defense Council (Kloss and Calarusse 2006) describes similar impacts attributed to conventional controls across the U.S. Storm sewers collect and discharge treated runoff to water bodies, while combined sewer and stormwater systems overflow during heavy rains, discharging both untreated sewage and stormwater into rivers and lakes. Both contribute to impaired water quality, flooding, habitat degradation, and stream bank erosion. The U.S. Environmental Protection Agency (EPA) estimates the costs of controlling combined sewer overflows (CSO) throughout the U.S. at approximately $56 billion. Developing and implementing stormwater management programs and urban-runoff controls will cost an additional $11 to $22 billion (Kloss and Calarusse 2006). This huge cost needs to be incurred every year unless a sustainable solution is put on the way.

In contrast to conventional stormwater controls, low-impact development (LID) techniques emphasize on-site treatment and infiltration of stormwater. The term low impact development encompasses a variety of stormwater management techniques. Examples include bioretention, bio-swales, rain gardens, green streets, and pervious pavers (U.S. EPA 2000). The name LID came into use around the late 1990s, however stormwater managers employed LID techniques prior to this. Technicians in Prince George's County, Maryland were some of the first to install what eventually became known as LID techniques in the early 1990s as an alternative to conventional stormwater controls. Soon after, a few communities in the Chesapeake Bay area followed, experimenting with a number of LID demonstration projects. Over time, interest in

LID as an alternative or complement to conventional controls grew, and so did the number of LID demonstration projects and case studies across the North America. The EPA reviewed the early literature on LID and described their assessment of these literatures in a report released in 2000 (U.S. EPA and Low Impact Development Center 2000). Their review assessed the availability and reliability of data on LID projects and the effectiveness of LID at managing stormwater. Past reports focused primarily on the potential stormwater-management benefits of LID, it concluded that LID controls could be more cost effective and have lower maintenance costs than conventional stormwater controls. The Center for Watershed Protection published one of the earliest studies that focused primarily on the economic aspects of “better site design,” which included many LID principles (Center for Watershed Protection 2001).

The relationship between imperviousness and environmental degradation has been well documented by Schueler (1995). With increasing imperviousness, it has been found that runoff peak and volumes, bank erosion and water temperature increase while water quality, aquatic and micro-invertebrate population decrease. Moreover, reducing the amount of directly connected impervious areas improves watercourse health and increases the potential for sustainable aquatic communities in stream (Jones et. al, 2002).

Eventually, to overcome the impacts of existing problem of conventional development practices a new concept of low impact development (LID) has been put in order for land development and stormwater management in different urban area. LID design strategies address the new development, retrofit and redevelopment. For development project, topography, vegetative cover and so on should be kept undisturbed as much as possible. LID techniques retrofit with exiting sites such as buildings, roads, parking areas, site features, and stormwater management plans.

Moreover, LID introduces redevelopment projects and builds on conventional design strategies by exploiting every surface in the infrastructures to perform a beneficial hydrologic function.

1.2 Problem Identification

Rainwater from most buildings, roofs, impervious roads and parking lots is connected by the storm sewer system. This is the big concern, because many storm sewer systems are combined with sanitary sewer systems. Eventually, heavy rainfall means untreated sewage from combined sewer system and other contaminants augment the pollution level of streams, lakes and other water bodies.

In the past, stormwater management practices were concentrated on reducing peak post-development runoff volume to minimize downstream flooding. This was typically accomplished by constructing stormwater detention ponds, which were designed as dry systems that would eventually discharge the entire detained volume of runoff to receiving waters (Abida et at, 2007). Hence, the detention ponds just redistributed the rate of runoff over a period of time but did not reduce the total volume of runoff. By the growing concern of contamination impact of urban runoff to receiving waters, stormwater management alternatives started to address the problem of water quality. Moreover, groundwater recharge and migration of changes in the hydrologic budget also became prime objectives. The concentration of pollutants in stormwater runoff is generally higher at the beginning of a storm and then decays as runoff continues (Livingstone 1988). This initial runoff with high pollutant loads is typically referred to as the first flash. Stormwater runoff has been identified as one of the leading causes of degradation in the water quality of receiving waters especially during first flash and this is mainly responsible for the discharge of an enormous quantity of pollutants (Lee and Bang, 2000). Various solutions for stormwater management have been identified and applied. Infiltration of a portion of runoff is the most effective solution which results in ground water recharge, low stream flow augmentation, water quality enhancement, and reduction in the total volume of runoff (Scheueler 1987; Stahre and Urbonas 1989; Horner 1999; Jan-Tai-Kuo et al 2001).

A performance assessment of the stormwater runoff infiltration system was carried out jointly by MOE and TRCA (2000) based on coordinated monitoring of rainfall, runoff and water quality. Pollutant concentration and flow rates at the infiltration system inlet could not monitored directly because of the multiplicity of overland flow and catch basin inputs to the system.

The Wet Weather Master Flow Management Study (2003) carried out by the city of Toronto has recommended a number of source stormwater management practices such as bioretention systems, roof leaders disconnection, rain water harvesting, and rain garden for stormwater management in the city in the next 25 years. Recommended practices also include measures at the sources, along drainage system and at the downstream end of drainage systems. In order to implement these practices, technical specifications and performance of these practices must be established (Li, 2008). However, technical specifications should be based on field test of the practices in terms of suitability, performance, construction and maintenance requirements.

A bioretention system was constructed at The Queensway Ave in Toronto by the city of Toronto to study performance of stormwater quantity and quality. This is a study of source control measures of stormwater management and focuses mainly on hydraulic performance of stormwater runoff for this system. This source control system is constructed under the sidewalk of the street, that’s why city termed it “sustainable sidewalk”. In this new concept, road runoff is intercepted by the catch basin and fed to the underground bioretention system through a corrugated perforated pipe. Eventually, a less amount of storm runoff enters into the storm sewer system instantly. And at the same time, water is stored and held back into bioretention system however excess water is drained to sewer system with delayed time.

1.3 Purpose

In conventional practices, stormwater runoff was treated as disposal. But, instead of conveying and treating stormwater through the large and costly end-of-pipe facilities located at the down of drainage areas, lot level control can addresses stormwater runoff by capturing and reducing its volume through small, cost-effective landscape features along with other various applications located at the lot level. This is accomplished by forming the landscape in such a fashion that land surface and other associated facilities can retard stormwater flow through depressions, surface roughness, meanderings topography and/or directing stormwater towards small-scale storage or underground and/or open bioretention systems those are dispersed throughout the region with the purpose of managing stormwater runoff in an evenly distributed manner. These lot level control systems allow for downsizing or elimination of stormwater ponds, curbs and gutters, thus saving on infrastructure and storm conveyance costs.

Urban stormwater management is still a big challenge for urban stormwater management authorities. Various lot level storm water control concepts were implemented to solve the problems. For redevelopment and retrofits of stormwater management facilities, various low impact development concepts are considered to be the best way to control stormwater runoff at lot level specifically for older zone of a city. Among others, underground bioretention system is a concept which has a great potential of lot level control of stormwater runoff. Hence, hydraulic characteristics and specification of underground bioretention system are important to ensure their proper functioning and objectives. Most of the bioretention systems introduced in different cities in North America and other parts of the world but standard specification and their sizing is not clear enough. Thus, more research is needed to ensure the technical conformity and performance before introducing large scale project of low impact development concepts. The main intention of this research is to develop a hydraulic design model and improve existing design specification. The purpose of the study is to analyze the hydraulic parameters and determine appropriate specification, thus the main objectives are as follows:

i. to develop a numerical hydraulic model that can be used to develop design specifications of underground bioretention system;
ii. to improve the current design approach and sizing of underground bioretention system by applying the numerical model.

This chapter discussed the rationale for undertaking this project. The following chapter is focused on literature review where information and thoughts of peer reviewed literature in relation to bioretention system were put forward to understand the underground bioretention system in stormwater management.

Chapter II

LITERATURE REVIEW

Best Management Practice (BMP) is a combination of practices that is an effective and practicable means of preventing or reducing the amount of pollution generated by non-point sources. Underground bioretention system is used for this study as a conveyance control of LID in the BMP for stormwater runoff. As bioretention system is related with bioretention soil characteristics, rainfall runoff, infiltration processes and so on, therefore this chapter reviewed the matters related to the bioretention system in the subsequent sections.

2.1 Best Management Practices (BMP)

Stormwater management BMPs are control measures taken to mitigate changes to both quantity and quality of urban runoff caused through changes to land use. Generally BMPs focus on water quality problems caused by increased impervious surface from land development. BMPs are designed to reduce storm water volume, peak flows, and/or nonpoint sources pollution through evapotranspiration, surface ponding, detention, and filtration or biological and chemical actions. Water quality concerns have intensified and storm water management practices have come under scrutiny as development occurs on an increasing percentage of the available land area in North America (http://www.toolbase.org/Technology-Inventory/Sitework/low-impact-development). With more stringent design requirements, costs for traditional collection and conveyance systems have risen sharply. Organizations from community groups to regional watershed authorities have become involved in this issue. It was realized indeed that LID techniques can offer developers a more cost effective way to address storm water management through site design modifications.

LID strategies allow land to be developed in an environmentally responsible manner to create a more "hydrologically functional" landscape.

The bioretention system contains bio-retention soil (described later), hence hydraulic characteristics of this soil must be known, specifically infiltration capacity, porosity, saturated water content, relative water content, saturated and unsaturated hydraulic conductivity, sorptivity, etc.

2.2 Low Impact Development (LID)

LID is an approach to land development (or re-development and/or retrofit) that works with nature to manage storm water as close to its source as possible. LID employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treat stormwater as resource rather than a waste product. There are many practices that have been used to adhere to these principles, such as bio-retention facilities, rain gardens, vegetated rooftops, rain barrels, and permeable pavements. By implementing LID principles and practices, water can be managed in a way that reduces the impact of built areas and promotes the natural movement of water within an ecosystem or watershed. Applied on a broad scale, LID can maintain or restore a watershed's hydrologic and ecological functions. LID has been characterized as a practice of sustainable stormwater by the Water Environment Research Foundation and others.

Several studies have been conducted to analyze the effectiveness of various LID practices based on hydrology and pollutant removal capabilities (USEPA, 2000). Bioretention areas, grass swales, permeable pavements and vegetated roof tops were the most common practices studied. These techniques reduce the amount of Effective Impervious Area (EIA) in a watershed. EIA is the directly connected impervious area to the storm drain system and contributes to increase watershed volumes and runoff rates. There are documented case studies that conclusively link urbanization and increased watershed imperviousness to hydrologic impacts on streams. Existing reports and case studies provide strong evidence that urbanization negatively affects streams and results in water quality problems such as loss of habitat, increased temperatures, sedimentation and loss of fish populations (USEPA, 1997). In general bioretention areas were found to be effective in reducing runoff volume and in treating the first flush (first ½ inch) of storm water. Results from three different studies indicate that removal efficiencies were quite good for both metals and nutrients (USEPA, 2000). Removal rates for metals were more consistent than for nutrients. Removal rates for metals ranged from 70–97% for lead, 43–97% for copper and 64–98% for zinc. Nutrient removal was more variable and ranged from 0–87% for phosphorus, 37–80% for Total Kjeldahl Nitrogen, <0–92% for ammonium and for nitrate <0–26%. Effluent volumes were lower than influent volumes. These studies were conducted by means of simulated rainfall events. Analysis of actual long-term rainfall events would produce more reliable data. Among others, bioretention system is considered to be suitable for redevelopment at urban areas, thus Toronto water has constructed an underground bioretention system in its urban location which will be investigated to confirm of its hydraulic and water quality performance.

2.3 Infiltration Processes

Infiltration is the entrance of water originating from rainfall, snowmelt or irrigation, from the soil surface into the top layer of the soil. Redistribution is the movement of water from point to point within the soil. These two processes cannot be separated because the rate of infiltration is strongly influenced by the rate of water movement within the soil. After each infiltration event, soil water movement continues to redistribute the water below the surface of the soil (Rawls et al., 1993). Many of the same factors that control infiltration rate also have an important role in the redistribution of water below the soil surface during and after infiltration. Thus, an understanding of infiltration and the factors that affect it is significant not only in the determination of surface runoff, but also in understanding subsurface movement and storage of water within a watershed (Skaggs and Khaleel, 1982).

The movement of water is always from higher energy state to lower energy state and the driving force for the movement is the potential difference between energy states. Three important forces affect the movement of water through soil. The first is gravitational force, or potential difference, which causes water to flow vertically downward. This is because the gravitational potential energy level of water at a given elevation in the soil profile is higher than that of water at a lower elevation. Also, if there is standing water on the surface, the weight of the ponded water exerts hydrostatic pressure which increases the rate of infiltration, also due to the gravitational force (Turner, 2006). The second force is adhesion or the attraction of the soil matrix for water. It is responsible for the phenomena of adsorption and capillarity. The matric or capillary potential refers to the energy state of the water molecules adsorbed onto the soil solids which is much reduced compared to that of bulk water (Hillel, 1998). To a lesser extent cohesion, which describes the attraction of water molecules to each other, lowers the energy state. Together adhesive and cohesive forces produce a suction force within soil that reduces the rate of movement of water below the soil surface. The higher the soil water content the weaker the suction force and the lower the matric potential difference. Third, the attraction of ions and other solutes towards water results in osmotic forces, that tends to reduce the energy level in the soil solution. Osmotic movement of pure water across a semi-permeable membrane into a soil solution is evidence of the lower energy state of the soil solution (Bolt and Miller, 1958; Hilhorst et al., 2001).

Factors that control infiltration rate include soil properties that are strongly affected by these three forces, such as hydraulic conductivity, diffusivity and water holding capacity. These soil properties are related to the characteristics of soil texture, structure, composition, and degree of compaction, which influence soil matric forces and pores space. Additionally, antecedent water content, type of vegetative or other ground cover, slope, rainfall intensity and movement and entrapment of soil air are important factors that also affect infiltration rates. The hydraulic conductivity is of critical importance to infiltration rate since it expresses how easily water flows through soil and is a measure of the soil's resistance to flow. The unsaturated hydraulic conductivity is a function of pressure head (Serrano, 1997) and distribution of water in the soil matrix. The saturated hydraulic conductivity (i.e., hydraulic conductivity at full saturation) is used as a parameter in many of the infiltration equations, since it is easier to determine than either the unsaturated hydraulic conductivity or the diffusivity.

Diffusivity is equal to the hydraulic conductivity divided by the differential water capacity (the rate of change of water content with soil water pressure), or the flux of water per unit gradient of water content in the absence of other force fields (SSSA, 1975). Since diffusivity is directly proportional to hydraulic conductivity, usually only the saturated hydraulic conductivity is used in the approximate infiltration equations.

Water holding capacity is the amount of water a soil can hold due to pore size distribution, texture, structure, percent of organic matter, chemical composition, and current water content. For saturated conditions, the water holding capacity is zero and the hydraulic head is positive (Skaggs and Khaleel, 1982). However, the water holding capacity influences the values of the average suction at the wetting front and sorptivity, as well as some of the empirical parameters. The soil texture that refers to the proportion of sand, silt, and clay that a soil comprises directly affects the hydraulic conductivity, diffusivity and water holding capacity. Soils with higher sand percentages have larger size particles, larger pores, lower water holding capacity and higher hydraulic conductivity, diffusivity and infiltration rates than clay soils which have smaller micropores and bind water molecules more tightly. Soil structure describes the adhesion and aggregation of soil particles and formation of plates, blocks, columns, lumps, and cracks and is affected by chemical composition of soil particles, amount of organic matter present, soil texture, water content, and activity of organisms such as earthworms, insects, fungi, plant roots and microbes. Soil structure affects the path by which water moves through the soil (Brady and Weil, 1999).

Micropores are generally less than a micrometer in width, and occur typically in clayey soils (Hillel, 1998). Water in these pores is referred to as adsorbed, bound or residual water because it is discontinuous and is affected by such phenomena as cation adsorption, hydration, anion exclusion and salt sieving, and therefore does not participate in normal flow behaviour (Hillel, 1998). Capillary pores are the typical pores in a medium textured soil that range in width from several micrometers to a few millimeters. Water in these pores obeys the laws of capillarity and Darcian flow (Hillel, 1998). A deep homogeneous soil (containing only capillary pores), such as is assumed in many infiltration equations, is subject to uniform flow in which the infiltration rate decreases as the moisture gradient declines. Macro pores are diverse structural pores that are relatively large compared to those in the surrounding soil (Beven and Germann, 1982). They are channels formed by biological activity such as that of plant roots and earthworms, and cracks and fissures caused by physical and chemical weathering processes (Beven and Germann, 1982). When empty of water, macro pores constitute barriers to capillary flow, permitting only slow film-creep along their walls. When filled with water however, macro pores permit very rapid, often turbulent, downward movement of water to lower layers of the soil profile (Hillel, 1998). This rapid channel drainage that often bypasses much of the soil matrix and can drastically alter infiltration rates is called preferential flow (Simunek et al. 2003). Even for relatively small earthworm channels, the flow rate in macro pores seems to be always higher than the rainfall intensity (Bouma et al., 1982). However, because of the inherent modeling difficulties, most infiltration equations assume uniform flow, ignoring the existence of preferential flow. Correct assessment of the internal hydrological behaviour of the soil profile is especially important for the simulation of pollutant transport processes or for assessment of land-use (Weiler, 2005).

Soil compaction results from applying pressure on the soil surface, which reduces pore space, damages soil structure, reduces the air available to plant roots and other soil organisms and reduces infiltration rates. Rainfall on bare soil can cause soil compaction. Often where soils have been plowed repeatedly with heavy equipment there is a hardened and compacted layer below the topsoil called a plow pan, which may impede redistribution. A naturally hardened layer called a fragipan may also obstruct the vertical movement of water (Brady and Weil, 1999).

Antecedent or initial water content affects the moisture gradient of the soil at the wetting front, the available pore space to store water and the hydraulic conductivity of the soil. Initial water content is therefore a critical factor in determining the rate of infiltration and the rate at which the wetting front proceeds through the soil profile. The drier the soil is initially, the steeper the hydraulic gradient and the greater the available storage capacity; both factors that increase infiltration rate (Skaggs and Khaleel, 1982). The wetting front proceeds more slowly in drier soils, because of the greater storage capacity, which fills as the wetting front proceeds.

Vegetation and other ground covers such as mulches and plant residues reduce soil temperature and evaporation from the soil surface, but vegetation also loses moisture through transpiration. Vegetation increases infiltration rates by loosening soil through root growth and along with natural mulches and plant residues, intercept raindrops, which compact and damage the structure of bare soil and cause surface sealing and crusting. Living and dead plant material also add organic matter to the soil which improves soil structure and water holding capacity and provide habitat for earthworms which further enhance the soil constitution and increase infiltration rates. Soil water content is also affected by seasonal changes in water use by plants, stage of plant growth, spacing of plants, type of vegetation, depth of roots, and extent of canopy coverage.

Slope also affects infiltration rate. A decrease in water infiltration rate was observed with increase in the slope steepness for grass covered slopes (Haggard et al., 2005; Huat et al., 2006). According to Haggard et al. (2005), the slope may have the greatest effect on surface runoff production and infiltration rate when the soil is close to saturation. On the other hand, there is evidence that on bare sloping land infiltration rates are higher than on bare flat land (Poesen, 1984). This effect is most likely due to reduced seal development on sloping land, as greater runoff velocities maintain a larger proportion of sediment particles in a suspended state resulting in more open pore structure (Römkens et al., 1985).

When the rainfall intensity exceeds the ability of the soil to absorb water, infiltration proceeds at the infiltration capacity. At the time of ponding, the infiltration capacity can no longer keep pace with the rainfall intensity and depression storage fills up and then overflows as runoff. If the rainfall has a higher intensity, depression storage will fill faster and time of runoff will occur sooner, after the time of ponding. Much of the decrease in infiltration rate seen in unprotected soils is attributed to surface sealing (Shirmohammadi, 1984). Vegetation protects the soil from raindrop splash by intercepting and absorbing the energy of the raindrops. Crusting is the drying out and hardening of the surface sealed layer. Crusting may cause immediate ponding with very low infiltration rate. A long soaking rain will tend to soften the crust so that after a time infiltration rate may increase.

Water moving into a soil profile displaces air, which is forced out ahead of the wetting front. If there is a barrier to the free movement of air, such as a shallow water table, or when a permeable soil is underlain by a relatively impermeable soil, the air becomes confined and the pressure becomes greater than atmospheric. Compressed air ahead of the wetting front and the counter flow of escaping air may drastically reduce infiltration rates (Shirmohammadi,1985). Wangemann et al. (2000) found that for dry soils and for interrupted flow the main retardant to infiltration was entrapped air, while for wet soils, reduced aggregate stability and surface sealing were the main causes for reduced infiltration rates. Le Van Phuc and Morel-Seytoux (1972) showed that for a two phase flow treatment of infiltration, infiltration rate after a certain time was well below the saturated hydraulic conductivity, which was considered to be a lower limit by all the previous authors. Infiltration tends to be increased for deeper water tables, since the impedance of the compressed air on infiltration is reduced and the soil profile tends to be drier compared to shallow water table conditions (Shirmohammadi, 1984).

2.4 Definition of Bioretention

Bioretention is the process in which contaminants and sediments are removed from stormwater runoff. Stormwater is collected into the treatment area which consists of a grass buffer strip, sand bed, ponding area, organic layer or mulch layer, planting soil, and plants. Runoff passes first over or through a sand bed, which slows the runoff's velocity, distributes it evenly along the length of the ponding area, which consists of a surface organic layer and/or groundcover and the underlying planting soil. The ponding area is graded, its center depressed. Water is ponded to a depth of 15 cm (5.9 in) and gradually infiltrates the bioretention area or is evapotranspired. The bioretention area is graded to divert excess runoff away from itself. Plants extract stored water in the bioretention area over a period of days into the underlying soils (EPA, 1999).

Each of the components of the bioretention area is designed to perform a specific function. The grass buffer strip reduces incoming runoff velocity and filters particulates from the runoff. The sand-bed also reduces the velocity, filters particulates, and spreads flow over the length of the bioretention area. Aeration and drainage of the planting soil are provided by the 0.5 m (20 in) deep sand bed. The ponding area provides a temporary storage location for runoff prior to its evaporation or infiltration. Some particulates not filtered out by the grass filter strip or the sand bed settles within the ponding area (Clar et. al., 2004).

The organic or mulch layer also filters pollutants and provides an environment conducive to the growth of microorganisms, which degrade petroleum based products and other organic material. This layer acts in a similar way to the leaf litter in a forest and prevents the erosion and drying of underlying soils. Planted groundcover reduces the potential for erosion as well, slightly more effectively than mulch. The maximum sheet flow velocity prior to erosive conditions is 0.3 meters per second (1 foot per second) for planted groundcover and 0.9 meters per second (3 feet per second) for mulch (EPA, 1999).

The clay in the planting soil provides adsorption sites for hydrocarbons, heavy metals, nutrients and other pollutants. Stormwater storage is also provided by the voids in the planting soil. The stored water and nutrients in the water and soil are then available to the plants for uptake. The layout of the bioretention area is determined after site constraints such as utilities location, underlying soils, existing vegetation, and drainage are considered. Sites with loamy sand soils are especially appropriate for bioretention because the excavated soil can be backfilled and used as the planting soil, thus eliminating the cost of importing planting soil. An unstable surrounding soil stratum and soils with clay content greater than 25 percent may preclude the use of bioretention, as would a site with slopes greater than 20 percent or a site with mature trees that would be removed during construction of the BMP. Present facility has tree plantation instead of grass, will be performed same function of bioretention, which is not exposed to ground surface rather installed in underground layer, between elevation of catch basin and sewer system, due to scarcity of surface area in urban sidewalk. Therefore, present facility may be termed as underground bioretention.

2.5 Bioretention Soil and its Functions

Bioretention areas function as soil and plant-based filtration devices that remove pollutants through a variety of physical, biological, and chemical treatment processes. A number of laboratory and field experiments have been conducted by the University of Maryland in conjunction with Prince George's County Department of Environmental Resources and the National Science Foundation in order to quantify the effectiveness of bioretention cells in terms of pollutant removal (Davis et al., 2001). In general, the studies have found that properly designed and constructed bioretention cells are able to achieve significant removal of heavy metals. Users of this technique can expect typical copper (Cu), zinc (Zn), and lead (Pb) reductions of greater than 90%, with only small variations in results. Removal efficiencies as high as 98% and 99% have been achieved for Pb and Zn. The mulch layer is credited with playing the greatest role in this uptake, with nearly all of the metal removal occurring within the top few inches of the bioretention system. Heavy metals affiliate strongly with the organic matter in this layer. On the other hand, phosphorus removal appears to increase linearly with depth and reach a maximum of approximately 80% by about 2 to 3 feet depth. The likely mechanism for the removal of the phosphorus is its sorption onto aluminum, iron, and clay minerals in the soil. TKN (nitrogen) removal also appears to depend on depth but showed more variability in removal efficiencies between studies. Average removal efficiency for cell effluent is around 60%. Generally 70 to 80% reduction in ammonia was achieved in the lower levels of sampled bioretention cells. Finally, nitrate removal is quite variable, with the bioretention cells demonstrating a production of nitrate in some cases due to nitrification reactions. Currently, the University of Maryland research group is looking at the possibility of incorporating into the bioretention cell design a fluctuating aerobic/anaerobic zone below a raised under

drainage pipe in order to facilitate denitrification and thus nitrate removal (Kim et al., 2000).

These studies indicate that in urban areas where heavy metals are the focal pollutants, shallow bioretention facilities with a significant mulch layer may be recommended. In residential areas, however, where the primary pollutants of concern are nitrogen and phosphorus, the depth dependence will require deeper cells that reach a minimum of approximately 2 to 3 feet. The bioretention system are also addressed the other pollutants of concern. For example, sedimentation can occur in the ponding area as the velocity of the runoff slows and solids fall out of suspension. Field studies at the University of Virginia have indicated 86% removal for Total Suspended Solids (TSS), 97% for Chemical Oxygen Demand (COD), and 67% for Oil and Grease. Yu et al. (1999) conducted study in laboratory media columns at the University of Maryland has demonstrated potential bioretention cell removal efficiencies greater than 98% for total suspended solids and oil/grease (Hsieh and Davis, 2002).

One of the primary objectives of LID site design is to minimize, detain, and retain post development runoff uniformly throughout a site so as to mimic the site's predevelopment hydrologic functions. Originally designed for providing an element of water quality control, bioretention cells can achieve quantity control as well (Coffman et al., 1999). By infiltrating and temporarily storing runoff water, bioretention cells reduce a site's overall runoff volume and help to maintain the predevelopment peak discharge rate and timing. The volume of runoff that needs to be controlled in order to replicate natural watershed conditions changes with each site based on the development's impact on the site's curve number. The bioretention cell sizing tool can be used to determine what cell characteristics are necessary for effective volume control. Note that the use of under drain can make the bioretention cell act more like a filter that discharges treated water to the storm drain system than an infiltration device. Regardless, the ponding capability of the cell will still reduce the immediate volume load on the storm drain system and reduce the peak discharge rate. Where the infiltration rate of in situ soils is high enough to preclude the use of under drains (at least 1inch/hr), increased groundwater recharge also results from the use of the bioretention cell. If used for this purpose, care should be taken to consider the pollutant load entering the system, as well as the nature of the recharge area. An additional hydrologic benefit of the bioretention cell is the reduction of thermal pollution. Heated runoff from impervious surfaces is filtered through the bioretention facility and cooled; one study observed a temperature drop of 12°C between influent and effluent water. This function of the bioretention cell is especially useful in areas such as the Pacific Northwest where cold water fisheries are important (EPA, 2000).

Bioretention cells are dynamic, living, and micro-ecological systems. They demonstrate how the landscape can be used to protect ecosystem integrity. The design of bioretention cells involves, among other things, the hydrologic cycle, nonpoint pollutant treatment, resource conservation, habitat creation, nutrient cycles, soil chemistry, horticulture, landscape architecture, and ecology (Winogradoff, and Coffman, 1999); the cell thus necessarily demonstrates a multitude of benefits. Beyond its use for stormwater control, the bioretention cell provides attractive landscaping. The increased soil moisture, evapotranspiration, and vegetation coverage creates a more comfortable local climate. Bioretention cells can also be used to reduce problems with on-site erosion and high levels of flow energy.

The success of bioretention technology depends on right design and proper mix of soil. If the soil aggregates are not properly adjusted stormwater flow through the bioretention media will be disturbed and eventually the goal of bioretention underground swale will be hampered. In bioretention system soil and plants are working together to provide flow control and effective filter media for many stormwater pollutants (Hinman et al, 2009). Soil mixes for bioretention areas need to balance three primary design objectives to provide optimum performance: (i) provide high enough infiltration rates to meet desired surface water drawdown and system dewatering, (ii) provide infiltration rates that are not too high in order to optimize pollutant removal capability, and (iii) provide a growth media that supports long-term plant and soil health.

The soil mix used in bioretention systems is important for determining flow control and water quality treatment performance. A study was conducted by Hinman et al. (2009) to understand and to provide bioretention soil mix (BSM) guidelines that: (i) meet performance objectives; (ii) include materials readily available; (iii) include materials that aggregate and compost suppliers can provide with adequate quality control and consistency; and (iv) also affordable. The focus of this study was on the aggregate component of the BSM. Four candidate aggregate samples were collected from various suppliers and locations. Laboratory analysis was conducted to determine aggregate gradation, as well as the organic matter content, hydraulic conductivity, cation exchange capacity, and available phosphorus of a specified aggregate compost bioretention soil mix. Hydraulic conductivity of bioretention soil mixes is strongly correlated to percent mineral aggregate passing the 200 sieve and that the fines should be less than five percent and ideally between two and four percent. Recent research (Hinman et al, 2009) indicates that bioretention soil is excellent treatment media for metals, hydrocarbons and sediment at moderate and higher infiltration rates. Accordingly, a relatively high infiltration rate will likely provide adequate soil contact and provide an equivalent media for enhanced treatment and protecting groundwater quality.

Compaction, percent fines (passing 200 sieve) and how well-graded the material is (coefficient of uniformity) strongly influence BSM hydraulic conductivity (Fowler and Robertson, 2007). One value of relative compaction (85 percent of maximum dry density) was selected as representative of typical field conditions in bioretention areas that do not have regular foot traffic. At constant relative compaction, the percent fines (passing #200 sieve) is a strong controlling factor in the permeability test (Hinman et al, 2009. see Figure 2.1). For the present study, average percent fineness (passing through sieve #200) was 1.155 with standard deviation was 0.12. Therefore, bioretention soil of corresponding study site has greater hydraulic conductivity.

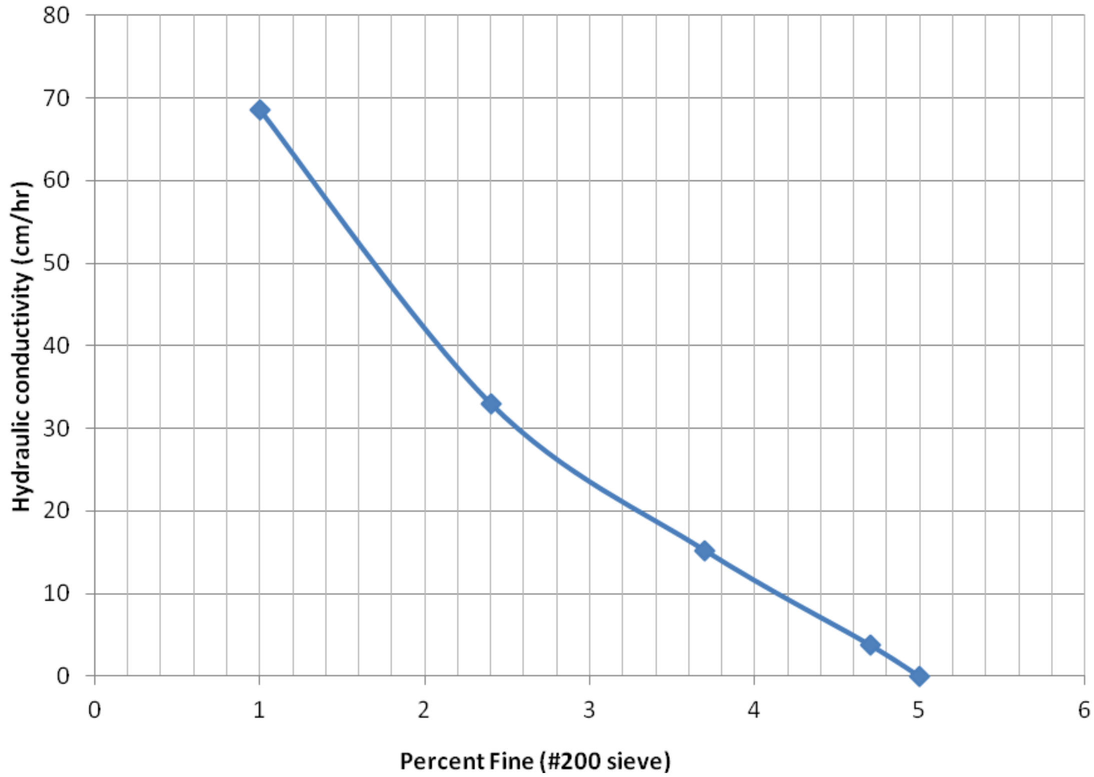


Fig. 2.1: Percent fines versus hydraulic conductivity (Curtis Hinman, 2009)

A performance assessment of a stormwater infiltration system (TRCA, 1997), an innovative swale and perforated pipe infiltration system, was conducted; and results revealed that quantity of runoff flow reduced 89 percent. A crude estimate of unsaturated hydraulic conductivity was determined as 1.4×10^{-5} m/s by a set of hydrant test (TRCA, 1997), corresponds to average infiltration rate of silty sand. Their results suggested that the areas with soil infiltration rates less than 4.2×10^{-6} m/s are not considered suitable for perforated pipe infiltration system.

