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UNIVERSITI TEKNOLOGI PETRONAS

DEVELOPMENT OF SOLID WASTE CLOG RESISTANT OPEN DRAIN SYSTEM WITH IMPROVED STORMWATER CONVEYANCE

By

DEDIMUNI CHARMAINE NADEESHA CHANDRASENA

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance of this thesis for the fulfillment of the requirements for the degree stated.

Signature: ______________________

Main Supervisor: AP DR. KHAMARUZAMAN WAN YUSOF

Signature: ______________________

Co-Supervisor: AP DR. ZAHIRANIZA MUSTAFFA

Signature: ______________________

Co-Supervisor: DR. MUHAMMAD RAZA UL MUSTAFA

Signature: ______________________

Head of Department: AP DR. NOOR AMILA WAN ABDULLAH ZAWAWI

Date: ______________________

DEVELOPMENT OF SOLID WASTE CLOG RESISTANT OPEN DRAIN SYSTEM WITH IMPROVED STORMWATER CONVEYANCE

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DEDIMUNI CHARMAINE NADEESHA CHANDRASENA

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SEPTEMBER 2017

DECLARATION OF THESIS

Title of thesis	DEVELOPMENT OF SOLID WASTE CLOG RESISTANT OPEN DRAIN SYSTEM WITH IMPROVED STORMWATER CONVEYANCE

I DEDIMUNI CHARMAINE NADEESHA CHANDRASENA

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Signature of Author

Signature of Supervisor

Permanent address:

NEAR SCHOOL
RANAPANADENIYA
RATGAMA
SRI LANKA

Name of Supervisor

AP DR. KHAMARUZAMAN
WAN YUSOF

Date : ____________________

Date : ____________________

DEDICATION

This thesis is dedicated

to

Professor E.R.N Gunawardhane

and

Major General Kamal Gunaratne.

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ABSTRACT

Low and Lower-Middle income countries in the world are often faced with adverse consequences of natural disasters due to unpreparedness and sparse resource allocation to improve and maintain their physical infrastructure. Urban drainage infrastructure of these countries is not structured or constructed with compatibility to handle the drainage needs of the present era. This study based on finding answers the research question, “Why drainage systems fail in Low and Lower-Middle Income countries?” The presence of litter in open drains has been identified as one of the crucial factors that interrupted the storm water conveyance following an in-depth analysis of peer literature and case study observations. The effects of floating litter and its influence on clogging the crucial points of the drainage channel have been identified as an untouched area in previous attempts to resolve this problem. Hence, “Mahasinghe-Chandrasena mathematical model,” $bl\frac{D(t)}{dt} = Q_{in} - \left[Q_{out} - k\ \frac{(bD(t)-c)^{1.83}}{\left(2D(t)-\left(d+\int_0^b\left(\sqrt{1+(flg)^2}+\sqrt{1+(slg)^2}\right)b\right)\right)^{0.83}}\right]$ was formulated to approximate the rate of spillover of a clogged drain owing to the effects generated by sunken and floating litter items. The model outcomes lead to the hypothetical solution; “operational problems in clogged drainage channels can be corrected through a clog resistant drain design”. Accordingly, a dual layer Solid Waste Clog Resistant Open Drain has invented and prototyped. The invented and conventional drains were tested for hydraulic efficiency under a range of flow rates of $0.013m^3/s$ to $0.027m^3/s$. The existing conventional clogged drain spilled over at an incoming flow rate of $0.013m^3/s$ while the improved Clog Resistant Open Drain unit did not spill over even at an incoming flow rate of $0.027m^3/s$. A numerical approximation supported by EPA SWMM 5.0 computer simulation platform was used to validate the experimental results of the existing and improved drain conditions. In general, the improved drain was capable of handling storm water flow twice the efficiency of the conventional drain.

ABSTRAK

Golongan negara-negara yang berpendapatan rendah dan sederhana rendah di dunia ini sering menghadapi kesan buruk becana alam yang berpunca dari tiadanya persiapan awal serta kurangnya peuntukan sumber yang dapat mengkekalkan dan memperbaiki infrastruktur fizikal tersebut. Infrastrukur sistem saliran perparitan terbuka bagi kawasan perbandaran negara-negara ini tidak berstruktur atau tidak dibina dengan keserasian untuk mengendalikan keperluan sistem saliran perparitan pada zaman ini. Kajian ini bertujuan untuk mencari jawapan kepada persoalan umum, "Mengapakah sistem perparitan bagi golongan negara-negara berpendapatan rendah dan sederhana rendah mengalami kegagalan?" Pendekatan analisis telah digunakan untuk memahami secara lebih mendalam terhadap masalah ini dan juga mencari punca serta kaedah bagi menyelesaikan masalah tersebut. Berdasarkan analisis mendalam dan pemerherhatian kajian analisis, kehadiran sampah sarap di dalam sistem perparitan terbuka telah dikenal pasti sebagai salah satu faktor penting yang menyebabkan gangguan aliran air ribut. Sebelum ini, persoalan terhadap kesan sampah sarap terapung dalam menjadi punca sistem perparitan tersumbat tidak disentuh dalam percubaan untuk menyelesaikan masalah tersebut. Satu model matematik telah digubal untuk mendapatkan anggaran kadar limpahan air daripada perparitan tersumbat yang dihasilkan oleh sampah sarap tenggelam dan terapung. Ini telah membawa kepada satu penyelesaian hypothetical, "Masalah operasi sistem pengaliran air dalam saluran perparitan tersumbat boleh diperbetulkan melalui reka bentuk struktur perparitan yang mempunyai rintangan daripada tersumbat." Satu sistem perparitan rintangan tersumbat yang mempunyai dwi lapisan serta perangkap sampah sarap telah direka bentuk dan diprototaip. Prototaip sistem perparitan terbuka dengan rintangan tersumbat ini bersama sistem perparitan yang sedia ada telah diuji kaji bagi kecekapakan hydraulic di bawah pelbagai kadar aliran $0.013m^3/s$ -$0.027m^3/s$. Sistem perparitan yang sedia ada menunjukkan limpahan air pada kadar aliran $0.013m^3/s$ dalam masa beberapa minit manakala sistem perparitan terbuka yang telah

diperbaiki dengan rintangan tersumbat tidak menunjukkan limpahan air walaupun pada kadar aliran $0.027m^3/s$. Satu anggaran berangka dengan EPA SWMM 5.0 platform simulasi Komputer telah digunakan untuk mengesahkan keputusan eksperimen bagi keadaan sistem perparitan sedia ada dan sistem perparitan yang diperbaiki dengan rintangan tersumbat. Sistem perparitan yang diperbaiki dengan rintangan tersumbat dapat mengurangkan jumlah banjir pada kadar separuh berbanding dengan sistem perparitan terbuka yang sedia ada dalam lingkungan kawasan kajian tersebut. Secara umumnya, sistem perparitan yang diperbaiki dengan rintangan tersumbat mampu mengendalikan aliran air ribut dengan kecekapan 2 kali ganda berbanding dengan sisterm perparitan sedia ada.

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
UN	United Nations
USA	United States of America

LIST OF NOMENCLATURE

A	Unit Area of Flow
b	Width of the Drainage Channel
C	Weighted Average Runoff Coefficient
D(t)	Flow Depth of the Channel at time “t”
E	Hydraulic Efficiency
E	Specific Energy
flg	Floating Litter Gradient
K	Conveyance of Flow
l	Length
n	Manning’s roughness value
ŋ	Conveyance Efficiency of a Drainage Channel
Q_c	Drainage Capacity
Q_{dr}	Rate of Drained
Q_{in}	Rate of Inflow
Q_{out}	Rate of Outflow
Q_r	Peak Runoff Rate
Q_{stg}	Rate of Stagnation of water
R	Hydraulic Radius
R^2	Coefficient of Determination
S	Drainage Gradient
Slg	Sunken Litter Gradient
t	Time
v	Flow Velocity
V	Flow Volume
Δz	Equidistance Height Grid

CHAPTER 1

INTRODUCTION

1.1 Socio-Spatial Challenges in Low and Lower-Middle-Income Countries

In 2015 the World Bank categorised about eighty countries as low and lower-middle-income recipients according to their per capita Gross National Income [1]. These countries face numerous socio-spatial challenges caused by poverty and inequality of resource distribution. Apart from that, these countries have often confronted with adverse consequences of natural disasters due to unpreparedness and sparse resource allocation to maintain and improve their physical infrastructure.

As pointed out by researchers, there are three common characteristics about emerging urban settlements in these countries [2-7]. First, coastal cities of these countries record the highest average rainfall compared to the centrally located cities. Second, many of the settlements are located on estuaries of rivers. Third, impermeable alluvial soil makes drainage difficult in those areas. Also, most of the cities in low and lower-middle-income countries are vulnerable to sea-level rise and intense storms [4]. Therefore, these cities increasingly struggle with problems related to storm water management.

The world has been rapidly urbanizing, and the increase in population density of low-income cities has led to more social and economic risks. According to the United Nations (UN), the annual urban population growth in the low and lower-middle-income countries is about 53 million or 2.2% [8]. These numbers imply the magnitude of socio-spatial issues that may arise in the future. Almost one-third of the urban population in the low and lower-middle income countries are now living in underserved settlements [1, 8-10]. Higher property prices and commuting costs constantly limit them from entering the regular housing market [2, 11, 12]. These settlements are located on steep hillsides or low-lying marshy areas and frequently subjected to flooding or erosion. Referred literature have proven that the impact of natural disasters in these countries was disproportionate and adversely affected the dwellers in informal settlements [5, 13].

1.2 Why are Floods More Frequent in Low and Lower-Middle-Income Countries?

Flooding is the most frequently occurring hazard event among all natural disasters [14-17]. It causes massive damages to the socio-spatial setting of the affected localities. There are several man-made factors which trigger the frequent occurrence of floods.

Much of the urban floods in low and lower-middle-income countries have been caused by poorly planned development efforts [18-20]. Flash floods have repeatedly been disturbing these cities as rain water do not properly drain through conventional drainage systems, stagnate over the ground and not infiltrate into the soil as expected. Urban flash floods differ markedly from riverine or coastal floods which occur as one-time events. It occurred frequently and triggered as a result of even by moderate rainfall. Researchers have identified the diminishing hydraulic capacity of urban drainage systems as the primary cause for more than 90% of flash flood events that happened in India during the past decade [18, 21]. These flood attacks caused by solid waste clogged drainage channels.

Uncoordinated disposal of urban litter has identified as the primary causative factor for drainage blockages in countries such as Malaysia [22]. As a result, the United Nations Development Program prepared a solid waste management plan and implemented the same for Penang city from 2008 [22]. Penang city solid waste management plan was a successful attempt since it focused on solid waste management and drainage improvement activities at the same time. Studies had shown that when these two issues addressed separately, the outcome is not satisfactory [23-26].

Urban flooding poses a serious challenge to development and the lives of people. Flood risks in the cities of low and lower-middle-income countries are high, can successfully manage by well-prepared drainage infrastructure [11, 27, 28]. As any physical construction has a defined lifetime, urban drainage infrastructure also needs well-timed rehabilitation [29-31]. Hence, proper and timely investment in urban drainage rehabilitation and improvement has identified as one of the important factors in flood management [32].

The effect of climate change is a critical factor to be considered in designing of future cities [33]. In addition to anticipate implications in the given time, one has to consider the population increase along with other factors and model the impact of climate change. The drainage system is an essential aspect of city development and designing. However, in low and lower-middle-income countries, it does not stress as a critical area that needs to be concerned [34, 35].