2.6 Design of Bioretention System

Traditional bioretention systems are usually located at a depression space nearby the parking lots and others impervious areas. But underground bioretention systems are usually located adjacent to or under the sidewalk of urban road systems or any other suitable vacant place where open surface space is limited. The main goals of these bioretention systems are to control the runoff water quality and quantity along with urban landscape development.

A traditional bioretention system is also referred as rain garden since its initial development and application (Clar,et al., 1993). It has rapidly become one of the most versatile and widely used BMPs throughout the North America and many parts of the world. It has recently also identified as a preferred site practice for green building design and LEEDS certification. A recent review of bioretention design guideline being used throughout the North America revealed that most design concepts contained in the original design manuals remain similar (Clar et. al., 1993).

The present collective knowledge related to the design and construction of bioretention systems is still relatively small. Clar et. al., (1993) has examined the possibility for improving or optimizing the design elements such as the allowable ponding depth, the minimum width and length parameters, the depth and type of soil/filter media, the design of bioretention as infiltration practices, and the selection of appropriate plant materials.

2.7 Allowable Ponding Depth

It is appeared that adequate discussion or guidance is not available on the technical basis for ponding depth of conventional bioretention systems. However, depending on local conditions, the allowable ponding depth criteria that are typically ranging from 150 mm to 450 mm (Lucas, 2005). A review of the technical factors that govern the determination and selection of this design parameter is worthwhile. It is important to remember that selecting a 300 mm depth instead of a 150 mm depth reduces the surface area of the facility by 50 percent and using a 600mm depth would further reduce the surface area requirement to 25 percent of the initial design thus generating substantial reductions in system construction cost.

Table 2.1. Maximum Allowable Ponding and Storage Depths (mm) (Clar & McCuen, 1984)

Soil Texture	Hydrologic Soil Group	F* (mm/hr)	Max Allowable Ponding Time (hrs)			Max Allowable Storage Time (hrs)		
			24	48	72	24	48	72
Sand	A	210.0	5040	10080	15120	12600	25200	37800
Loamy sand	A	61.0	1464	2928	4392	3660	7320	10980
Sandy loam	B	26.0	624	1248	1872	1560	3120	4680
Loam	B	13.0	312	624	936	780	1560	2340
Silt Loam	C	7.0	168	336	504	420	840	1260
Sandy clay loam	C	4.0	96	192	288	240	480	720
Clay loam	D	2.0	48	96	144	120	240	360
Silty clay laom	D	1.5	36	72	108	90	180	270
Sandy clay	D	1.2	29	58	87	725	145	218
Silty clay	D	1.0	24	48	72	60	120	180
Clay	D	0.5	12	24	36	30	60	90

Table 2.1, was developed as part of the Maryland Standards and Specifications for Infiltration Practices (Clar & McCuen, 1984). The table provides the maximum allowable ponding time for each USDA textural classification, based on various allowable ponding time strategies. The most common ponding time strategy being used by local governments is 48 hours, although a good case could be made for a 72 hours policy. It can be observed that all A, B, and C hydrologic soil groups can meet the 150 mm ponding criteria with a 48 hour dewatering strategy. All A and B

soils as well as the silt loam (F = 7.0) can meet the 300 mm ponding depth with a 48 hour dewatering strategy. Also it can be observed that all A and B soils can meet 600 mm ponding criteria with a 48 hour dewatering strategy. Consequently it appeared that most local criteria for ponding depth were under utilizing the infiltration capacities of existing soils and may be directly responsible for unnecessary expenses in the application of LID practices such as bioretention.

2.8 Dimension of Bioretention System

A review on the dimension of bioretention system revealed that many local design guidance manuals for its design include criteria for minimum and maximum values of width and length parameters that are presented in Table 2.2 (Lucas, 2005). The most common guidance follows the initial recommendations developed by Prince George's County (Clar, et al, 1993) which recommends a minimum width range of 3000-4500 mm and a minimum length of 9000-12000 mm. Practical experience, however, indicates that the actual minimum width is only 1200 mm. This would consist of a bioretention cell with a 610 mm bottom width, 150 mm ponding depth and 2:1 side slope and no freeboard allowance. If a freeboard depth of 150 mm is provided, then the minimum width increases to 1830 mm. A system of this size might be found on a residential lot and can be used for handling runoff from a roof downspout or driveway. Practical experience also suggested that there is no science based limit on a maximum value for length and width. However, the actual maximum value for width will typically be determined by considerations for the reach of the equipment used to excavate the cell and apply the bioretention soil mix, as well as the topography of the site.

Table 2.2 Bioretention Criteria for Length and Width (Lucas, 2005)

Source	Length (mm)	Width (mm)
Prince George's Co, DER, MD (Clar, et al, 1993)	> 9000-12000	>3000-4500
Pennsylvania (PACD, 2001)	Same as PGDER	Same as PGDER
New York (NYSDEC)	Sized according to Darcy's law	
US EPA	US EPA	US EPA
Vermont (VTDEC)	Length:width = 2:1	
Los Angeles, CA	> 12000	4500-7600
Georgia (ARC, 2001)	Identical to Vermont manual	
North Carolina (Hunt & White)	Sized according to Darcy's law	
Vancouver (GVSDD, 1999)	> 5000	> 3000
Idaho (IDDEQ, 2001)	Surface area < 0.41 ha	

2.9 Bioretention Soil and Depth

The bioretention soil media and its depth are probably the least understood aspect of the bioretention design (Clar et. al.,1993). The initial concern with respect to the specification of a soil was to provide a well drained soil and a suitable growth medium for the plant species. The initial guidelines for soil material was based on the properties of soil (Table 2.1) and three soil textural classifications such as loamy sand, sandy loam and loam were selected. It can be observed that these three soil types all had infiltration rates of 13.2 mm per hour. The sand has high conductivity rate at 210 mm per hour so it has a concern related to droughty soils and plant survival. Clar et. al., (1993) recommended based on years of experience that bioretention media should be a mixture of 50-60 % sand and 20 % well aged organic matters such as double shredded mulch, pine fines or composted leaf mulch.

The depth of soil media must be sufficient to ensure that the plant material would have a suitable growth medium.

2.10 Design of Bioretention System as an Infiltration Practice

A research found that stormwater practitioners perceived bioretention primarily as a filter BMP to be used for water quality control (Clar et.al., 1993). This perception greatly undervalues the potential of bioretention practices to provide quantity control including both volume and peak discharge control for both small and large storm events. However, with the growing awareness and understanding, many local stormwater programs moving towards volume control, thus bioretention system as an infiltration practice becomes more important. In the present state, there is a very little guidance available for the design of bioretention as an infiltration practice. However, a couple of recent exceptions include the RECARGA model developed by the University of Wisconsin (2006), and the New Jersey groundwater recharge spreadsheet (NJ 2004). Some local programs adopted minimum infiltration rates ranging from 13.2 mm to 26 mm to ensure that complete dewatering of the infiltration facility would occur. In the course of progress of development, many jurisdictions are emphasized from a single function control strategy for peak discharge to a multiple parameter control strategies that include; groundwater recharge, water quality control, channel protection and peak discharge.

The RECARGA model (Fig. 2.2) illustrates how this information can be used to design a combination system that provides an infiltration reservoir and an under drain for positive dewatering of excessive flows. In addition Table 2.1 demonstrates that when sandy soils are present the contribution of bioretention infiltration systems can make a significant contribution to volume control.

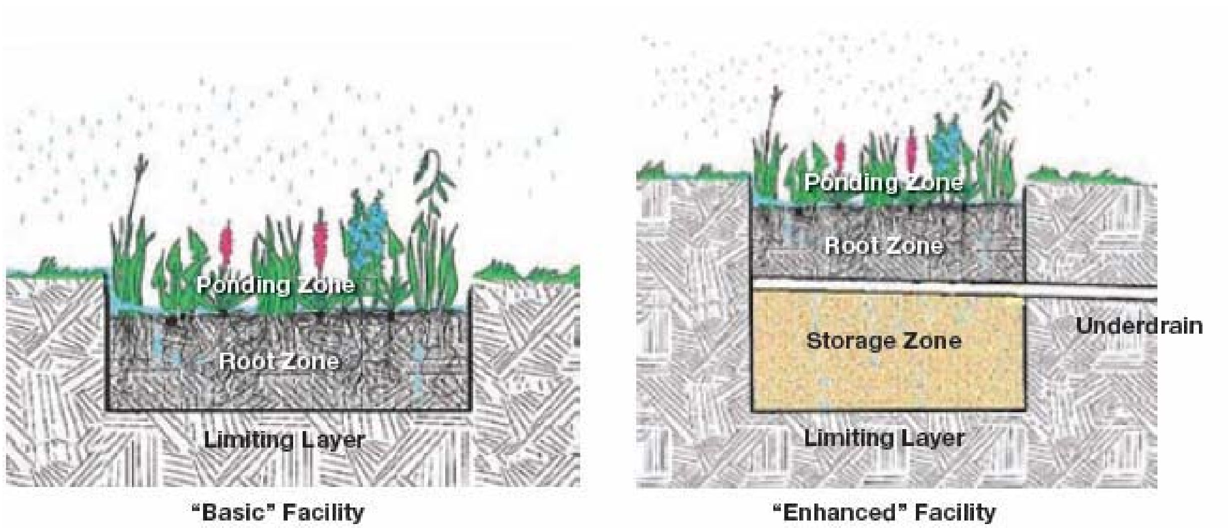


Fig. 2.2 Basic Bioretention Models (Wisconsin, 2006)

2.11 Plant Materials

The role of plant materials in bioretention design is still poorly documented and understood. The type of plant materials that should be used, the density of planting and the benefits of plant materials are all issues that need to be better documented. Some stormwater designers are concerned that having a dense plant material coverage could reduce the volume available for water storage and reduce infiltration. However, all of the bioretention systems that we have observed appear to function better as the plant density increases. In general we would recommend that the entire bottom and sides of the bioretention area be planted. The recommended plant spacing for each plant species will generally ensure that at establishment at least 50 % or more of the bioretention system surface is open. This will change over time as the plants mature and grow, and if that should prove to be a concern, which to date if we have not seen, the plant density could be reduced and the removed plant could be transferred to another site. In general the plant roots should improve the permeability of the soil mixture, not impede it. Ongoing research related to soil infiltration rates associated with plant materials is concluding that there are many natural processes that re effective in restoring and/or enhancing infiltration rates is soils (Lucas and Greenway, 2007). They report that vegetation roots penetrate confining layers, opening up soil structure, and root turnover promotes the formation of macropores. The beneficial effects of native plants on infiltration rates is reported to persists even in depositional situations where sediments accumulates, which is a very important characteristic for a stormwater BMP. They conclude that the presence of vegetation can result in infiltration rates several orders of magnitude higher than predicted by underlying soil properties.

With respect to the selection of plant materials it is generally recommended that common natives species be used. Many local programs such as Prince

George's County, MD have developed extensive listings of suitable plant materials, and also provide guidance on their soil and light preferences.

The above discussion of selected design elements and considerations related to bioretention design and construction technology. The main intent is to stimulate and encourage further review and improvement in understanding and utilization of this control practice. However, there are a number of opportunities and challenges related to many of the design parameters of the bioretention system. These include the allowable ponding depth, the minimum width and length parameters, the depth and type of soil / filter media, the design of bioretention as an infiltration practice and the proper selection and use of plant materials.

From the literature review, it is apparent that a very few information on underground bioretention system are available. Underground bioretention system is designed to capture stormwater and reduce runoff volume for downstream. The soil mix used in bioretention systems is important for determining flow control and water quality treatment performance. Therefore, bioretention system plays a vital role in stormwater management system. This chapter described BMP, LID, infiltration process, definition of bioretention system, bioretention soil and its function, application of bioretention system. The next chapter is focused on the development of hydraulic design model for underground bioretention system.

Chapter III

METHODOLOGY

To develop a hydraulic design model of underground bioretention system, rainfall intensity, catchment area and biorentention soil characteristics must be known. This chapter focuses on rainfall intensity, catchment area and development of hydraulic model by the development of mass balance equations and solve those numerical equations by using *f*solve function of Matlab program.

3.1 Rainfall Intensity

Toronto has a semi-continental climate, with a warm, humid summer and a cold winter. Toronto's climate is modified by its location on the shores of Lake Ontario. An overall annual average climatic condition that represents the Toronto is shown in Appendix A.

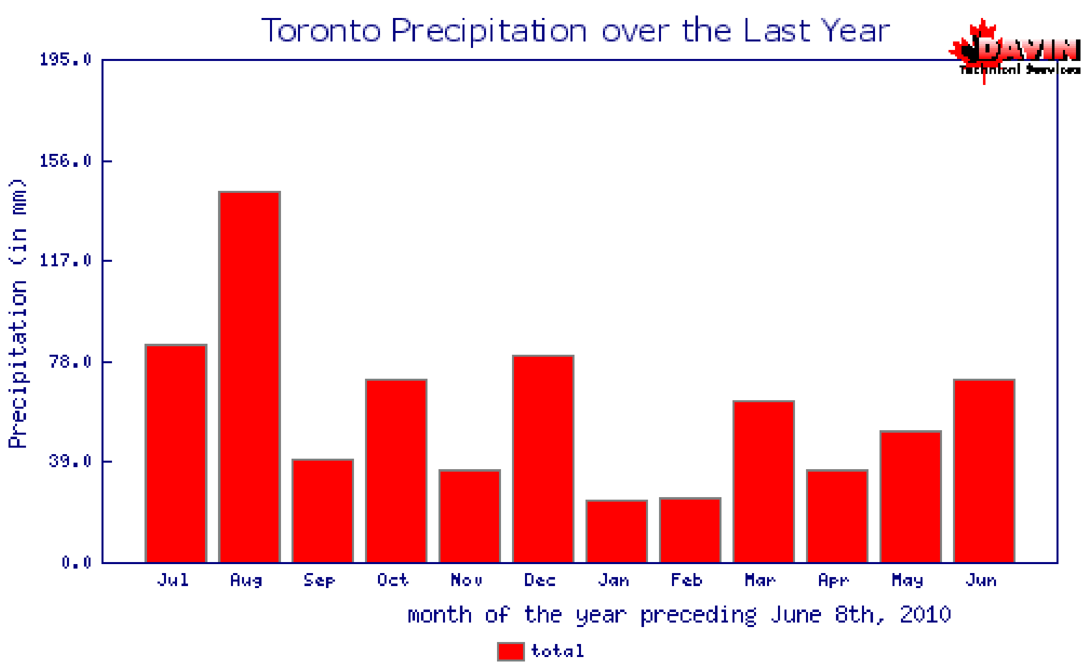


Fig.3.1: Recent year of rainfall (Toronto weather statistics)

The weather station **TORONTO** is at about 43.70°N 79.40°W with a height about 116m (380 feet) above sea level. A yearly rainfall data is copied from the website of Toronto weather statistics and presented in Fig. 3.1.

The design of municipal water management infrastructures (sewers, stormwater management ponds or detention basins, street curbs and gutters, catch basins, swales, etc) are typically based on the use of local rainfall Intensity Duration Frequency (IDF) curve, developed using historical rainfall time series data. A representative IDF curve of Toronto and region is reproduced in Fig. 3.2.

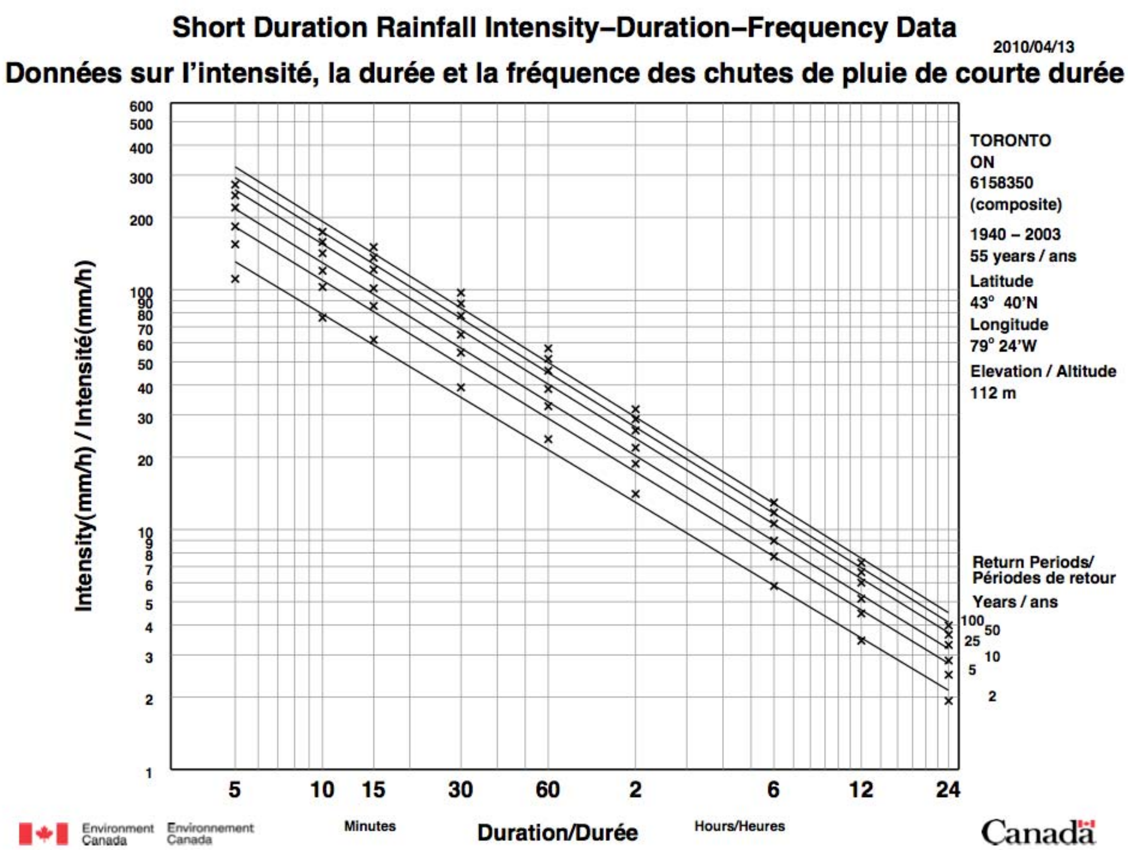


Fig. 3.2: IDF curve for Toronto (http://climate.weatheroffice.gc.ca/ponds_servs/index_f.html)

The Silva Cell Inc (technology provider) has designed underground bioretention system at the Queensway Ave in the City of Toronto. The system was designed to capture a typical rainfall event in Toronto of 25 mm in 24 hours. The design also noted that fifty percent events of Toronto's annual precipitation are less than 5 mm (0.19 inch) (Source:www.deeproot.com).

3.2 Underground Bioretention System of Sustainable Sidewalk

Toronto Water, the city's water authority, has undertaken a project to evaluate the capacity and performance of the underground bioretention system of the technology provider for managing surface runoff and removal of pollutants. In conjunction with Ryerson University and Deep Root Canada Corp., the city installed a proof-of-concept bioretention system (Fig. 3.3).

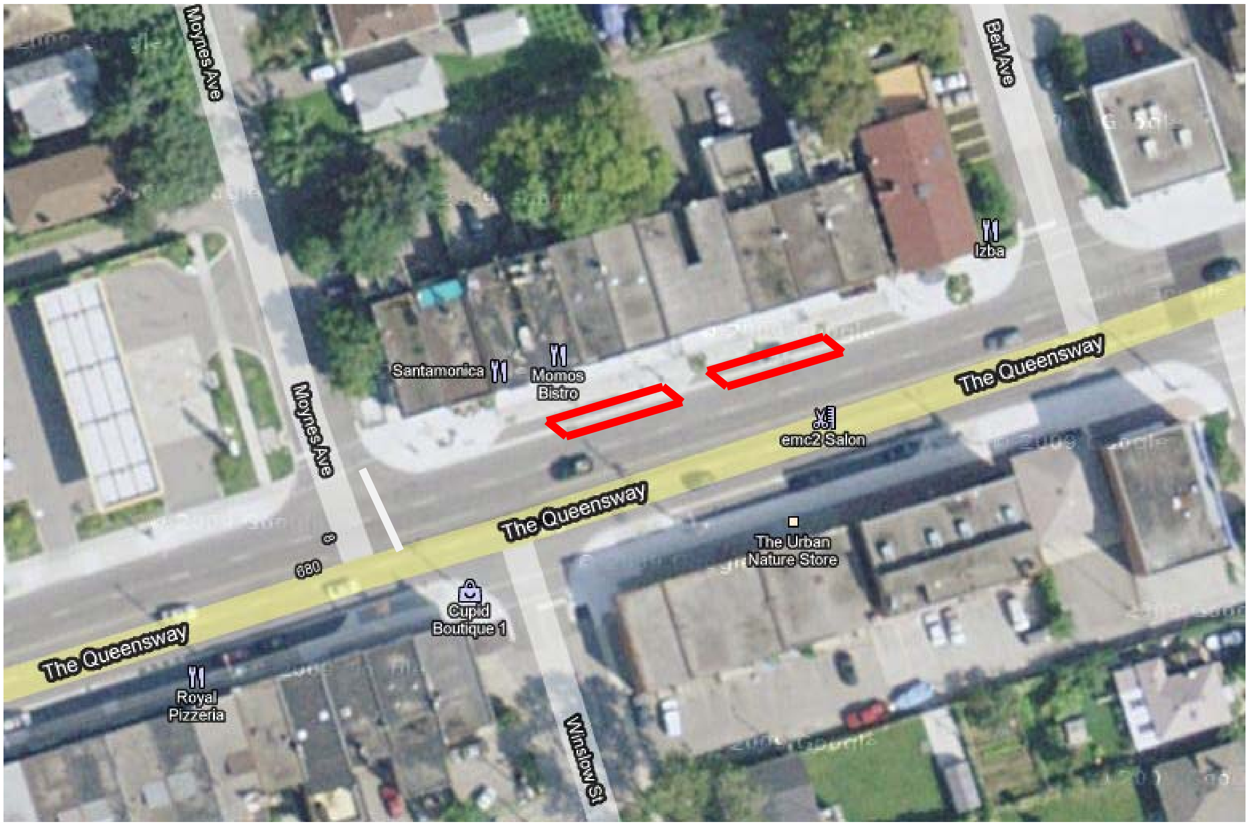


Fig. 3.3: Site Location of Bioretention System (Google Earth, 2010)

The project site is located on the north side of The Queensway Avenue between Moynes and Berl Avenue in Toronto (Fig. 3.3). The underground bioretention system is located at red rectangular boxes (Fig. 3.3).

Pave-Al, the contractor, excavated two trenches for two underground bioretention systems, each of two frames deep and with spots for two trees opening, that straddled the sidewalk area and the parking bays. The trenches were excavated to fit each of bioretention system of size 18.08m x 3.2m with a depth 1.20m (detailed design is shown in Appendix B). The bottom of the trench was constructed by pouring concrete with a thick of 15 cm (6 inch) for the size of bioretention system. The catchment area of each bioretention system is about 385 m^2.

Fig. 3.4: Installation of underground Bioretention System

A 20 cm (8 inch) PVC pipe was installed from the street catch basin to the top layer of the bioretention system, and diverts the surface runoff from the roadway and adjacent sidewalk into the underground bioretention system. A horizontally laid 15 cm (6 inches) perforated PVC pipe loop conveyed the surface runoff that is assumed to be distributed evenly throughout the bioretention soil. The runoff water infiltrates into bioretention soil through the perforations and reaches the bottom of the system (Fig. 3.4). A 20 cm (8 inches) perforated PVC flow control pipe is installed at the bottom of the trench which exfitrates runoff water from bioretention soil to flow control pipe and carry these exfiltrated runoff to storm sewer system. Since the bottom of the system has concrete layer, runoff water can only seep/percolate along the side of the bioretention system. This system captures all of the runoff from the crown of the street to the building face and from one end of the block to the other (catchment area is 385 m^2). The bioretention soil of the system can clean, retain and detain all the runoff water produced from its catchment. The system also meets AASHTO H-20 loading requirements to support parking (Fig. 3.5). The system installation provides almost 16 m^3 (600 ft^3) of bioretention soil per tree. Once the two trees in each of the trenches mature, they will also strengthen the efficiency of the stormwater management by evapotranspirating infiltrated rainwater out of the bioretention soil through their roots systems, and intercept and evaporate some of the rainfall using canopies (Fig. 3.5). Toronto Water, in collaboration with Ryerson University has planned to install the monitoring equipment to track the stormwater quantity and quality of runoff water in and out of the bioretention cell. They decided to continue to monitor the system’s ability and performance to manage stormwater in 10 to 20 years fully to see the bioretention system continuing to nurture large, mature trees and supporting an effective and more ecological stormwater system.

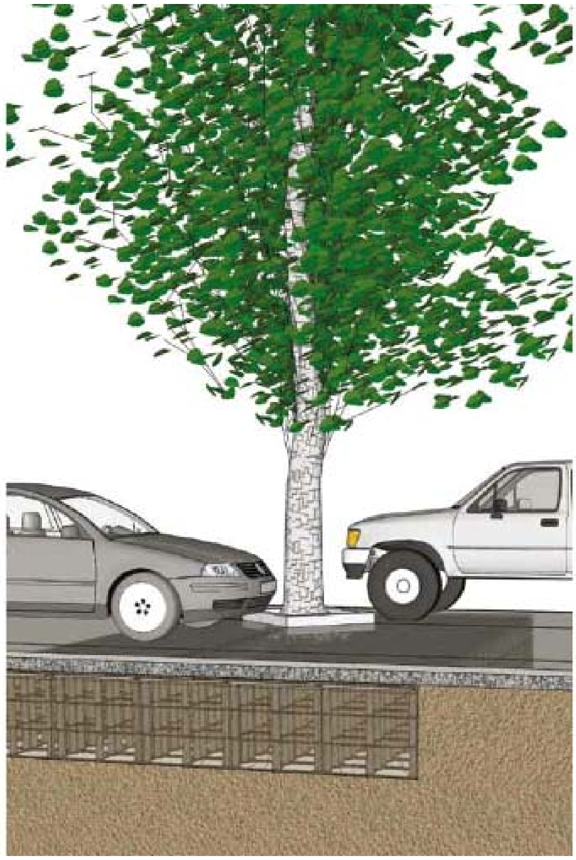


Fig. 3.5: Tree cell of underground Bioretention (Source:www.deeproot.com)

3.3 Development of A Hydraulic Design Model

In a bioretention system, runoff water first enters into catch basin from street surface and sidewalk. On the basis of grate efficiency of the catch basin, it delivers runoff water to bioretention system through the perforated upper flow distribution pipe. Then runoff water infiltrates into bioretention soil and eventually reaches at the bottom of the bioretention system. A bottom flow control perforated pipe intercepts runoff from the bioretention cell. From the flow control pipe, the runoff water flows to a manhole and then discharges to the street storm sewer. For well drained bioretention soil, this runoff flows from the catch basin to the street sewer without much detention. Hence, simultaneous hydrologic routing between each component of the underground bioretention system may not be necessary. Therefore, mass balance calculations are applied to determine the unknown water depth of each component of the bioretention system in a consecutive manner for each time step. The mass balance equation of each component of the bioretention system was developed in the following sections.

3.3.1 Flow in Upper Distribution Pipe (P1)

When designing the underground bioretention system, the upper distribution pipe diameter and its length are important design parameters. The specification of pipe diameter and length should be in such a way that it satisfies the design objectives of the underground bioretention system is to capture a certain portion of a 10 years design storm and convey it to the street sewer with delayed time, the distribution pipe diameter and its length are primary design parameters. Pipe P1 is installed along the side of the rectangular cell to form a loop with the assumption that runoff water will enter into P1 and distribute to the entire cell in fashion of rainfall (Fig. 3.6). To establish this assumption of uniform distribution of runoff through the perforation of pipe, the number of perforation and their alignment across the circumference of the pipe is also important. If the position of a perforation is at the bottom of the pipe, runoff will start to flow when it finds an opening, and flow may not advance unless inflow is greater that the outflow though perforations. This condition may create piping problem through the bioretention cell and runoff water will not proceed to the tail end and assumption of uniform distribution will not be fulfilled.

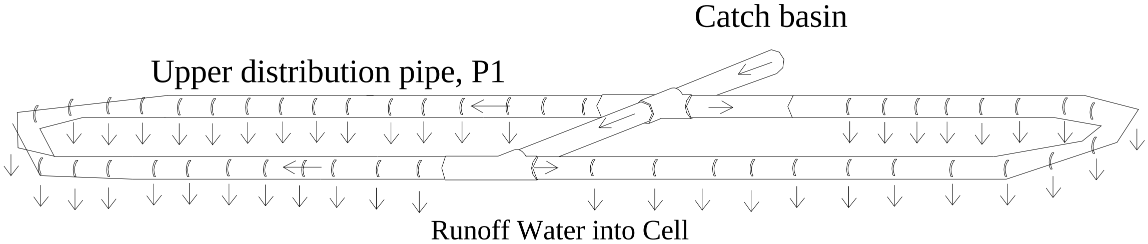


Fig. 3.6: Upper Pipe Alignment Loop

To avoid this situation and establish uniform distribution of flow into the cell perforation opening must not be positioned at the bottom of the pipe. Rather it should be placed as shown in Fig. 3.7.

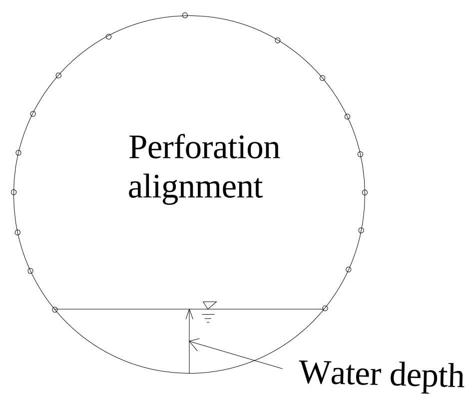


Fig. 3.7: Perforation Alignment of Pipe

This could be performed by not to open any perforation at bottom surface of the pipe (Fig. 3.7). As a result, a head of water will build up at the bottom layer along the pipe loop (Fig. 3.6) and runoff water will start to flow into bioretention cell at the same time uniformly.

Length of the pipe depends on the size of the cell. However, number of pipe row along the cell depends on the width of the cell. It is assumed that one pipeline per meter width of cell to be enough for uniform space distribution. Eventually, perforated opening area of distribution pipeline will be increased with the increase of width of the cell.

3.3.2 Model Criteria

The rainfall intensity, duration and their return period are quite uncertain for a particular event. Underground bioretention system is a minor source control measure of urban stormwater management. According to its size it can not capture whole event of any big rainfall event. As such, depending on grate efficiency a percent of runoff will be entering into catch basin and remaining amount will splash over the grate. Hence, the main criteria of the underground bioretention system is to capture certain percent of a design storm(e.g. 10 years Chicago rainfall).

3.3.3 Model Parameters

The conditions, scenarios, infrastructures involved in underground bioretention system could be included as a parameter for more detail research and investigation. However, for the present hydraulic study of underground bioretention systems, the following design parameters are considered:

Diameter of upper pipe, D_{p1}

Diameter of flow control pipe, D_{p2}

Length of upper pipe length, L_1

Length of bioretention cell, L_2

Length of flow control pipe, L_3

Width of bioretention cell, W

Height of bioretention cell, H_{bc}

Hydraulic conductivity of native soil, K_{ns}

Soil properties (such as porosity), ρ

Grate efficiency

Elevation of catch basin and storm sewer

Position of flow control pipe

In the hydraulic design model diameter of upper pipe (D_{p1}), flow control pipe (D_{p2}), length of upper pipe (L_1), bioretention cell (L_2), width of bioretention cell (W), height of bioretention cell (H_{bc}), length of flow control pipe (L_3), hydraulic conductivity of native soil (K_{ns}), and soil porosity (ρ) are directly integrated in the development of mass balance equation. However, other parameters are not directly integrated into the mass balance equation of the model for simplicity.

3.3.4 Runoff

The runoff is that part of rainfall which is neither retained on land surface nor infiltrated into the soil, and that flows over the land surface. The rainfall runoff also express as rainfall excess or effective rainfall.

The bioretention system receives rainfall runoff from asphalt road and concrete surface of sidewalk. A sketch of a bioretention system was shown in Fig. 3.8. In this system runoff water first flows into the catch basin. The catch basin has dead storage of height *H,* and runoff water does not flow through its connected distribution pipe until the dead storage is full.

The mass balance concept is applied for analyzing the hydraulic condition of the bioretention system. The general conservation of mass balance is shown in Equation 3.1.

$$\Delta Q_{in}\Delta t = \Delta Q_{out}\Delta t + \Delta S \qquad (3.1)$$

where, Q_{in} is the average inflow enters into the bioretention system at a time step Δt in L^3/T; Q_{out} is the of average outflow exits from the system during time step Δt in L^3/T; ΔS is the change of storage in the bioretention system at a time step of L^3 and Δt is the time step in T.

The Equation 3.1 can be rearranged into the following equation:

$$\Delta S = (\Delta Q_{in} - \Delta Q_{out})\Delta t \qquad (3.2)$$

The average inflow between the time step $\Delta t_{(n)}$ and $\Delta t_{(n+1)}$ can be calculated as follows:

$$\Delta Q_{in} = \frac{1}{2}[Q_{in(n+1)}\Delta t + Q_{in(n)}\Delta t] \qquad (3.3)$$

This general mass balance equation was applied to the (i) catch basin, (ii) distribution pipe, (iii) bioretention cell, (iv) flow control pipe, and (v) sewer manhole.

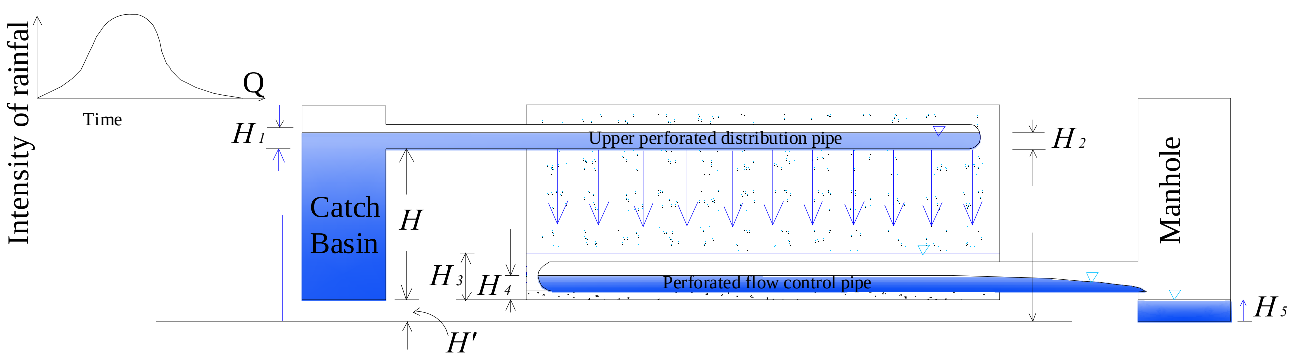


Fig. 3.8: Definition Sketch of Bioretention System Cross Section

3.3.5 Mass Balance at Catch Basin

When runoff volume is greater than initial abstraction then runoff water enters into catch basin. The catch basin has dead storage to trap gravel, sand, silt and other dirt of larger particles. Obviously, no outflow occurs until this dead storage is filled by runoff water. The dead storage volume of catch basin may be computed as follows:

$$V_{cbdead} = A_{cb} H \qquad (3.4)$$

where, V_{cbdead} is dead storage volume, A_{cb} is the cross sectional area and, H is the dead storage height of catch basin. When runoff water fills the dead storage volume ($A_{cb}H$), runoff water starts to flow from the catch basin to the distribution pipe P1. Hence, if $\sum Q\Delta t > A_{cb}H$, the average runoff that enters into the catch basin from impervious street and sidewalk can be calculated as (detailed is in Appendix C):

$$\Delta Q_{cbin} = \frac{1}{2}\Phi A_{catmt}\left[i_{(n+1)} + i_{(n)}\right] E \qquad (3.5)$$

where ΔQ_{cbin} is average inflow rate of runoff into catch basin, and E is grate efficiency.

When the water depth at the entrance of P1 is above the centerline then the flow is considered as orifice flow and if the flow depth is below the centerline of the P1 then the flow is treated as weir flow.

Initially water depth is below the center line of P1 thus the flow is considered as weir flow, and the flow coefficients for both orifice and weir behaviour are computed by adopting EPA SWMM Manual, 2008 (see detail in Appendix D) as follows:

$$Q_{orif} = A_{p1} * \sqrt{2g} * \frac{2C_d}{D_{p1}} * H_1^{1.5} \qquad (3.6)$$

Now, the above orifice equation is used to compute the flow from catch basin to P1, thus Q_{orif} is transformed into Q_{cbout} as follows:

$$Q_{cbout} = A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_1^{1.5} \qquad (3.7)$$

where, D_{p1} is diameter of the distribution pipe [L], H_1 is water depth in catch basin above the invert level of the distribution pipe [L], Q_{cbout} is the outflow from the catch basin to pipe P1 [L^3/T], A_{p1} is the cross section area of the pipe P1 [L^2] Thus, the average outflow of runoff from catch basin to pipe P1 is:

$$\Delta Q_{cbout} = \frac{Q_{cbout(n+1)} + Q_{cbout(n)}}{2} \qquad (3.8)$$

or

$$\Delta Q_{cbout} = \frac{1}{2}\left[A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_{1(n+1)}^{1.5} + A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_{1(n)}^{1.5}\right] \quad (3.9)$$

The change of storage volume in the catch basin was denoted by ΔS_{cb}. The conservation of mass balance equation at the catch basin is defined as:

$$\Delta S_{cb} = [\Delta Q_{cbin} - \Delta Q_{cbout}]\Delta t \qquad (3.10)$$

and, $\Delta S_{cb} = A_{cb}[H_{1(n+1)} - H_{1(n)}]$ (3.11)

Therefore,

$$A_{cb}\left[H_{1(n+1)} - H_{1(n)}\right] = \frac{\Delta t}{2}\Phi A_{catmt}\left[i_{(n+1)} + i_{(n)}\right]E - \frac{\Delta t}{2}\left[A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_{1(n+1)}^{1.5} + A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_{1(n)}^{1.5}\right] \quad (3$$

$$A_{cb}\left[H_{1(n+1)} - H_{1(n)}\right] = \frac{\Delta t}{2}\Phi E A_{catmt} i_{(n+1)} + \frac{\Delta t}{2}\Phi E A_{catmt} i_{(n)} - \frac{\Delta t}{2}A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_{1(n+1)}^{1.5} - \frac{\Delta t}{2}A_{p1}$$

where, Q_{cbin} is the volume of rainfall runoff directly entering the catch basin.

3.3.6 Mass Balance at Distribution Pipe

The average inflow into the distribution pipe is equal to the average outflow from the catch basin, inasmuch as same outflow is flowing from catch basin to upper distribution pipe of bioretention system.

Therefore, average inflow of runoff into P1 is as follows:

$$\Delta Q_{p1in} = \Delta Q_{cbout} = \frac{1}{2\left[A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_{1(n+1)}^{1.5} + A_{p1}\sqrt{2g}\frac{2C_d}{D_{p1}}H_{1(n)}^{1.5}\right]} \quad (3.14)$$

When runoff water flows from the catch basin to the distribution pipe it passes through a short length (2.4 m) of solid pipe and remaining length is a perforated pipe (35.0 m) that formed a single loop. These pipes are associated with Tee joints and bents. There are minor losses involved when pipe is flowing full, however these minor losses were considered as insignificant.

The distribution pipe (P1) allows infiltration along its length to bioretention cell through perforations. The infiltration rate through the perforation depends on the inflow rate as well as soil water level surrounding the pipe. The outflow diagram from upper distribution pipe is shown in Fig. 3.9.

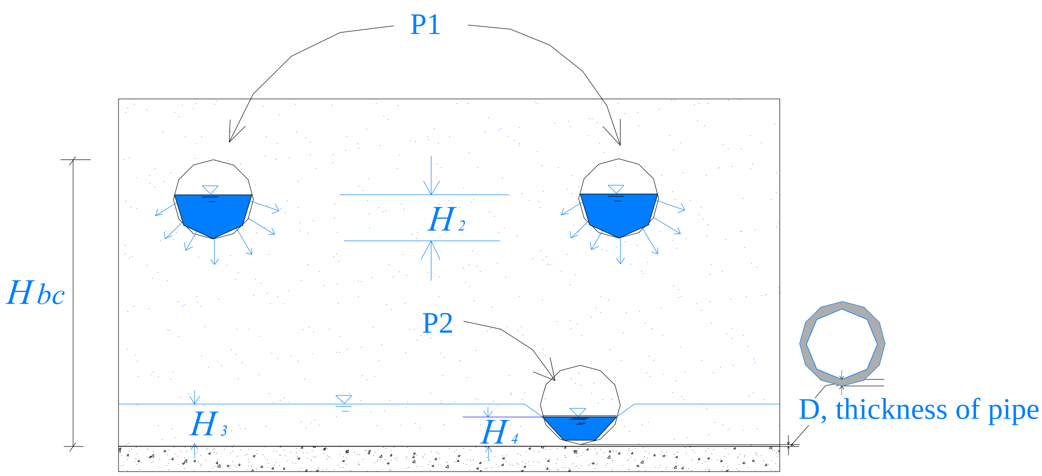


Fig. 3.9: Outflow from upper distribution pipe

The outflow from P1 is assumed as orifice flow. The orifice flow rate from the perforated pipe to bioretention cell is a function of pipe length, slope, size and shape of the orifices, number of orifices and their orientation around the circumference, and water depth in the pipe. However, discharge through perforated opening is determined by simulation of flow as a function of H_2 as follows:

$$Q_{P1out} = C\left(2756{H_2}^3 - 245.47{H_2}^2 + 6.75H_2\right) \qquad (3.15)$$

where, Q_{P1out} is outflow from the perforated distribution pipe, C is coefficient and this equation is generated using SWMM5 model. In this simulation, discharge through the perforated pipe was computed as function of water depth.

Hence, the average discharge of water from the distribution pipe to the bioretention cell is calculated as:

$$\Delta Q_{p1out} = \frac{Q_{p1out(n+1)} + Q_{p1out(n)}}{2} \qquad (3.16)$$

$$\Delta Q_{p1out} = \frac{C}{2\left[2756H_{2(n+1)}^{3} - 245.47H_{2(n+1)}^{2} + 6.75H_{2(n+1)} + 2756H_{2(n)}^{3} - 245.47H_{2(n)}^{2} + 6.75H_{2(n}\right.}$$

Therefore, the conservation of mass balance equation at the distribution pipe is written as:

$$\Delta S_{p1} = [\Delta Q_{p1in} - \Delta Q_{p1out}]\Delta t \qquad (3.18)$$

$$2756H_{2(n+1)}^{3} - 245.47H_{2(n+1)}^{2} + 6.75H_{2(n+1)} + 2756H_{2(n)}^{3} - 245.47H_{2(n)}^{2}$$

where, A_{wetp1} is wetted area of perforated distribution pipe, L_1 is the length of pipe P1. The wetted area of the distribution pipe is computed as a function of water depth as follows (for details see appendix E): $A_{wetp1} = 0.1196\ H_2$ (3.20)

Substituting the value of A_{wetp1} in equation 3.19 the following equation is derived.

$$0.1196L_1\ H_{(2(n+1))} - 0.1196L_1\ H_{(2(n))} = \Delta t/2[A_{p1}\sqrt{2g}\ \ [2C]_{d}/D_{p1}\ \ [H_1(n+1)]^{1.5} + A$$

3.3.7 Mass Balance at the Bioretention Cell

It was assumed that the average inflow into bioretention cell is equal to the average outflow from the distribution pipe, P1. Therefore, average inflow into bioretention cell is as follows:

$$\Delta Q_{bcin} = \frac{C}{2}\left[2756H_{2(n+1)}^{3} - 245.47H_{2(n+1)}^{2} + 6.75H_{2(n+1)} + 2756H_{2(n)}^{3} - 245.47H_{2(n)}^{2} + 6.75H_{2(n)}\right]$$

where, ΔQ_{Bcin} is average inflow to bioretention cell.

If the bioretention cell is empty of water, no outflow occurs from the cell to the flow control pipe (P2) until the dead storage volume of the bioretention cell is filled up. The dead storage volume at bioretention cell (V_{bodead}) may be calculated as follows:

$$V_{bodead} = WL_2D\rho \qquad (3.23)$$

where, L_2 is the length [L], W is the width [L], D is depth [L] of dead storage water at the of bioretention cell, and ρ is the porosity of bioretention soil [%].

Hence, there are two cases in bioretention cell,

i) if $\sum \Delta t \Delta Q_{boin} < V_{bodead}$ for certain interval of time, no outflow occurs from bioretention cell to P2.

ii) if $\sum \Delta t \Delta Q_{boin} > V_{bodead}$ for certain interval of time, outflow occurs from bioretention cell to P2.

Present study is mainly intended to case (ii). Note that the bottom of the cell is made out of thick concrete slab hence there is no possibility of water to be percolated downward. However, side of the bioretention cell trench is exposed to surrounding native soil thus there is possibility of water to be seeped out through the surrounding wall of bioretention cell. Seepage height around the wall depends on the height of saturated water depth in the bioretention cell. Therefore, seeping or exfiltration rate of water from the bioretention cell to its surrounding wall may be calculated as following:

$$Q_{seepageout} = 2(L_2 + W)(H]_3[\square)K_{ns}rs \qquad (3.24)$$

where, (H_s) is saturated depth of water level into bioretention cell [L], K_{ns} is the hydraulic conductivity of native soil [L/T] , r is reduction factor to account for clogging which depends on the number of years of use, and s is hydraulic gradient [L/L], assumed conservatively to be 1.0 m/1m (Abida et al., 2007).

Therefore, average of seepage during the time step is as follows:

$$\Delta Q_{seepageout} = (L_s + W) K_{ns} r s \left[H_{s(n+1)} + H_{s(n)} \right] \qquad (3.25)$$

where, $H_{s(n+1)}$ is saturated depth at the end of time step, and $H_{s(n)}$ is the saturated depth at the beginning of the time step.

The exfiltration rate from the bioretention cell to the flow control pipe (P2) depends on depth of water above the invert level of the inner layer of P2, and size and number of perforations (orifices) under saturated depth. Note that, similar to the perforated distribution pipe P1, P2 is also placed into the bioretention cell horizontally. Since the pipe P2 has no slope, water flows from P2 to the downstream manhole only by developing head inside of P2. In a fully saturated soil, water flows from the bioretention cell to flow control pipe P2 along the path shown in Fig 3.7 (lower part of the figure).

The outflow from bioretention system can be determined by orifice equation as follows:

$$Q_{bcout} = C' A_{orips} \sqrt{2gH_s} \qquad (3.26)$$

Where, C' is coefficient orifice flow, A_{orips} is orifice opening within water depth H_s and it is computed as:

$A_{orips} = 0.0113H_s$ (3.27) (detail is shown in appendix F)

Substituting the value of Eq. (3.27) in equation 3.26, we can get the following:

$$Q_{bcout} = 0.0113C'\sqrt{2gH_s}^{1.5} \qquad (3.28)$$

Therefore, average inflow from bioretention cell to P2 can be written as follows:

$$\Delta Q_{bcout} = \frac{1}{2}0.0113\,[C'\left[H_{3(n+1)}]^{1.5} + H_{3(n)}{}^{1.5}\right] \qquad (3.29)$$

where Q_{bcout} is outflow of water from the bioretention cell to P2.

As the saturated depth increases, outflow from the bioretention cells to P2 also increases.

Now, the conservation of mass on the bioretention cell is defined as:

$$\Delta S = [\Delta Q_{bcin} - \Delta Q_{seepageout} - \Delta Q_{bcout}]\Delta t \qquad (3.30)$$

3.3.8 Mass Balance at Flow Control Pipe, P2

The inflow of runoff water into P2 is equal to outflow from bioretention cell. Therefore, average inflow into P2 is determined from the same orifice equation (3.29) as follows:

$$\Delta Q_{P2in} = \frac{1}{2}0.0113\,[C'\left[H_{3(n+1)}]^{1.5} + H_{3(n)}{}^{1.5}\right] \qquad (3.32)$$

Where, C' is coefficient orifice flow, A_{orips} is orifice opening within water depth H_s

The P2 is placed horizontally and connected to the manhole of the city's sewer system. As P2 is horizontal, water does not flow until a head is built up in the pipe P2. The outflow of water from P2 is computed by orifice flow equation derived by SWMM (mentioned earlier) as follows:

$$Q_{p2out} = C'' A_{p2} \sqrt{2gH_4} \qquad (3.33)$$

where, $C'' = \frac{2C_d}{D_{p2}}$ (obtained from similar derivation of SWMM model)

Therefore, average outflow ΔQ_{p2out} during the time step is as follows:

$$\Delta Q_{p2out} = \frac{1}{2}\frac{2C_d}{D_{p2}} A_{p2}\sqrt{2g}\left[H_{4(n+1)}{}^{1.5} + H_{4(n)}{}^{1.5}\right] \qquad (3.34)$$

$$\Delta Q_{p2out} = \frac{C_d}{D_{p2}} A_{p2}\sqrt{2g}\left[H_{4(n+1)}{}^{1.5} + H_{4(n)}{}^{1.5}\right] \qquad (3.35)$$

Therefore, the conservation of mass balance equation at P2 of the bioretention system is defined as:

$$\Delta S = [\Delta Q_{p2in} - \Delta Q_{p2out}]\Delta t \qquad (3.36)$$

$$A_{wetp2(n+1)}L_3 - A_{wetp2(n)}L_3 = \frac{\Delta t}{2} 0.0113 [C'\left[H_{3(n+1)}\right]^{1.5} + H_{3(n)}{}^{1.5}\,] - \frac{\Delta t C_d}{D_{p2}} A_{p2}\sqrt{2g}\left[H_{4(n+1)}{}^{1.5} + H_{4(n)}{}^{1.}\right.$$

where, A_{wetp2} is wetted area of perforated flow control pipe, and L_3 is the length of pipe P2. Wetted area of P2 may be computed as follows (details are shown in appendix F):

$$A_{wetp2} = 0.1196H_4 \qquad (3.38)$$

Now putting the value of A_{wetp2} in equation (3.39) we can get the following:

$$0.1196L_3H_{4(n+1)} - 0.1196L_3H_{4(n)} = \frac{\Delta t}{2} 0.0113 [C'\left[H_{3(n+1)}\right]^{1.5} + H_{3(n)}{}^{1.5}\,] - \frac{\Delta t C_d}{D_{p2}} A_{p2}\sqrt{2g}\left[H_{4(n+1)}{}^{1.5} + H_4\right.$$

3.3.9 Mass Balance at Manhole

The average inflow of water into manhole is equal to the outflow from P2. Therefore, average inflow into manhole is:

$$\Delta Q_{mhin} = \frac{C_d}{D_{p2}} A_{p2} \sqrt{2g} \left[H_{4(n+1)}{}^{1.5} + H_{4(n)}{}^{1.5} \right] \qquad (3.40)$$

The outflow of water from manhole may be computed by similar orifice flow equation derived by SWMM (mentioned earlier) as follows:

$$Q_{mhout} = C''' A_{mhexit} \sqrt{2gH_5} \qquad (3.41)$$

$$Q_{mhout} = A_{mhexit} \sqrt{2g} \frac{2C_d}{D_{mhexit}} H_5{}^{1.5} \qquad (3.42)$$

where, $C''' = \frac{2C_d}{D_{mhexit}}$ (obtained from similar derivation of SWMM Model), Q_{mhout} is outflow from manhole, A_{mhexit} is flow area, and H_5 is flow depth.

Therefore, average outflow from manhole during the time step is as follows:

$$\Delta Q_{mhout} = A_{mhexit} \sqrt{2g} \frac{C_d}{D_{mhexit}} \left[[H]_{5(n+1)}{}^{1.5} + H_{5(n)}{}^{1.5} \right] \qquad (3.43)$$

Therefore, the conservation of mass flow balance equation at manhole is written as:

$$\Delta S = [\Delta Q_{mhin} - \Delta Q_{mhout}] \Delta t \qquad (3.44)$$

$A_{\downarrow}mh\ [H_{\downarrow}5(n+1) - H_{\downarrow}5(n) = [C_{\downarrow}d/D_{\downarrow}p2\ \ A_{\downarrow}p2\ \sqrt{2g}\ [\ [H_{\downarrow}4(n+1)]\ \uparrow 1.5 + [H_{\downarrow}4(n)]\ \uparrow 1.5\ ] - A_{\downarrow}mhexit$

3.4 Development of Mathematical Model

The purpose of the mathematical model discussed below is to determine the depth of water level [$H_{1(n+1)}$, $H_{2(n+1)}$, $H_{3(n+1)}$, $H_{4(n+1)}$, $H_{5(n+1)}$], at a finite time step based on current time of the system and predicted rainfall. Since there are five unknowns in the hydraulic model in the previous section, it is possible to solve the equation without having any other equation. However, the Newton-Raphson method (detailed as shown in Appendix F) is used to solve the five equations simultaneously. Since most of the unknowns in mass balance equations are in rational exponential forms, substitution method is applied to simplify the unknowns before solving the system of algebraic equations. The following substitution of dependent variables is made prior to proceeding with the solution:

$X1 = \sqrt{H_1}$

$X2 = \sqrt{H_2}$

$X3 = H_3$

$X4 = \sqrt{H_4}$

$X5 = \sqrt{H_5}$

Therefore, H_1, H_2, H_3, H_4 and H_5 can be rewritten as follows:

$H_1 = X1^2$

$H_2 = X2^2$

$H_3 = X3$

$H_4 = X4^2$

$$H_5 = X5^2$$

Now the mass balance equation for catch basin (eq. 3.13) can be modified as:

$$A_{cb}\left[(X1^2)_{(n+1)} - (X1^2)_{(n)}\right] = \Delta t\left[\frac{1}{2}\Phi A_{catmt}\{i_{(n+1)} + i_{(n)}\}\right]E - A_{p1}\sqrt{2g}\frac{C_d}{D_{p1}\left[X1^2{}_{(n+1)} + X1^2{}_{(n)}\right]}$$

Further expanding the equation 3.46, results in the following expression:

$$A_{cb}(X1^2)_{(n+1)} - A_{cb}(X1^2)_{(n)} = \left[\frac{\Delta t}{2}\Phi A i_{(n+1)} + \frac{\Delta t}{2}\Phi A i_{(n)}\right]E - \Delta t A_{p1}\sqrt{2g}\frac{C_d}{D_{p1}}X1^2{}_{(n+1)} - \Delta t A_{p1}\sqrt{2g}\frac{C_d}{D_{p1}}$$

$$\Delta t A_{p1}\sqrt{2g}\frac{C_d}{D_{p1}}X1^2{}_{(n+1)} + A_{cb}(X1^2)_{(n+1)} - A_{cb}(X1^2)_{(n)} + \Delta t A_{p1}\sqrt{2g}\frac{C_d}{D_{p1}}X1^2{}_{(n)} - \frac{\Delta t}{2}E\Phi A i_{(n+1)} - \frac{\Delta t}{2}$$

Similarly, mass balance in pipe P1 (eq. 3.21) can be modified to:

$$X2_{(n)})$$

Further rearranging of equation 3.49, results in the following equation:

$$\Delta t A_{p1}\sqrt{2g}\frac{C_d}{D_{p1}}X1_{(n+1)}{}^2 + \Delta t A_{p1}\sqrt{2g}\frac{C_d}{D_{p1}}X1_{(n)}{}^2 - 0.1177L_1 X2^2{}_{(n+1)} + 0.1177L_1 X2^2{}_{(n)} - \frac{\Delta t}{2}2756X2_{(n+1)}{}^6 +$$

The mass balance equation (3.31) in the bioretention cell can be modified as:

$$0.2L_s W X3_{(n+1)} - 0.2L_s W X3_{(n)} = \frac{\Delta t}{2}2756X2_{(n+1)}{}^6 - \frac{\Delta t}{2}245.47X2_{(n+1)}{}^4 + \frac{\Delta t}{2}6.75X2_{(n+1)}{}^2 + \frac{\Delta t}{2}2756X2_{(n)}{}^6 -$$

Further rearranging the equation 3.51, we can get following:

$$\frac{\Delta t}{2}2756X2_{(n+1)}{}^{6}-\frac{\Delta t}{2}245.47X2_{(n+1)}{}^{4}+\frac{\Delta t}{2}6.75X2_{(n+1)}{}^{2}-0.2L_{s}WX3_{(n+1)}+0.2L_{s}WX3_{(n)}+\frac{\Delta t}{2}2756X2_{(n)}{}^{6}-$$

The mass balance equation (3.39) in the flow control pipe P2 can be modified as:

$$0.1177L_{s}X4^{2}{}_{(n+1)}-0.1177L_{s}X4^{2}{}_{(n)}=\frac{\Delta t}{2}0.0113C\sqrt{2g}X3^{1.5}{}_{(n+1)}+\frac{\Delta t}{2}0.0113C\sqrt{2g}X3^{1.5}{}_{(n)}-\Delta tA_{p2}\sqrt{2g}\frac{C_d}{D_{p2}}$$

Further rearranging the above equation, we can get the following:

$$0.1177L_{s}X4^{2}{}_{(n+1)}+\Delta tA_{p2}\sqrt{2g}\frac{C_d}{D_{p2}}X4^{3}{}_{(n+1)}-\frac{\Delta t}{2}0.0113C\sqrt{2g}X3^{1.5}{}_{(n+1)}+\Delta tA_{p2}\sqrt{2g}\frac{C_d}{D_{p2}}X4^{3}{}_{(n)}-\frac{\Delta t}{2}0.011$$

The mass balance equation (3.45) can be modified as:

$$A_{mh}X5^{2}{}_{(n+1)}-A_{mh}X5^{2}{}_{(n)}=\Delta tA_{p2}\sqrt{2g}\frac{C_d}{D_{p2}}X4^{3}{}_{(n+1)}+\Delta tA_{p2}\sqrt{2g}\frac{C_d}{D_{p2}}X4^{3}{}_{(n)}-\Delta tA_{mhexit}\sqrt{2g}\frac{C_d}{D_{mhexit}}X5^{3}{}_{(n+}$$

Further rearranging above equation, the following is obtained:

$$\Delta tA_{mhexit}\sqrt{2g}\frac{C_d}{D_{mhexit}}X5^{3}{}_{(n+1)}+A_{mh}X5^{2}{}_{(n+1)}-\Delta tA_{p2}\sqrt{2g}\frac{C_d}{D_{p2}}X4^{3}{}_{(n+1)}-A_{mh}X5^{2}{}_{(n)}+\Delta tA_{mhexit}\sqrt{2g}\frac{C}{D_{mh}}$$

Equations (3.48), (3.50), (3.52), (3.54) and (3.56) are fundamental nonlinear system of algebraic equations for the mathematical model. These equations are directly solved using Matlab program to determine the water depth in the catch basin ($H_1$1) , the distribution pipe (H_2), the bioretention cell(H_3), the flow control pipe(H_4), and the manhole (H_5) at different time steps.

Chapter IV

RESULTS AND DISCUSSIONS

Matlab *fsolve* function was employed to solve five nonlinear algebraic equations (eq. 3.48, eq. 3.50, eq.3.52, eq. 3.54, and eq. 3.56) simultaneously. The model was tested by the rainfall data of design storm of 10 years Chicago rainfall (Appendix A). The detailed numerical modeling results can be found in Appendix H. Figure 4.1 provides a graphical presentation of numerical model results. Figure 4.1 illustrates the water level in the catch basin (H_1), distribution pipe (H_2), bioretention cell (H_3), flow control pipe (H_4), and in the manhole (H_5). The water level at different parts of bioretention system represented the absolute elevation at different time steps.

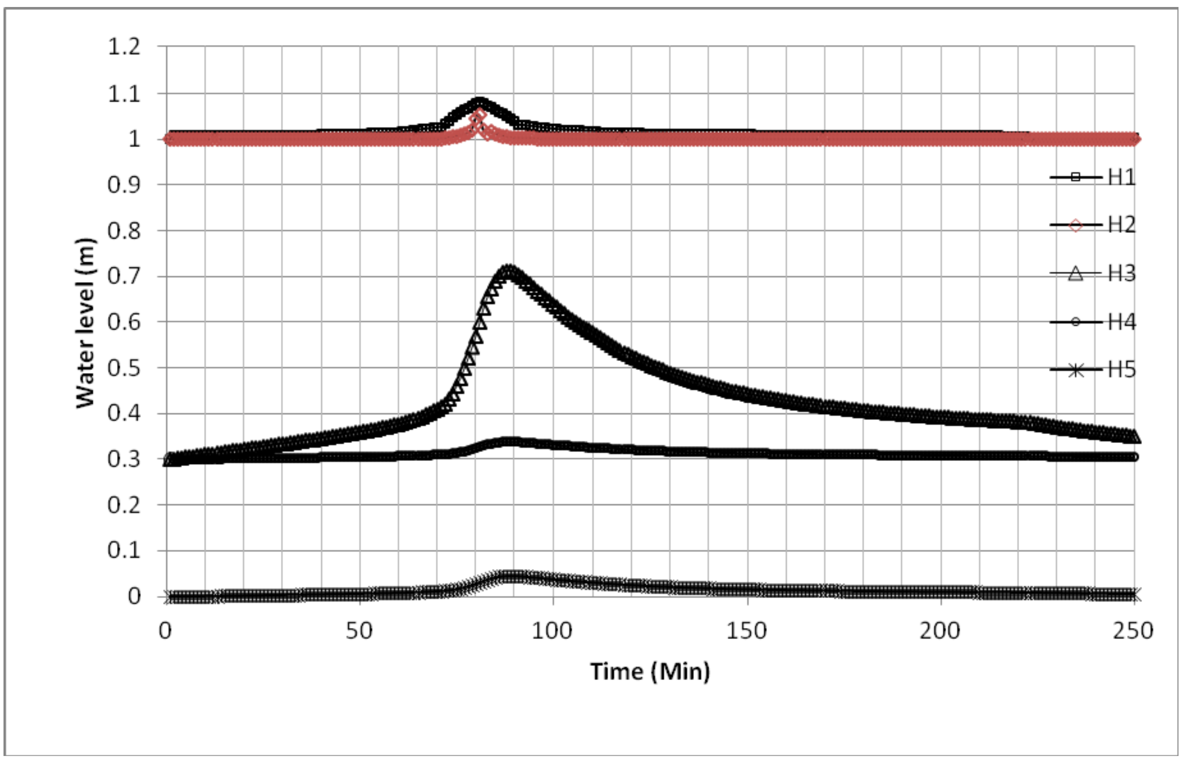


Fig. 4.1: Water level at different parts of bioretention system at different time step

Application of optimum pipe diameter is economic and can avoid any unexpected hydraulic issues in the bioretention system. A 10 years Chicago design storm event is introduced to the model, and run results appeared that the depth of water level in the pipe is increased gradually with the increase of rainfall intensity. And water level has reached its peak at a depth of 0.082 m. Note that, diameter of upper distribution pipe is 0.15 m which almost double of peak flow depth. This indicates that selected pipe diameter (0.15 m) is over estimated for 10 years design storm. However, perforated opening area of the pipe and their spacing and alignment are also important factors. According to manufacturers record opening diameter of a perforation is 4.25 mm and area of each opening is 0.14135 cm^2, hence opening area of the selected pipe is 34.27 cm^2 per meter. It is also mentioned that the perforation spacing is 7.2 cm both along and cross the direction of the pipe.

4.1 Upper Distribution Pipe (P1)

The rainfall intensity at the beginning of the rainfall event is low so it takes 6 minutes to fill the dead storage volume of catch basin. After that the runoff water starts to flow into pipe P1. In the catch basin, peak runoff water level (H_1) is reached at of 0.082 m after 81 minutes of 240 minutes duration of rainfall. It indicates that the water level in the catch basin is above the centerline of P1 for a minute and water level before and after peak remains below the centerline of the P1.

On the other hand, peak runoff water level (H_2) in the distribution pipe is also reached at 0.082 m after 81 minutes of rainfall. Here, it can be noted that water level 0.082 m is an average depth in the pipe P1. And this is possible if the perforation alignment and pipe placement is considered as shown in Fig. 4.3, otherwise runoff water starts to flow instantly when it reaches at first perforated opening of P1 and continues to advance the water front when inflow is greater than outflow through the first opening.

4.2 Bioretention Cell

Height of bioretention cell is important because storage capacity of it increases with the increase of cell height. Off course, soil properties (void space) also important for the same reason.

In the present modeling study, the peak water level (H_3) in the bioretention cell is built up a head of 0.55 m in soil cell after 87 minutes of rainfall. It is revealed that the peak water level is slightly higher than half of the height (0.80 m) bioretention cell. The model results indicated that if the hydraulic conductivity of bioretention soil reduced by the subsidence and compaction with the age of the bioretention system still the system could pass the runoff flow without causing any unexpected overflow from bioretention cell.

4.3 Flow Control Pipe

The elevation of flow control pipe can make a difference in passive storage capacity of bioretention system. As shown earlier in Fig. 2.2, the elevation of flow control in the enhanced system is higher than basic system and this allows a considerable amount of storage in bioretention system.

In the present modeling study peak water level (H_4) in flow control pipe (P2) is 0.047 m and it is reached at 88 minutes of rainfall. However, designed diameter of flow control pipe is 0.20 m that is also appeared over estimated.

4.4 Manhole

The manhole is end part of the bioretention system that drains the runoff water to sewer system. In designing of bioretention system, sewer elevation is important but designer has no option to change this. However, based on the sewer elevation designer should accommodate and design the bioretention system. In the modelling results peak water level (H_5) in manhole is 0.056 m that is reached at the same time as the peak flow in P2.

4.5 Runoff Diversion Capacity of the Bioretention System

The runoff volume generated for a 10 years design storm of 4 hrs duration is 21.06 m^3. It is determined that the average grate efficiency is 84 percent. Therefore 17.69 m^3 of runoff water will enter into the bioretention system. The size of the bioretention cell is 18.02 m x 3.20 m x 0.80 m. The textural class of bioretention cell is sand (see appendix G) and average porosity is 0.437 (Mays, 2005). Therefore, the bioretention cell can store 20.16 m^3 (18.02 m x 3.20 m x 0.80 m x 0.437) of runoff water in its void space if the outlet elevation of flow control pipe is at the same elevation of the top distribution pipe. Therefore, the bioretention cell has more capacity to store runoff water from the grate. However, in the present set up the outlet elevation of P2 is 0.80 m below the elevation of P1. Nevertheless the peak runoff water level at bioretention cell was found to be 0.55 m. Thus, bioretention cell is still occupying 13.86 m^3 (18.02 x 3.20 x 0.55 x 0.437) of runoff water that could be drained gradually over time. Therefore, the diversion efficiency of the bioretention system is 66 percent.