This research project evaluated the storm water handling abilities of urban drainage systems at low and lower middle-income-countries. The study aimed to identify the factors that led failing of conventional drainage systems in these countries and to propose key engineering design modifications to accommodate the system requirements of high-density urban areas adequately.

1.3 General Description of the Study Area

This subsection covers the general depiction of the case study area under five categories.

- Topography

  Madampitiya is a low-income settlement located in the vicinity of the Kelani River flood plains in the Western Province of Sri Lanka. This area is a low-lying marshy land at very low altitude (1 m above MSL) resulting in a reduced flow rate in the canal system.

- Human settlement pattern

The total population of the settlement is about 3000 inhabitants. There are about 551 connected low-income housing units located in the concerned area. Connected low-income housing units occupy nearly 75% of the land area. Canal bank encroachments, obstructing natural and man-made drainage paths by new constructions and linear urbanisation along the water bodies are the key features identified relating to the urban fabric of this area.

- Rainfall pattern

Colombo receives rainfall mainly from two monsoon seasons. From May to September the South-Eastern monsoon brings the highest rainfall in the city, and North-Western monsoon also brings considerable rain from November to February. From 15th to 16th May 2016 the entire area experienced a harsh flood caused by 40mm/hr rainfall. The total rainfall recorded was 256 mm for 24 hours.

- River and Canal system in the Kelani River Delta

The study area comprised natural and man-made drainage channels and streams which also accommodates receiving waters from primary drainage channels. St Sebastian canal was one of those built in 1706. It originated at the northern point of the Kelani River mouth and flows through Bloemendhal, to the Beira Lake and finally outfalls to the sea. The Colombo canal system has developed into three levels; micro drainage canals, secondary canals and primary canals.

- Flood frequency

Illegal developments in canal reservations have caused difficulties in canal maintenance, thus reducing the carrying capacity. Flood water retention areas of the catchment have also been reduced due to illegal constructions. Less impervious areas and more pervious areas due to rapid development have resulted in a faster surface runoff. Therefore, floods are common in this area even during a mild rainfall. Due to man-made and natural causes which trigger the risk of floods, this area has identified as one of the top ten flood-prone regions located in Metro Colombo by Western Province Disaster Management Task Force in 2014. The location map of the study area is shown in Figure 1.1 below.

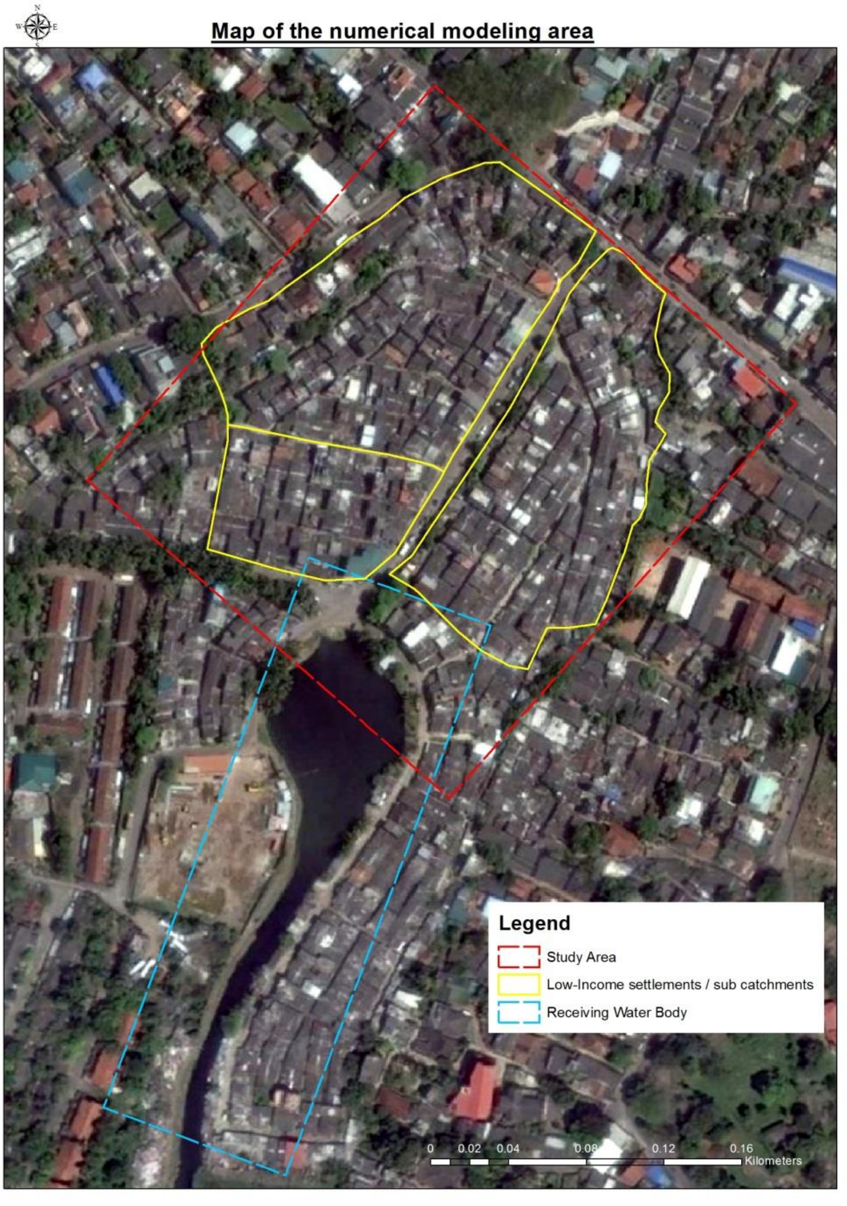


Figure 1.1: Location map of the Study Area (Coordinates 6.96170 N 79.87520E)

1.3.1 What needs to be addressed of the Drainage Infrastructure in the Case Study Area?

The concerned area is a densely populated low-income urban settlement. Most of the housing units are haphazardly built without proper plans. Dilapidated open drains located along the interior roads are clogged with the litter more often. Encroachment and obstruction of natural and man-made drainage paths is a common phenomenon.

Petain to these observations and physical setting of the case study area, there is a timely necessity of concern about the "population influence" on drainage infrastructure, for example population density and growth rate in the respective location, per capita income and consumption patterns, per capita solid waste generation, solid waste disposing habits of the settlers etc.,

Moreover, these settlements should be highly prepared to take up the intense risks generated by abrupt climate change scenario.

1.4 Problem Formulation

Flood control is a local issue with a global importance. Presently, poorly prepared cities in low and lower-middle-income countries subjected to increasing flood hazards than the cities in other regions of the world. Firstly, these cities have not invested much in drainage infrastructure. Secondly, the ailing infrastructure is expected to serve their increasing population. Thirdly, they expect it to work without maintenance. Fourthly, they have never been able to provide the location of specific solutions for their drainage problems.

The present urbanisation scenario in these cities is creating an imbalance between the urban runoff volume generated and the effective drainage capacity for a proper conveyance of it. On the one hand, urban runoff volume increases directly with increasing of impervious surfaces, but on the other hand, urban drainage capacity is decreasing due to litter clogging and sedimentation. Therefore, the existing, deteriorated drainage systems are not capable of effectively accommodate the rainfall received.

The nature of the contribution from urbanisation and climate change to flash floods in densely populated cities in low and lower-middle-income countries is fundamentally different from cities in high-income countries. These differences have not satisfactorily addressed in past research studies of urban drainage management. Therefore, there is a need to re-analyses and develop an efficient engineering defence mechanism that would provide a solution or minimise the stormwater handling problems. Thus, most of the countries in the developing world urgently need a comprehensive drainage system design which can withstand the effects generated by climate change and urbanisation.

1.5 Thesis Statement

Clogged drainage channels cause travel time delays and increase the rate of stagnation of storm water. It can be corrected through a clog resistant drain design that traps litter items, provides a clear channel for conveyance, by enhancing the hydraulic characteristics and flow of storm water in open drains.

1.6 Objectives of the Research

The objective of this research is to identify and find ways to resolve operational deficiencies in open storm drains of low and lower-middle-income countries through improved engineering design solution. This has been achieved by formulating a clog resistant open drain unit, resulting from this work.

This study included following specific research activities to accomplish this primary objective.

a) To assess the litter holding capacity of a drain using analytical and numerical approaches

b) To design a clog resistant open drain unit for uninterrupted stormwater conveyance

c) To optimise the performance of clog resistant open drain unit through experimental and numerical approaches

It is envisioned that the outcome of this study, will allow planners and engineers a simple and readily adaptable design alternative to solve the complex issue of urban flood management in underdeveloped and resource constrained urban areas of low and lower-middle income countries.

1.7 Scope and Limitations of the Research

Since this research study focused on the stormwater conveyance of urban drainage systems in low and lower-middle income countries, the scope was generally limited to evaluating the efficiency of the existing open drains and failures of these systems. The following constraints are resulted from this limited scope.

a) The general research area was limited to "low-income urban settlements" of "low and lower-middle income", countries.

b) The evaluated physical infrastructure type was the "open drains" which operationally specialised for "stormwater conveyance".

c) This was a prototype based experimental study. Therefore, all the real world drainage scenarios that needed to be tested were replicated in a Laboratory Modular Channel which commonly named as Laboratory Flume.

d) Hydraulic efficiency of Clog Resistant Open Drain unit was tested on a single prototype design. No alternative design options were considered.

e) For laboratory testing of the Clog Resistant Open Drain, the rainfall simulated as a "point source" that carrying water from the upstream.

1.8 Structure of the Thesis

This thesis comprised five chapters. Chapter One contains a brief introduction on the background of the study including the formulation of research problem scope and the research objectives.

The related research findings previously reported in the scientific literature were examined and reviewed in Chapter Two. Reviewed literature highlighted the weaknesses in existing drainage systems and further investigated the impact of litter accumulation on channel hydraulics. This chapter is organised into three sections namely, examining the flood hazards in low-income countries with a particular consideration on Asia, investigating the impact of litter accumulation on channel hydraulics and the identification of research gaps, respectively.

Chapter Three systematically describes the full research methodology including the procedure of experimentation and numerical analysis. Section 3.4 of this chapter provides specific details of numerical analysis carried out to narrow down the magnitude of this problem to the case study level.

The analysis of the results obtained from the experimental measurements and numerical analysis outlined in the research methodology section is presented in Chapter Four.

Chapter Five summarises and concludes significant research findings from this study and describe the future research activities.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter mainly articulates the most significant research findings in the reviewed literature. The reviewed literature was narrowed down to examine how the urban drainage system fails in low and lower-middle-income countries. Previous research works have confirmed the inadequacy and inability of handling the storm water by the existing urban drainage systems in these countries. Moreover, this study has also discovered the hidden causes behind the drainage system failures. This chapter comprised three sections including a general overview of flood hazards in low and lower-middle-income countries with a particular consideration on Asia, investigating the impact of litter accumulation on channel hydraulics and the engineering procedures that followed to prevent clogged drains in urban settlements.

2.2 Analytical Approach

The analytical approach of the problem of interest dates back to 17th century, where the key elements of the method were originated. It is focused on determining the causes of the problem followed by an in-depth analysis. This approach is a logical way to trace down the causes of a problem. It enables researchers to find ways to resolve the root causes to eliminate the problem at the source of generation [36]. The current study has used the analytical approach to discover the causes of inefficient drainage infrastructure since it has been identified as a complex socio-spatial problem which cannot be solved in a single step.