4.6 Hydraulics of Bioretention System

It is mentioned earlier that a perforated pipe (P1) of diameter 0.15 m is installed to distribute runoff water into the bioretention cell. The pipe has openings all along its circumference with certain space in between. The diameter of each perforated opening on the pipe circumference is 0.00424m. However, 40 water opening are measured, which has given water opening area 5.654 cm^2 in 0.165 m of the pipe or 34.27 cm^2 per meter of the pipe. These perforated openings are considered as an orifice. For pipe P1, collective flow formula through its openings are derived as a function of flow depth [i.e., $Q_{P1out}=f(H_2)$] by SWMM program and this Q_{P1out} is introduced to mass balance equation in P1. Since Q_{P1out} is not a free flow rather restricted by surrounding soil, therefore a factor is introduced and its value is assumed 0.20 to balancing the model.

Similar perforated openings are existed in flow control pipe P2. Flow through these openings are computed as a function of water depth (H_4) in P2 i.e., $Q_{P2out}=f(H_4)$.

The hydraulic model can run simultaneously, and each parameter can be varied to evaluate the impacts or effects to others parameters. Thus, the size of the each hydraulic parameter can be varied and adjusted accordingly for specific design requirement. To understand the model clearly an example of an application of the model is introduced in the next chapter.

4.7 Sensitivity Analysis of the Model

Sensitivity analysis of the model is performed by systematically changing parameters in the model to determine the effects of such changes. This sensitivity analysis reflects the relationship between input and the output of the mathematical model.

4.7.1 Model Response in Change of Bioretention Cell Height

Bioretention cell height is gradually increased from its original height (0.80m) as 10%, 20%, 30% and decreased as -10%, -20%, -30%. The effects of cell height in bioretention system are presented in Fig. 4.2.

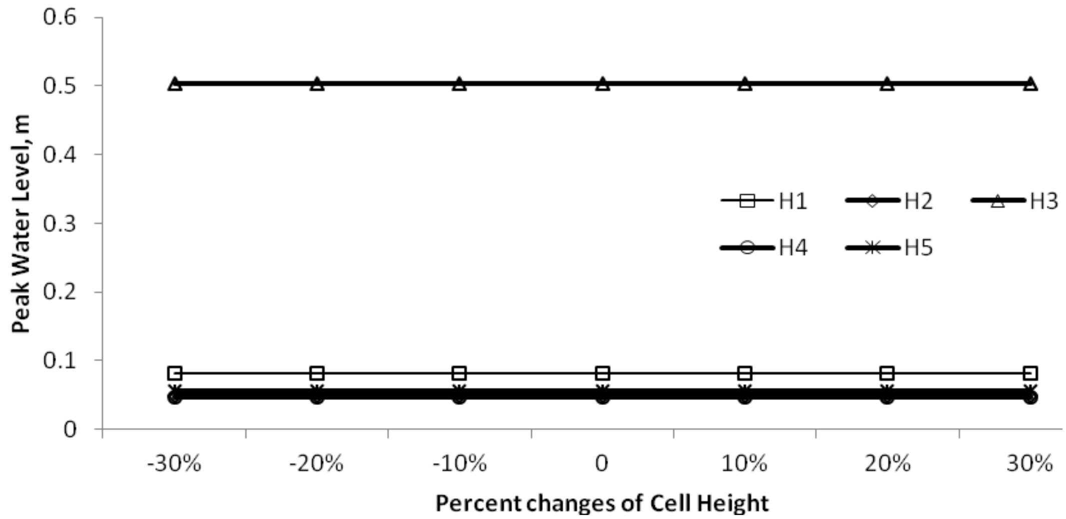


Fig. 4.2: Variation of water level with the change of bioretention cell height

It is revealed that there is no effect of cell height on peak water level variation in bioretention system.

4.7.2 Model Response due to Change of Pipe Diameter (P1)

The diameter of upper distribution pipe is gradually increased from its original diameter (0.15m) as 10%, 20%, 30% and decreased as -10%, -20%, -30%. The effects of these changes in bioretention system are presented in Fig. 4.3. It is appeared that peak water level (H_1) in catch basin increased with decrease of pipe diameter of P1. No significant changes of peak water levels are observed in others parts (H_2, H_3, H_4 & H_5) of bioretention system.

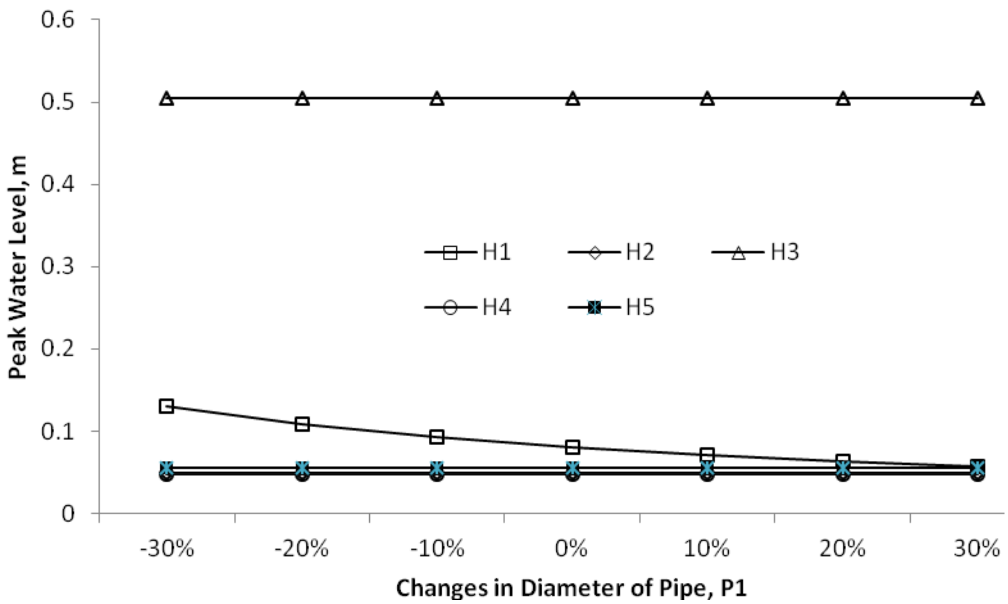


Fig. 4.3: Variation of water level with the change of diameter

4.7.3 Model Response due to Change of Rainfall Intensity

The model is run with design storm of various return periods to observe the scenario of peak water level in different parts of the bioretention system. Model results are summarized and presented in Table 4.1. It is appeared that peak water level in different parts of bioretention system such as catch basin (H_1), upper distribution pipe (H_2), bioretention cell (H_3), flow control pipe (H_4) and manhole (H_5) are increased with the increase of higher rate of rainfall intensity (Table 4.1). In catch basin, it is apparent from model results that the peak runoff water level is gradually increased and reached to 0.082 m and receded gradually (Appendix H) after a minute. Similarly, peak water levels are reached to 0.091 m and 0.109 m, respectively for the return period of 25 years and 100 years in catch basin.

It indicated that bioretention system might not overflow during the storm of 25 years return period and above. However, peak water levels are stayed below their crown level in pipe P1, bioretention cell, flow-control pipe (P2) and manhole.

Table 4.1: Peak water level in different rainfall intensity

Chicago rainfall intensity	H_1	H_2	H_3	H_4	H_5
2 yrs	0.057	0.045	0.339	0.032	0.038
10 yrs	0.082	0.049	0.499	0.047	0.056
25 yrs	0.091	0.056	0.569	0.053	0.063
100yrs	0.109	0.070	0.705	0.066	0.078

This indicated that no possibility of flow congestion or overflow in P1, bioretention cell, P2 and manhole. However, the bioretention system is design and constructed in such a way that when catch basin will be filled, runoff water would be splashed over the grate of catch basin.

Chapter V

Model Application

The design criteria, size and specification of conventional bioretention system are improving with the course of time, research, development and application. However, design criteria and its related matters on underground bioretention system are inadequate. The purpose of hydraulic modeling of underground bioretention system is to improve its design criteria, size and specification thereby controlling runoff water quality and quantity. This section will highlight the facts and findings of hydraulic design model for underground bioretention system and an example of how to use this model for similar facility will be presented.

5.1 Present Model Work

Present numerical hydraulic model has emphasized on the design specification for underground bioretention system. As mentioned earlier that this system has included a catch basin that collected street runoff, a perforated distribution pipe that fed runoff to the bioretention cell, a bioretention cell that contains bioretention soil which conveys runoff water to bottom of the cell, and a flow control pipe that flow water from cell to city sewer via a manhole.

5.1.1 Catch Basin

The runoff rate of an event can be computed from rainfall intensity and catchment area. The catch basin has standard design specification including its grate for every municipalities, thus street runoff that enters into catch basin can be calculated by using empirical formula (Akan and Houghtalen, 2003) as shown in Appendix C (Fig. C.2). However, depending on the catchment area number of catch basin for an underground bioretention system might be added. The hydraulic design model of underground bioretention system doesn’t change any parameters of catch basin.

5.1.2 Distribution Pipe

If the outflow from catch basin is known then the outflow from distribution pipe to cell can be computed from the model for any number and size of opening. The volume of runoff can be computed by using the model. If the total flow rate through the medium is higher than the flow rate into flow control pipe then a saturated depth in the cell will be built up.

5.1.3 Size of Underground Bioretention System

The size of the underground bioretention system widely varied depending on local condition as described earlier. The construction of underground bioretention system is getting popularity in densely urbanized downtown where surface space is limited. Therefore, size of underground bioretention system should be matched with the space of sidewalks and/or parking bays. The width of sidewalk is limited between property line and street curbs, therefore width of bioretention system should not be more than the width of sidewalk. However, the length of the bioretention system can be extended depending on the requirement of storage volume for a particular catchment area.

The depth of the underground bioretention system is limited between the elevation of street level and the top of storm sewer pipe. The present model can be matched with any size of underground bioretention system according to the site condition.

Fig 5.1 has represented the potential storage volume for underground bioretention system. In Fig. 5.1 (a) flow control pipe is placed on the bottom slab which makes the bioretention system with sufficient active storage but no passive storage is available thus most part of the runoff water will be drained by gravity. In Fig. 5.1 (b), the flow control pipe is placed above the bottom slab to form a plenty of passive storage but less active storage for runoff water.

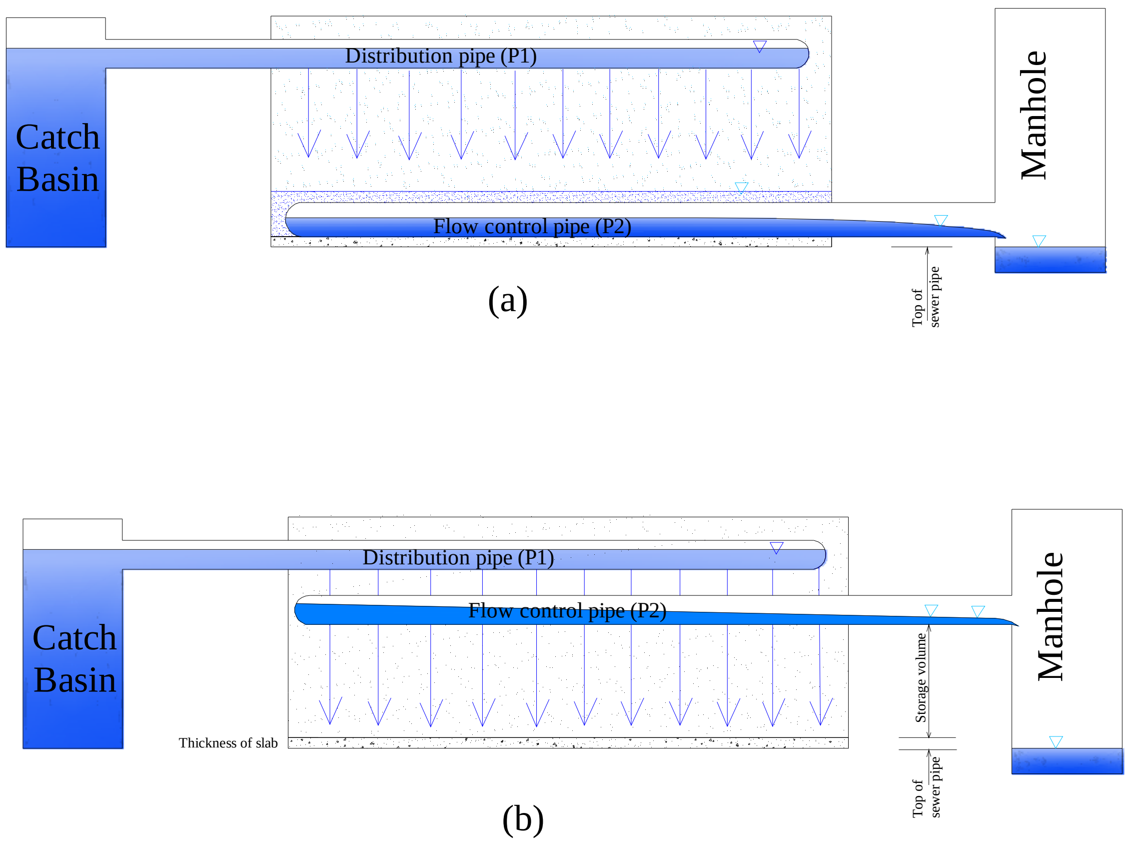


Fig. 5.1 Storage Volume in underground bioretention system

5.2 Exercise of the Model

For example, a municipality is planning to construct an underground bioretention system at a location of old downtown where surface space is limited. They want to build it under the sidewalk. The sidewalk width of the proposed site is 3.00m where length can be extended as long as it is required. The catchment area on the street that will be feeding to a nearest catch basin is 400 m^2. The grade of catch basin is 91.50 m and the elevation of storm sewer pipe top is 90.43

m. The municipality also want to plant some species of plant at the location of underground bioretention system that needs adequate water even during dry days. The municipality requested for proposal (RFP) from a consulting firm to design and construct the expected underground bioretention system.

In response to RFP, underground bioretention consultant of the consulting firm realized that they had developed a hydraulic design model for underground bioretention system and they can apply their model for this project. Instantly, consultant tried to figure out the given data and compared them with the data requirement for the model. Following step by step procedures can be adopted to develop and analyze the model.

5.2.1 Step by Step Procedure

Step-1

Required data for the model:

i. A_{catmt} , Catchment area (L^2)

ii. Φ, Runoff coefficient

iii. Δt , Time step, (T)

iv. L, Length of bioretention system (L)

v. W, Width of bioretention system (L)

vi. L_1,Length of distribution pipe (L)

vii. L_2, Length of flow control pipe (L)

viii. i, Rainfall data (L/T)

ix. D_{p1},Diameter of distribution pipe (L)

x. D_{p2}, Diameter of flow control pipe (L)

xi. D_{mhexit}, Diameter of manhole exit, (L)

xii. A_{cb}, Cross sectional area of catch basin (L^2)

xiii. A_{bc}, Cross sectional area of bioretention cell (L^2)

xiv. H_{bc}, Height of bioretention cell (L)

xv. K_{ns}, Hydraulic conductivity of native soil (L/T)

xvi. r, Reduction factor to account for clogging which depends on the number of years of use (Abida et al., 2007)

xvii. s Hydraulic gradient [L/L], assumed conservatively to be 1.0 m/1m (Abida et al., 2007).

xviii. A_{wetp1}, Wetted area as function of water depth in distribution pipe

xix. A_{wetp2}, Wetted area as function of water depth in flow control pipe

Step-2

Open Matlab Program and write down the parameters and their values in each line.

Add data to model

i. A_{catmt} =400

ii. Φ=0.98

iii. Δt =60

iv. L=19.0

v. W=3.0

vi. L_1=35.0

vii. L_2=18.0

viii. i, 10 years Chicago rainfall data

ix. D_{p1}=0.15

x. D_{p2}=0.20

xi. D_{mhexit},=0.30

xii. A_{cb}=0.60 x 0.60

xiii. A_{bc}=19.0x 3.0

xiv. H_{bc}=91.50-90.43-0.30 (Free space)=0.77

xv. K_{ns}=0.0000018

xvi. r=0.8,

xvii. s =1.0, assumed conservatively to be 1.0 m/1m (Abida et al., 2007).

xviii. A_{wetp1}, Wetted area as function of water depth in distribution pipe

xix. A_{wetp2}, Wetted area as function of water depth in flow control pipe

Step-3

Write down the mass balance equations in *fsolve* function

Step-4

Set the conditions

Step-5

Run the model. If there is no error and run the model is run successfully then check results of the water level in various parts of bioretention system at different time step.

5.2.2 Model Results

The model results of water depth at different time steps in catch basin (H_1), distribution pipe (H_2), bioretention cell (H_3), flow control pipe (H_4) and manhole (H_5) are shown in Appendix J.

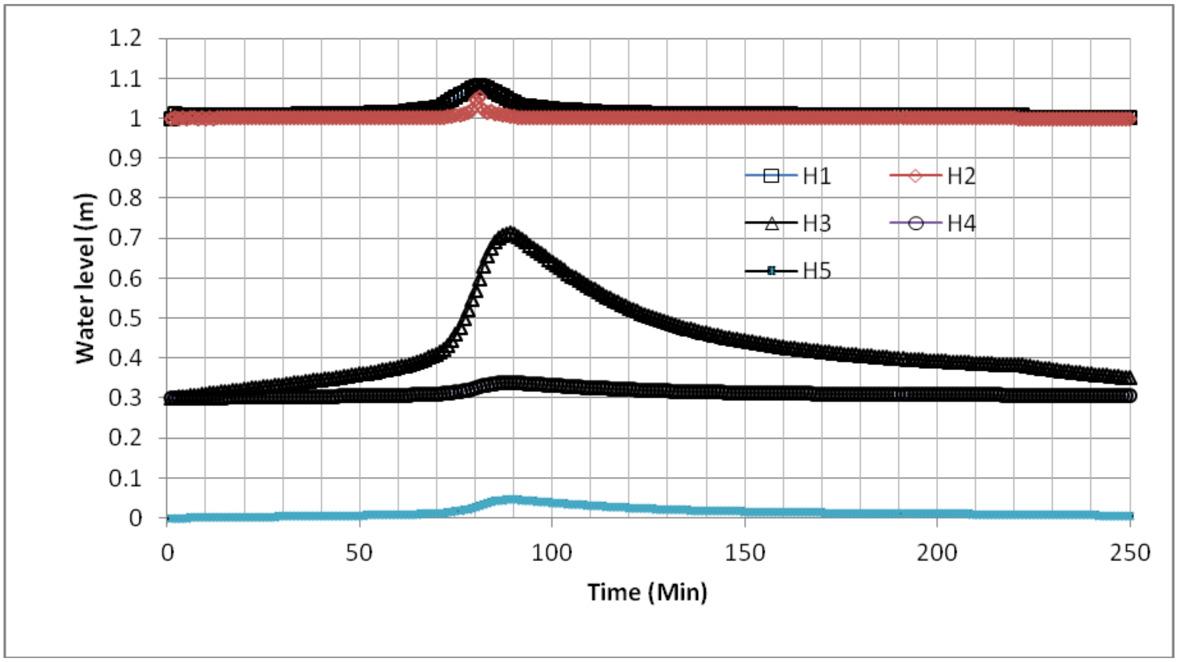


Fig. 5.2:Water level with time in different parts of bioretention system

Model results (Fig. 5.2) represented that peak water level in catch basin and P1 were respectively 0.083 m and 0.052 m after 81 minutes of rainfall. It was also revealed that except for 1 minute of peak, flow depth from catch basin to P1 is below the centerline of the pipe P1. However, peak water level (0.4117 m) in bioretention cell is observed after 89 minutes of rainfall begin. Noteworthy that peak water level in flow control pipe and manhole are respectively 0.039 m and 0.046 m at the same time of after 89 minutes of rainfall. Model results indicated that there is no overflow in any of the component in bioretention system.

5.2.3 Pipe Diameter

To determine the right size of distribution pipe, diameter is reduced from 0.15m to 0.10 m, and run the model. It is observed that peak water depth in catch basin was 0.143 m that is 0.043 m above the crown level of P1. The diameter of P1 further reduced to 0.08 m and run the model to observe the scenario. It is found that the peak water depth in catch basin is 0.193 m, which is 0.113 m higher than the crown level of P1.

Again, diameter of P1 is changed to 0.12 m and run the model. It is appeared that the peak water depth in catch basin is 0.1122m that is the best adjustment for distribution pipe diameter if the system is designed for 10 years design storm. Note that there is no significant difference of water level in P1, bioretention cell, P2 and manhole is observed due to the change of diameter of P1.

5.2.4 Storage Capacity

The Fig. 5.3 represents the bioretention system that is designed for proposed site of the municipality. The main difference between the Fig. 5.3 (a) and (b) is the elevation of flow control pipe. In Fig. 5.3 (a) the elevation of flow control pipe is as low as on the bottom slab, so substantial part of the cell is an active storage, wherein water is hold by soil particle by its field capacity, but no passive storage is available. However, flow control pipe can be placed at different elevation depending on the site condition and storage requirement. If the flow control pipe is placed at its maximum possible higher elevation, it can be stored maximum volume of runoff water that eventually will reduce the downstream flooding as well as support the plants. Since, proposed site is expected to be planting, thus passive storage for the system is essential.

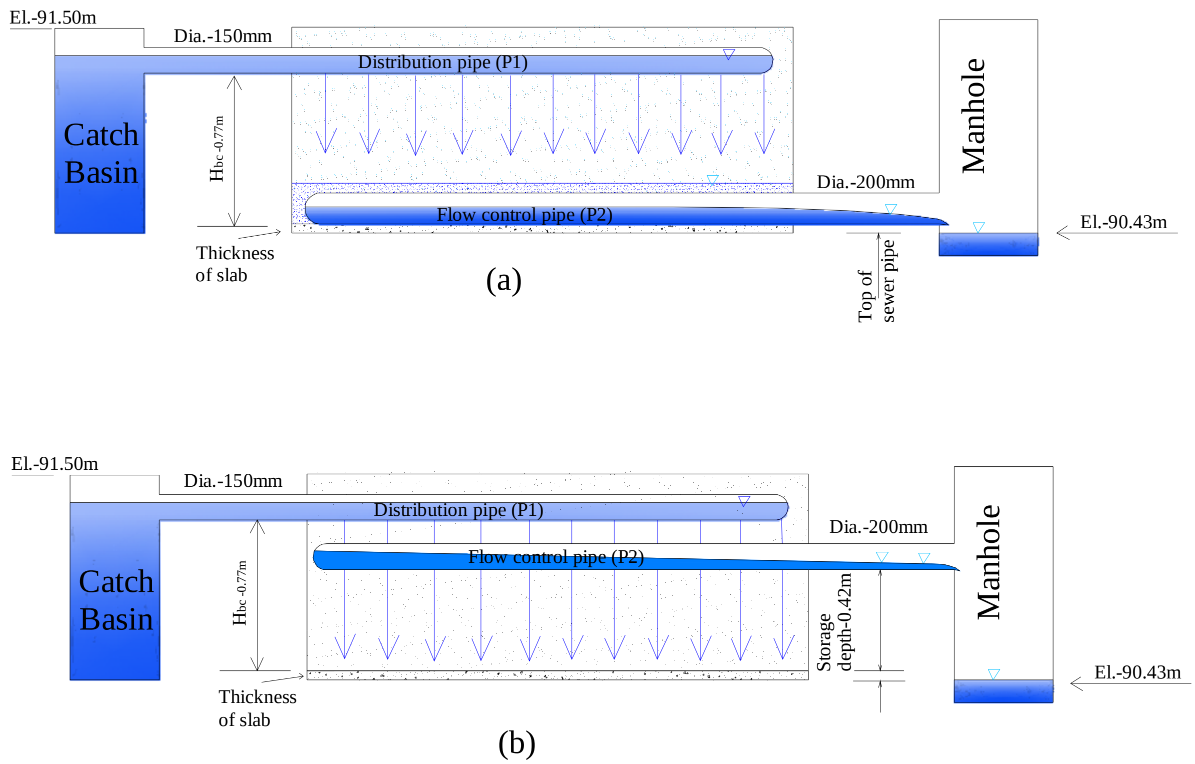


Fig. 5.3: Underground bioretention system

A 10 years Chicago storm for the duration of 4 hrs can generate 22.33 m^3 of rainfall over the catchment area. It is assumed that the runoff coefficient for impervious surface is 0.98, thus runoff volume from 400 m^2 of catchment area is 21.88 m^3. It is determined that the average grate efficiency is 84 percent by using empirical formula (Akan and Houghtalen, 2003). Therefore, the amount of runoff water entering into catch basin is 18.47 m^3 and runoff bypass is 3.41 m^3.

The porosity of bioretention soil is assumed to be 0.42 (Mays, 2005), therefore passive storage capacity in bioretention system is [(3.00 x 19.00 x 0.42) x0.42] 10.05 m^3. This is indicated that 8.42 m^3 (18.47 – 10.05) of water could be drained from bioretention system to storm sewer and remaining volume (10.05 m^3) of runoff will be stored in the cell. Again, storage capacity is greatly varied with elevation of flow control pipe. Therefore, storage capacity of case (b) is higher than case (a) in Fig 5.3.

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

The hydraulic design model developed in this thesis is important for the design of the bioretention system in most downtown area of the municipalities. The requirements of specification standard for underground bioretention system need extensive studies as well as monitoring by design and build facilities.

6.1 Conclusions

This research is undertaken to develop a numerical hydraulic design model that might be useful to design similar underground bioretention systems similar to that constructed at The Queensway Avenue in Toronto. The underground bioretention system includes five components such as catch basin, distribution pipe, bioretention cell, flow control pipe and manhole. Five mass balance equations for five components are developed and *fsolve* function of Matlab program is employed to solve these equations simultaneously. A 10 years Chicago storm event is used to illustrate the application of the model under different design scenarios.

Based on hydraulic model analyses, water level in each component of underground bioretention system is determined for different time steps. It is appeared that peak water level in each component of the underground bioretention system is below its corresponding crown level. It is implied that the diameter of upper distribution pipe is larger than its requirement. From the model analysis it is shown that 0.12 m diameter of upper distribution pipe can adequately drain the 10 years flow entering the grate. In fact, the upper distribution pipe of the Queensway's underground bioretention system is conservatively designed with diameter of 0.15m.

The peak water level in bioretention cell is 0.55 m, which is 0.25 m below its design maximum height of 0.80 m. As mentioned in Chapter V, the flow control pipe can be positioned 0.25 m higher from bottom concrete slab level. This will allow permanent storage in the bioretention cell.

The bioretention cell has void space that can occupy 20.16 m^3 whereas total runoff water entering the grate is 17.69 m^3. However, the bioretention system does not provide a lot of detention. As 10 years runoff enters and exits the system quickly, the system captures all the runoff entering the grate.

The flow control pipe allows cell water to enter it through its perforations. This water eventually conveys to street sewer system through manhole. The perforated opening area is increased with the increase of pipe diameter. The Queensway underground bioretention facility is designed with flow control pipe diameter of 0.20 m. In the model sensitivity analysis the diameter of the flow control pipe was increase and decrease to observe any impact to other component of bioretention cell. However, no significant impact or change is observed. Only the water level in catch basin increases with the increase of the upper distribution pipe diameter. There was no significant change of model results for other design parameters. Further, existing size of the flow control pipe doesn’t create any flow back up in bioretention cell, and is considered to be adequate.

The manhole in bioretention system is designed using the local city design standard where bioretention system designer’s options are limited. The standard size and elevation of storm sewer system should have to be considered as base condition in designing the bioretention system.

Sensitivity analysis is performed by systematically changing different parameters of bioretention system. Only water level in catch basin increases with the decrease of upper distribution pipe diameter however there is no significant change of other parameters.

In this hydraulic design model all the parameters are solved by the *f*solve function of Matlab program and can be simulated simultaneously . Therefore, relative changes of all parameters due to change of any one parameter can be determined. In the model, each parameter can be varied to evaluate the impacts or effects to others parameters. Thus, the size of the each hydraulic parameter can be varied and adjusted accordingly for specific design requirement. To understand the model clearly an example of an application of the model was introduced in Chapter V.

The grate efficiency is an important factor in the design of underground bioretention systems. The grate controls the volume of water to be entered into catch basin and eventually into the bioretention system. The grate efficiency is not directly incorporated to the model rather its entering efficiency is calculated and presented in Appendix C (Fig. C.2). Runoff flow for the model is generated from a design storm of 10 years Chicago rainfall. The grate efficiency for this event of rainfall is decreased with the increase of rainfall intensity and runoff; and efficiency is observed at its lowest level when the rainfall intensity is in peak. However, in reality bioretention system is only captured a portion of runoff but not all. For large rainfall events the bioretention system will be completely saturated with water and the runoff water will be overflowed the grate of the catch basin. For small rainfall events in which the runoff is equal or less than the capacity of the grate, the bioretention system captures all the runoff.

The alignment of the perforated opening of the upper distribution pipe is a very important design parameter because it controls the flow distribution through the pipe. If the perforated opening is positioned at the bottom of the distribution pipe, most of the flow may dissipate in the front length of the pipe. As a result, development of uniform flow throughout the pipe will not be established. Therefore, special attention is needed in the design of perforation alignment. In fact, if there is no perforation at the bottom part of the pipe, the flow can be distributed uniformly throughout the whole pipe.

6.2 Recommendations

The model is developed on the basis of the hydraulic parameters of the bioretention system constructed at Queensway Avenue in Toronto. This model is run with theoretically developed using mass balance equations for each component of the system. According to the hydraulic computation of numerical model, it is appeared that water level in each component of bioretention system is below its maximum capacity. However, the model requires calibration and validation with field data. Therefore, collection of field data and verification of the model is recommended.

The primary goal of constructing underground bioretention system at Queensway Avenue is to control runoff water at lot level and to evaluate the runoff water quality and quantity. The hydraulic capacity of underground bioretention system is determined theoretically but water quality issues are not investigated. So, collecting and monitoring field data in respect of runoff quantity and quality is strongly recommended.

The orientation and spacing of the perforated opening in upper distribution pipe are not incorporated to the model. Inclusion of these design parameters and further development of model are highly recommended.

The underground bioretention system can include plantation spots. Urban plantation strategy is developed from the concept of forestry and landscape architecture. The urban street environment is mainly covered with asphalt and concrete where thermal flux and radiation is high. As a result transpiration from urban plant is also high (Higashima et.al., 2007). The bioretention cell in urban environment is covered with concrete slab. Therefore no soil evaporation will be taken place from bioretention cell, and only transpiration will only be occur through the leaf of the plant.

Transpiration of plant depends on many factors such as growth stage, age of plant, sunlight hour, radiation, wind, location and so on (Hagishima et. al., 2007). A study showed that the average transpiration rate of medium size plant is 204.5 g/day/tree (Hagishima et. al., 2007). Based on this reference it is assumed that a medium size plant can transpire 0.21 m^3 per day. The average daily seepage through the native surrounding soil is [0.0000018 m/s x 2(3+19) m x 3600 s] 0.06 m^3/day. Therefore, passive storage water can be used by plant at least [10.05 m3/(0.21+0.06) m^3/day] 37 days.