2.3 The Numerical Approach

The numerical approach involves study, development, and analysis of algorithms to approximate numerical solution to a mathematical problem. It is known that the modern history of numerical approach is started with the pioneering work of "Numerical inverting of matrices of higher order" by J Von Numen and HH Golstine [37, 38]. The present study has used EPA SWMM 5.0 computer simulation platform for comparison and numerical analysis of experimental results.

2.3.1 EPA SWMM Computer Simulation Platform

Storm Water Management Model developed by US Environmental Protection Agency is commonly known as EPA SWMM 5.0. It is an open source computer simulation platform which generates hydrology-hydraulics and water quality simulation models. This software package has been commonly used in sewer and stormwater studies for planning, analysis, and designing of urban drainage systems [39].

2.4 Law of Conservation of Mass in a Drain

The law of conservation of mass is a scientific theory discovered by Antoine Lavoisier in 1785. According to this law, the matter neither be created nor destroyed, but can be changed into a different form of matter. Conservation of mass is still a widely used principle in many fields, including hydraulics [40]. In open channel hydraulics, this principle is used in the analysis of the flowing fluid [41, 42].

If the inflow volume is controlled and the other parameters keep unchanged, for an unsteady water flow, which is disturbed or interrupted by external or internal cause;

Volume entering per unit time = Volume leaving per unit time + Increase of Volume within the entity per unit time

Therefore, an increase in volume within the entity per unit time is referred to volume stagnate per unit time in drainage or the "rate of stagnation of water".

2.5 Urban Flash flood

A high-intensity rainfall over the most critical location in a catchment can cause a flash flood. This location could be a hydro-catchment, highly modified area by urbanisation, or a storm conduit intersection in topographic lows. A flash flood occurs as a sudden hydrological response created by respective location to the causative rainfall [43]. It is a short duration flood attack which rises and falls quite rapidly [44].

Researchers specifically claim three reasons for the occurrence of flash floods in Asia. Firstly, the loss of infiltration capacity due to impervious cover in an urban catchment. Secondly, the dilapidated drainage system which was not capable of accommodating increased runoff resulted by the modified catchment. Thirdly, the presence of litter and debris in the stormwater drainage channels that interrupted the conveyance process [18, 45].

2.6 The Impact of Urbanization and Climate Change on the Occurrence of Flash flood

Climate change and urbanisation together altered the infrastructural requirements in urban areas, for instance, urban drainage system. Urbanisation makes more areas impervious by construction, change of use or partitioning. An Impervious surface makes infiltration difficult and steeper the recession curve. It reduces the lag time or the difference between precipitation volume and runoff volume. It increased the peak flow and reduced the time to attain flood peak. Hence, stream channels adjust for the altered flow condition to accommodate increased runoff in various ways by degrading the channel, eroding banks or flooding more area. Moreover, the respective area will become hydrologically sensitive location which needs more developmental precautions like resilient infrastructure.

The requirements mentioned above claim hyper sensitive modification in storm drainage system to prepare for drastic changes undergoing in the respective catchment. In most cases, the storm drainage systems redesigned with lower return periods [46-48].

2.7 Flashflood Hazards in Developing Asia at a Glance

Flood control is a local issue with a global importance. At present, poorly planned cities in developing regions, particularly in Asia, are hit hardest by increasing flood hazards compared to cities in the developed region [49-52]. Asia has the most visible landmass on earth concerning the space and spiralling population. Consequently, the Asian continent has to suffer most from the adverse impacts generated by population and spatial factors. It is forecasted that 50% of Asians will be living in urban areas by 2025 [8, 18]. Rapid urbanisation is considered the primary cause for emerging socio-spatial problems of this continent [53-55].

Excluding man-made issues such as war and crime, Asia is considered the most disaster-prone space on earth. The Asian continent is a naturally prone to various kinds of floods [56-58]. Flooding has killed 3,604,429 people in the past three decades during 1980-2010 and has made 18,236,759 people homeless in Asia [58]. This number is ten times higher than the number of victims from similarly recorded events in Europe and America [58]. Flash floods are a recurrent hazardous event for many Asian cities. As Jonkman [58] specified, the world's worst 45 flash floods with the highest number of people being affected occurred in China, India, Bangladesh, and Pakistan. As a result, their economies were forced to spend billions of dollars on flood mitigation and rehabilitation work [59].

The primary purpose of any urban drainage system is to control stormwater runoff. The inadequacy of which has been proven as one of the leading causes of intense flood attacks [17, 60, 61]. Therefore, the situation mentioned above gives rise to two important arguments about the efficiency and adequacy of urban drainage systems in low and lower-middle-income countries in Asia. Subsequent sections of this chapter will examine the adequacy of the existing urban drainage systems to mitigate the impact from future flood hazards.

2.8 An overview of Urban Drainage System

The urban drainage system or the conveyance system is designed to handle two types of flow circulating in an urban environment: waste water and storm water. Stormwater originates from rainfall events, while wastewater originates from the domestic, industrial, commercial or agricultural activity. There are two components in an urban drainage system that carries out this function: a pipe network and an open channel network. According to Butler [62] the whole urban drainage infrastructure system is known as sewerage. It consists of pipes, manholes, receiving drains, pumping stations and so on. There are two types of conventional sewerage systems, the combined system and the separate system. In a combined system, wastewater and storm water flow together in the same pipe. In a separate system, waste water and stormwater are kept in separate pipes.

The open channel network of an urban drainage system is designed to convey surface water and storm water runoff. It consists of open storm drains, secondary and primary drainage channels. The secondary and primary channels in an open channel network act as an outfall for open storm drain (figure 2.2). This open storm drains also mentioned as artificial drains, micro drains, side drains or tertiary drains in different literature [29, 63-67]

The open storm drains are responsible for the conveyance of stormwater runoff. Excess storm water that flows over the earth's surface is known as surface runoff. Impervious land surfaces in urban areas generate higher volumes of surface runoff during a rain event due to less infiltration and percolation ability. Hence, there is a need to remove this water from urban spaces rapidly to prevent unnecessary risks. For instance, immovable water on road layers increases the motor vehicle accidents caused by hydroplaning [68]. However, the stormwater conveyance process in open drains is interrupted by clogged litter. The presence of litter in a drain reduces its effective hydraulic capacity. As a result, the volume of water transported through the drain network for a given time period is reduced. In addition, delaying the conveyance of storm water would possibly lead to stagnation, channel spillovers, and flash floods.

Increasing the capacity of open storm drains by changing depth and width is not always possible due to the limitation of space or design restrictions. For instance, most of the open storm drains situated in high-density urban areas, and informal settlements cannot be widened anymore. Moreover, the maximum allowable width of an open storm drain is between 0.5m to 0.6m as illustrated in Figure 2.1 [67, 69-72]. In such situations, an ideal practicable solution would be expediting the drainage conveyance impacting the hydraulic characters of the flow. However, this goal cannot be achieved with the presence of clogged litter in a drain.

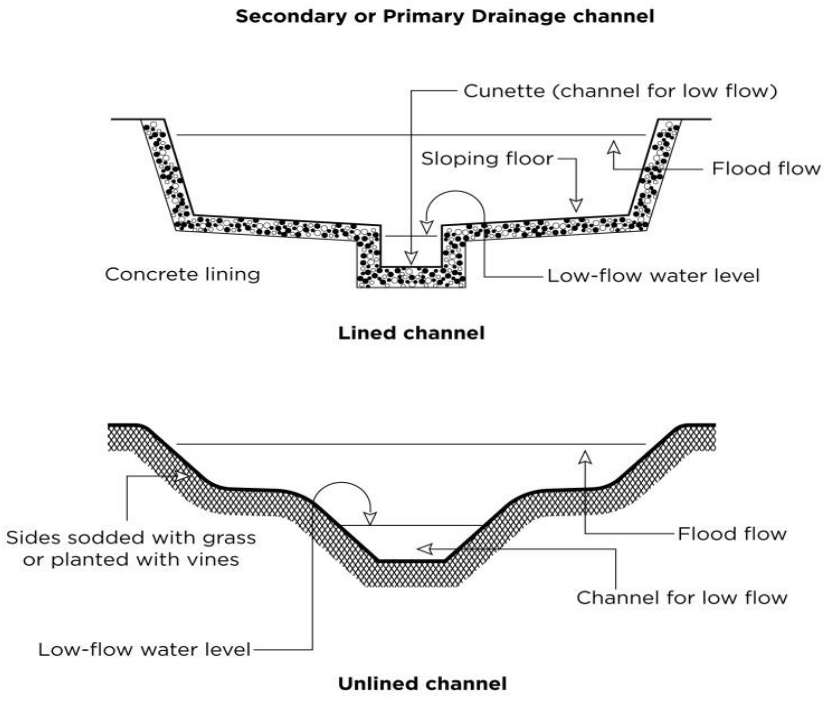


Figure 2.1: Partial section of Secondary or Primary Drainage

While the above-mentioned facts stress the need of uninterrupted drainage conveyance to prevent adverse impacts caused by flood hazards, the solution needs to be exercised at the point of generation of the problem. Therefore, further research on clog resistant drain designs would be helpful to address better the issues generated by clogged drains.

2.8.1 Drainage Conveyance (K)

In open channel hydraulics, the term conveyance is used to describe the cross-sectional properties of a channel. This can also be a measure of carrying capacity of the channel cross section [73, 74]. It depends on the channel geometry and roughness but independent from channel bed gradient. Maintaining a proper cross section in drains considered as an important factor in flood management. For that, a drain should be preserved the adequate hydraulic capacity to fully accommodate the peak runoff generated in the catchment [75, 76].

2.8.2 Discharge Capacity of the Drain (Q_c) and Peak Rate of Discharged (Q_p)

The required drain capacity to transport the runoff generated in a respective area is known as the "Discharge Capacity of the drain" (Q_c). It is also referred to as "Drainage Capacity" in different pieces of literature [77-79]. It is usually measured by the metric units of cubic meters per second (m^3/s). Discharge Capacity of the drain should adequate to accommodate the Peak Runoff (Q_r) generated in an area. For proper conveyance and management of the runoff peak flows, the discharge capacity of the drain should be equal or larger than the peak runoff rate generated in the respective area. Manning's formula is used to compute the "Discharge Capacity of the drain" [80, 81]. The discharge capacity of the drain depends on its size, geometry, the values of roughness coefficient (n) and the channel bed gradient.

Peak runoff (Q_r) or the Peak rate of discharged (Q_p) is the maximum runoff occurs in a respective catchment as a result of maximum rainfall intensity [82]. It is usually measured by the metric units of cubic meters per second (m^3/s). It is important to identify the real catchment area determined by the drainage system, to provide solutions for drainage management problems.

The Rational Formula has been using for calculating the Peak runoff rate of catchment areas below 20 acres [83, 84]. It is still a popular and widely used method in Hydrology and Hydraulic researchers [85]. However, the Rational Formula cannot compute the total runoff volume generated in the respective catchment, unless the user assumes total storm duration. According to the Rational formula, the peak runoff rate produced by a catchment is directly related to “catchment area” (A), “runoff coefficient” (C) and “rainfall intensity” (i) [84]. Runoff coefficient and the peak runoff rate are of a predefined catchment is dependent on various factors such as topography, vegetation cover, soil type, climatic characteristics and human effects [86, 87].

The Runoff Coefficient (C) is a dimensionless value which indicates the volume of runoff resulted in the volume of rainfall received. A larger Runoff Coefficient value reveals the low infiltration and percolation ability of areas that produced a higher volume of runoff [88]. Runoff coefficient has identified as a crucial parameter for flood peak discharge. The major factors influencing the runoff coefficient are the soil type, permeability, land use and gradient of an area. Although the values allocated for runoff coefficient are commonly used by many drainage manuals, the high-income countries now adopt regional specific data and a customised design criterion for premeditate area-sensitive parameters. The C factor value is area-sensitive and region specific. It depends on hydrogeological parameters like soil porosity, soil water content, topography and drainage basin mean temperature [88]. In the USA, the C factor values allocated for arid areas are different from tropical areas. However, the engineering design practices in developing countries have not adapted to follow these standards until now. Therefore, an up-to-date modification is needed for coefficient values that estimate urban drainage system requirements.

2.8.3 Design and Performance Considerations of Open Storm Drains

The hydraulic capacity of open drains is limited by the storm water management guidelines and design restrictions imposed by the respective authorities. For instance, in Malaysia, the maximum allowable width of uncovered open drains and covered open drains varies between 0.5m to1.2m while the maximum allowable depth of uncovered open drains is 0.6m [69]. The maximum allowable depth of covered open drain ranges from 0.6m to 1.2m. It is advisable to keep the drainage gradient higher than 0.005 to maintain an adequate flow velocity [67, 70-72, 89]. A partial section of an existing open drain is depicted in Figure 2.2.

Open storm drains are designed to remove rainwater from roads properties, open spaces into secondary and primary drainage channels. Also, open storm drains are specifically meant to reduce the unnecessary force generated by flowing water [68]. Open storm drains are designed to carry a sub-critical flow with a Froude number value below 1 ($F < 1$) [67, 70-72]. Froude number is a dimensionless value which defined as the ratio of characteristic velocity to gravitational velocity. Moreover, the Froude number is used to determine the resistance of partially submerged objects moving through the water [90]. The Froude number shall fall within the range of 0.7 to 0.8 to secure adequate flow efficiency [91]. The main objective of the flow management of an open drain is to prevent it from attaining hydraulic jumps and excessive sourcing. A hydraulic jump occurs when the upstream flow is supercritical with a Froude number value higher than 1 ($F > 1$).

The velocity of the flow of a concrete-lined drain shall not be greater than 3m/s, and for unlined earth canals, this value is limited to 1.5 m/s. Minimum velocity of flow shall not be lower than 1m/s during wet weather period. However, in their studies on urban drainage research Butler and Ghani [78, 92] always encouraged keeping the flow velocity of an open drain at 0.9 m/s for better performance of its self-cleaning ability. Many researchers mentioned keeping the average flow velocity of an open drain between the range of 0.7m/s to 0.9 m/s for effective flow management and preventing unnecessary risks such as the discharge higher flow water volumes to receiving water bodies within a short time period [67, 69-72]. Increasing of peak discharge to the receiving waters can lead to floods by exceeding its capacity. However, most of the open storm drains of low and lower-middle income countries are regularly faced to flow interruptions caused by clogged litter and cannot maintain an adequate velocity between 0.7m/s to 0.9 m/s [30, 52, 93].

There is a significant difference between recommended minimum velocity to be kept in stormwater drains of low, middle and high-income countries. The "Urban Subsurface Drainage, ASCE Manuals and Reports on Engineering Practice No. 95" recommended a minimum velocity of 0.6 m/s and European drainage regulations, for instance, Portugal recommended a minimum velocity of 0.7 m/s [47]. However, minimum velocities imposed in low and middle-income countries such as India, Philippine, Malaysia, and Thailand were 0.9 m/s [45, 69, 78, 94]. The reason for this difference is that the effort to be made for enhancing the self-cleansing ability of drainage system. In low and middle-income countries, storm flows carrying a considerable amount of litter and debris items which make self-cleansing process more difficult.

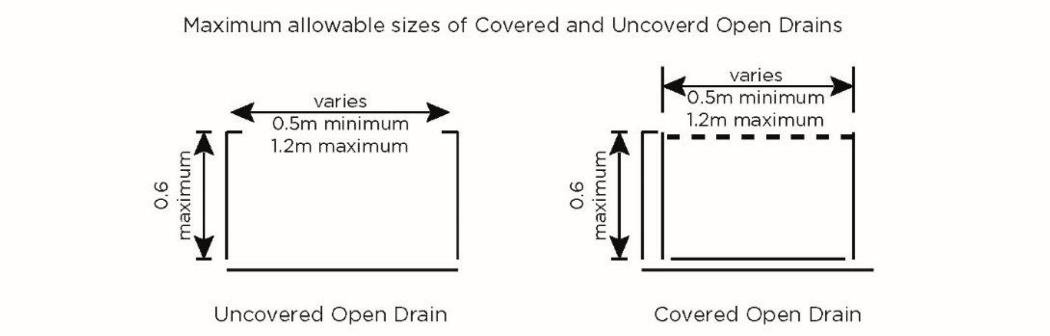


Figure 2.2: Partial section of Existing Open Drain

2.8.4 Causes behind Drainage System Failures in Low and Lower-Middle Income Countries

Tucci [95] has studied urban drainage issues in low and lower-middle income countries for decades. Most of his studies are based on countries such as Malaysia, India, Bangladesh, and Indonesia situated in the humid tropical climate zone. According to his conclusions; densely populated Asian cities can be vulnerable to flash floods due to unplanned urbanisation and flood-plain encroachments. Many of the urban squatter settlements are built in flood-prone areas and steep hillsides. These shelters are built out of semi-permanent materials. They upgrade to permanent building materials after some time, but shelters are still not provided with basic physical infrastructures such as water supply, waste disposal, and drainage [96].

These squatter settlements are often illegal and the Municipal authorities are not bound to provide infrastructure facilities to them. In such a situation, as Tucci [95] mentioned, squatters tend to dispose their waste into the nearest drain or open space since they do not have any other option regarding disposing of household garbage.

2.8.4.1 Contribution from Litter Items

The problem of urban litter has been directly connected to consumption patterns and disposing habits of the people living in the respective areas. The per capita Municipal waste generation rate in low and lower-middle-income countries ranges from 0.3kg to 1.5kg per person/per day [97-100]. As the number of population increases, it generates more street litter unless an efficient waste collection system operates. However, litter loads left uncollected in an area also depends on the waste disposal habits of the people. For instance, indiscriminate waste dumping becomes a common habit for people in low and lower-middle income countries due to the absence of rules and regulations. Likewise, this situation is very much controlled in countries like Singapore by imposing rigid rules. According to the literature, the percentage of Municipal waste left uncollected in low and lower-middle-income countries varies 20% to 40% [95, 101-103]. As mentioned by researchers these litter items are finally deposited in nearest open drains.

Current urban drainage design practices are based on the assumption that drains receive runoff only from precipitation events [104]. The "population factor" is considered at the design stage of combine drainage systems or sewer systems, because the sewer requirements and the population size are directly related [105, 106]. However, the more relevant effect of the "impact of population agglomeration" is not considered although contemporary research studies have proved the profound influence of "population agglomeration effects" on the urban drainage systems. The main impact of population on drainage systems is through the disposal of litter that obstructs the natural or artificial drainage lines [23, 107]. As such, current drainage designs are not adequately equipped to handle the input and accumulation of urban litter and result in a sudden spillover of the drains even under moderate rainfall events.

Keeping solid waste out of the drains is a necessity in drainage management in high-density cities affected by uncontrolled population growth in low and lower-middle income countries [78, 108-111]. Several studies on the use of solid waste traps to prevent waste particles from entering into the drainage channels are described in the literature. Armitage [65] reports on fifty different waste trap designs and has found only seven that showed much promise under South African conditions. The climate in South Africa, South and South East Asia is mainly tropical. Moreover, many countries in Asian region shares similar socio-environmental conditions to South Africa. Therefore, the South African example and experience in the usage of drainage solid waste traps could apply to Asian region in many instances. However, as Armitage [65] mentioned, many of these traps are ineffective at trapping and holding urban waste under practical drainage conditions.

It has also been shown that existing waste trapping mechanisms used in storm drainages are only capable of "spot capturing" of solid waste [112]. Once captured, collected waste needs to be removed to restore the functionality of the trap. This activity will require additional manpower and machinery (forklift) adding to the cost of maintenance. These devices are designed to act as central traps or collection mechanisms. No records were found of an extended waste trapping mechanism that separates waste from stormwater at the entry point to the drain, allowing the maintenance of the full design capacity of the drain.

2.8.4.2 The Effects of Changes in Urban Form

The urban form of the cities of low and lower-middle income countries has been regularly changed during the past hundred years. High rise buildings have been erected along major transport routes. Cityscapes redecorated with boulevards, pavements, walkways and impermeable spaces. New development has created the need of discharging more water quantities from impermeable spaces [113]. The consumption patterns of the city inhabitants have changed and manufactured disposable items such as polyethene, plastic, glass and paper waste, which find their way into the drainage systems. This situation also creates a need for introducing a mechanism to prevent litter entering into the open drains at agglomeration points of the city such as transport terminals, hospitals, public schools and public markets. However, the drainage systems of these cities were never really changed following the changing face of the urban form. Therefore, conveyance process of urban drainage system has become more sensitive to disposed litter that they receive [104, 114].

Table 2.1 illustrates and briefly describes on regular flash flood affected four cities in lower-middle income category, which situated in Asia through a comparison of its main urban features.All four cities considered here were major ports under British India Company and Dutch India Company. They were constructed and restructured according to European urban norms and standards [115-117]. Settlements of those cities were planned, mostly in the Gridiron form [115, 118]. The Gridiron township layout allows the ease of movement for immigrants to traverse from port cities in inner land areas.

The patterns that evolve in a city's urban settlement are triggered by higher in-migration from rural areas. This is primarily a social phenomenon. Hence it is very difficult to provide a structure for urbanisation. When the present urban forms of low-income colonized cities were considered, it can be clearly seen that what has evolved is far different from the initial townscape plans drawn in the early 1900s. City population increased, urban areas congested, environmentally sensitive areas encroached, and illegal constructions occurred and improvised settlements expanded. Due to these unpredicted social hazards, the entire urban form has changed.

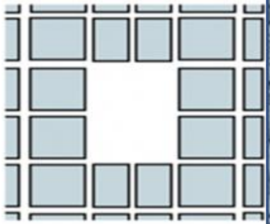
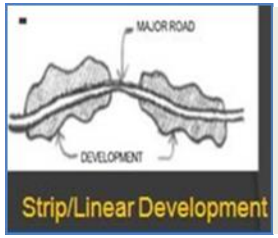
Table 2.2 describes the salient features of the initial Gridiron urban form and the present "Linear" urban form. The current urban forms of these cities no longer belong to any logical urban structure. Therefore, the drainage designs which were planned and constructed according to an urban structure which existed more than hundred years ago no longer applies to these cities.