APPENDIX A

Design Storm Data

Table A.1: Average daily temperature and precipitation at Toronto

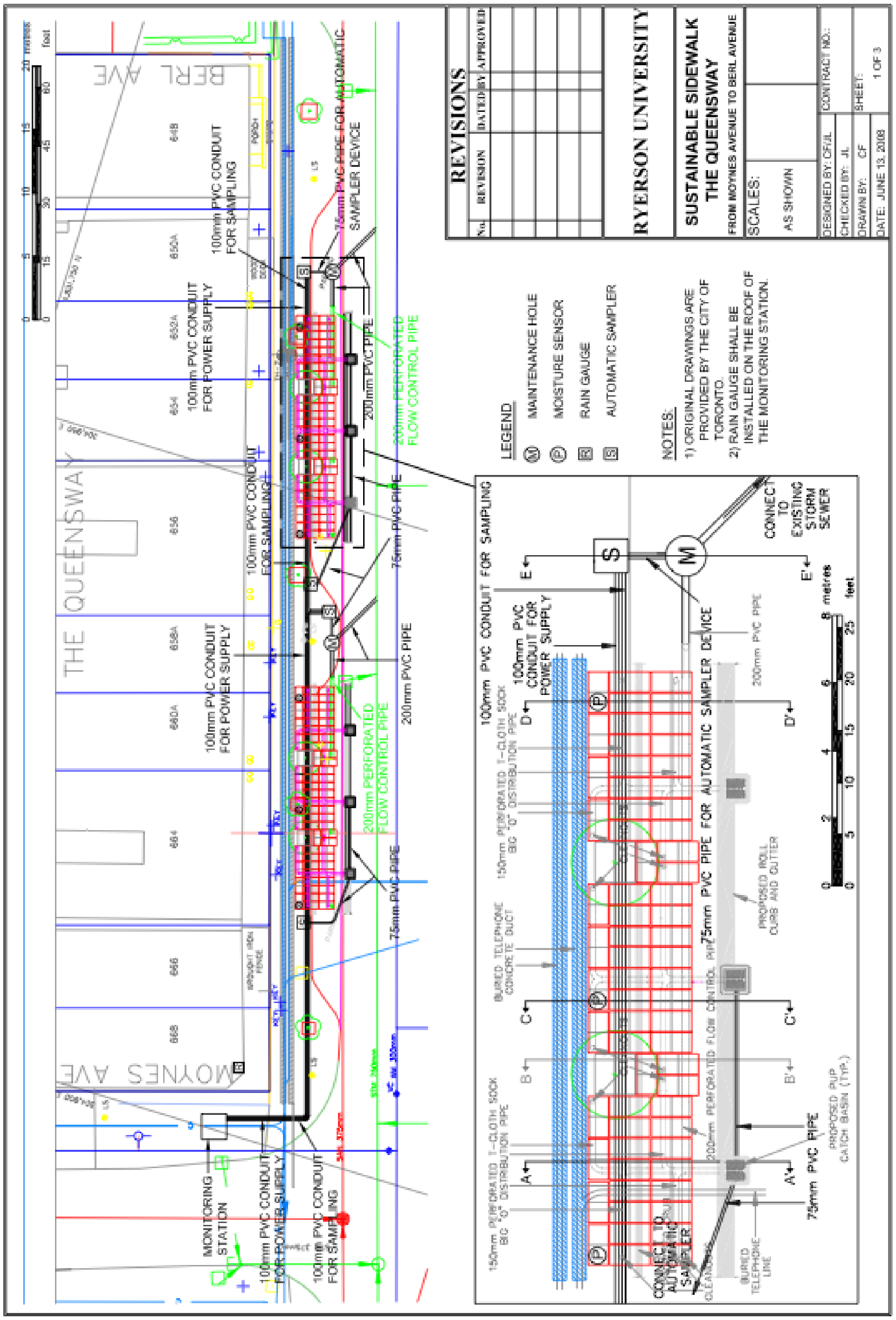
Month	Average Daily Temp (^{O}C)	Av. Daily Minimum Temp. (^{O}C)	Av. hours Sunshine (per day)	Av. Days with Rainfall	Av. Days with Snowfall	Av. Depth of Snow on Ground (cm)	Average Wind speed (km per hr)
Jan.	-1	-7	2.8	5	12	7	18
Feb.	0	-6	3.9	5	9	7	17
Mar.	5	-2	5.0	8	6	3	17
Apr.	11	4	6.2	11	2	0	17
May	18	10	7.4	12	0	0	14
Jun.	24	15	8.3	11	0	0	13
Jul.	26	18	8.9	10	0	0	12
Aug.	25	17	7.8	11	0	0	11
Sep.	21	13	6.3	11	0	0	12
Oct.	14	7	4.8	11	0	0	13
Nov.	7	2	2.8	11	3	0	16
Dec.	2	-4	2.4	7	10	3	16

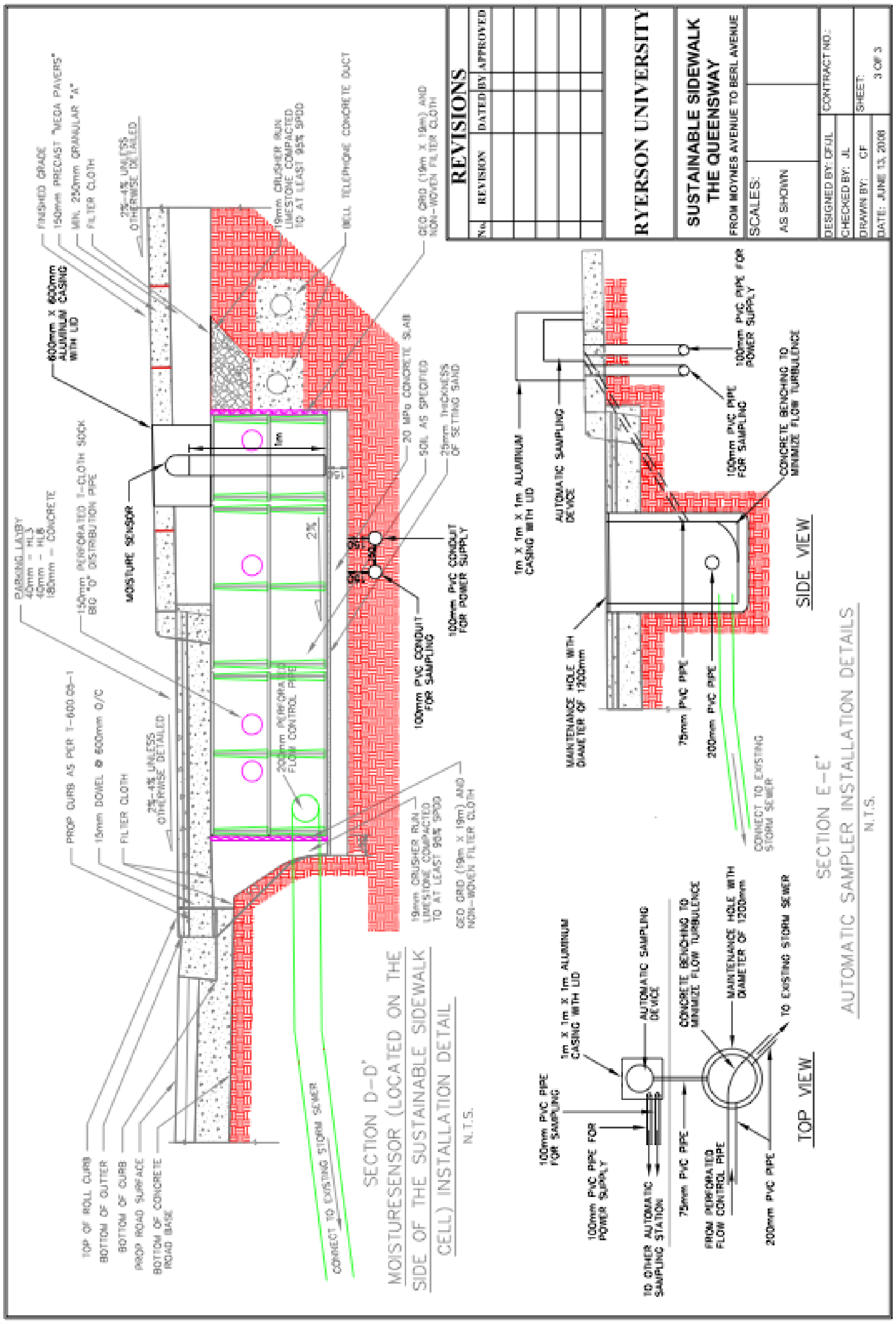
Table A2 : Chicago rainfall for different return period

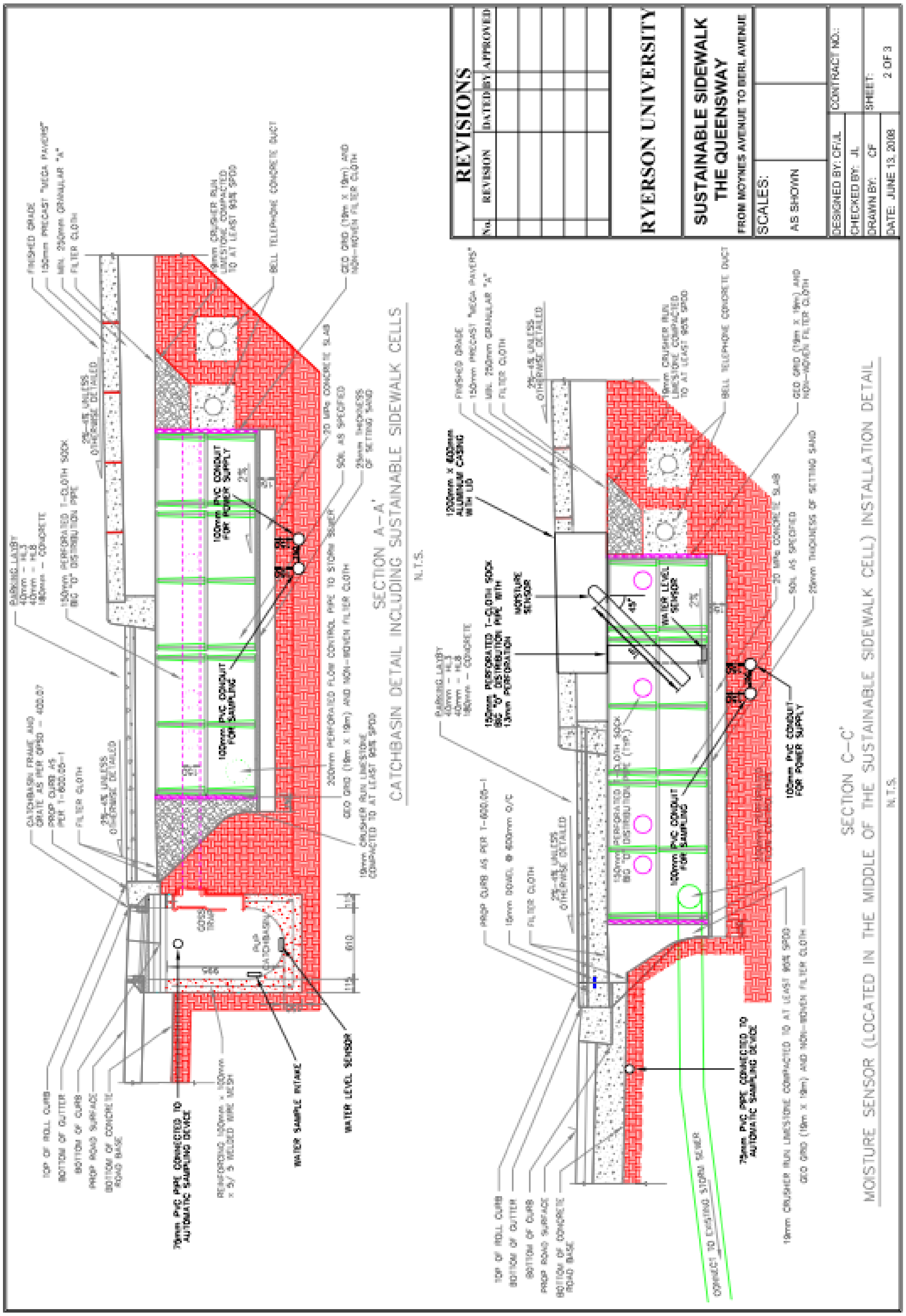
Time	Chicago Rainfall (mm/hr)			
	2 yrs	10 yrs	25 yrs	100 yrs
0:10	3.25	3.58	4.24	4.50
0:20	3.56	3.99	4.98	5.05
0:30	3.96	4.50	5.61	5.82
0:40	4.52	5.21	6.45	6.83
0:50	5.31	6.27	7.70	8.41
1:00	6.55	8.00	9.70	11.07
1:10	8.94	11.51	13.64	16.87
1:20	16.92	24.82	27.69	41.07
1:30	78.82	133.60	158.85	205.92
1:40	20.98	32.00	35.08	54.56
1:50	13.00	17.93	20.60	28.17
2:00	9.88	12.95	15.24	19.28
2:10	8.15	10.31	12.32	14.83
2:20	7.01	8.66	10.44	12.12
2:30	6.20	7.52	9.14	10.31
2:40	5.59	6.65	8.15	9.02
2:50	5.11	6.02	7.39	8.03
3:00	4.72	5.49	6.78	7.24
3:10	4.39	5.05	6.27	6.60
3:20	4.11	4.70	5.84	6.10
3:30	3.89	4.39	5.49	5.66
3:40	3.68	4.14	5.18	5.28
3:50	3.51	3.91	4.90	4.98
4:00	3.35	3.71	4.65	4.70

Appendix B

Fig. B.1: Detail Design of Bioretention System




REVISIONS
RYERSON UNIVERSITY
SUSTAINABLE SIDEWALK
THE QUEENSWAY
FROM MOYNES AVENUE TO BERL AVENUE
SCALES:
AS SHOWN
SECTION D-D'
MOISTURESENSOR (LOCATED ON THE SIDE OF THE SUSTAINABLE SIDEWALK CELL) INSTALLATION DETAIL
N.T.S.
SECTION E-E'
AUTOMATIC SAMPLER INSTALLATION DETAILS
N.T.S.
SIDE VIEW
TOP VIEW



REVISIONS
No.
REVISION
DATED
BY
APPROVED
RYERSON UNIVERSITY
SUSTAINABLE SIDEWALK
THE QUEENSWAY
FROM MOYNES AVENUE TO BERL AVENUE
SCALES:
AS SHOWN
DESIGNED BY: CF/JL
CHECKED BY: JL
DRAWN BY: CF
DATE: JUNE 13, 2008
CONTRACT NO.:
SHEET:
2 OF 3
SECTION A-A'
CATCHBASIN DETAIL INCLUDING SUSTAINABLE SIDEWALK CELLS
N.T.S.
SECTION C-C'
MOISTURE SENSOR (LOCATED IN THE MIDDLE OF THE SUSTAINABLE SIDEWALK CELL) INSTALLATION DETAIL
N.T.S.
WATER LEVEL SENSOR
WATER SAMPLE INTAKE
100mm PVC CONDUIT FOR POWER SUPPLY
100mm PVC CONDUIT FOR SAMPLING
CONNECT TO EXISTING STORM SEWER

APPENDIX C

Flow Through Grate Inlet

Rainfall on road surface produces runoff and this runoff flows along the gutter of the street, and grate of catch basin is on the way of flow. Indeed, all runoff water will not be entered into catch basin rather splashover the grate specifically during intensive rainfall. The efficiency of grate inlet depends on inlet type, gutter characteristics and flow in gutter. Runoff produces from low intensity and short duration rainfall might be entered into catch basin fully but runoff produced from the rainfall of high intensity might not be entered into catch basin fully. To determine the efficiency of grate inlet, the total gutter flow is treated as having two parts: frontal flow and side flow (Akan and Houghtalen, 2003). The frontal flow is the portion of the flow of the total gutter flow within the width of the inlet. It was expressed as (Akan and Houghtalen, 2003):

$$Q_W = Q[1 - (1 - [W/T)]^{2.67} \qquad (C.1)$$

where, Q_W is frontal discharge, W width of the depressed gutter or inlet, T is total spread of water in the gutter. And, $Q_s = Q - Q_W$, where, Q_s is side discharge corresponding to the flow outside the width of the inlet (*T*-*W*).

The ratio of R_f of frontal intercepted flow to total frontal flow is expressed as

$R_f = \frac{Q_{wi}}{Q_w} = 1.0 - K_f(V - V_o)$ for $V > V_o$ and $R_f = 1.0$ for $V \leq V_o$, where K_f is conversion (0.295 s/m in metric unit and 0.09 s/ft in customary U S units), Q_{wi} is frontal flow intercepted, V is velocity of flow in the gutter, and V_o is splashover velocity.

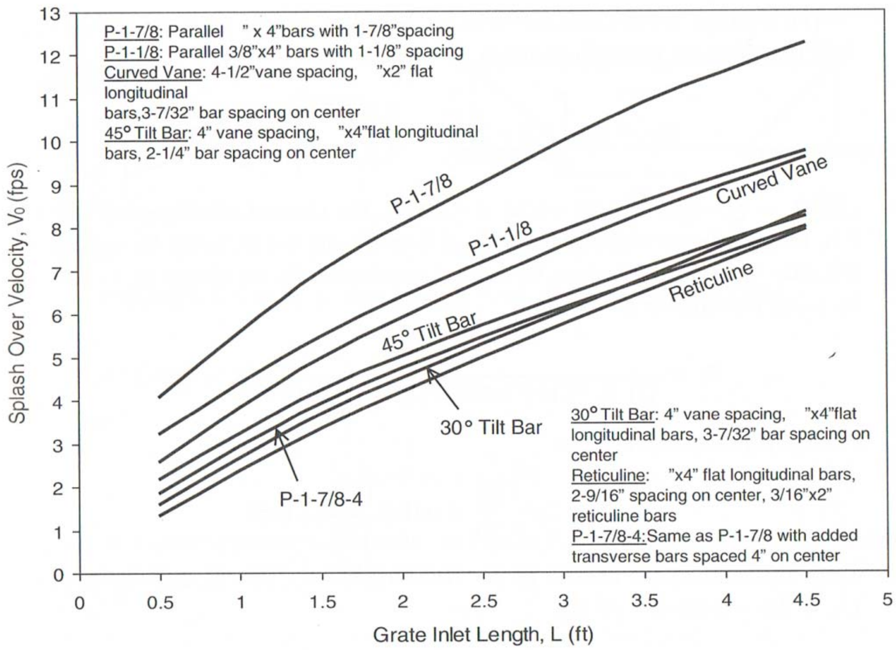


Fig. C.1: Splashover velocity, After Johnson and Chang (1984)

The splashover velocity is the minimum velocity that will cause some water to shoot over the inlet. This velocity depends on the gutter length and type. Fig. C-1 displays the splashover velocities for several standard grates tested by Federal Highway Administration of US.

The ratio R_s of intercepted side flow to total side flow is expressed as

$$R_f = \frac{Q_{si}}{Q_s} = \frac{1}{1 + \left[\frac{K_s V^{1.8}}{\left[(S)_x L^{2.3}\right)}\right]} \qquad (C.2)$$

where, Q_{si} is side flow intercepted, K_s is conversion factor (0.0828 $\frac{m^{0.2}}{s^{1.8}}$ for metric and 0.15 $ft^{0.2}/s^{1.8}$ for U S), and L is length of grate.

The efficiency E of grate inlet is evaluated by using following equation (Akan and Houghtalen, 2003):

$$E = R_f \frac{Q_W}{Q} + R_s \frac{Q_s}{Q} \qquad (C.8)$$

Therefore, percent of rainfall runoff entering into the catch basin will be calculated from the above equation. The grate efficiency of runoff generated from a design storm of 10 years Chicago rainfall is calculated for 385 m^2 of catchment and presented in Fig. C.2. It is clearly evident that all the runoff water will not be entering into catch basin. The grate efficiency decreases with the increase of rainfall intensity and the grate efficiency is lowest at peak intensity of rainfall and runoff.

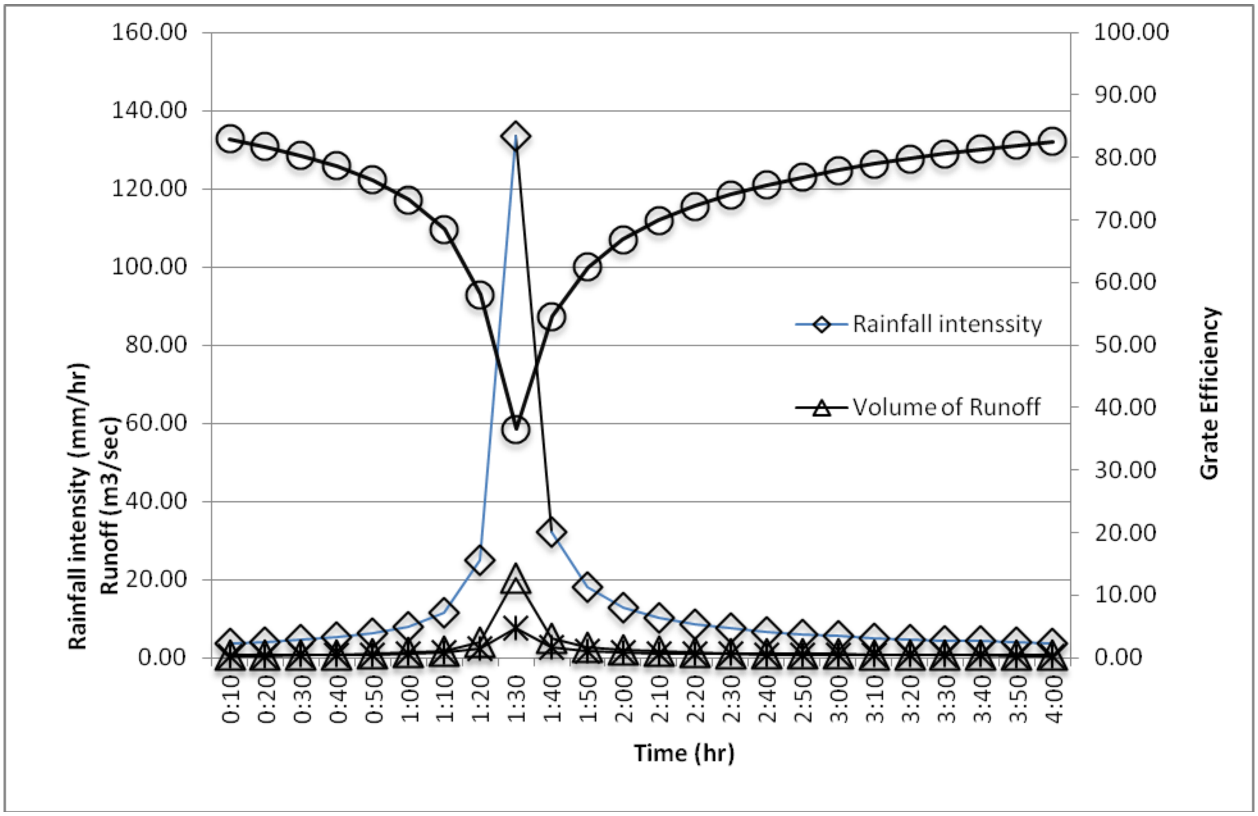


Fig. C.2: Grate Efficiency for runoff of a design storm of 10 Years Chicago Rainfall

Rainfall Runoff

The total catchment area of bioretention system is 385 m^2. The surface runoff from the catchment is computed by runoff coefficient method as follows:

$$R = \Phi i\, A_{catmt} \qquad (C.1)$$

R = runoff, L^3T^{-1}

Φ = Runoff coefficient (for asphalt street, C=0.70 to 0.95, Akan and Houghtalen, 2003)

i = Rainfall intensity, LT^{-1}

A_{catmt} = catchment area, L^2

If rainfall is measured at each time step, then rainfall volume at time beginning and end of time step are $\Delta t A_{catmt} i_{(n)}$, and $\Delta t A_{catmt} i_{(n+1)}$, respectively, where i is rainfall intensity and Δt is time step. Therefore, average rainfall volume in each time step Δt, termed runoff volume Q_{cbin}, can be written as:

$$Q_{cbin} = \Delta t \Phi A_{catmt} \left[\frac{i_{(n+1)} + i_{(n)}}{2}\right] E \qquad (C.2)$$

Hereafter, runoff flow produces at any given time step Δt is indicated as Q_{cbin}. The infiltration and interception on road surface are assumed to be zero, however, very little rainfall will be intercepted as surface wetness i.e., initial abstraction. Therefore, $Q = 0$ if $i\Delta t \leq I_a$ and $Q \geq 0$ if $i\Delta t \geq I_a$ where I_a is the initial abstraction.

Note that rainfall on road surface produces runoff that flows along the gutter of the street, and is intercepted by the grate of catch basin. All runoff water will not enter the catch basin during high intensity of rainfall. The efficiency of grate inlet depends on inlet type, gutter characteristics and flow in gutter. The runoff produced by low intensity rainfall might enter the catch basin fully, but runoff produced from the rainfall of high intensity might not be entered into catch basin fully (detailed computation procedures of grate efficiency was shown in Appendix C).

APPENDIX D

Orifice Coefficient by SWMM

Initially water depth is below the center line of P1 thus the flow is considered as weir flow, and the flow coefficients for both orifice and weir behaviour are computed as follows (EPA SWMM Manual, 2008):

Defined, $H_{crit} = \frac{D_{p1}}{2}$, where H_{crit} is critical water depth and D_{p1} is the orifice opening height.

Computed the flow coefficients (where A_{p1} is the area of the opening):

$$C_{orif} = A_{p1} * \sqrt{2g} * C_d \qquad (D.1)$$

$$C_{weir} = A_{p1} * \sqrt{2g} * C_d * \sqrt{H_{crit}} \qquad (D.2)$$

During flow routing, degree of submergence (f) and head (*H*) at the current time step are computed as follows:

Defined:

$H_u =$ upstream head (from node with higher head),

H_d =downstream head (from node of lower head),

$H_{crest} =$ elevation of bottom of opening,

$H_{crown} =$ elevation of top of opening,

$H_{midpt} =$ elevation of midpoint of opening,

For side orifices:

$$f = \frac{[(H)]_u - H_{crest})}{[(H)]_{crown} - H_{crest})} =$$ 1.0, (at least)

if f<1.0 then $H_u - H_{crest} = H_1$ and $H_{crown} - H_{crest} = D_{p1}$

else if H_d < H_{midpt} then $H = H_u - H_{midpt}$

else $H = H_u - H_d$

$$f = \min\left[1.0, \frac{H}{H_{crit}}\right],$$

Flow (Q_{orif}) through orifice is computed as follows:

if f<1.0 then $Q_{orif} = C_{weir} * f^{1.5}$

else $Q_{orif} = C_{orif} * \sqrt{H}$

Having followed the above method of derivation, orifice flow from catch basin to the distribution pipe is computed as follows:

$$H_{crit} = \frac{D_{p1}}{2} \qquad (D.3)$$

$$C_{orif} = A_{p1} * \sqrt{2g} * C_d \qquad (D.4)$$

$$C_{weir} = A_{p1} * \sqrt{2g} * C_d * \sqrt{H_{crit}} \qquad (D.5)$$

$$C_{weir} = A_{p1} * \sqrt{2g} * C_d * \sqrt{\frac{D_{p1}}{2}}$$ substituting the value of H_{crit}

Again, $Q_{orif} = C_{weir} * f^{1.5}$

$$Q_{orif} = A_{p1} * \sqrt{2g} * C_d * \sqrt{\frac{D_{p1}}{2}} * f^{1.5}$$ substituting the value of C_{weir}

$$Q_{orif} = A_{p1} * \sqrt{2g} * C_d * \sqrt{\frac{D_{p1}}{2}} * \left[\left[\frac{H_1}{\frac{D_{p1}}{2}} \right] \right]^{1.5}$$ substituting the value of f

$$Q_{orif} = A_{p1} * \sqrt{2g} * C_d * \sqrt{\frac{D_{p1}}{2}} * \left[\left[\frac{H_1}{\frac{D_{p1}}{2}} \right] \right]^{1.5} \qquad (D.6)$$

$$Q_{orif} = A_{p1} * \sqrt{2g} * C_d * \sqrt{\frac{D_{p1}}{2}} * \left(\frac{2H_1}{D_{p1}} \right)^{1.5} \qquad (\mathrm{D.7})$$

$$Q_{orif} = A_{p1} * \sqrt{2g} * C_d * \sqrt{\frac{D_{p1}}{2}} * \sqrt{\frac{2H_1}{D_{p1}}} * \frac{2H_1}{D_{p1}} \qquad (D.8)$$

$$Q_{orif} = A_{p1} * \sqrt{2g} * C_d * \sqrt{H_1} * \frac{2H_1}{D_{p1}} \qquad (D.9)$$

$$Q_{orif} = A_{p1} * \sqrt{2g} * \frac{2C_d}{D_{p1}} * H_1^{1.5} \qquad (D.10)$$

APPENDIX E

Stage-Storage Curve Relationship

To calculate the wetted area of flow section of circular pipe formula of Table 2-1 (Chow, 1973) was used. According to Chow (1973):

The wetted area of circular pipe, $A_{wetp1} = \frac{1}{8(\theta - sin\theta)D_{p1}^{2}}$ and

the top width $T = 2\sqrt{H_2(D_{p1} - H_2)}$.

Table: E.1:Wetted area of distribution pipe at different depth of water

H_2	D_{p1}	Top width (T)	θ	Rad	T/D_{p1}	$sin\theta$	A_{wetp1}
0.000	0.150	0.000	0.000	0.000	0.000	0.000	0.000
0.010	0.150	0.075	25.000	0.436	0.499	0.008	0.001
0.020	0.150	0.102	50.000	0.872	0.680	0.015	0.002
0.030	0.150	0.120	75.000	1.308	0.800	0.023	0.004
0.040	0.150	0.133	100.000	1.744	0.884	0.030	0.005
0.050	0.150	0.141	125.000	2.181	0.943	0.038	0.006
0.060	0.150	0.147	150.000	2.617	0.980	0.046	0.007
0.070	0.150	0.150	175.000	3.053	0.998	0.053	0.008
0.080	0.150	0.150	200.000	3.489	0.998	0.061	0.010
0.090	0.150	0.147	225.000	3.925	0.980	0.068	0.011
0.100	0.150	0.141	250.000	4.361	0.943	0.076	0.012
0.110	0.150	0.133	275.000	4.797	0.884	0.084	0.013
0.120	0.150	0.120	300.000	5.233	0.800	0.091	0.014
0.130	0.150	0.102	325.000	5.669	0.680	0.099	0.016
0.140	0.150	0.075	350.000	6.106	0.499	0.106	0.017
0.150	0.150	0.000	360.000	6.280	0.000	0.109	0.017

Now, wetted area of circular pipe at different depth was graphically presented in Fig. E.1. And root means square relation was developed as follows:

$A_{wetp1} = 0.1196\ H_2$, and this relation was used in mass balance equation 3.20.

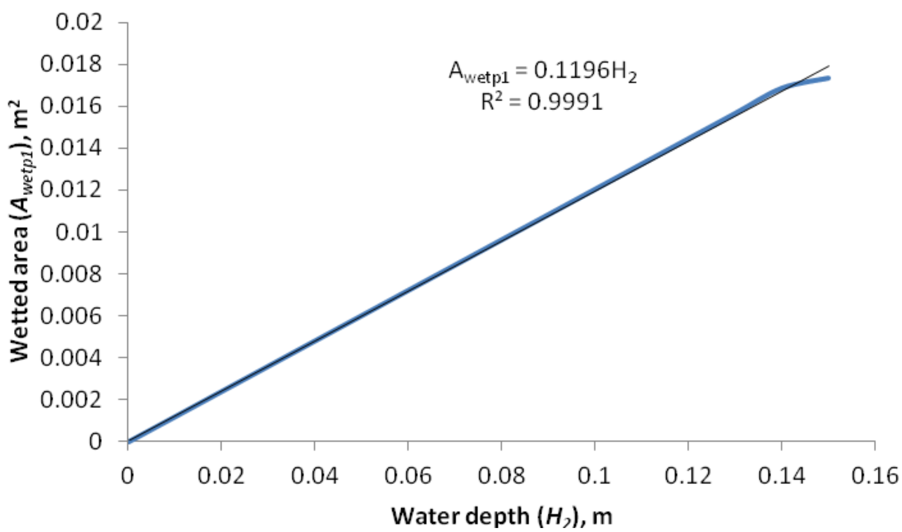


Fig. E.1: Wetted area as a function of water depth in P1(Stage-Storage Curve)

APPENDIX F

Pipe Manufacturer's Data

From the reference report no. 4149-1 (File 50284-07) of Oxford Plastic Inc which is dated on February 14, 1992, water opening for perforated pipe was measured. The report provided that 40 openings were measured in 165 mm length of pipe which has given 5.65 cm^2 or 34.27 cm^2 per meter of pipe. Based on this reference, it is appeared that opening diameter of the perforation is 4.25 mm and area of each opening is 0.14135 cm^2. The perimeter of 20 cm pipe is 125.66 cm and 40 opening was measured in 16.5 cm length, therefore perforation spacing is 7.2 cm both along and cross direction of the pipe. Therefore, total opening area of 35 m of pipe is 0.12 m^2 [(35m x 34.27cm^2)/10000]. The Fig. F.1 represents the assumed orientation of the perforation along the perimeter of the pipe. Based on this orientation, perforation area at different level of water depth in the pipe are determined and plotted in Fig. F.2, and root means square equation is generated which is used in equation 3.30 of section 3.5.

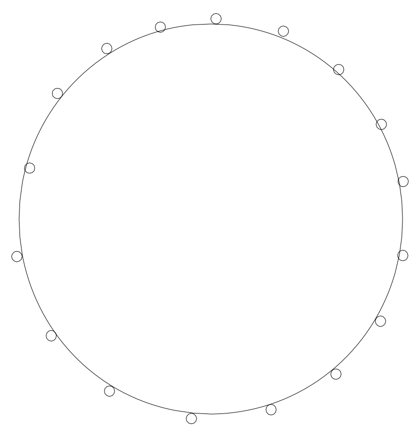


Fig. F.1: Orientation of perforation along the perimeter of pipe

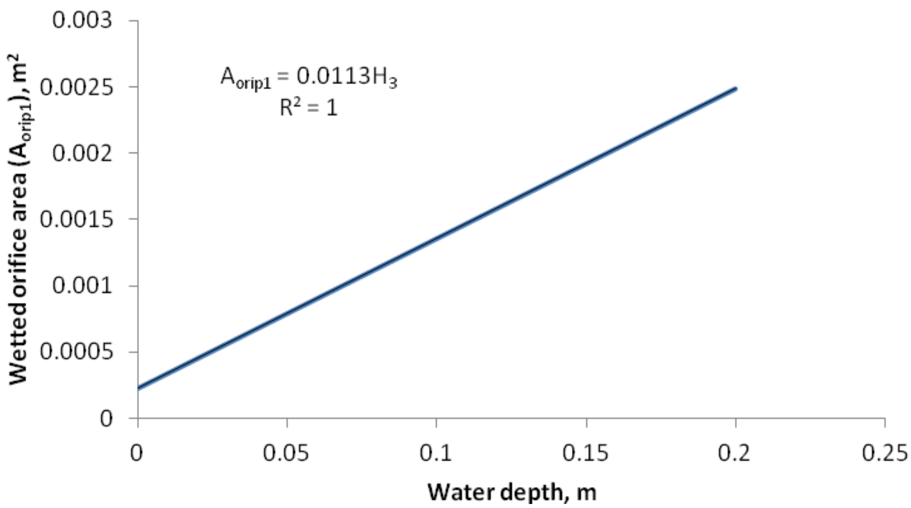


Fig. F.2: Wetted orifice area as a function of water depth in P2

APPENDIX G

Bioretention Soil Properties

Soils can be enormously complex systems of organic and inorganic components. For the present study purpose soil texture, hydraulic conductivity and carbon contents were taken into consideration.

Soil texture refers to the relative proportion of sand, silt and clay size particles in a sample of soil. Clay size particles are the smallest being less than .002 mm in size. Silt is a medium size particle falling between .002 and .05 mm in size. The largest particle is sand with diameters between .05 for fine sand to 2.0 mm for very coarse sand.

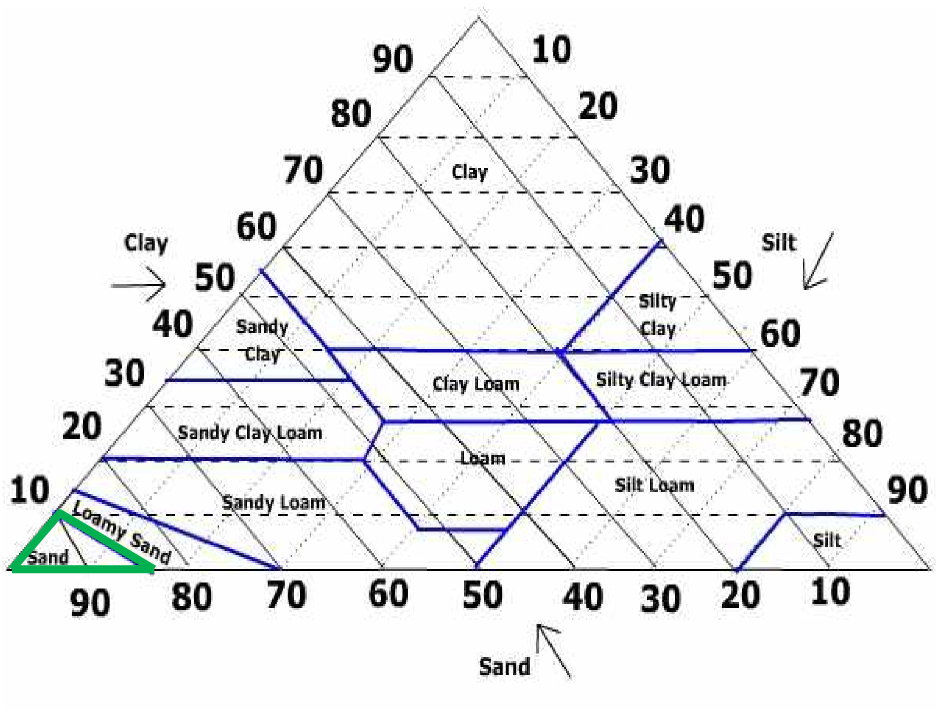


Fig. G.1: Soil Textural Triangle

Soils that are dominated by clay are called fine textured soils while those dominated by larger particles are referred to as coarse textured soils. Soil scientists are usually use soil texture triangle to define the textural class of a particular sample which is shown in Fig. G.1.

The sides of the soil texture triangle are scaled for the percentages of sand, silt, and clay. Clay percentages on the left side of the triangle are read from left to right across the triangle (dashed lines). Silt runs from the top to the bottom along the right side and is read from the upper right to lower left (light, dotted lines). The percentage of sand increases from right to left along the base of the triangle. Sand is read from the lower right towards the upper left portion of the triangle (bold, solid lines). The boundaries of the soil texture classes are highlighted in blue. The intersection of the three sides on the triangle gives the texture class. Percent sand, silt and clay were calculated as follows:

$$Percent\ sand = \frac{\textbf{Mass retain between the sieve opening 0.05 to 2.00 mm}}{\textbf{Total mass of the sample}} x100$$

$$Percent\ silt = \frac{\textbf{Mass retain between the sieve opening 0.002 to 0.05 mm}}{\textbf{Total mass of the sample}} x100$$

$$Percent\ clay = \frac{\textbf{Mass retain in the sieve opening less than 0.002 mm}}{\textbf{Total mass of the sample}} x100$$

Grain size analysis was performed according to the sieve test method practised by R.J Salvas, (1991) which was followed after ASTM standard. Four different samples were taken for grain size analysis (Table G.1-G.4) and average value was used to compute percent sand, silt and clay. The soil sample of present study exist more than 98 percent sand and remaining less than 2 percent is clay. Therefore, according to the method of soil textural triangle study sample is sand which represented by green line in Fig. G.1.

Results of Sieve tests were shown in Table G.1- G.4

Table G.1: Sieve analysis result of bioretention soil sample 1

Specimen No: 1	Date: May 22, 2009		Tested by: Zulhash Uddin	
Sieve no.	Mass Retained (M), gm	Percent Retained	Cumulative Percent Retained	Cumulative Percent Passing
4	20.61	4.122	4.122	95.878
10	95.62	19.124	23.246	76.754
20	112.70	22.540	45.786	54.214
40	126.49	25.298	71.084	28.916
100	123.98	24.796	95.880	4.120
200	11.87	2.374	98.254	1.746
Pan	8.73	1.746	100.00	0.000

Table G.2: Sieve analysis result of bioretention soil sample 2

Specimen No: 2	Date: May 22, 2009		Tested by: Zulhash Uddin	
Sieve no.	Mass Retained (M), gm	Percent Retained	Cumulative Percent Retained	Cumulative Percent Passing
4	32.74	6.548	6.548	93.452
10	101.84	20.368	26.916	73.084
20	115.88	23.176	50.092	49.908
40	114.66	22.932	73.024	26.976
100	114.42	22.884	95.908	4.092
200	15.16	3.032	98.940	1.060
Pan	5.30	1.060	100.000	0.000

Table G.3: Sieve analysis result of bioretention soil sample 3

Specimen No: 3	Date: May 22, 2009		Tested by: Zulhash Uddin	
Sieve no.	Mass Retained (M), gm	Percent Retained	Cumulative Percent Retained	Cumulative Percent Passing
4	19.50	3.900	3.900	96.100
10	100.01	20.002	23.902	76.098
20	112.69	22.538	46.440	53.560
40	122.15	24.430	70.870	29.130
100	123.98	24.796	95.666	4.334
200	16.16	3.232	98.898	1.102
Pan	5.51	1.102	100.000	0.000

Table G.4: Average of grain size analysis of bioretention soil

Specimen No: Average	Date: May 22, 2009		Tested by: Zulhash Uddin	
Sieve no.	Mass Retained (M), gm	Percent Retained	Cumulative Percent Retained	Cumulative Percent Passing
4	24.283	4.857	4.857	95.143
10	99.157	19.831	24.688	75.312
20	113.757	22.751	47.439	52.561
40	121.100	24.220	71.659	28.341
100	120.793	24.159	95.818	4.182
200	14.397	2.879	98.697	1.303
Pan	6.513	1.303	100.000	0.000

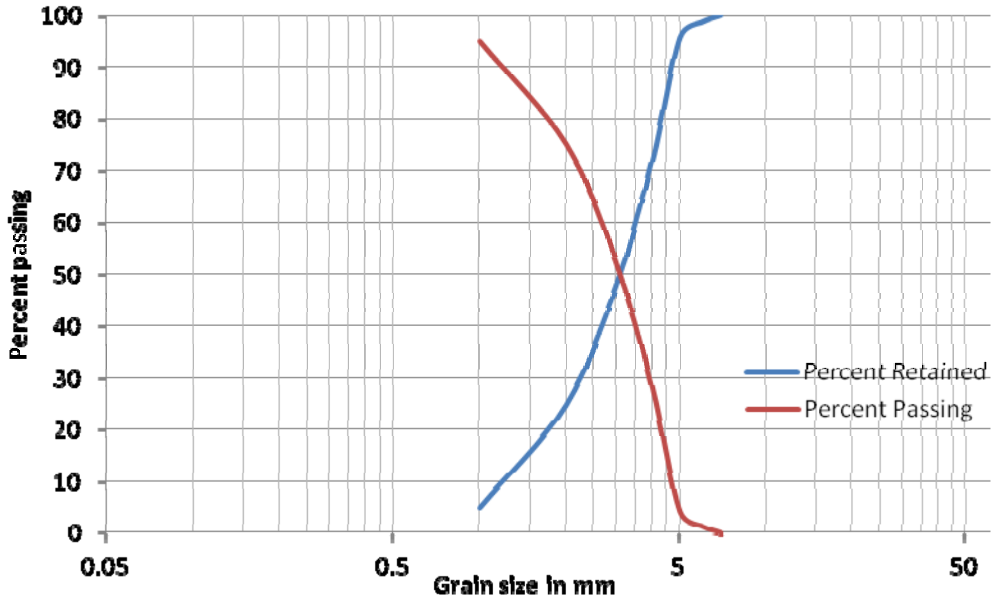


Fig. G.2: Grain size distribution curve

APPENDIX H

Matlab Program for Numerical Analysis

H.1 Matlab Program for Numerical Model of Bioretention System

```
clc

clear all

format long g

%Rainfall data (m/sec)

i_n=[0.00000099
0.00000101
0.00000102
0.00000103
0.00000105
0.00000106
0.00000107
0.00000108
0.00000110
0.00000111
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0
0];


%DATA REQUIRED For MODEL

A_catmt=385;

%disp(i_n1)

QET_n=0;

QET_n1=0;

g=9.1;

W=3.55;

K_ns=.0000018;

r=0.8;

s=1;

rs=r*s;

I_n=1;

I_n1=2;

d_p1=0.15;

d_p2=0.20;

%Hdes=dead storage height of catc basin

Hdes_n1=0.8;

Hdes_n=0.8;

L1=35;
```

```
L2=17.33;

L3=16;

fi=0.98;

%area of bioretention cell calculation
A_bc=L1*.30;

A_cb=0.61^2;

%cross sectional area

A_p1=pi*d_p1^2/4;

A_p2=pi*d_p2^2/4;

A_mh=pi*1.2^2/4;

A_mhexit=pi*.3^2/4;

H_bc=0.8;

D_p1=0.15;

D_p2=0.20;

D_mhexit=0.30;

C_d=0.60;

C=0.60;

i_n1=0;

%time step

delta_t=60;

% heights at t=0, boundary situation

H1_n = 0;

H2_n = 0;

H3_n = 0;

H4_n = 0;

H5_n = 0;

% constant value of H(primes)
```

```
% substitue height variables into x variables in order to eliminate square
root expression in orifice equation
X1_n = sqrt(H1_n);
X2_n = sqrt(H2_n);
X3_n = H3_n;
X4_n = sqrt(H4_n);
X5_n = sqrt(H5_n);
fprintf(' Step      X1_n1    X2_n1    X3_n1    X4_n1    X5_n1    X1_n
X2_n     X3_n     X4_n     X5_n      H1        H2        H3        H4        H5
\n')
% set stopping conditions and maximum iteration runs
error = 1*10^(-5);

iter=0;
itermax=5;
% Coefficient from Mass Balance

aa1=delta_t*A_p1*sqrt(2*g)*(C_d/D_p1);
aa2=A_cb;
aa3=A_cb*Hdes_n1;
aa4=0.5*delta_t*fi*A_catmt*E;
bb1=.6*0.5*delta_t*2756;
bb2=.6*0.5*delta_t*245.47;
bb3=.6*0.5*delta_t*6.75;
bb4=0.1177*L1;
cc1=0.2*L2*W;
cc2=delta_t*(L2+W)*K_ns*r*s;
cc3=0.5*delta_t*QET_n;
```

```
cc4=0.8*0.5*delta_t*0.0113*C*sqrt(2*g);

dd1=0.1177*L3;

dd2=delta_t*A_p2*sqrt(2*g)*(C_d/D_p2);

ee1=delta_t*A_mhexit*sqrt(2*g)*(C_d/D_mhexit);

ee2=A_mh;


for kk=1:400

if kk+1>length(i_n)

    i_n(kk+1,1)=0;

    i_n(kk,1)=0;

end


f=@(x)[aa1*x(1)^3+aa2*x(1)^2+aa3+aa1*X1_n^3-aa2*X1_n^2-aa3-aa4*i_n(kk+1,1)-
aa4*i_n(kk,1);
aa1*x(1)^3-bb1*x(2)^6+bb2*x(2)^4-bb3*x(2)^2-bb4*x(2)^2+aa1*X1_n^3-
bb1*X2_n^6+bb2*X2_n^4-bb3*X2_n^2+bb4*X2_n^2;
bb1*x(2)^6-bb2*x(2)^4+bb3*x(2)^2-cc1*x(3)-cc2*x(3)+bb1*X2_n^6-
bb2*X2_n^4+bb3*X2_n^2-cc2*X3_n+cc1*X3_n-cc3*QET_n1-cc3*QET_n-cc4*x(3)^1.5-
cc4*X3_n^1.5;
dd1*x(4)^2+dd2*x(4)^3-cc4*x(3)^1.5+dd2*X4_n^3-cc4*X3_n^1.5-dd1*X4_n^2;
ee1*x(5)^3+ee2*x(5)^2-dd2*x(4)^3-ee2*X5_n^2+ee2*X5_n^3-dd2*X4_n^3];


options = optimset('Display','off');




R=fsolve(f,[0.0001 0.0001 0.0001 0.0001 0.0001],options);
```

```
X1_n1=R(1,1);

X2_n1=R(1,2);

X3_n1=R(1,3);

X4_n1=R(1,4);

X5_n1=R(1,5);


fprintf('%8.0f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f
%8.5f %8.5f %8.5f %8.5f
%8.5f\n',kk,X1_n1,X2_n1,X3_n1,X4_n1,X5_n1,X1_n,X2_n,X3_n,X4_n,X5_n,X1_n^2,X2_
n^2,X3_n,X4_n^2,X5_n^2)

X1_n = X1_n1;

X2_n = X2_n1;

X3_n = X3_n1;

X4_n = X4_n1;

X5_n = X5_n1;


end
```

H.2 Model Results

Step	X1_n1	X2_n1	X3_n1	X4_n1	X5_n1	X1_n	X2_n	X3_n	X4_n	X5_n	H1	H2	H3	H4	H5
1	0.10132	0.01227	0.00148	0.00376	-0.00192	0	0	0	0	0	0.0000	0.00000	0.00000	0.00000	0.00000
2	0.06984	0.00769	0.00352	0.00994	0.00472	0.10132	0.01227	0.00148	0.00376	-0.00192	0.0103	0.00015	0.00148	0.00001	0.00000
3	0.09497	0.01086	0.00523	0.01586	0.00987	0.06984	0.00769	0.00352	0.00994	0.00472	0.0049	0.00006	0.00352	0.00010	0.00002
4	0.0794	0.00928	0.00718	0.02107	0.01589	0.09497	0.01086	0.00523	0.01586	0.00987	0.0090	0.00012	0.00523	0.00025	0.00010
5	0.09188	0.0102	0.00896	0.02548	0.02173	0.0794	0.00928	0.00718	0.02107	0.01589	0.0063	0.00009	0.00718	0.00044	0.00025
6	0.0837	0.00999	0.01085	0.02915	0.02687	0.09188	0.0102	0.00896	0.02548	0.02173	0.0084	0.00010	0.00896	0.00065	0.00047
7	0.09025	0.00989	0.01265	0.03228	0.03122	0.0837	0.00999	0.01085	0.02915	0.02687	0.0070	0.00010	0.01085	0.00085	0.00072
8	0.08631	0.01038	0.01449	0.03504	0.03491	0.09025	0.00989	0.01265	0.03228	0.03122	0.0082	0.00010	0.01265	0.00104	0.00097
9	0.0899	0.00986	0.01629	0.03753	0.0381	0.08631	0.01038	0.01449	0.03504	0.03491	0.0075	0.00011	0.01449	0.00123	0.00122
10	0.08754	0.01054	0.01808	0.03981	0.04093	0.0899	0.00986	0.01629	0.03753	0.0381	0.0081	0.00010	0.01629	0.00141	0.00145
11	0.08951	0.00984	0.01982	0.04192	0.04349	0.08754	0.01054	0.01808	0.03981	0.04093	0.0077	0.00011	0.01808	0.00159	0.00168
12	0.08877	0.01069	0.02156	0.04389	0.04584	0.08951	0.00984	0.01982	0.04192	0.04349	0.0080	0.00010	0.01982	0.00176	0.00189
13	0.08999	0.00998	0.02328	0.04575	0.04803	0.08877	0.01069	0.02156	0.04389	0.04584	0.0079	0.00011	0.02156	0.00193	0.00210
14	0.08977	0.01081	0.02498	0.04751	0.05007	0.08999	0.00998	0.02328	0.04575	0.04803	0.0081	0.00010	0.02328	0.00209	0.00231
15	0.0906	0.01015	0.02666	0.04918	0.05201	0.08977	0.01081	0.02498	0.04751	0.05007	0.0081	0.00012	0.02498	0.00226	0.00251
16	0.09044	0.01088	0.02832	0.05078	0.05385	0.0906	0.01015	0.02666	0.04918	0.05201	0.0082	0.00010	0.02666	0.00242	0.00271
17	0.09121	0.0103	0.02995	0.0523	0.05559	0.09044	0.01088	0.02832	0.05078	0.05385	0.0082	0.00012	0.02832	0.00258	0.00290
18	0.0913	0.01098	0.03157	0.05376	0.05726	0.09121	0.0103	0.02995	0.0523	0.05559	0.0083	0.00011	0.02995	0.00274	0.00309
19	0.09188	0.01047	0.03316	0.05516	0.05885	0.0913	0.01098	0.03157	0.05376	0.05726	0.0083	0.00012	0.03157	0.00289	0.00328
20	0.0921	0.01108	0.03473	0.05651	0.06038	0.09188	0.01047	0.03316	0.05516	0.05885	0.0084	0.00011	0.03316	0.00304	0.00346
21	0.09258	0.01063	0.03629	0.0578	0.06185	0.0921	0.01108	0.03473	0.05651	0.06038	0.0085	0.00012	0.03473	0.00319	0.00365
22	0.09307	0.01122	0.03782	0.05906	0.06326	0.09258	0.01063	0.03629	0.0578	0.06185	0.0086	0.00011	0.03629	0.00334	0.00383
23	0.09354	0.01084	0.03934	0.06027	0.06462	0.09307	0.01122	0.03782	0.05906	0.06326	0.0087	0.00013	0.03782	0.00349	0.00400
24	0.09402	0.01135	0.04085	0.06145	0.06595	0.09354	0.01084	0.03934	0.06027	0.06462	0.0088	0.00012	0.03934	0.00363	0.00418
25	0.09449	0.01104	0.04234	0.06259	0.06723	0.09402	0.01135	0.04085	0.06145	0.06595	0.0088	0.00013	0.04085	0.00378	0.00435
26	0.09496	0.01149	0.04382	0.0637	0.06847	0.09449	0.01104	0.04234	0.06259	0.06723	0.0089	0.00012	0.04234	0.00392	0.00452
27	0.09541	0.01123	0.04528	0.06478	0.06968	0.09496	0.01149	0.04382	0.0637	0.06847	0.0090	0.00013	0.04382	0.00406	0.00469
28	0.09587	0.01163	0.04672	0.06583	0.07085	0.09541	0.01123	0.04528	0.06478	0.06968	0.0091	0.00013	0.04528	0.00420	0.00486
29	0.09632	0.01142	0.04816	0.06685	0.072	0.09587	0.01163	0.04672	0.06583	0.07085	0.0092	0.00014	0.04672	0.00433	0.00502
30	0.09677	0.01177	0.04957	0.06785	0.07311	0.09632	0.01142	0.04816	0.06685	0.072	0.0093	0.00013	0.04816	0.00447	0.00518
31	0.09741	0.01164	0.05097	0.06882	0.07419	0.09677	0.01177	0.04957	0.06785	0.07311	0.0094	0.00014	0.04957	0.00460	0.00534
32	0.09808	0.01199	0.05238	0.06978	0.07525	0.09741	0.01164	0.05097	0.06882	0.07419	0.0095	0.00014	0.05097	0.00474	0.00550
33	0.09871	0.01189	0.05378	0.07072	0.07629	0.09808	0.01199	0.05238	0.06978	0.07525	0.0096	0.00014	0.05238	0.00487	0.00566
34	0.09936	0.01221	0.05519	0.07165	0.07732	0.09871	0.01189	0.05378	0.07072	0.07629	0.0097	0.00014	0.05378	0.00500	0.00582
35	0.0998	0.01211	0.05658	0.07257	0.07833	0.09936	0.01221	0.05519	0.07165	0.07732	0.0099	0.00015	0.05519	0.00513	0.00598
36	0.10039	0.01239	0.05797	0.07347	0.07933	0.0998	0.01211	0.05658	0.07257	0.07833	0.0100	0.00015	0.05658	0.00527	0.00614
37	0.10103	0.01235	0.05935	0.07435	0.0803	0.10039	0.01239	0.05797	0.07347	0.07933	0.0101	0.00015	0.05797	0.00540	0.00629
38	0.10162	0.0126	0.06073	0.07522	0.08127	0.10103	0.01235	0.05935	0.07435	0.0803	0.0102	0.00015	0.05935	0.00553	0.00645
39	0.10224	-0.01259	0.06211	0.07608	0.08221	0.10162	0.0126	0.06073	0.07522	0.08127	0.0103	0.00016	0.06073	0.00566	0.00660
40	0.10282	0.01282	0.06349	0.07693	0.08315	0.10224	-0.01259	0.06211	0.07608	0.08221	0.0105	0.00016	0.06211	0.00579	0.00676
41	0.10376	-0.01288	0.06487	0.07777	0.08407	0.10282	0.01282	0.06349	0.07693	0.08315	0.0106	0.00016	0.06349	0.00592	0.00691
42	0.10475	0.01317	0.06629	0.07862	0.085	0.10376	-0.01288	0.06487	0.07777	0.08407	0.0108	0.00017	0.06487	0.00605	0.00707
43	0.10567	-0.01325	0.06774	0.07947	0.08593	0.10475	0.01317	0.06629	0.07862	0.085	0.0110	0.00017	0.06629	0.00618	0.00722
44	0.10645	-0.01349	0.0692	0.08033	0.08686	0.10567	-0.01325	0.06774	0.07947	0.08593	0.0112	0.00018	0.06774	0.00632	0.00738
45	0.10732	-0.01357	0.07068	0.0812	0.0878	0.10645	-0.01349	0.0692	0.08033	0.08686	0.0113	0.00018	0.06920	0.00645	0.00754
46	0.10825	-0.01383	0.07219	0.08206	0.08874	0.10732	-0.01357	0.07068	0.0812	0.0878	0.0115	0.00018	0.07068	0.00659	0.00771
47	0.10911	-0.01392	0.07372	0.08293	0.08969	0.10825	-0.01383	0.07219	0.08206	0.08874	0.0117	0.00019	0.07219	0.00673	0.00788
48	0.11	-0.01416	0.07527	0.0838	0.09064	0.10911	-0.01392	0.07372	0.08293	0.08969	0.0119	0.00019	0.07372	0.00688	0.00804
49	0.11068	-0.01423	0.07683	0.08467	0.09159	0.11	-0.01416	0.07527	0.0838	0.09064	0.0121	0.00020	0.07527	0.00702	0.00822
50	0.11151	-0.01445	0.0784	0.08554	0.09254	0.11068	-0.01423	0.07683	0.08467	0.09159	0.0123	0.00020	0.07683	0.00717	0.00839
51	0.11309	-0.0147	0.08002	0.08642	0.09349	0.11151	-0.01445	0.0784	0.08554	0.09254	0.0124	0.00021	0.07840	0.00732	0.00856
52	0.11475	-0.01508	0.08175	0.08733	0.09447	0.11309	-0.0147	0.08002	0.08642	0.09349	0.0128	0.00022	0.08002	0.00747	0.00874
53	0.11614	-0.01531	0.08356	0.0883	0.09549	0.11475	-0.01508	0.08175	0.08733	0.09447	0.0132	0.00023	0.08175	0.00763	0.00892
54	0.11767	-0.01566	0.08546	0.08929	0.09655	0.11614	-0.01531	0.08356	0.0883	0.09549	0.0135	0.00023	0.08356	0.00780	0.00912
55	0.11915	-0.01592	0.08745	0.09032	0.09764	0.11767	-0.01566	0.08546	0.08929	0.09655	0.0139	0.00025	0.08546	0.00797	0.00932
56	0.12061	-0.01625	0.08952	0.09138	0.09878	0.11915	-0.01592	0.08745	0.09032	0.09764	0.0142	0.00025	0.08745	0.00816	0.00953
57	0.1219	-0.01649	0.09166	0.09246	0.09994	0.12061	-0.01625	0.08952	0.09138	0.09878	0.0146	0.00026	0.08952	0.00835	0.00976
58	0.12326	-0.01679	0.09385	0.09357	0.10114	0.1219	-0.01649	0.09166	0.09246	0.09994	0.0149	0.00027	0.09166	0.00855	0.00999
59	0.12464	-0.01705	0.09612	0.09469	0.10235	0.12326	-0.01679	0.09385	0.09357	0.10114	0.0152	0.00028	0.09385	0.00876	0.01023
60	0.12595	-0.01735	0.09845	0.09584	0.10359	0.12464	-0.01705	0.09612	0.09469	0.10235	0.0155	0.00029	0.09612	0.00897	0.01048

61	0.13033	-0.01823	0.10105	0.09706	0.10487	0.12595	-0.01735	0.09845	0.09584	0.10359	0.0159	0.00030	0.09845	0.00918	0.01073
62	0.13497	-0.01926	0.10417	0.09849	0.1063	0.13033	-0.01823	0.10105	0.09706	0.10487	0.0170	0.00033	0.10105	0.00942	0.01100
63	0.1389	-0.0201	0.10779	0.10015	0.10795	0.13497	-0.01926	0.10417	0.09849	0.1063	0.0182	0.00037	0.10417	0.00970	0.01130
64	0.14294	-0.02102	0.11187	0.102	0.10984	0.1389	-0.0201	0.10779	0.10015	0.10795	0.0193	0.00040	0.10779	0.01003	0.01165
65	0.14651	-0.02181	0.1164	0.10402	0.11192	0.14294	-0.02102	0.11187	0.102	0.10984	0.0204	0.00044	0.11187	0.01040	0.01206
66	0.15012	-0.02265	0.12132	0.10619	0.11419	0.14651	-0.02181	0.1164	0.10402	0.11192	0.0215	0.00048	0.11640	0.01082	0.01253
67	0.1534	-0.0234	0.12663	0.10849	0.11661	0.15012	-0.02265	0.12132	0.10619	0.11419	0.0225	0.00051	0.12132	0.01128	0.01304
68	0.15667	-0.02418	0.13229	0.11088	0.11915	0.1534	-0.0234	0.12663	0.10849	0.11661	0.0235	0.00055	0.12663	0.01177	0.01360
69	0.15963	-0.02488	0.13826	0.11337	0.12181	0.15667	-0.02418	0.13229	0.11088	0.11915	0.0245	0.00058	0.13229	0.01230	0.01420
70	0.16263	-0.0256	0.14451	0.11591	0.12455	0.15963	-0.02488	0.13826	0.11337	0.12181	0.0255	0.00062	0.13826	0.01285	0.01484
71	0.18246	-0.03044	0.15315	0.1191	0.12765	0.16263	-0.0256	0.14451	0.11591	0.12455	0.0265	0.00066	0.14451	0.01344	0.01551
72	0.20069	-0.03547	0.1666	0.12388	0.13189	0.18246	-0.03044	0.15315	0.1191	0.12765	0.0333	0.00093	0.15315	0.01419	0.01629
73	0.21456	-0.03936	0.18455	0.13026	0.13784	0.20069	-0.03547	0.1666	0.12388	0.13189	0.0403	0.00126	0.16660	0.01535	0.01740
74	0.22803	-0.04346	0.20657	0.13778	0.14532	0.21456	-0.03936	0.18455	0.13026	0.13784	0.0460	0.00155	0.18455	0.01697	0.01900
75	0.23912	-0.04692	0.23233	0.14616	0.15395	0.22803	-0.04346	0.20657	0.13778	0.14532	0.0520	0.00189	0.20657	0.01898	0.02112
76	0.25004	-0.05052	0.26137	0.15514	0.16341	0.23912	-0.04692	0.23233	0.14616	0.15395	0.0572	0.00220	0.23233	0.02136	0.02370
77	0.25947	-0.05375	0.29335	0.16448	0.17341	0.25004	-0.05052	0.26137	0.15514	0.16341	0.0625	0.00255	0.26137	0.02407	0.02670
78	0.26877	-0.05706	0.32782	0.17403	0.18373	0.25947	-0.05375	0.29335	0.16448	0.17341	0.0673	0.00289	0.29335	0.02705	0.03007
79	0.27701	0.06013	0.36441	0.18363	0.1942	0.26877	-0.05706	0.32782	0.17403	0.18373	0.0722	0.00326	0.32782	0.03029	0.03376
80	0.28518	0.06327	0.4027	0.19319	0.20468	0.27701	0.06013	0.36441	0.18363	0.1942	0.0767	0.00362	0.36441	0.03372	0.03771
81	0.2783	0.06088	0.43772	0.20175	0.2146	0.28518	0.06327	0.4027	0.19319	0.20468	0.0813	0.00400	0.40270	0.03732	0.04190
82	0.26998	0.05753	0.46417	0.20813	0.22283	0.2783	0.06088	0.43772	0.20175	0.2146	0.0775	0.00371	0.43772	0.04070	0.04605
83	0.26213	0.05492	0.48278	0.21248	0.22879	0.26998	0.05753	0.46417	0.20813	0.22283	0.0729	0.00331	0.46417	0.04332	0.04965
84	0.2528	-0.0515	0.49446	0.21524	0.23277	0.26213	0.05492	0.48278	0.21248	0.22879	0.0687	0.00302	0.48278	0.04515	0.05235
85	0.24372	-0.04864	0.4999	0.21658	0.23509	0.2528	-0.0515	0.49446	0.21524	0.23277	0.0639	0.00265	0.49446	0.04633	0.05418
86	0.23295	-0.04504	0.49987	0.21671	0.23596	0.24372	-0.04864	0.4999	0.21658	0.23509	0.0594	0.00237	0.49990	0.04691	0.05527
87	0.22203	-0.04182	0.49492	0.21575	0.23559	0.23295	-0.04504	0.49987	0.21671	0.23596	0.0543	0.00203	0.49987	0.04696	0.05568
88	0.20893	-0.03785	0.48565	0.21384	0.23409	0.22203	-0.04182	0.49492	0.21575	0.23559	0.0493	0.00175	0.49492	0.04655	0.05550
89	0.19497	-0.03406	0.47249	0.21104	0.23159	0.20893	-0.03785	0.48565	0.21384	0.23409	0.0437	0.00143	0.48565	0.04573	0.05480
90	0.17767	0.0294	0.45591	0.20741	0.22815	0.19497	-0.03406	0.47249	0.21104	0.23159	0.0380	0.00116	0.47249	0.04454	0.05363
91	0.1743	0.0285	0.4381	0.20335	0.22402	0.17767	0.0294	0.45591	0.20741	0.22815	0.0316	0.00086	0.45591	0.04302	0.05205
92	0.17225	0.02801	0.42149	0.19943	0.21969	0.1743	0.0285	0.4381	0.20335	0.22402	0.0304	0.00081	0.43810	0.04135	0.05018
93	0.16887	0.02715	0.40595	0.19573	0.21553	0.17225	0.02801	0.42149	0.19943	0.21969	0.0297	0.00078	0.42149	0.03977	0.04826
94	0.1665	0.02657	0.39131	0.19216	0.21156	0.16887	0.02715	0.40595	0.19573	0.21553	0.0285	0.00074	0.40595	0.03831	0.04645
95	0.16298	0.02572	0.37747	0.18874	0.20775	0.1665	0.02657	0.39131	0.19216	0.21156	0.0277	0.00071	0.39131	0.03693	0.04476
96	0.16025	0.02505	0.3643	0.18542	0.20407	0.16298	0.02572	0.37747	0.18874	0.20775	0.0266	0.00066	0.37747	0.03562	0.04316
97	0.15668	0.02421	0.35174	0.1822	0.20051	0.16025	0.02505	0.3643	0.18542	0.20407	0.0257	0.00063	0.36430	0.03438	0.04165
98	0.1536	0.02347	0.3397	0.17905	0.19704	0.15668	0.02421	0.35174	0.1822	0.20051	0.0246	0.00059	0.35174	0.03320	0.04020
99	0.14981	0.02261	0.32811	0.17598	0.19366	0.1536	0.02347	0.3397	0.17905	0.19704	0.0236	0.00055	0.33970	0.03206	0.03883
100	0.14633	0.02179	0.31691	0.17296	0.19034	0.14981	0.02261	0.32811	0.17598	0.19366	0.0224	0.00051	0.32811	0.03097	0.03750
101	0.14455	-0.0214	0.30625	0.17002	0.18709	0.14633	0.02179	0.31691	0.17296	0.19034	0.0214	0.00047	0.31691	0.02992	0.03623
102	0.14348	-0.02114	0.29629	0.16722	0.18396	0.14455	-0.0214	0.30625	0.17002	0.18709	0.0209	0.00046	0.30625	0.02891	0.03500
103	0.14186	-0.0208	0.28698	0.16457	0.18099	0.14348	-0.02114	0.29629	0.16722	0.18396	0.0206	0.00045	0.29629	0.02796	0.03384
104	0.14065	-0.02051	0.27824	0.16204	0.17815	0.14186	-0.0208	0.28698	0.16457	0.18099	0.0201	0.00043	0.28698	0.02708	0.03276
105	0.13894	-0.02015	0.27	0.15962	0.17545	0.14065	-0.02051	0.27824	0.16204	0.17815	0.0198	0.00042	0.27824	0.02626	0.03174
106	0.1376	-0.01983	0.26221	0.15729	0.17286	0.13894	-0.02015	0.27	0.15962	0.17545	0.0193	0.00041	0.27000	0.02548	0.03078
107	0.13589	-0.01949	0.25483	0.15506	0.17037	0.1376	-0.01983	0.26221	0.15729	0.17286	0.0189	0.00039	0.26221	0.02474	0.02988
108	0.13442	-0.01914	0.2478	0.1529	0.16797	0.13589	-0.01949	0.25483	0.15506	0.17037	0.0185	0.00038	0.25483	0.02404	0.02903
109	0.13278	-0.01881	0.24111	0.15082	0.16566	0.13442	-0.01914	0.2478	0.1529	0.16797	0.0181	0.00037	0.24780	0.02338	0.02822
110	0.13122	-0.01845	0.23472	0.14881	0.16343	0.13278	-0.01881	0.24111	0.15082	0.16566	0.0176	0.00035	0.24111	0.02275	0.02744
111	0.12229	-0.01666	0.22812	0.14674	0.16121	0.13122	-0.01845	0.23472	0.14881	0.16343	0.0172	0.00034	0.23472	0.02214	0.02671
112	0.12017	-0.0161	0.22128	0.14455	0.1589	0.12229	-0.01666	0.22812	0.14674	0.16121	0.0150	0.00028	0.22812	0.02153	0.02599
113	0.12071	-0.01631	0.21486	0.14242	0.15655	0.12017	-0.0161	0.22128	0.14455	0.1589	0.0144	0.00026	0.22128	0.02089	0.02525
114	0.1191	-0.0159	0.20887	0.14041	0.15429	0.12071	-0.01631	0.21486	0.14242	0.15655	0.0146	0.00027	0.21486	0.02028	0.02451
115	0.11921	-0.01599	0.20323	0.1385	0.15215	0.1191	-0.0159	0.20887	0.14041	0.15429	0.0142	0.00025	0.20887	0.01972	0.02381
116	0.1178	-0.01565	0.19793	0.13667	0.15011	0.11921	-0.01599	0.20323	0.1385	0.15215	0.0142	0.00026	0.20323	0.01918	0.02315
117	0.11772	-0.01568	0.19293	0.13493	0.14816	0.1178	-0.01565	0.19793	0.13667	0.15011	0.0139	0.00024	0.19793	0.01868	0.02253
118	0.11656	-0.01541	0.18821	0.13326	0.14629	0.11772	-0.01568	0.19293	0.13493	0.14816	0.0139	0.00025	0.19293	0.01821	0.02195
119	0.11625	-0.01537	0.18375	0.13167	0.14451	0.11656	-0.01541	0.18821	0.13326	0.14629	0.0136	0.00024	0.18821	0.01776	0.02140
120	0.11524	-0.01516	0.17952	0.13014	0.1428	0.11625	-0.01537	0.18375	0.13167	0.14451	0.0135	0.00024	0.18375	0.01734	0.02088