Table 2.1: Description of the Regularly Flash Flood Affected Four Cities in Asia

	Mumbai	**Dhaka**	**Jakarta**	**Colombo**
Location	The city comprised originally of a group of 7 islands; many reclaimed areas are just 5 meters above the low tide sea level [119].	The city is positioned about 1-5m above Mean Sea Level [120].	Positioned in a low-lying fan-shaped flat land area intersected by thirteen rivers. Around 40 percent of the city is between one to one and a half meters below sea-level [121].	Located in the flood plains of the Kelani River [122].
Initial Urban form	Gridiron form	Gridiron form	Gridiron form	Gridiron form
Present urban form	Ribbon development	Ribbon development	Ribbon development	Ribbon development
Population density	31,700/km^2	44,500/km^2	9,600/km^2	9,800/km^2
Daily floating population	158,200 [123]	250,000 [124]	350,000 [125, 126]	400,000 [8]
Percentage of urban slums	54% [123]	54.9% [127]	62% [125]	47 % [8]

	Mumbai	Dhaka	Jakarta	Colombo
Identified causes of flash floods	Inadequate storm water drainage system [119]	Illegal occupation of drainage canals and wetlands by encroachers, and blocking of drainage due to solid waste [128]	15 percent of Jakarta's total solid waste (about 1,000 tons per day) is discharged into the city's drainage [102].	Improper disposal of garbage to the drainage system [122]
Details of the storm water drainage system	Open road side drainages, Works under gravity Constructed in 1900 British colonial era [119] Drain capacity decreased by waste clogging, illegal constructions reported on the top of drainage system [129, 130]	Open road side drainages Constructed in The British colonial era [124] Drain capacity decreased by waste clogging, illegal constructions reported on the top of drainage system [131, 132]	Open road side drainages. Works under gravity. Constructed in the Dutch colonial era [121] Drain capacity decreased by waste clogging, illegal constructions reported on the top of the drainage [102, 126]	Open road side drainages, Works under gravity Constructed in 1910 British colonial era [133] Drain capacity decreased by waste clogging, illegal constructions reported on the top of drainage system [134]

Table 2.2: Comparison of Gridiron Urban Form with Linear / Ribbon Development

	Gridiron Urban Form	**Linear/ Ribbon Development**
Shape	 	 
Standard of the urban form	Recognized urban development pattern. Still continuing properly in many low-density towns in Europe, America and Asia.	Informal urban development pattern.
Features	Type of a city plan in which streets run at right angles to each other, forming a grid. Land parcels are sometimes rectangular, sometimes square.	Haphazard and dense development along major transport routes of a city.
History	Initially started in medieval towns as well as the cities of Athens and Rome in ancient times. Heavily applied in British colonies.	Originated as a result of unplanned/rapid urbanization.
Street patterns	Regular geometric street patterns. Straight streets and intersections at exactly right angles. Planned drainages along streets.	Irregular street arrangements

At present these cities are densely populated and generally develop along major transport routes. Their urban form is Linear not by design but by default [135]. Informal settlements make up the majority of the urban population. Most of the time, they tend to make shelters in low-lying sensitive land parcels or top or adjacent to existing urban drainages [102, 119]. This leads to interruption of natural drainage patterns of the area.

In addition to other factors considered, urban drainage designs of low and lower-middle income countries must consider the effects of changing phase of urban structure, consuming patterns and litter disposing patterns of settlers, population agglomeration in common areas like transport terminals, floating and commuting population who do not reside in the city but travel back and forth regularly between home and work. Therefore, a drainage design which is capable of handling the matters pertaining to urbanisation and urban system dynamics is urgently required.

2.9 Investigate the Impact of Litter Accumulation on Channel Hydraulics

Clogging is the accumulation of solid matter in a drainage channel which leads partial or total blockage of the system. As Ellis [136] mentioned, the main cause of the frequent clogging is the traditional design of drainage system which ignores effects generated by gross pollutants. A clogged drainage is able to cause series of hydraulic effects related to velocity losses, increasing the resistance against the flow and decreasing the conveyance efficiency of the channel [28, 78, 137-139]. Low velocities allow considerable time for sediment settling in the channel bed and which also enhanced the clogging effect.

2.9.1 The Storm Litter Flow

The flow in urban storm drains carry litter and debris in bulk densities. The resistance generated by “litter” and “debris” in stormwater flow is significantly different due to the differences in its physical and material texture. Litter and debris are different in size, density, the pattern of concentration and distribution over the stormwater flow. However, these terms have been used for similar meaning in different literature. Hence, litter in stormwater flow is misinterpreted commonly as debris. These inconsistencies have caused incorrect estimation of flow resistance in drains. It finally resulted in an undersized storm water management system which highly depends on reliable data.

Considering the above-mentioned facts, a storm water flow which transports higher percentage of litter is mention as "storm litter flow" in this study. Storm litter flow is a flow carrying industrially processed disposables such as plastic, polyethene, rubber latex and glass products. Furthermore, a storm water flow which transports higher percentage of debris is mention as "storm debris flow" in this study. Storm debris flow is a flow carrying remains of non-industrial materials such as fragmented rock rush down mountainsides, water laden masses of soil, driftwood and dried leaves.

Litter in stormwater flow mostly exists as clusters or clots as shown in figure 2.3. The composition of a storm litter sample completely depends on the consumption patterns of population in the respective catchment. According to Armitage [65], storm litter sample composed with 50% of polythene and plastics. However, research findings of Reiser et.al [140] mentioned it as 40% of the total number of disposed items found on the east coast of Tasmania. In Asia, this number accounted a much higher value than Africa and Australia which exceeds 60% [11, 99, 102, 141]. The density of common polyethene, plastic and rubber latex products is lower than water. Therefore, litter clots in storm drain tend to float with wet weather flow.

Figure 2.3: Litter clots in a model-drain

2.9.2 The Impact of Floating Litter in Open Drains

Many researchers have identified floating litter as a global problem [136, 142-147]. Floating litter primarily originate from roadside spaces and transported by surface runoff into the open drains. Then, these are flushed frontward through secondary and primary drainage channels into receiving water bodies. Each year, around 8 million tonnes of floating litter ends up in oceans [144, 148]. Mobility and transportability of floating litter particles in urban drainage network have been identified as an interaction between channel geometry and litter quantum [144, 145]. Floating litter can be broadly divided into three categories as the macro (>20mm), mezzo (2mm-20mm) and micro (< 2mm), based on the diameter of particles [145]. However, the transportability of macro litter items through open drains is considerably lower than the mezzo and micro-particles. A limitation of previous research on transportability of floating litter is non-consideration of the lower mobility and higher clogging ability of macro litter items in narrow drainage channels.

According to researchers, plastic items dominate floating litter in terms of a number of items present in a sample [145]. The density of plastic is lower than water. Fresh water has a density of about 1000 kgm^{-3} at temperature 04^{o}C and the density of sea water is about 1027 kgm^{-3}. The average material density of common plastic waste is about 965 kgm^{-3} [149]. Hence, the plastic matter floats on freshwater and marine environments and is transported through storm drainage network unless it is clogged and stopped at a crucial point of a channel. Though floating litter either gets clogged or ends up in oceans, it triggers considerable threat to the terrestrial and marine environments. The clogged open-drains cause intense flood attacks while litter in the oceans leads to the habitat loss of marine ecology.

Global production of plastics and polythene has increased by 500% for the last three decades [145]. Parallel to that, plastic consumption has increased rapidly in Low and lower-middle-income countries [145]. According to the researchers, some countries in low and lower-middle income category like India, Sri Lanka, China and Vietnam are identified as world's worst marine polluters [146, 147]. Generally, higher quantities of floating litter washed into the drainage network from densely populated urban areas. Uncoordinated disposal habits of people and inefficiency of Municipal garbage collection services lead to urban litter circulating haphazardly in open environments. Faris and Van Dyck [150, 151] claim that 80% of marine litter enters the ocean by land via natural and man-made drainage systems. This stresses the need for a mechanism which prevents entering litter into surface drains at the points of generation.

There is a considerable body of literature available on floating litter in the marine environment, but no published studies are found describing its influence on the conveyance efficiency of the surface drainage network to the best of the author's knowledge. This area has been surprisingly neglected in urban drainage research niche as the majority of its literature has only focused on the effects of the presence of sunken litter or debris in open drains. However, it is important to study the impact of floating litter in open drains and channels and the subsequent clogging of drains. Hence, there should be a framework which quantifies the influences of floating litter on hydraulic elements of the open channel flow such as velocity, flow depth and frictional factor.

2.9.3 Crucial Point Clogging of a Drainage System

Litter particles are not uniformly distributed along the drainage channels. Especially, the floating litter items with higher transportability can mobilise along the channel as the inflow receiving from the upstream. If a crucial operation point in the drainage line, for example, a downstream node, junction of a conduit, mouth of a trash barrier or an outfall point is clogged with floating litter particles, the stormwater conveyance process in the channel may break down, and water will tend to stagnate around the clogged area. It will then lead to a sudden spillover of drainage water. Hence a limitation of this literature on floating litter items is that the non-consideration of the effects generated by its mobility and transportability in open drains.

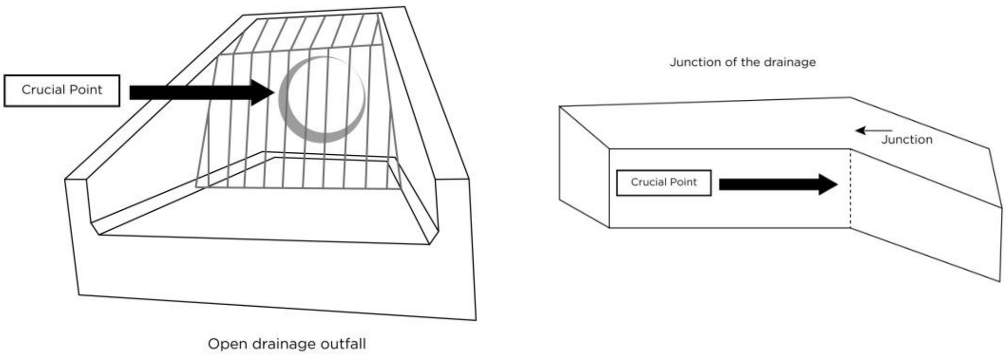


Figure 2.4: Crucial operation points of Open Drain

2.9.4 Breaking the "Litter Threshold" of Open Drains

Any open drain has a certain capacity to hold litter without breaking its conveyance ability. Before attaining the very point it tends to spill over, a drain was at the "stable stage." At the stable stage, drainage outflow rate is always similar or greater than the inflow rate. Hence, little or no storm flow accumulation (flow stagnation) happens inside the drain. A drain can keep out outflow rate greater as long as it keeps the drainage outfall free of clogging. However, it is difficult to actually achieve and keep this stability state for a clogged drainage since the unpredictable effects caused by the mobility and transportability of litter items. However, the system equilibrium of a clogged will break due to two reasons. First, it exceeds litter holding capacity by adding another set of litter into the drain. Second, floating litter items in the drain flush frontward with the flow and clog a crucial point such as an outfall. Once the equilibrium breaks, stagnation starts, and the drainage system tend to spill over at the end. However, little or no research has been done on assessing the litter holding capacity of open drains.

2.9.5 Roughness Coefficient for Clogged Drains

It is commonly assumed that the resistance to the flow when other physical parameters are kept unchanged depends on the roughness coefficient [152]. In other words, roughness coefficient is the only influencing factor to the velocity of the flow. If resistance is higher, the velocity is lower. According to Chow [81], physical conditions of an open channel have a considerable influence on its flow characteristics. Those physical conditions such as channel slope, shape, surface roughness, entrance condition are considered and substantially addressed in the studies pertain to Manning's roughness coefficient.

Manning's roughness coefficient or "Manning's n" generally means the roughness of forming materials in the wetted perimeter of the channel. In his book, Open Channel Hydraulics, Chow [81] has considerably discussed the practical difficulties of determining the real roughness value of an open drainage channel. Chow [81] identified ten key factors which affect the real value of Manning's roughness coefficient. Those factors are surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstruction, size and shape of the channel, stage and discharge, seasonal change, suspended material and bed load. Hence the value of Manning's "n" is highly variable and depends on various intangible factors in addition to surface roughness [153].

Jarret [154], identified key limitations of the Manning's formula, especially its applicability on the open channel flow subjected to sedimentation and debris movement. The conventional hydraulic analysis such as Manning's formula is not applicable for above-mentioned scenarios because of the uneven distribution of the debris along the drainage channel. According to Jarret [154] the "debris flow" in a channel is a heterogeneous mixture of water and different sizes of sediment particles. Largest rocks may concentrate at the channel surface and edges of the sediment deposits. The sunken debris items cause irregularities in channel cross sectional shape. It affects the discharge, depth, wetted perimeter and the channel gradient. Therefore, the hydraulic geometry at every single location of the channel is different from each other. Hence, each cross section should be computed differently for different discharges.