121	0.11478	-0.01508	0.17551	0.12867	0.14116	0.11524	-0.01516	0.17952	0.13014	0.1428	0.0133	0.00023	0.17952	0.01694	0.02039
122	0.11401	-0.01491	0.1717	0.12726	0.13959	0.11478	-0.01508	0.17551	0.12867	0.14116	0.0132	0.00023	0.17551	0.01656	0.01993
123	0.11361	-0.01484	0.16808	0.12591	0.13808	0.11401	-0.01491	0.1717	0.12726	0.13959	0.0130	0.00022	0.17170	0.01619	0.01949
124	0.11306	-0.01473	0.16466	0.12461	0.13663	0.11361	-0.01484	0.16808	0.12591	0.13808	0.0129	0.00022	0.16808	0.01585	0.01907
125	0.11262	-0.01465	0.16141	0.12337	0.13525	0.11306	-0.01473	0.16466	0.12461	0.13663	0.0128	0.00022	0.16466	0.01553	0.01867
126	0.11208	-0.01454	0.15832	0.12218	0.13392	0.11262	-0.01465	0.16141	0.12337	0.13525	0.0127	0.00021	0.16141	0.01522	0.01829
127	0.11162	-0.01445	0.15538	0.12103	0.13264	0.11208	-0.01454	0.15832	0.12218	0.13392	0.0126	0.00021	0.15832	0.01493	0.01793
128	0.11093	-0.01431	0.15257	0.11993	0.13141	0.11162	-0.01445	0.15538	0.12103	0.13264	0.0125	0.00021	0.15538	0.01465	0.01759
129	0.11041	-0.01421	0.14988	0.11886	0.13022	0.11093	-0.01431	0.15257	0.11993	0.13141	0.0123	0.00020	0.15257	0.01438	0.01727
130	0.10991	-0.01411	0.1473	0.11783	0.12908	0.11041	-0.01421	0.14988	0.11886	0.13022	0.0122	0.00020	0.14988	0.01413	0.01696
131	0.10938	-0.01401	0.14484	0.11684	0.12797	0.10991	-0.01411	0.1473	0.11783	0.12908	0.0121	0.00020	0.14730	0.01388	0.01666
132	0.10886	-0.01391	0.14248	0.11588	0.1269	0.10938	-0.01401	0.14484	0.11684	0.12797	0.0120	0.00020	0.14484	0.01365	0.01638
133	0.10848	-0.01384	0.14021	0.11495	0.12587	0.10886	-0.01391	0.14248	0.11588	0.1269	0.0119	0.00019	0.14248	0.01343	0.01610
134	0.10814	-0.01377	0.13805	0.11406	0.12488	0.10848	-0.01384	0.14021	0.11495	0.12587	0.0118	0.00019	0.14021	0.01321	0.01584
135	0.10761	-0.01367	0.13598	0.1132	0.12392	0.10814	-0.01377	0.13805	0.11406	0.12488	0.0117	0.00019	0.13805	0.01301	0.01559
136	0.10723	-0.0136	0.13399	0.11236	0.12299	0.10761	-0.01367	0.13598	0.1132	0.12392	0.0116	0.00019	0.13598	0.01281	0.01536
137	0.10672	-0.0135	0.13208	0.11155	0.12209	0.10723	-0.0136	0.13399	0.11236	0.12299	0.0115	0.00018	0.13399	0.01263	0.01513
138	0.1063	-0.01342	0.13024	0.11077	0.12122	0.10672	-0.0135	0.13208	0.11155	0.12209	0.0114	0.00018	0.13208	0.01244	0.01491
139	0.10597	-0.01336	0.12847	0.11001	0.12038	0.1063	-0.01342	0.13024	0.11077	0.12122	0.0113	0.00018	0.13024	0.01227	0.01469
140	0.1054	-0.01325	0.12676	0.10927	0.11956	0.10597	-0.01336	0.12847	0.11001	0.12038	0.0112	0.00018	0.12847	0.01210	0.01449
141	0.10501	-0.01317	0.1251	0.10856	0.11877	0.1054	-0.01325	0.12676	0.10927	0.11956	0.0111	0.00018	0.12676	0.01194	0.01429
142	0.10464	-0.0131	0.12351	0.10786	0.11799	0.10501	-0.01317	0.1251	0.10856	0.11877	0.0110	0.00017	0.12510	0.01178	0.01411
143	0.10425	-0.01303	0.12197	0.10718	0.11724	0.10464	-0.0131	0.12351	0.10786	0.11799	0.0110	0.00017	0.12351	0.01163	0.01392
144	0.10404	-0.01299	0.1205	0.10653	0.11652	0.10425	-0.01303	0.12197	0.10718	0.11724	0.0109	0.00017	0.12197	0.01149	0.01375
145	0.10369	-0.01293	0.11908	0.1059	0.11581	0.10404	-0.01299	0.1205	0.10653	0.11652	0.0108	0.00017	0.12050	0.01135	0.01358
146	0.10327	-0.01285	0.11771	0.10528	0.11513	0.10369	-0.01293	0.11908	0.1059	0.11581	0.0108	0.00017	0.11908	0.01121	0.01341
147	0.10308	-0.01281	0.11639	0.10469	0.11447	0.10327	-0.01285	0.11771	0.10528	0.11513	0.0107	0.00017	0.11771	0.01108	0.01326
148	0.10271	-0.01274	0.11511	0.10411	0.11383	0.10308	-0.01281	0.11639	0.10469	0.11447	0.0106	0.00016	0.11639	0.01096	0.01310
149	0.10229	-0.01266	0.11388	0.10355	0.11321	0.10271	-0.01274	0.11511	0.10411	0.11383	0.0106	0.00016	0.11511	0.01084	0.01296
150	0.10208	-0.01262	0.11268	0.103	0.1126	0.10229	-0.01266	0.11388	0.10355	0.11321	0.0105	0.00016	0.11388	0.01072	0.01282
151	0.10153	-0.01252	0.11152	0.10247	0.11201	0.10208	-0.01262	0.11268	0.103	0.1126	0.0104	0.00016	0.11268	0.01061	0.01268
152	0.10124	-0.01247	0.11038	0.10194	0.11143	0.10153	-0.01252	0.11152	0.10247	0.11201	0.0103	0.00016	0.11152	0.01050	0.01255
153	0.10093	-0.01241	0.10928	0.10143	0.11086	0.10124	-0.01247	0.11038	0.10194	0.11143	0.0103	0.00016	0.11038	0.01039	0.01242
154	0.10063	-0.01235	0.10821	0.10093	0.11031	0.10093	-0.01241	0.10928	0.10143	0.11086	0.0102	0.00015	0.10928	0.01029	0.01229
155	0.10031	-0.0123	0.10717	0.10044	0.10977	0.10063	-0.01235	0.10821	0.10093	0.11031	0.0101	0.00015	0.10821	0.01019	0.01217
156	0.1	-0.01224	0.10617	0.09997	0.10925	0.10031	-0.0123	0.10717	0.10044	0.10977	0.0101	0.00015	0.10717	0.01009	0.01205
157	0.09969	-0.01218	0.10519	0.0995	0.10873	0.1	-0.01224	0.10617	0.09997	0.10925	0.0100	0.00015	0.10617	0.00999	0.01193
158	0.09937	-0.01212	0.10423	0.09905	0.10823	0.09969	-0.01218	0.10519	0.0995	0.10873	0.0099	0.00015	0.10519	0.00990	0.01182
159	0.09905	-0.01206	0.1033	0.09861	0.10774	0.09937	-0.01212	0.10423	0.09905	0.10823	0.0099	0.00015	0.10423	0.00981	0.01171
160	0.09873	-0.012	0.1024	0.09817	0.10726	0.09905	-0.01206	0.1033	0.09861	0.10774	0.0098	0.00015	0.10330	0.00972	0.01161
161	0.0986	-0.01198	0.10152	0.09775	0.10679	0.09873	-0.012	0.1024	0.09817	0.10726	0.0098	0.00014	0.10240	0.00964	0.01151
162	0.09813	-0.0119	0.10066	0.09733	0.10634	0.0986	-0.01198	0.10152	0.09775	0.10679	0.0097	0.00014	0.10152	0.00955	0.01140
163	0.09792	-0.01185	0.09982	0.09693	0.10589	0.09813	-0.0119	0.10066	0.09733	0.10634	0.0096	0.00014	0.10066	0.00947	0.01131
164	0.0977	-0.01182	0.09901	0.09653	0.10545	0.09792	-0.01185	0.09982	0.09693	0.10589	0.0096	0.00014	0.09982	0.00939	0.01121
165	0.09748	-0.01177	0.09822	0.09614	0.10502	0.0977	-0.01182	0.09901	0.09653	0.10545	0.0096	0.00014	0.09901	0.00932	0.01112
166	0.09707	-0.0117	0.09744	0.09576	0.1046	0.09748	-0.01177	0.09822	0.09614	0.10502	0.0095	0.00014	0.09822	0.00924	0.01103
167	0.0968	-0.01165	0.09668	0.09538	0.10419	0.09707	-0.0117	0.09744	0.09576	0.1046	0.0094	0.00014	0.09744	0.00917	0.01094
168	0.09661	-0.01162	0.09594	0.09502	0.10378	0.0968	-0.01165	0.09668	0.09538	0.10419	0.0094	0.00014	0.09668	0.00910	0.01085
169	0.09636	-0.01157	0.09522	0.09466	0.10338	0.09661	-0.01162	0.09594	0.09502	0.10378	0.0093	0.00013	0.09594	0.00903	0.01077
170	0.09616	-0.01154	0.09452	0.09431	0.10299	0.09636	-0.01157	0.09522	0.09466	0.10338	0.0093	0.00013	0.09522	0.00896	0.01069
171	0.09571	-0.01146	0.09383	0.09396	0.10261	0.09616	-0.01154	0.09452	0.09431	0.10299	0.0093	0.00013	0.09452	0.00889	0.01061
172	0.09545	-0.01141	0.09314	0.09362	0.10224	0.09571	-0.01146	0.09383	0.09396	0.10261	0.0092	0.00013	0.09383	0.00883	0.01053
173	0.09525	-0.01137	0.09248	0.09328	0.10187	0.09545	-0.01141	0.09314	0.09362	0.10224	0.0091	0.00013	0.09314	0.00876	0.01045
174	0.095	-0.01133	0.09182	0.09295	0.1015	0.09525	-0.01137	0.09248	0.09328	0.10187	0.0091	0.00013	0.09248	0.00870	0.01038
175	0.09478	-0.01129	0.09119	0.09263	0.10114	0.095	-0.01133	0.09182	0.09295	0.1015	0.0090	0.00013	0.09182	0.00864	0.01030
176	0.09454	-0.01124	0.09056	0.09231	0.10079	0.09478	-0.01129	0.09119	0.09263	0.10114	0.0090	0.00013	0.09119	0.00858	0.01023
177	0.09431	-0.0112	0.08995	0.09199	0.10045	0.09454	-0.01124	0.09056	0.09231	0.10079	0.0089	0.00013	0.09056	0.00852	0.01016
178	0.09407	-0.01116	0.08936	0.09169	0.10011	0.09431	-0.0112	0.08995	0.09199	0.10045	0.0089	0.00013	0.08995	0.00846	0.01009
179	0.09404	-0.01115	0.08878	0.09139	0.09978	0.09407	-0.01116	0.08936	0.09169	0.10011	0.0089	0.00012	0.08936	0.00841	0.01002
180	0.09386	-0.01112	0.08822	0.0911	0.09946	0.09404	-0.01115	0.08878	0.09139	0.09978	0.0088	0.00012	0.08878	0.00835	0.00996
181	0.09358	-0.01107	0.08767	0.09082	0.09914	0.09386	-0.01112	0.08822	0.0911	0.09946	0.0088	0.00012	0.08822	0.00830	0.00989

182	0.09337	-0.01104	0.08713	0.09054	0.09884	0.09358	-0.01107	0.08767	0.09082	0.09914	0.0088	0.00012	0.08767	0.00825	0.00983
183	0.09311	-0.01099	0.0866	0.09026	0.09853	0.09337	-0.01104	0.08713	0.09054	0.09884	0.0087	0.00012	0.08713	0.00820	0.00977
184	0.09289	-0.01095	0.08608	0.08999	0.09823	0.09311	-0.01099	0.0866	0.09026	0.09853	0.0087	0.00012	0.08660	0.00815	0.00971
185	0.09263	-0.0109	0.08557	0.08972	0.09794	0.09289	-0.01095	0.08608	0.08999	0.09823	0.0086	0.00012	0.08608	0.00810	0.00965
186	0.0924	-0.01086	0.08506	0.08945	0.09764	0.09263	-0.0109	0.08557	0.08972	0.09794	0.0086	0.00012	0.08557	0.00805	0.00959
187	0.09215	-0.01082	0.08456	0.08918	0.09735	0.0924	-0.01086	0.08506	0.08945	0.09764	0.0085	0.00012	0.08506	0.00800	0.00953
188	0.09212	-0.01081	0.08407	0.08893	0.09707	0.09215	-0.01082	0.08456	0.08918	0.09735	0.0085	0.00012	0.08456	0.00795	0.00948
189	0.09192	-0.01078	0.0836	0.08867	0.09679	0.09212	-0.01081	0.08407	0.08893	0.09707	0.0085	0.00012	0.08407	0.00791	0.00942
190	0.09164	-0.01073	0.08313	0.08843	0.09652	0.09192	-0.01078	0.0836	0.08867	0.09679	0.0085	0.00012	0.08360	0.00786	0.00937
191	0.09142	-0.01069	0.08267	0.08818	0.09625	0.09164	-0.01073	0.08313	0.08843	0.09652	0.0084	0.00012	0.08313	0.00782	0.00932
192	0.09115	-0.01064	0.08221	0.08794	0.09598	0.09142	-0.01069	0.08267	0.08818	0.09625	0.0084	0.00011	0.08267	0.00778	0.00926
193	0.09113	-0.01064	0.08177	0.0877	0.09572	0.09115	-0.01064	0.08221	0.08794	0.09598	0.0083	0.00011	0.08221	0.00773	0.00921
194	0.09092	-0.0106	0.08133	0.08746	0.09546	0.09113	-0.01064	0.08177	0.0877	0.09572	0.0083	0.00011	0.08177	0.00769	0.00916
195	0.09064	-0.01055	0.0809	0.08723	0.0952	0.09092	-0.0106	0.08133	0.08746	0.09546	0.0083	0.00011	0.08133	0.00765	0.00911
196	0.09041	-0.01051	0.08047	0.087	0.09495	0.09064	-0.01055	0.0809	0.08723	0.0952	0.0082	0.00011	0.08090	0.00761	0.00906
197	0.09035	-0.0105	0.08006	0.08677	0.0947	0.09041	-0.01051	0.08047	0.087	0.09495	0.0082	0.00011	0.08047	0.00757	0.00902
198	0.09017	-0.01047	0.07965	0.08655	0.09445	0.09035	-0.0105	0.08006	0.08677	0.0947	0.0082	0.00011	0.08006	0.00753	0.00897
199	0.08986	-0.01042	0.07925	0.08633	0.09421	0.09017	-0.01047	0.07965	0.08655	0.09445	0.0081	0.00011	0.07965	0.00749	0.00892
200	0.08987	-0.01042	0.07885	0.08611	0.09397	0.08986	-0.01042	0.07925	0.08633	0.09421	0.0081	0.00011	0.07925	0.00745	0.00888
201	0.08964	-0.01038	0.07846	0.0859	0.09374	0.08987	-0.01042	0.07885	0.08611	0.09397	0.0081	0.00011	0.07885	0.00742	0.00883
202	0.08935	-0.01033	0.07808	0.08569	0.09351	0.08964	-0.01038	0.07846	0.0859	0.09374	0.0080	0.00011	0.07846	0.00738	0.00879
203	0.08934	-0.01032	0.0777	0.08548	0.09328	0.08935	-0.01033	0.07808	0.08569	0.09351	0.0080	0.00011	0.07808	0.00734	0.00874
204	0.08912	-0.01029	0.07733	0.08528	0.09305	0.08934	-0.01032	0.0777	0.08548	0.09328	0.0080	0.00011	0.07770	0.00731	0.00870
205	0.08882	-0.01024	0.07696	0.08507	0.09283	0.08912	-0.01029	0.07733	0.08528	0.09305	0.0079	0.00011	0.07733	0.00727	0.00866
206	0.08881	-0.01023	0.0766	0.08487	0.09261	0.08882	-0.01024	0.07696	0.08507	0.09283	0.0079	0.00010	0.07696	0.00724	0.00862
207	0.08859	-0.0102	0.07625	0.08468	0.09239	0.08881	-0.01023	0.0766	0.08487	0.09261	0.0079	0.00010	0.07660	0.00720	0.00858
208	0.08852	-0.01018	0.0759	0.08448	0.09218	0.08859	-0.0102	0.07625	0.08468	0.09239	0.0079	0.00010	0.07625	0.00717	0.00854
209	0.08834	-0.01015	0.07556	0.08429	0.09197	0.08852	-0.01018	0.0759	0.08448	0.09218	0.0078	0.00010	0.07590	0.00714	0.00850
210	0.08801	-0.01009	0.07522	0.0841	0.09176	0.08834	-0.01015	0.07556	0.08429	0.09197	0.0078	0.00010	0.07556	0.00711	0.00846
211	0.08802	-0.0101	0.07488	0.08391	0.09156	0.08801	-0.01009	0.07522	0.0841	0.09176	0.0078	0.00010	0.07522	0.00707	0.00842
212	0.08778	-0.01006	0.07455	0.08373	0.09135	0.08802	-0.0101	0.07488	0.08391	0.09156	0.0078	0.00010	0.07488	0.00704	0.00838
213	0.08772	-0.01004	0.07423	0.08355	0.09115	0.08778	-0.01006	0.07455	0.08373	0.09135	0.0077	0.00010	0.07455	0.00701	0.00835
214	0.08753	-0.01001	0.07391	0.08337	0.09096	0.08772	-0.01004	0.07423	0.08355	0.09115	0.0077	0.00010	0.07423	0.00698	0.00831
215	0.0872	-0.00995	0.07359	0.08319	0.09076	0.08753	-0.01001	0.07391	0.08337	0.09096	0.0077	0.00010	0.07391	0.00695	0.00827
216	0.08721	-0.00996	0.07328	0.08301	0.09056	0.0872	-0.00995	0.07359	0.08319	0.09076	0.0076	0.00010	0.07359	0.00692	0.00824
217	0.08696	-0.00992	0.07297	0.08283	0.09037	0.08721	-0.00996	0.07328	0.08301	0.09056	0.0076	0.00010	0.07328	0.00689	0.00820
218	0.0869	-0.0099	0.07266	0.08266	0.09018	0.08696	-0.00992	0.07297	0.08283	0.09037	0.0076	0.00010	0.07297	0.00686	0.00817
219	0.08671	-0.00987	0.07236	0.08248	0.08999	0.0869	-0.0099	0.07266	0.08266	0.09018	0.0076	0.00010	0.07266	0.00683	0.00813
220	0.08661	-0.00985	0.07206	0.08231	0.0898	0.08671	-0.00987	0.07236	0.08248	0.08999	0.0075	0.00010	0.07236	0.00680	0.00810
221	0.08644	-0.00983	0.07177	0.08215	0.08962	0.08661	-0.00985	0.07206	0.08231	0.0898	0.0075	0.00010	0.07206	0.00678	0.00806
222	0.04733	-0.00429	0.07074	0.08172	0.08932	0.08644	-0.00983	0.07177	0.08215	0.08962	0.0075	0.00010	0.07177	0.00675	0.00803
223	-0.04733	0	0.06865	0.08072	0.08862	0.04733	-0.00429	0.07074	0.08172	0.08932	0.0022	0.00002	0.07074	0.00668	0.00798
224	0.04734	-0.00401	0.06663	0.07948	0.08749	-0.04733	0	0.06865	0.08072	0.08862	0.0022	-0.00002	0.06865	0.00652	0.00785
225	-0.04734	0	0.06473	0.07834	0.08623	0.04734	-0.00401	0.06663	0.07948	0.08749	0.0022	0.00002	0.06663	0.00632	0.00766
226	0.04734	-0.00375	0.06288	0.07722	0.085	-0.04734	0	0.06473	0.07834	0.08623	0.0022	-0.00002	0.06473	0.00614	0.00744
227	-0.04734	0	0.06113	0.07613	0.08379	0.04734	-0.00375	0.06288	0.07722	0.085	0.0022	0.00001	0.06288	0.00596	0.00722
228	0.04734	-0.0035	0.05943	0.07507	0.08262	-0.04734	0	0.06113	0.07613	0.08379	0.0022	-0.00001	0.06113	0.00580	0.00702
229	-0.04734	0	0.05782	0.07404	0.08148	0.04734	-0.0035	0.05943	0.07507	0.08262	0.0022	0.00001	0.05943	0.00564	0.00683
230	0.04734	-0.00327	0.05626	0.07304	0.08037	-0.04734	0	0.05782	0.07404	0.08148	0.0022	-0.00001	0.05782	0.00548	0.00664
231	-0.04734	0	0.05477	0.07206	0.07929	0.04734	-0.00327	0.05626	0.07304	0.08037	0.0022	0.00001	0.05626	0.00533	0.00646
232	0.04734	-0.00306	0.05333	0.07111	0.07824	-0.04734	0	0.05477	0.07206	0.07929	0.0022	-0.00001	0.05477	0.00519	0.00629
233	-0.04734	0	0.05196	0.07019	0.07721	0.04734	-0.00306	0.05333	0.07111	0.07824	0.0022	0.00001	0.05333	0.00506	0.00612
234	0.04734	-0.00286	0.05063	0.06929	0.07621	-0.04734	0	0.05196	0.07019	0.07721	0.0022	-0.00001	0.05196	0.00493	0.00596
235	-0.04734	0	0.04936	0.06841	0.07524	0.04734	-0.00286	0.05063	0.06929	0.07621	0.0022	0.00001	0.05063	0.00480	0.00581
236	0.04734	0.00267	0.04812	0.06755	0.07429	-0.04734	0	0.04936	0.06841	0.07524	0.0022	-0.00001	0.04936	0.00468	0.00566
237	-0.04734	0	0.04695	0.06672	0.07337	0.04734	0.00267	0.04812	0.06755	0.07429	0.0022	0.00001	0.04812	0.00456	0.00552
238	0.04734	0.00249	0.0458	0.0659	0.07247	-0.04734	0	0.04695	0.06672	0.07337	0.0022	-0.00001	0.04695	0.00445	0.00538
239	-0.04734	0	0.04471	0.06511	0.07159	0.04734	0.00249	0.0458	0.0659	0.07247	0.0022	0.00001	0.04580	0.00434	0.00525
240	0.04734	0.00233	0.04364	0.06433	0.07073	-0.04734	0	0.04471	0.06511	0.07159	0.0022	-0.00001	0.04471	0.00424	0.00512
241	-0.04734	0	0.04262	0.06357	0.06989	0.04734	0.00233	0.04364	0.06433	0.07073	0.0022	0.00001	0.04364	0.00414	0.00500
242	0.04734	0.00218	0.04163	0.06283	0.06907	-0.04734	0	0.04262	0.06357	0.06989	0.0022	-0.00001	0.04262	0.00404	0.00488

367	-0.04734	-0.00001	0.00682	0.02543	0.02787	0.04734	0.00003	0.00689	0.02556	0.028	0.0022	0.00000	0.00689	0.00065	0.00078
368	0.04734	0.00003	0.00676	0.02531	0.02773	-0.04734	-0.00001	0.00682	0.02543	0.02787	0.0022	0.00000	0.00682	0.00065	0.00078
369	-0.04734	0.00001	0.00669	0.02519	0.0276	0.04734	0.00003	0.00676	0.02531	0.02773	0.0022	0.00000	0.00676	0.00064	0.00077
370	0.04734	0.00003	0.00663	0.02507	0.02747	-0.04734	0.00001	0.00669	0.02519	0.0276	0.0022	0.00000	0.00669	0.00063	0.00076
371	-0.04734	0	0.00657	0.02495	0.02734	0.04734	0.00003	0.00663	0.02507	0.02747	0.0022	0.00000	0.00663	0.00063	0.00075
372	0.04734	0.00003	0.0065	0.02484	0.02721	-0.04734	0	0.00657	0.02495	0.02734	0.0022	0.00000	0.00657	0.00062	0.00075
373	-0.04734	0.00001	0.00644	0.02472	0.02709	0.04734	0.00003	0.0065	0.02484	0.02721	0.0022	0.00000	0.00650	0.00062	0.00074
374	0.04734	0.00003	0.00638	0.0246	0.02696	-0.04734	0.00001	0.00644	0.02472	0.02709	0.0022	0.00000	0.00644	0.00061	0.00073
375	-0.04734	0	0.00632	0.02449	0.02683	0.04734	0.00003	0.00638	0.0246	0.02696	0.0022	0.00000	0.00638	0.00061	0.00073
376	0.04734	0.00003	0.00627	0.02438	0.02671	-0.04734	0	0.00632	0.02449	0.02683	0.0022	0.00000	0.00632	0.00060	0.00072
377	-0.04734	0	0.00621	0.02427	0.02659	0.04734	0.00003	0.00627	0.02438	0.02671	0.0022	0.00000	0.00627	0.00059	0.00071
378	0.04734	0.00003	0.00615	0.02416	0.02647	-0.04734	0	0.00621	0.02427	0.02659	0.0022	0.00000	0.00621	0.00059	0.00071
379	-0.04734	0	0.0061	0.02405	0.02634	0.04734	0.00003	0.00615	0.02416	0.02647	0.0022	0.00000	0.00615	0.00058	0.00070
380	0.04734	0.00003	0.00604	0.02394	0.02622	-0.04734	0	0.0061	0.02405	0.02634	0.0022	0.00000	0.00610	0.00058	0.00069
381	-0.04734	0	0.00599	0.02383	0.02611	0.04734	0.00003	0.00604	0.02394	0.02622	0.0022	0.00000	0.00604	0.00057	0.00069
382	0.04734	0.00003	0.00593	0.02372	0.02599	-0.04734	0	0.00599	0.02383	0.02611	0.0022	0.00000	0.00599	0.00057	0.00068
383	-0.04734	-0.00001	0.00588	0.02362	0.02587	0.04734	0.00003	0.00593	0.02372	0.02599	0.0022	0.00000	0.00593	0.00056	0.00068
384	0.04734	0.00003	0.00583	0.02351	0.02576	-0.04734	-0.00001	0.00588	0.02362	0.02587	0.0022	0.00000	0.00588	0.00056	0.00067
385	-0.04734	-0.00001	0.00578	0.02341	0.02564	0.04734	0.00003	0.00583	0.02351	0.02576	0.0022	0.00000	0.00583	0.00055	0.00066
386	0.04734	0.00003	0.00573	0.0233	0.02553	-0.04734	-0.00001	0.00578	0.02341	0.02564	0.0022	0.00000	0.00578	0.00055	0.00066
387	-0.04734	0.00002	0.00568	0.0232	0.02542	0.04734	0.00003	0.00573	0.0233	0.02553	0.0022	0.00000	0.00573	0.00054	0.00065
388	0.04734	0.00003	0.00563	0.0231	0.02531	-0.04734	0.00002	0.00568	0.0232	0.02542	0.0022	0.00000	0.00568	0.00054	0.00065
389	-0.04734	0.00001	0.00558	0.023	0.02519	0.04734	0.00003	0.00563	0.0231	0.02531	0.0022	0.00000	0.00563	0.00053	0.00064
390	0.04734	0.00003	0.00553	0.0229	0.02509	-0.04734	0.00001	0.00558	0.023	0.02519	0.0022	0.00000	0.00558	0.00053	0.00063
391	-0.04734	0.00001	0.00548	0.0228	0.02498	0.04734	0.00003	0.00553	0.0229	0.02509	0.0022	0.00000	0.00553	0.00052	0.00063
392	0.04734	0.00003	0.00543	0.0227	0.02487	-0.04734	0.00001	0.00548	0.0228	0.02498	0.0022	0.00000	0.00548	0.00052	0.00062
393	-0.04734	0.00001	0.00539	0.0226	0.02476	0.04734	0.00003	0.00543	0.0227	0.02487	0.0022	0.00000	0.00543	0.00052	0.00062
394	0.04734	0.00004	0.00534	0.02251	0.02466	-0.04734	0.00001	0.00539	0.0226	0.02476	0.0022	0.00000	0.00539	0.00051	0.00061
395	-0.04734	0.00001	0.0053	0.02241	0.02455	0.04734	0.00004	0.00534	0.02251	0.02466	0.0022	0.00000	0.00534	0.00051	0.00061
396	0.04734	0.00004	0.00525	0.02232	0.02445	-0.04734	0.00001	0.0053	0.02241	0.02455	0.0022	0.00000	0.00530	0.00050	0.00060
397	-0.04734	0.00001	0.00521	0.02222	0.02434	0.04734	0.00004	0.00525	0.02232	0.02445	0.0022	0.00000	0.00525	0.00050	0.00060
398	0.04734	0.00004	0.00516	0.02213	0.02424	-0.04734	0.00001	0.00521	0.02222	0.02434	0.0022	0.00000	0.00521	0.00049	0.00059
399	-0.04734	0.00001	0.00512	0.02204	0.02414	0.04734	0.00004	0.00516	0.02213	0.02424	0.0022	0.00000	0.00516	0.00049	0.00059
400	0.04734	0.00004	0.00508	0.02194	0.02404	-0.04734	0.00001	0.00512	0.02204	0.02414	0.0022	0.00000	0.00512	0.00049	0.00058