In his research Jarret [154] precisely described this using "different roughness areas" in a channel [155]. Different roughness areas indicate the distinct debris and vegetation clusters presence along the drainage channel. While considering this condition, a single composite roughness value has been calculated for the channel using the equation 2.1 which has been simplified from Chow [81].

$$n_c = \frac{p_1\, n_1 + p_2\, n_2 + p_m n_m}{p} \tag{2.1}$$

Where,

n_c is the composite n value for the channel

P_1, P_2, P_m are wetted perimeter for each roughness area

n_1, n_2, n_m are roughness coefficient pertain to each wetted perimeter

P is the total wetted perimeter for the channel

Much research has been conducted on the open channel flows with fully submerged obstructions since the 19th century. Though, in general, these studies have been limited to the presence of debris, rock and gravel particles in the drainage.

Currently, most of the open drains in low-income urban settlements are clogged with sunken and floating litter items such as plastic waste, glass, clothes, timber and dried leaves [65]. Large quantities of these urban litters are unevenly distributed along the drainage channels and make the storm water conveyance process more difficult. The overall effect generated from the sunken and floating litter items over the open channel flow is totally different from the debris flows in the channel. The channel roughness coefficient or the resistance value is significantly influenced by these obstructions, especially floating litter is considered.

Sunken and floating litter in a clogged drain is highly movable and changes its stance with time (t) and distance (x). To approximate the spillover time of a clogged drain, there is a need of quantifying the resistance or the effect generated by movable sunken and floating litter items. For that, a suitable mathematical formula, which is sensitive to temporal changes in a storm litter flow, is needed. However, too many things are uncertain in Manning's formula, for example, the roughness coefficient. The formula is highly sensitive to the roughness coefficient value, but there's no approved or acceptable method of setting it. The problem gets worse in clogged drains and as sunken and floating litter items are subjected to temporal changes.

2.9.5.1 Litter Distribution along the Drainage Channels

The sunken and floating litter particles along the drainage channel can be moved with higher velocity flow and stagnated or deposited at various positions along the drainage channel. This leads to decrease the hydraulic capacity of open drains, which commonly mentioned as “drainage capacity losses”. The size and the size distribution of the litter clots in the drainage channels cause cross-sectional irregularities [73, 154]. These irregularities change the width and depth of the flow. Where the rate of channel width to depth is small, larger adjustments are needed for the hydraulic analysis. This situation can be avoided by proper location of sunken and floating litter particles in open drain.

The degree of effect generated by floating and sunken litter generally depends on its diameter, type or material, density, capacity, weight, distribution, stance and the area occupied by the channel [81]. However, once the litter carrying capacity or the litter "litter equilibrium" of an open drain is broken or a crucial point of the channel gets clogged, these factors become non-considerable since the rate of stagnation of water becomes the only governing factor of stormwater conveyance in open drains.

2.10 Unclogging a Clogged Drain

Dredging and cleaning are conventional methods used to clear a clogged open drains and storm drainage channels. It involves heavy machinery, for example, hydro-pneumatic flow jets, metallic strings, rollers and vacuum tankers. Since this process is manually operated, it also involves much manpower and time. As Parkinson [100, 156] mentioned, the manual cleaning efficiency of a clogged drainage channel is about 15km/per month.

New urbanists believe that they can change the human behaviour through design [157-159]. The situation discussed above pertains to the informal settlements, have explored some crucial facts to be addressed in new a drainage design initiative. As a minimum, even the outskirt of an urban area needs an extended waste trapping mechanism throughout the existing open drains to prevent clogging. There is an urgent need of maintaining a clear channel to facilitate fast conveyance of storm water which prevents unnecessary stagnation [160, 161]. In a situation of a clogged drainage channel, it is advisable to re-route the water cause even with a temporary external channel. Since dredging and cleaning of the drainage channel are not under the duty of municipal garbage collectors, there needs to be a mechanism which facilitates Municipal garbage workers for easy removal of flushed and fallen litter from the drainage channels.

2.11 Present Solutions Applied to Prevent Clogging of Drains

According to many researchers, settlers in low-income urban settlements are under the impression that the open drains are a convenient place for disposing of litter and household garbage [2, 12, 26]. Moreover, the water that flows over rooftops, paved surfaces and street belts in these areas carry a certain amount of litter along with it to the receiving water bodies. Preventing the entry of litter particles into the open drains at the point of generation is considered an utmost necessity for the prevention of clogging in primary channels and receiving water bodies [69]. Drainage channels thus cleared are capable of handling events such as unexpected watercourse received from upstream. Hence, covering the open drains by grates is a general practice used to avoid clogging in open drains (see Figure 2.5).

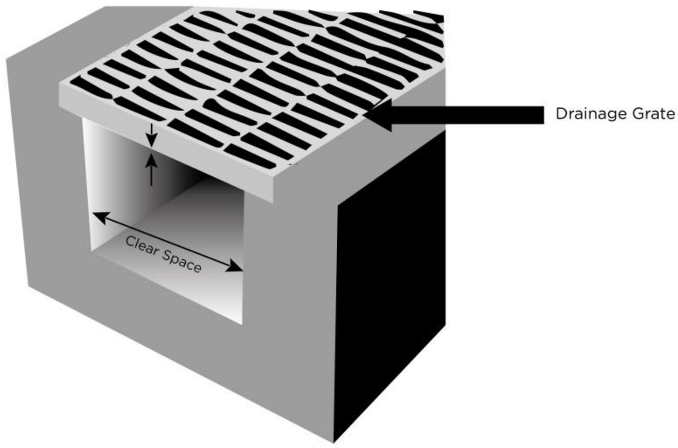


Figure 2.5: Covered Open Drain

People, who live closer to receiving water bodies in low-income settlements, generally use this water for their daily needs. Pollution of primary drainage channels with litter and stagnate for a long time may lead to bacterial overgrowth which causes series of health issues [2]. By introduction of a new drainage design, which is capable of trapping litter from the moving watercourse, the water could be made safe for domestic purposes after further purification as needed.

A mechanism which enables temporary collection of fallen litter particles instead of covering the whole drain by a perforated cover is considered a practical solution for low-income cities with solid waste management problems [138, 156, 162]. Though allow some room to retain litter or garbage items is not considered as a purpose of any open drainage system, this simplest act may lead to an effective change in the urban litter and stormwater management. Even today, haphazardly disposed litter and household garbage spread throughout the streets with the next rainfall and leads to an unpleasant situation which also can cause health problems [23]. Therefore, designing a new drainage which can sustainably handle urban storm water and Municipal garbage as a temporary entity would be a prominent technical solution to overcome these issues. However, it should strictly be a temporary retaining followed by removal as it would again disturb the conveyance process of the drain.

2.12 Research Gap Identification

Many researchers have identified the impact of the resistance force created by sunken litter against the stormwater flow within open drains [81, 163-165]. Manning (1889), Chow (1959) and Jarrett (1984) [81, 155] have mentioned it as the obstruction to the free flow of water, especially when channel vegetation and debris flow is considered. These studies were conducted decades ago and no analytical research has taken place in last 10 years to address the litter holding capacity of open drains. As Armitage (2000) [65, 66] points out, the usage of polyethene, plastic, and PVC matter has considerably increased in this decade. Recent studies have also identified that accumulation and floating of plastic in the riverine, marine and coastal environment have resulted in serious physical environmental problems including pollution and spatial distortion [149, 151]. It has been experimentally proved that the deposition of solid matter like debris and vegetation has a considerable effect on the hydraulic features of the storm flow. Moreover, researchers have assigned justifiable numerical values for the roughness and resistance generated from sunken obstructions, for example, debris and rock particles in open channel flow [81, 155]. However, minimal or no research has been done to describe the effects generated by the unpredictable behaviour of floating litter such as polyethene and plastics on the open-drain operation. These may allow flow stagnation of a drainage channel by clogging the crucial points and leads to sudden spillovers. These significant gaps have been carefully studied and addressed in the formulation and testing of the clog resistant open drain unit described in the follow-up chapters.

2.13 Conclusion

Urban drainage is considered a most urgently needed infrastructure for low and lower-middle-income countries. Increasing of impermeable spaces in these areas make the natural infiltration process more difficult. Clogged drains cause intense spillovers, which lead to flash floods if the drainage capacity is not adequate for proper conveyance. Urban poor obviously tends to settle on lands by obstructing natural drainage paths. However, good urban physical planning and design solutions may help avoid many conditions get worse. This chapter highlighted weaknesses in existing drainage systems in four cities of lower-middle income countries and justified the need for introducing a new drainage design manual. The rationale put forward in this chapter has been guided by the practical numerical solution stated in chapter three.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Open drains are used for the conveyance of storm water and real-time flood management. In this analysis, stormwater conveyance is taken as the fundamental purpose and the flood management as the operational constraint. Further, optimizing the research findings of analytical approach through an experimental and numerical procedure is described in this section. In the analytical approach, stormwater flow through the drainage system is modelled using the Law of Conservation of Mass, with the intention of yielding a class of mathematical formulae. Moreover, in the numerical approach, it considered the empirical data and experimental results obtained. Finally, fit them into the SWMM 5.0 computer simulation platform to guarantee the compatibility.

3.2 The use of Analytical Approach in this Study

The purpose of using the analytical approach for this study was to formulate the research problem through a mathematical model to assess the spillover time of open drain. The spillover time of open drain has derived from the "rate of stagnation of water" in a clogged drain. Approximation of spillover time in open drains will help to formulate a real-time flood monitoring and warning system. Finally, a clog resistant open drain design was developed to provide a solution at the source of the problem.

The use of analytical approach in this study is shown in figure 3.1

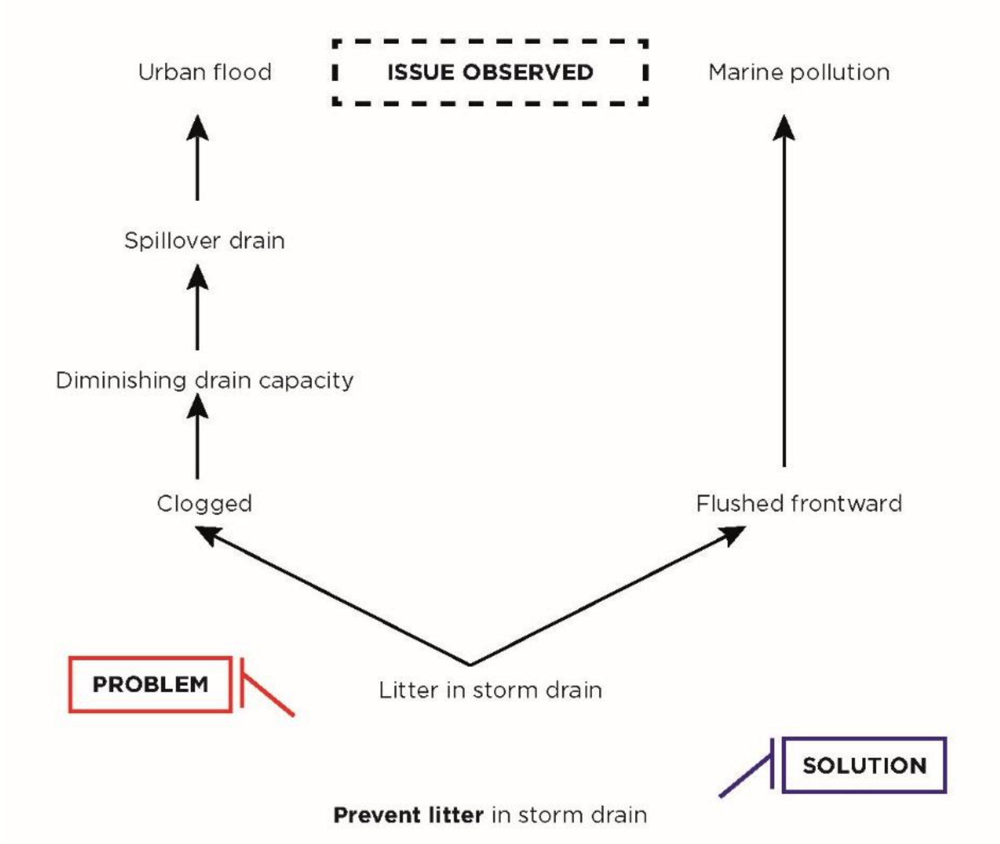


Figure 3.1: The use of analytical approach in this study

3.3 An Overview of the Research Methodology

This section summarised the complete research methodology pertaining to this study. The research methodology applied in this study comprises five different stages namely, (i) initial numerical screening of the case study area, (ii) laboratory replication of the case study area, (iii) development of clog resistant open drain, (iv) laboratory experimentation on the hydraulic characteristics of clog resistant open drain, (v) computer model simulation and validation for existing and improved drainage conditions respectively.