APPENDIX I

Matlab Program for Model Application

I.1 Matlab Program for Numerical Model of Bioretention System

```
clc

clear all

format long g

% Solve nonlinear system F(x)=0 using NewtonÌs method

% input data

%Rainfall data (m/sec)

i_n=[0.00000099
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0.00000103
0.00000105
0.00000106
0.00000107
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0.00000107
0.00000106
0.00000106
0.00000105
0.00000105
0.00000104
0.00000104
0.00000103
0
0
0
0
0];


%DATA UIRED For MODEL

A_catmt=400;

%disp(i_n1)

QET_n=0;

QET_n1=0;

g=9.1;

W=3.00;

K_ns=.0000018;

r=0.8;

s=1;

rs=r*s;

I_n=1;

I_n1=2;

d_p1=0.15;

d_p2=0.20;

%Hdes=dead storage height of catc basin

Hdes_n1=0.8;
```

```
Hdes_n=0.8;


L1=19.00;
L2=35.00;
L3=18.00;
fi=0.98;
I_a=0;
%area of bioretention cell calculation
A_bc=L1*.30;
A_cb=0.61^2;
%cross sectional area
A_p1=pi*d_p1^2/4;
A_p2=pi*d_p2^2/4;
A_mh=pi*1.2^2/4;
A_mhexit=pi*.3^2/4;
H_bc=0.8;
D_p1=0.15;
D_p2=0.20;
D_mhexit=0.30;
C_d=0.60;
C=0.60;
i_n1=0;


%time step
delta_t=60;


% heights at t=0, boundary situation
H1_n = 0;
```

```
H2_n = 0;

H3_n = 0;

H4_n = 0;

H5_n = 0;


% constant value of H(primes)


% substitue height variables into x variables in order to eliminate square
root expression in orifice equation
X1_n = sqrt(H1_n);
X2_n = sqrt(H2_n);
X3_n = H3_n;
X4_n = sqrt(H4_n);
X5_n = sqrt(H5_n);


fprintf(' Step      X1_n1    X2_n1    X3_n1    X4_n1    X5_n1    X1_n
X2_n     X3_n     X4_n     X5_n      H1         H2        H3        H4        H5
\n')


% set stopping conditions and maximum iteration runs
error = 1*10^(-5);


iter=0;
itermax=5;
% Coefficient from Mass Balance


aa1=delta_t*A_p1*sqrt(2*g)*(C_d/D_p1);
```

```
aa2=A_cb;
aa3=A_cb*Hdes_n1;
aa4=0.5*delta_t*fi*A_catmt*E;
bb1=.6*0.5*delta_t*2756;
bb2=.6*0.5*delta_t*245.47;
bb3=.6*0.5*delta_t*6.75;
bb4=0.1177*L1;
cc1=0.2*L2*W;
cc2=delta_t*(L2+W)*K_ns*r*s;
cc3=0.5*delta_t*QET_n;
cc4=0.8*0.5*delta_t*0.0113*C*sqrt(2*g);
dd1=0.1177*L3;
dd2=delta_t*A_p2*sqrt(2*g)*(C_d/D_p2);
ee1=delta_t*A_mhexit*sqrt(2*g)*(C_d/D_mhexit);
ee2=A_mh;


for kk=1:250
if kk+1>length(i_n)
    i_n(kk+1,1)=0;
    i_n(kk,1)=0;
end


f=@(x)[aa1*x(1)^3+aa2*x(1)^2+aa3+aa1*X1_n^3-aa2*X1_n^2-aa3-aa4*i_n(kk+1,1)-
aa4*i_n(kk,1);
aa1*x(1)^3-bb1*x(2)^6+bb2*x(2)^4-bb3*x(2)^2-bb4*x(2)^2+aa1*X1_n^3-
bb1*X2_n^6+bb2*X2_n^4-bb3*X2_n^2+bb4*X2_n^2;
```

```
bb1*x(2)^6-bb2*x(2)^4+bb3*x(2)^2-cc1*x(3)-cc2*x(3)+bb1*X2_n^6-
bb2*X2_n^4+bb3*X2_n^2-cc2*X3_n+cc1*X3_n-cc3*QET_n1-cc3*QET_n-cc4*x(3)^1.5-
cc4*X3_n^1.5;
dd1*x(4)^2+dd2*x(4)^3-cc4*x(3)^1.5+dd2*X4_n^3-cc4*X3_n^1.5-dd1*X4_n^2;
ee1*x(5)^3+ee2*x(5)^2-dd2*x(4)^3-ee2*X5_n^2+ee2*X5_n^3-dd2*X4_n^3];

options = optimset('Display','off');
R=fsolve(f,[0.0001 0.0001 0.0001 0.0001 0.0001],options);

X1_n1=R(1,1);
X2_n1=R(1,2);
X3_n1=R(1,3);
X4_n1=R(1,4);
X5_n1=R(1,5);

fprintf('%8.0f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f %8.5f
%8.5f %8.5f %8.5f %8.5f
%8.5f\n',kk,X1_n1,X2_n1,X3_n1,X4_n1,X5_n1,X1_n,X2_n,X3_n,X4_n,X5_n,X1_n^2,X2_
n^2,X3_n,X4_n^2,X5_n^2)
X1_n = X1_n1;
X2_n = X2_n1;
X3_n = X3_n1;
X4_n = X4_n1;
X5_n = X5_n1;

end
```

I.2 Model Results

Step	X1_n1	X2_n1	X3_n1	X4_n1	X5_n1	X1_n	X2_n	X3_n	X4_n	X5_n	H1	H2	H3	H4	H5
1	0.10269	0.01262	0.00092	0.00365	-0.00021	0	0	0	0	0	0	0	0	0	0
2	0.07054	0.00756	0.00216	0.00711	0.00283	0.10269	0.01262	0.00092	0.00365	-0.00021	0.01055	0.00016	0.00092	0.00001	0
3	0.0963	0.01129	0.00321	0.0111	0.00612	0.07054	0.00756	0.00216	0.00711	0.00283	0.00498	0.00006	0.00216	0.00005	0.00001
4	0.08026	0.00917	0.00441	0.015	0.01022	0.0963	0.01129	0.00321	0.0111	0.00612	0.00927	0.00013	0.00321	0.00012	0.00004
5	0.09315	0.01065	0.00553	0.01856	0.01458	0.08026	0.00917	0.00441	0.015	0.01022	0.00644	0.00008	0.00441	0.00022	0.0001
6	0.08467	0.00992	0.00672	0.02169	0.01876	0.09315	0.01065	0.00553	0.01856	0.01458	0.00868	0.00011	0.00553	0.00034	0.00021
7	0.09148	0.01032	0.00785	0.02443	0.02254	0.08467	0.00992	0.00672	0.02169	0.01876	0.00717	0.0001	0.00672	0.00047	0.00035
8	0.08735	0.01037	0.00903	0.02683	0.02584	0.09148	0.01032	0.00785	0.02443	0.02254	0.00837	0.00011	0.00785	0.0006	0.00051
9	0.0911	0.01026	0.01019	0.029	0.02872	0.08735	0.01037	0.00903	0.02683	0.02584	0.00763	0.00011	0.00903	0.00072	0.00067
10	0.08862	0.01057	0.01137	0.03097	0.03126	0.0911	0.01026	0.01019	0.029	0.02872	0.0083	0.00011	0.01019	0.00084	0.00082
11	0.09069	0.01019	0.01252	0.0328	0.03355	0.08862	0.01057	0.01137	0.03097	0.03126	0.00785	0.00011	0.01137	0.00096	0.00098
12	0.08988	0.01077	0.01368	0.0345	0.03563	0.09069	0.01019	0.01252	0.0328	0.03355	0.00822	0.0001	0.01252	0.00108	0.00113
13	0.09116	0.0103	0.01485	0.03611	0.03755	0.08988	0.01077	0.01368	0.0345	0.03563	0.00808	0.00012	0.01368	0.00119	0.00127
14	0.09091	0.01092	0.01601	0.03764	0.03935	0.09116	0.0103	0.01485	0.03611	0.03755	0.00831	0.00011	0.01485	0.0013	0.00141
15	0.09177	0.01043	0.01718	0.03911	0.04106	0.09091	0.01092	0.01601	0.03764	0.03935	0.00826	0.00012	0.01601	0.00142	0.00155
16	0.09159	0.01102	0.01834	0.04053	0.0427	0.09177	0.01043	0.01718	0.03911	0.04106	0.00842	0.00011	0.01718	0.00153	0.00169
17	0.09239	0.01056	0.01951	0.04189	0.04426	0.09159	0.01102	0.01834	0.04053	0.0427	0.00839	0.00012	0.01834	0.00164	0.00182
18	0.09246	0.01115	0.02067	0.0432	0.04576	0.09239	0.01056	0.01951	0.04189	0.04426	0.00854	0.00011	0.01951	0.00175	0.00196
19	0.09307	0.01071	0.02184	0.04447	0.04721	0.09246	0.01115	0.02067	0.0432	0.04576	0.00855	0.00012	0.02067	0.00187	0.00209
20	0.09327	0.01127	0.023	0.04571	0.04861	0.09307	0.01071	0.02184	0.04447	0.04721	0.00866	0.00011	0.02184	0.00198	0.00223
21	0.09377	0.01085	0.02417	0.04691	0.04996	0.09327	0.01127	0.023	0.04571	0.04861	0.0087	0.00013	0.023	0.00209	0.00236
22	0.09426	0.01143	0.02533	0.04808	0.05128	0.09377	0.01085	0.02417	0.04691	0.04996	0.00879	0.00012	0.02417	0.0022	0.0025
23	0.09475	0.01105	0.0265	0.04922	0.05256	0.09426	0.01143	0.02533	0.04808	0.05128	0.00889	0.00013	0.02533	0.00231	0.00263
24	0.09523	0.01158	0.02767	0.05034	0.05381	0.09475	0.01105	0.0265	0.04922	0.05256	0.00898	0.00012	0.0265	0.00242	0.00276
25	0.0957	0.01124	0.02885	0.05144	0.05504	0.09523	0.01158	0.02767	0.05034	0.05381	0.00907	0.00013	0.02767	0.00253	0.0029
26	0.09617	0.01173	0.03003	0.05251	0.05624	0.0957	0.01124	0.02885	0.05144	0.05504	0.00916	0.00013	0.02885	0.00265	0.00303
27	0.09664	0.01143	0.03121	0.05357	0.05742	0.09617	0.01173	0.03003	0.05251	0.05624	0.00925	0.00014	0.03003	0.00276	0.00316
28	0.0971	0.01188	0.03239	0.05461	0.05857	0.09664	0.01143	0.03121	0.05357	0.05742	0.00934	0.00013	0.03121	0.00287	0.0033
29	0.09756	0.01161	0.03357	0.05562	0.0597	0.0971	0.01188	0.03239	0.05461	0.05857	0.00943	0.00014	0.03239	0.00298	0.00343
30	0.09801	0.01204	0.03476	0.05662	0.06081	0.09756	0.01161	0.03357	0.05562	0.0597	0.00952	0.00013	0.03357	0.00309	0.00356
31	0.09866	0.01183	0.03594	0.0576	0.0619	0.09801	0.01204	0.03476	0.05662	0.06081	0.00961	0.00014	0.03476	0.00321	0.0037
32	0.09934	0.01226	0.03714	0.05858	0.06298	0.09866	0.01183	0.03594	0.0576	0.0619	0.00973	0.00014	0.03594	0.00332	0.00383
33	0.09998	0.01209	0.03835	0.05954	0.06404	0.09934	0.01226	0.03714	0.05858	0.06298	0.00987	0.00015	0.03714	0.00343	0.00397
34	0.10064	0.01249	0.03957	0.0605	0.0651	0.09998	0.01209	0.03835	0.05954	0.06404	0.01	0.00015	0.03835	0.00355	0.0041
35	0.10108	0.0123	0.04079	0.06145	0.06614	0.10064	0.01249	0.03957	0.0605	0.0651	0.01013	0.00016	0.03957	0.00366	0.00424
36	0.10168	0.01267	0.04202	0.06238	0.06718	0.10108	0.0123	0.04079	0.06145	0.06614	0.01022	0.00015	0.04079	0.00378	0.00437
37	0.10233	0.01255	0.04325	0.06331	0.0682	0.10168	0.01267	0.04202	0.06238	0.06718	0.01034	0.00016	0.04202	0.00389	0.00451
38	0.10292	0.01289	0.04449	0.06422	0.06921	0.10233	0.01255	0.04325	0.06331	0.0682	0.01047	0.00016	0.04325	0.00401	0.00465
39	0.10355	0.01279	0.04574	0.06513	0.07021	0.10292	0.01289	0.04449	0.06422	0.06921	0.01059	0.00017	0.04449	0.00412	0.00479
40	0.10414	0.01311	0.04699	0.06603	0.0712	0.10355	0.01279	0.04574	0.06513	0.07021	0.01072	0.00016	0.04574	0.00424	0.00493
41	0.1051	0.01309	0.04826	0.06693	0.07219	0.10414	0.01311	0.04699	0.06603	0.0712	0.01085	0.00017	0.04699	0.00436	0.00507
42	0.1061	0.01347	0.04956	0.06783	0.07317	0.1051	0.01309	0.04826	0.06693	0.07219	0.01105	0.00017	0.04826	0.00448	0.00521
43	0.10703	0.01347	0.05089	0.06874	0.07416	0.1061	0.01347	0.04956	0.06783	0.07317	0.01126	0.00018	0.04956	0.0046	0.00535
44	0.10782	0.01379	0.05223	0.06965	0.07515	0.10703	0.01347	0.05089	0.06874	0.07416	0.01146	0.00018	0.05089	0.00473	0.0055
45	0.10869	0.01379	0.0536	0.07057	0.07615	0.10782	0.01379	0.05223	0.06965	0.07515	0.01162	0.00019	0.05223	0.00485	0.00565
46	0.10964	0.01414	0.05499	0.07148	0.07715	0.10869	0.01379	0.0536	0.07057	0.07615	0.01181	0.00019	0.0536	0.00498	0.0058
47	0.11051	0.01415	0.0564	0.0724	0.07815	0.10964	0.01414	0.05499	0.07148	0.07715	0.01202	0.0002	0.05499	0.00511	0.00595
48	0.11141	0.01447	0.05783	0.07332	0.07916	0.11051	0.01415	0.0564	0.0724	0.07815	0.01221	0.0002	0.0564	0.00524	0.00611
49	0.1121	0.01447	0.05928	0.07425	0.08016	0.11141	0.01447	0.05783	0.07332	0.07916	0.01241	0.00021	0.05783	0.00538	0.00627
50	0.11294	0.01477	0.06074	0.07517	0.08117	0.1121	0.01447	0.05928	0.07425	0.08016	0.01257	0.00021	0.05928	0.00551	0.00643
51	0.11454	0.01496	0.06225	0.0761	0.08218	0.11294	0.01477	0.06074	0.07517	0.08117	0.01276	0.00022	0.06074	0.00565	0.00659
52	0.11623	0.01541	0.06383	0.07705	0.08321	0.11454	0.01496	0.06225	0.0761	0.08218	0.01312	0.00022	0.06225	0.00579	0.00675
53	0.11763	0.01558	0.06548	0.07804	0.08426	0.11623	0.01541	0.06383	0.07705	0.08321	0.01351	0.00024	0.06383	0.00594	0.00692
54	0.11918	0.016	0.06719	0.07905	0.08535	0.11763	0.01558	0.06548	0.07804	0.08426	0.01384	0.00024	0.06548	0.00609	0.0071
55	0.12068	0.01621	0.06896	0.08009	0.08646	0.11918	0.016	0.06719	0.07905	0.08535	0.0142	0.00026	0.06719	0.00625	0.00728
56	0.12216	0.0166	0.0708	0.08115	0.08761	0.12068	0.01621	0.06896	0.08009	0.08646	0.01456	0.00026	0.06896	0.00641	0.00748
57	0.12346	0.01678	0.0727	0.08224	0.08878	0.12216	0.0166	0.0708	0.08115	0.08761	0.01492	0.00028	0.0708	0.00659	0.00767
58	0.12484	0.01715	0.07465	0.08334	0.08997	0.12346	0.01678	0.0727	0.08224	0.08878	0.01524	0.00028	0.0727	0.00676	0.00788
59	0.12624	0.01736	0.07666	0.08446	0.09117	0.12484	0.01715	0.07465	0.08334	0.08997	0.01559	0.00029	0.07465	0.00695	0.00809
60	0.12757	0.01772	0.07873	0.08559	0.0924	0.12624	0.01736	0.07666	0.08446	0.09117	0.01594	0.0003	0.07666	0.00713	0.00831

61	0.13201	0.01858	0.08098	0.08678	0.09367	0.12757	0.01772	0.07873	0.08559	0.0924	0.01627	0.00031	0.07873	0.00733	0.00854
62	0.13671	0.01967	0.08357	0.08812	0.09503	0.13201	0.01858	0.08098	0.08678	0.09367	0.01743	0.00035	0.08098	0.00753	0.00877
63	0.14069	0.02048	0.0865	0.08961	0.09655	0.13671	0.01967	0.08357	0.08812	0.09503	0.01869	0.00039	0.08357	0.00776	0.00903
64	0.14478	0.02146	0.08975	0.09126	0.09824	0.14069	0.02048	0.0865	0.08961	0.09655	0.01979	0.00042	0.0865	0.00803	0.00932
65	0.1484	0.02223	0.09332	0.09304	0.10008	0.14478	0.02146	0.08975	0.09126	0.09824	0.02096	0.00046	0.08975	0.00833	0.00965
66	0.15204	0.02312	0.09719	0.09493	0.10207	0.1484	0.02223	0.09332	0.09304	0.10008	0.02202	0.00049	0.09332	0.00866	0.01002
67	0.15537	0.02385	0.10134	0.09694	0.10418	0.15204	0.02312	0.09719	0.09493	0.10207	0.02312	0.00053	0.09719	0.00901	0.01042
68	0.15868	-0.02468	0.10578	0.09903	0.10641	0.15537	0.02385	0.10134	0.09694	0.10418	0.02414	0.00057	0.10134	0.0094	0.01085
69	0.16168	-0.02536	0.11047	0.10121	0.10873	0.15868	-0.02468	0.10578	0.09903	0.10641	0.02518	0.00061	0.10578	0.00981	0.01132
70	0.16472	-0.02613	0.11541	0.10346	0.11114	0.16168	-0.02536	0.11047	0.10121	0.10873	0.02614	0.00064	0.11047	0.01024	0.01182
71	0.18481	-0.03111	0.12193	0.10616	0.11381	0.16472	-0.02613	0.11541	0.10346	0.11114	0.02713	0.00068	0.11541	0.0107	0.01235
72	0.20327	-0.03622	0.13155	0.10996	0.11727	0.18481	-0.03111	0.12193	0.10616	0.11381	0.03416	0.00097	0.12193	0.01127	0.01295
73	0.21732	-0.04021	0.14416	0.11497	0.12196	0.20327	-0.03622	0.13155	0.10996	0.11727	0.04132	0.00131	0.13155	0.01209	0.01375
74	0.23096	-0.0444	0.15962	0.12091	0.12783	0.21732	-0.04021	0.14416	0.11497	0.12196	0.04723	0.00162	0.14416	0.01322	0.01487
75	0.24219	-0.04794	0.1778	0.12762	0.13467	0.23096	-0.0444	0.15962	0.12091	0.12783	0.05334	0.00197	0.15962	0.01462	0.01634
76	0.25325	-0.05165	0.19853	0.13492	0.14229	0.24219	-0.04794	0.1778	0.12762	0.13467	0.05866	0.0023	0.1778	0.01629	0.01814
77	0.2628	-0.05494	0.22169	0.14267	0.15049	0.25325	-0.05165	0.19853	0.13492	0.14229	0.06414	0.00267	0.19853	0.0182	0.02025
78	0.27222	-0.05837	0.24708	0.15074	0.15913	0.2628	-0.05494	0.22169	0.14267	0.15049	0.06906	0.00302	0.22169	0.02035	0.02265
79	0.28056	-0.06151	0.27455	0.15904	0.16807	0.27222	-0.05837	0.24708	0.15074	0.15913	0.0741	0.00341	0.24708	0.02272	0.02532
80	0.28883	-0.06476	0.30391	0.16746	0.17722	0.28056	-0.06151	0.27455	0.15904	0.16807	0.07871	0.00378	0.27455	0.02529	0.02825
81	0.28186	-0.06216	0.33204	0.17536	0.18615	0.28883	-0.06476	0.30391	0.16746	0.17722	0.08343	0.00419	0.30391	0.02804	0.03141
82	0.27344	-0.05883	0.35555	0.18182	0.19405	0.28186	-0.06216	0.33204	0.17536	0.18615	0.07945	0.00386	0.33204	0.03075	0.03465
83	0.26549	0.05604	0.37462	0.18686	0.20042	0.27344	-0.05883	0.35555	0.18182	0.19405	0.07477	0.00346	0.35555	0.03306	0.03765
84	0.25604	0.05262	0.38951	0.19074	0.20537	0.26549	0.05604	0.37462	0.18686	0.20042	0.07048	0.00314	0.37462	0.03492	0.04017
85	0.24684	0.04961	0.40043	0.19356	0.2091	0.25604	0.05262	0.38951	0.19074	0.20537	0.06556	0.00277	0.38951	0.03638	0.04218
86	0.23593	0.04598	0.40763	0.19543	0.21172	0.24684	0.04961	0.40043	0.19356	0.2091	0.06093	0.00246	0.40043	0.03746	0.04372
87	0.22487	-0.04263	0.41133	0.19644	0.21335	0.23593	0.04598	0.40763	0.19543	0.21172	0.05566	0.00211	0.40763	0.03819	0.04483
88	0.21161	0.03861	0.41174	0.19666	0.21408	0.22487	-0.04263	0.41133	0.19644	0.21335	0.05057	0.00182	0.41133	0.03859	0.04552
89	0.19746	0.0347	0.40906	0.19612	0.21396	0.21161	0.03861	0.41174	0.19666	0.21408	0.04478	0.00149	0.41174	0.03867	0.04583
90	0.17994	0.02995	0.40349	0.19489	0.21305	0.19746	0.0347	0.40906	0.19612	0.21396	0.03899	0.0012	0.40906	0.03846	0.04578
91	0.17653	0.02908	0.39641	0.19321	0.2115	0.17994	0.02995	0.40349	0.19489	0.21305	0.03238	0.0009	0.40349	0.03798	0.04539
92	0.17445	0.02854	0.38933	0.19146	0.20966	0.17653	0.02908	0.39641	0.19321	0.2115	0.03116	0.00085	0.39641	0.03733	0.04473
93	0.17104	0.0277	0.38225	0.18973	0.20777	0.17445	0.02854	0.38933	0.19146	0.20966	0.03043	0.00081	0.38933	0.03666	0.04396
94	0.16863	0.02708	0.37517	0.18797	0.20587	0.17104	0.0277	0.38225	0.18973	0.20777	0.02926	0.00077	0.38225	0.036	0.04317
95	0.16507	0.02623	0.36809	0.1862	0.20395	0.16863	0.02708	0.37517	0.18797	0.20587	0.02844	0.00073	0.37517	0.03533	0.04238
96	0.16231	0.02553	0.36099	0.1844	0.20201	0.16507	0.02623	0.36809	0.1862	0.20395	0.02725	0.00069	0.36809	0.03467	0.04159
97	0.15869	0.02469	0.35388	0.18258	0.20004	0.16231	0.02553	0.36099	0.1844	0.20201	0.02634	0.00065	0.36099	0.034	0.04081
98	0.15557	0.02392	0.34675	0.18075	0.19806	0.15869	0.02469	0.35388	0.18258	0.20004	0.02518	0.00061	0.35388	0.03334	0.04002
99	0.15173	-0.02306	0.33961	0.17889	0.19605	0.15557	0.02392	0.34675	0.18075	0.19806	0.0242	0.00057	0.34675	0.03267	0.03923
100	0.14821	-0.0222	0.33244	0.177	0.19401	0.15173	-0.02306	0.33961	0.17889	0.19605	0.02302	0.00053	0.33961	0.032	0.03843
101	0.1464	-0.02183	0.32538	0.17511	0.19196	0.14821	-0.0222	0.33244	0.177	0.19401	0.02197	0.00049	0.33244	0.03133	0.03764
102	0.14532	-0.02155	0.31855	0.17326	0.18992	0.1464	-0.02183	0.32538	0.17511	0.19196	0.02143	0.00048	0.32538	0.03066	0.03685
103	0.14368	-0.02121	0.31195	0.17146	0.18793	0.14532	-0.02155	0.31855	0.17326	0.18992	0.02112	0.00046	0.31855	0.03002	0.03607
104	0.14246	-0.0209	0.30556	0.16969	0.18598	0.14368	-0.02121	0.31195	0.17146	0.18793	0.02064	0.00045	0.31195	0.0294	0.03532
105	0.14072	-0.02055	0.29936	0.16796	0.18408	0.14246	-0.0209	0.30556	0.16969	0.18598	0.02029	0.00044	0.30556	0.0288	0.03459
106	0.13936	-0.02021	0.29334	0.16626	0.18221	0.14072	-0.02055	0.29936	0.16796	0.18408	0.0198	0.00042	0.29936	0.02821	0.03388
107	0.13763	-0.01987	0.28748	0.1646	0.18038	0.13936	-0.02021	0.29334	0.16626	0.18221	0.01942	0.00041	0.29334	0.02764	0.0332
108	0.13614	-0.0195	0.28177	0.16296	0.17857	0.13763	-0.01987	0.28748	0.1646	0.18038	0.01894	0.00039	0.28748	0.02709	0.03254
109	0.13448	-0.01918	0.27621	0.16134	0.1768	0.13614	-0.0195	0.28177	0.16296	0.17857	0.01853	0.00038	0.28177	0.02655	0.03189
110	0.1329	-0.0188	0.27079	0.15975	0.17505	0.13448	-0.01918	0.27621	0.16134	0.1768	0.01809	0.00037	0.27621	0.02603	0.03126
111	0.12384	-0.01696	0.2652	0.15812	0.1733	0.1329	-0.0188	0.27079	0.15975	0.17505	0.01766	0.00035	0.27079	0.02552	0.03064
112	0.12172	-0.01642	0.25942	0.15641	0.17149	0.12384	-0.01696	0.2652	0.15812	0.1733	0.01534	0.00029	0.2652	0.025	0.03003
113	0.12226	-0.01662	0.25388	0.15471	0.16964	0.12172	-0.01642	0.25942	0.15641	0.17149	0.01481	0.00027	0.25942	0.02446	0.02941
114	0.12063	-0.01621	0.24856	0.15308	0.16783	0.12226	-0.01662	0.25388	0.15471	0.16964	0.01495	0.00028	0.25388	0.02394	0.02878
115	0.12074	-0.0163	0.24345	0.1515	0.16607	0.12063	-0.01621	0.24856	0.15308	0.16783	0.01455	0.00026	0.24856	0.02343	0.02817
116	0.11931	-0.01595	0.23853	0.14996	0.16437	0.12074	-0.0163	0.24345	0.1515	0.16607	0.01458	0.00027	0.24345	0.02295	0.02758
117	0.11923	-0.01599	0.23379	0.14846	0.16271	0.11931	-0.01595	0.23853	0.14996	0.16437	0.01423	0.00025	0.23853	0.02249	0.02702
118	0.11805	-0.0157	0.22923	0.147	0.1611	0.11923	-0.01599	0.23379	0.14846	0.16271	0.01422	0.00026	0.23379	0.02204	0.02647
119	0.11774	-0.01568	0.22483	0.14558	0.15953	0.11805	-0.0157	0.22923	0.147	0.1611	0.01394	0.00025	0.22923	0.02161	0.02595

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210	0.08914	0.01029	0.0866	0.09026	0.09852	0.08948	0.01035	0.08709	0.09051	0.0988	0.00801	0.00011	0.08709	0.00819	0.00976
211	0.08915	0.01029	0.08611	0.09001	0.09824	0.08914	0.01029	0.0866	0.09026	0.09852	0.00795	0.00011	0.0866	0.00815	0.00971
212	0.08891	0.01025	0.08564	0.08976	0.09797	0.08915	0.01029	0.08611	0.09001	0.09824	0.00795	0.00011	0.08611	0.0081	0.00965
213	0.08885	0.01024	0.08517	0.08951	0.0977	0.08891	0.01025	0.08564	0.08976	0.09797	0.0079	0.00011	0.08564	0.00806	0.0096
214	0.08865	0.01021	0.08471	0.08927	0.09743	0.08885	0.01024	0.08517	0.08951	0.0977	0.00789	0.0001	0.08517	0.00801	0.00954
215	0.08832	0.01015	0.08426	0.08903	0.09717	0.08865	0.01021	0.08471	0.08927	0.09743	0.00786	0.0001	0.08471	0.00797	0.00949
216	0.08832	0.01015	0.08381	0.08879	0.09691	0.08832	0.01015	0.08426	0.08903	0.09717	0.0078	0.0001	0.08426	0.00793	0.00944
217	0.08808	0.01011	0.08337	0.08855	0.09665	0.08832	0.01015	0.08381	0.08879	0.09691	0.0078	0.0001	0.08381	0.00788	0.00939
218	0.08802	0.01009	0.08293	0.08832	0.09639	0.08808	0.01011	0.08337	0.08855	0.09665	0.00776	0.0001	0.08337	0.00784	0.00934
219	0.08782	0.01006	0.0825	0.08809	0.09614	0.08802	0.01009	0.08293	0.08832	0.09639	0.00775	0.0001	0.08293	0.0078	0.00929
220	0.08772	0.01004	0.08208	0.08787	0.09589	0.08782	0.01006	0.0825	0.08809	0.09614	0.00771	0.0001	0.0825	0.00776	0.00924
221	0.08755	0.01002	0.08167	0.08765	0.09565	0.08772	0.01004	0.08208	0.08787	0.09589	0.00769	0.0001	0.08208	0.00772	0.0092
222	0.04778	0.00421	0.08079	0.08728	0.09534	0.08755	0.01002	0.08167	0.08765	0.09565	0.00766	0.0001	0.08167	0.00768	0.00915
223	-0.04778	0	0.07927	0.08658	0.0948	0.04778	0.00421	0.08079	0.08728	0.09534	0.00228	0.00002	0.08079	0.00762	0.00909
224	0.04778	0.00406	0.07779	0.08574	0.09401	-0.04778	0	0.07927	0.08658	0.0948	0.00228	-0.00002	0.07927	0.0075	0.00899
225	-0.04778	0	0.07636	0.08495	0.09314	0.04778	0.00406	0.07779	0.08574	0.09401	0.00228	0.00002	0.07779	0.00735	0.00884
226	0.04778	0.00391	0.07495	0.08417	0.09228	-0.04778	0	0.07636	0.08495	0.09314	0.00228	-0.00002	0.07636	0.00722	0.00868
227	-0.04778	0	0.07359	0.0834	0.09144	0.04778	0.00391	0.07495	0.08417	0.09228	0.00228	0.00002	0.07495	0.00708	0.00852
228	0.04778	-0.00377	0.07227	0.08264	0.09061	-0.04778	0	0.07359	0.0834	0.09144	0.00228	-0.00001	0.07359	0.00696	0.00836
229	-0.04778	0	0.07098	0.0819	0.08979	0.04778	-0.00377	0.07227	0.08264	0.09061	0.00228	0.00001	0.07227	0.00683	0.00821
230	0.04778	-0.00364	0.06972	0.08118	0.08899	-0.04778	0	0.07098	0.0819	0.08979	0.00228	-0.00001	0.07098	0.00671	0.00806
231	-0.04778	0	0.0685	0.08046	0.0882	0.04778	-0.00364	0.06972	0.08118	0.08899	0.00228	0.00001	0.06972	0.00659	0.00792
232	0.04778	-0.0035	0.06731	0.07976	0.08743	-0.04778	0	0.0685	0.08046	0.0882	0.00228	-0.00001	0.0685	0.00647	0.00778
233	-0.04778	0	0.06615	0.07907	0.08667	0.04778	-0.0035	0.06731	0.07976	0.08743	0.00228	0.00001	0.06731	0.00636	0.00764
234	0.04778	-0.00338	0.06502	0.07839	0.08592	-0.04778	0	0.06615	0.07907	0.08667	0.00228	-0.00001	0.06615	0.00625	0.00751
235	-0.04778	0	0.06392	0.07772	0.08519	0.04778	-0.00338	0.06502	0.07839	0.08592	0.00228	0.00001	0.06502	0.00614	0.00738
236	0.04778	-0.00325	0.06284	0.07707	0.08447	-0.04778	0	0.06392	0.07772	0.08519	0.00228	-0.00001	0.06392	0.00604	0.00726
237	-0.04778	0	0.06179	0.07642	0.08376	0.04778	-0.00325	0.06284	0.07707	0.08447	0.00228	0.00001	0.06284	0.00594	0.00713
238	0.04778	-0.00314	0.06077	0.07579	0.08306	-0.04778	0	0.06179	0.07642	0.08376	0.00228	-0.00001	0.06179	0.00584	0.00702
239	-0.04778	0	0.05977	0.07516	0.08237	0.04778	-0.00314	0.06077	0.07579	0.08306	0.00228	0.00001	0.06077	0.00574	0.0069
240	0.04778	-0.00302	0.0588	0.07455	0.0817	-0.04778	0	0.05977	0.07516	0.08237	0.00228	-0.00001	0.05977	0.00565	0.00678
241	-0.04778	0	0.05785	0.07394	0.08103	0.04778	-0.00302	0.0588	0.07455	0.0817	0.00228	0.00001	0.0588	0.00556	0.00667
242	0.04778	-0.00291	0.05692	0.07335	0.08038	-0.04778	0	0.05785	0.07394	0.08103	0.00228	-0.00001	0.05785	0.00547	0.00657
243	-0.04778	0	0.05602	0.07276	0.07973	0.04778	-0.00291	0.05692	0.07335	0.08038	0.00228	0.00001	0.05692	0.00538	0.00646
244	0.04778	-0.00281	0.05513	0.07219	0.0791	-0.04778	0	0.05602	0.07276	0.07973	0.00228	-0.00001	0.05602	0.00529	0.00636
245	-0.04778	0	0.05427	0.07162	0.07848	0.04778	-0.00281	0.05513	0.07219	0.0791	0.00228	0.00001	0.05513	0.00521	0.00626
246	0.04778	-0.00271	0.05343	0.07106	0.07786	-0.04778	0	0.05427	0.07162	0.07848	0.00228	-0.00001	0.05427	0.00513	0.00616
247	-0.04778	0	0.05261	0.07051	0.07726	0.04778	-0.00271	0.05343	0.07106	0.07786	0.00228	0.00001	0.05343	0.00505	0.00606
248	0.04778	0.00261	0.0518	0.06997	0.07666	-0.04778	0	0.05261	0.07051	0.07726	0.00228	-0.00001	0.05261	0.00497	0.00597
249	-0.04778	0	0.05101	0.06944	0.07607	0.04778	0.00261	0.0518	0.06997	0.07666	0.00228	0.00001	0.0518	0.0049	0.00588
250	0.04778	0.00252	0.05024	0.06891	0.0755	-0.04778	0	0.05101	0.06944	0.07607	0.00228	-0.00001	0.05101	0.00482	0.00579

APPENDIX J

Runoff Generation in 10 Years Chicago Rainfall

Table J.1: Runoff volume generated in hrs of 10 years Chicago rainfall

10 years Chicago Rainfall		
Time	Rainfall intensity (mm/hr)	Volume of runoff (m3/10min)
0:10	3.58	0.24
0:20	3.99	0.27
0:30	4.50	0.30
0:40	5.21	0.35
0:50	6.27	0.42
1:00	8.00	0.53
1:10	11.51	0.77
1:20	24.82	1.65
1:30	133.60	8.91
1:40	32.00	2.13
1:50	17.93	1.20
2:00	12.95	0.86
2:10	10.31	0.69
2:20	8.66	0.58
2:30	7.52	0.50
2:40	6.65	0.44
2:50	6.02	0.40
3:00	5.49	0.37
3:10	5.05	0.34
3:20	4.70	0.31
3:30	4.39	0.29
3:40	4.14	0.28
3:50	3.91	0.26
4:00	3.71	0.25
Total		**22.33**

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