3.3.1 Initial Numerical Screening of the Case study Area in Madampitiya Colombo 15 Ward, Sri Lanka

The initial screening relates to the area of the case study that has been conducted to get a real understanding of the present stormwater system demand. Hence, the effective drainage capacity (Q_c) and the peak flow rate (Q_r) of the concerned catchment has been calculated initially as explained in subsection 3.4.4.

Basic data that belong to the case study area was collected by the Department of Meteorology Sri Lanka, Colombo Municipal Council and Sri Lanka Land Reclamation and Development Corporation. Once the initial numerical calculation part has completed, the SWMM 5.0 model was simulated for the concerned area. The objectives of the initial numerical screening in the case study area were,

1. to understand the real time system demand created by the peak flow rate
2. to calculate the effective drainage capacity as the system is clogged or obstructed by litter items
3. to assess the "litter handling capacity of drain" and detect the breaking point of the "drainage system equilibrium"

3.3.2 Laboratory Replication of the Case Study Area

This study has been driven by the laboratory evaluation of the prototype based experimental scenario. Prototype drainage has been created inside the hydraulics laboratory of Universiti Teknologi PETRONAS.

3.3.3 Design Development of the "Clog Resistant Open Drain Unit"

Solid waste clog resistant open drain has been designed considering the research findings of the analytical approach in this study.

Analysis of the modes of failure of current urban drainage designs as stated in the Literature review and the experimental findings pertain to the behaviour of a clogged drain in an event of a rainfall was thoroughly considered in this section. This analysis identified the following features to be desirable in future open drain designs that will help management of storm water.

- Prevention of solid wastes from entering the drainage channel as early as possible by using a suitable trapping mechanism
- The trap should not interfere with the normal operation of the drain
- A mechanism that would allow easy removal of trapped solid waste, hence the trap is functional all the time
- Maintenance of a clear channel for stormwater conveyance at all times, especially during times of unexpected heavy rainfall
- A design that would allow local inhabitants to easily monitor the status of traps and alert the authorities
- A design that could be constructed easily with commonly available materials used for constructing drains and that could be easily adapted to retrofitting conventional drains in problem areas

3.3.4 Testing for Hydraulic Characteristics of the Clog Resistant Open Drain Design

A prototype of newly developed solid waste clog resistant drainage unit was been fixed to the Laboratory modular flow channel and was tested for velocity changes with different litter amounts clogged in the channel. The objective of this experimental segment was to practically prove the litter handling ability of the solid waste clog resistant drainage during the event of a rainfall.

3.3.5 Numerical Approach for the Storm Water System Demand

The numerical approach aims to compare the effects generate on storm water conveyance process of the case study area by existing conventional drain and improved clog resistant open drain unit. EPA Storm Water Management Model-(SWMM) version 5.0 was used for the simulation. The case study area has been divided to three sub-catchments. The model replicated the flow behaviour of storm water runoff in the catchment areas during a rainfall and numerically defined for the amount of runoff received, the behaviour of the channel node, outfall, link flow and conduit surcharge. The initial numerical simulation results have been used to understand the real-time storm water system demand for the development of clog resistant open drain unit.

The flowchart of research methodology is shown in Figure 3.2.

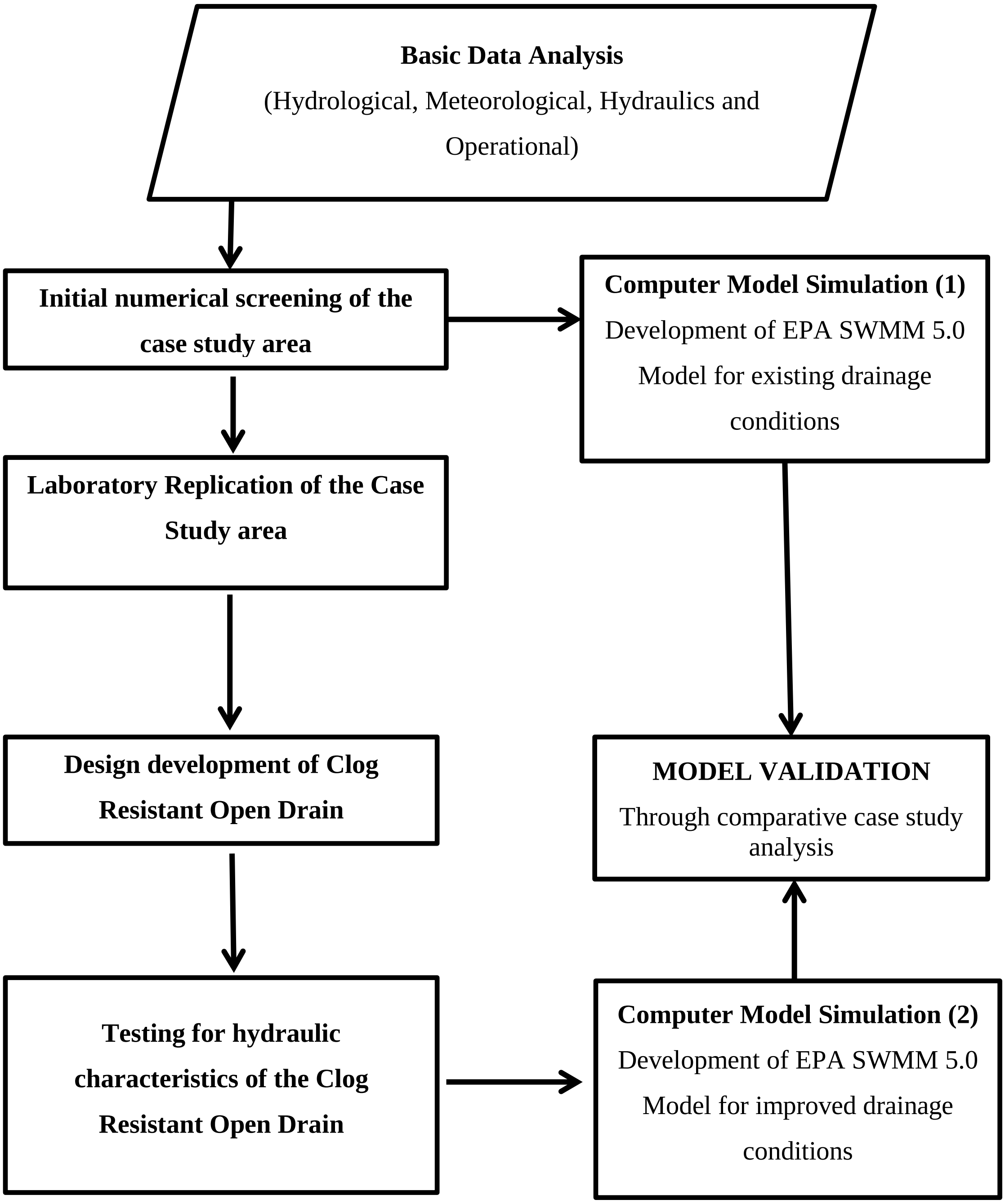


Figure 3.2: General flowchart of Research Methodology

3.4 Numerical Analysis and Modelling of the Real Time System Demand Pertaining to the Case Study Area

In this section, a practical numerical method has been provided to estimate real-time system demand pertaining to the surface water circulation and stormwater conveyance of the study area.

3.4.1 Determination of the Weighted Average Runoff Coefficient (C) of the Case Study Area

Runoff coefficient values were obtained from the runoff coefficient table of urban storm water management manual[69]. Weighted average runoff coefficient (C) was computed by using the following equation [84, 166].

$$\text{Weighted } C = \frac{\sum C_{individual\ area} \times A_{individual\ area}}{Total\ area} \quad (3.1)$$

Where, C is the runoff coefficient and A is the catchment area.

3.4.2 Estimation of the Peak Runoff (Q_r) of the Case Study Area

The peak runoff pertaining to the case study area has been computed using the Rational formula [67, 72, 84]:

$$Q_r = \frac{1}{360} CiA \quad (3.2)$$

Where,

Q_r =peak runoff at the point of the design (m^3/s)

C =runoff coefficient

i =Average rainfall intensity (mm/hr)

A =catchment area (ha)

3.4.3 Calculation of the Total Litter Load in Drainage Channels of the Case Study Area

The effect of clogged litter items in stormwater conveyance system is a crucial factor in this study. Urban litter percentage in storm drains was estimated by using the undermentioned formula developed by Armitage and Rooseboom [65] from the study of springs and Robinson Canal data in South Africa.

The total litter load clogged in micro drainage channels is given as;

$$T = \sum f_{sci.}(v_i + B_i).A_i \tag{3.3}$$

Where,

T = Total litter loads clogged in micro drainage channels (m^3/yr)

f_{sci} = street cleaning factor for each land use (this number varies from 1.0 for regular street cleaning to about 6.0 for the non-existent/ complete collapse of service)

V_i = vegetation load for each land use (varies from 0.0 m^3/ha.yr to poorly vegetated areas to about 0.5 m^3/ha.yr for densely vegetated areas)

B_i = basic litter load uncollected for each land use (B_i value depends on the effectiveness of Municipal garbage collection service in a respective area. It varies from 0.0 m^3/ha.yr to fully serviced areas to about 0.5 m^3/ha.yr for poorly serviced areas)

A_i = area of the each land use (ha)

However, the constant values assigned in the original formula were slightly modified to fit with the objectives of this study. The original formula developed by Armitage and Rooseboom [65] put more weight on commercial and industrial waste circulating in the area, but the present study thoroughly focused on the residential waste that circulates in the informal settlements of the compact cities. Hence, the value of B_i, basic litter load for each land use was re-weighted as indicated in table 3.2 taking into consideration the average Municipal solid waste generation rate and the basic litter load left uncollected in the different settlement areas. These values extracted from the Literature pertaining to this study [102, 167].

Table 3.1: Estimates of basic litter load uncollected for each settlement (Bi)[65]

Low-income informal settlements	0.5 m^3/ha.yr
Middle-income condominium settlements (high-rises)	0.3 m^3/ha.yr
Middle-income condominium settlements (single units attached)	0.3 m^3/ha.yr
Common settlement area located in the urban-rural fringe	0.2 m^3/ha.yr

3.4.4 Calculation of the Effective Drainage Discharge Rates Q_c of the Case Study Area

Discharge rate Q_c of the open drain which serves the study area has been calculated using the Manning formula [81];

$$Q_c = \frac{1}{n} AR^{2/3} S^{1/2} \tag{3.4}$$

Q_c =effective discharge capacity of the drain m^3/s

n = roughness coefficient pertain to the micro drain

A = unit area of the flow (m^2)

P = wetted perimeter (m)

R = hydraulic radius (m)

S = bed gradient of the drainage

Pre-estimated Manning’s n values by Chow (1959) [81] has been used for primary screening of drainage hydraulics in case study area.

3.5 Laboratory Experimental Analysis of the Micro Drainage Operation Pertaining to the Case Study Area

The laboratory experimental procedure consisted of two stages. Stage One was carried out in the laboratory flume. It demonstrated the existing conventional drain situated in the study area. In Stage Two, the solid waste clog resistant open drain was inserted and partitioned the laboratory flume into a dual layer channel. The pictorial representation of the prototypes used in both stages is depicted in Figure 3.3 and 3.4.

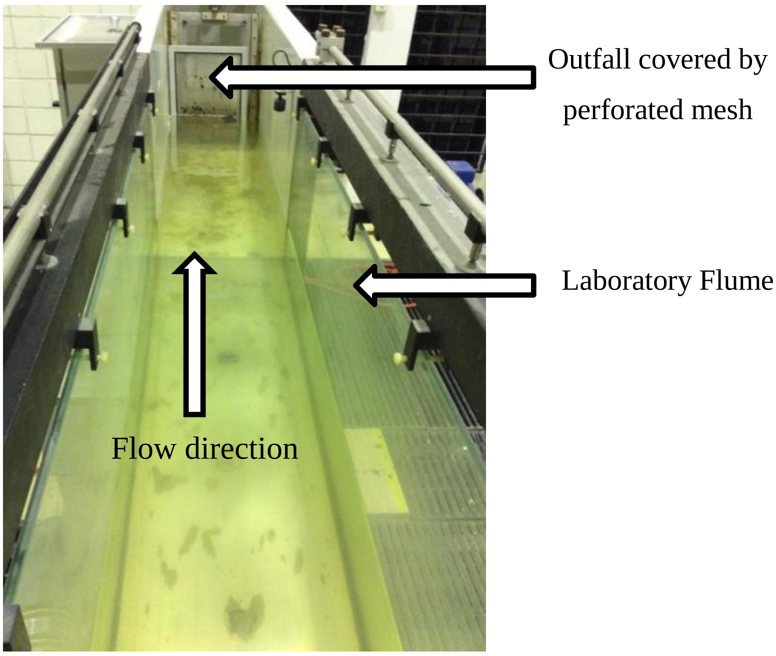


Figure 3.3: Conventional drain (Prototype used in the experiment stage 01)

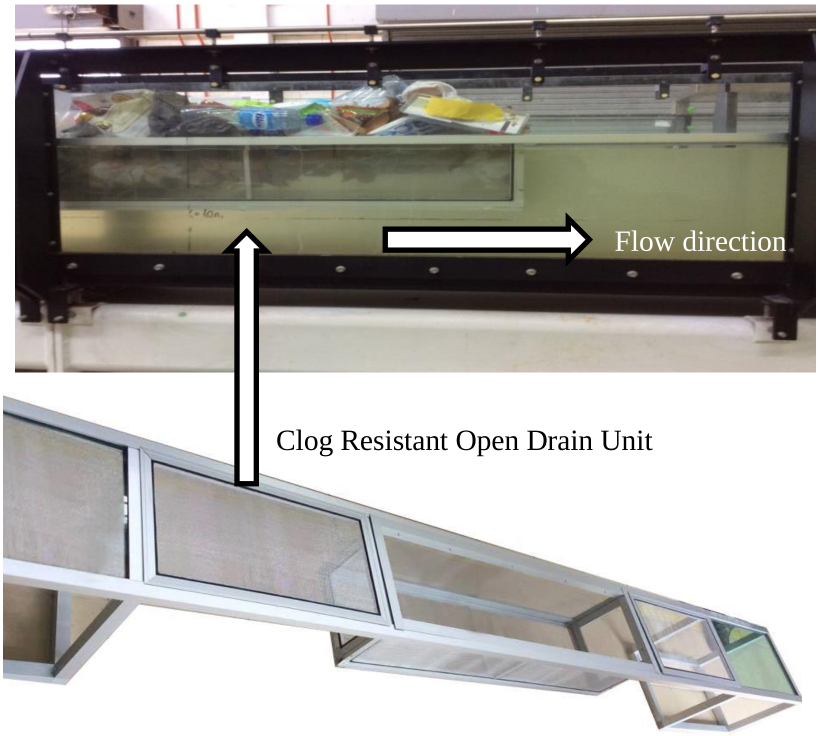


Figure 3.4: Solid Waste Clog Resistant Open Drain
(Prototype used in the experiment stage 02)

3.5.1 Laboratory Experimental Procedure – Stage 01

All experiments were conducted at the Hydraulics Laboratory, Universiti Teknologi PETRONAS using Laboratory Flume with an experimental length of 10m, width of 0.3m and the height of 0.45m. The schematic diagram of the experimental flume is shown in Figure 3.5.

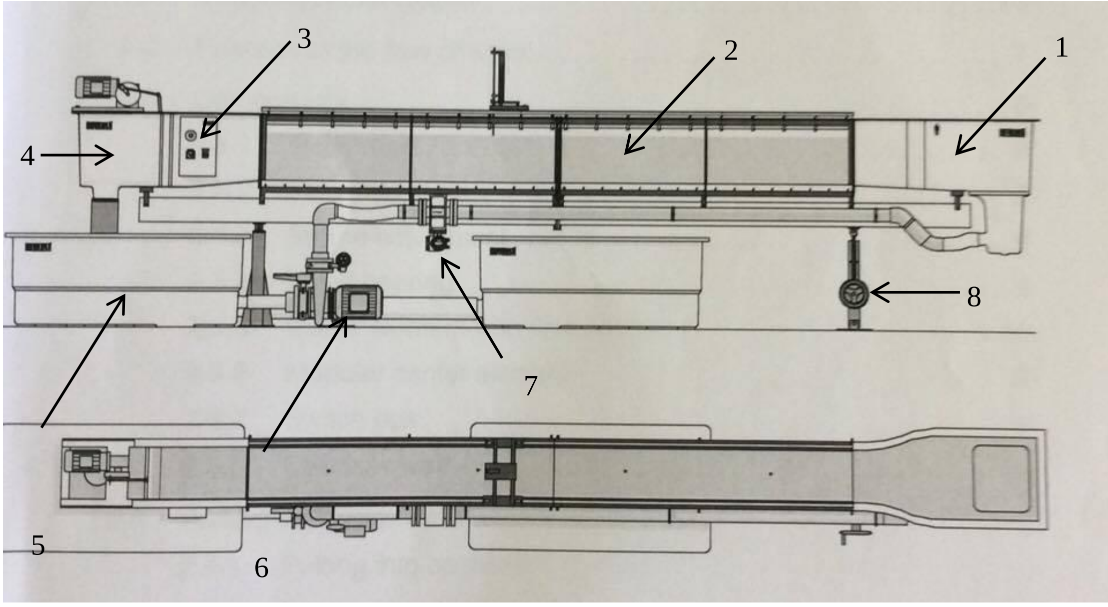


Figure 3.5: HM 162 Laboratory Flume

1 – Inlet Element 2 – Experimental Section 3 – Switch 4 – Outlet Element

5 – Water Tank 6 – Pump 7 – Flow Rate Sensor 8 – Inclination Adjustment

Three practical micro drainage scenarios were selected, artificially created inside the modular flow channel and tested flow velocity changes at different gradients (S_0) and flow rates (Q). These experimental scenarios were;

a. Case 01 - The control case, which represents the perfect drainage situation free from any type of obstruction. This experiment scenario was also used to estimate the surface roughness value of the Laboratory Flume (see Figure 3.6).

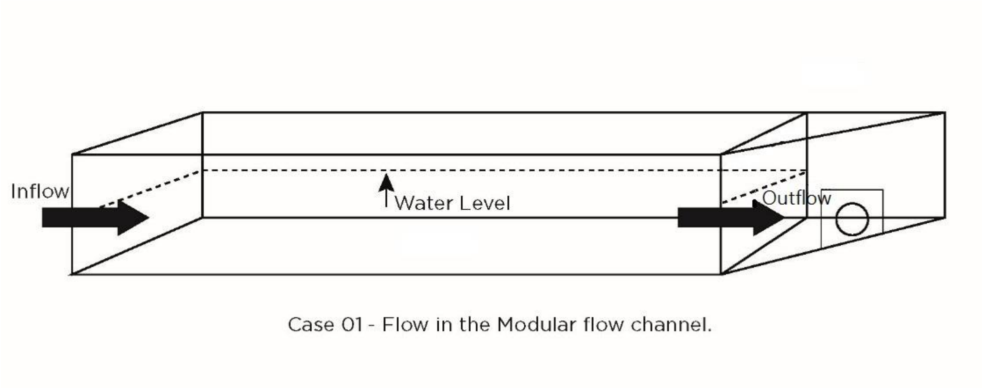
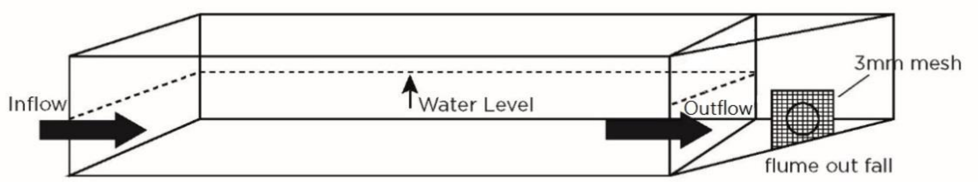


Figure 3.6: Control Case

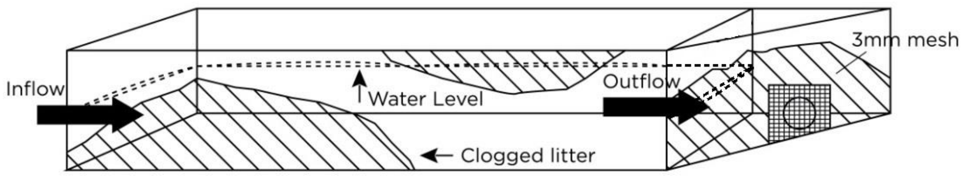
b. Case 02 - The modular flow channel where the downstream outfall is vertically covered by a mesh with a spacing of 3mm. This experiment scenario was used to observe the effects of a conventional trash trap inserted at the flume outfall on the drainage water flow (see Figure 3.7)



Case 02 - Outfall of the Modular flow channel, covered by mesh.

Figure 3.7: Perfect Drain Condition, Zero Clogging

c. Case 03 - The modular flow channel where downstream outfall is vertically covered by a mesh and clogged with 1kg to 7kg of sunken and floating litter items (see Figure 3.8). This experiment scenario was used to observe the "litter effect" which generated against on the drainage water flow. It also observed the stance and distribution of floating and sunken litter items and the changes of hydraulic features of the drainage.



Case 03 - Outfall covered by mesh & clogged.

Figure 3.8: Worst Drain Condition, Clogged Drain

3.5.2 Objectives of the Experimental Procedure

This experiment segment investigated and examined the magnitude of the resistance generated by a clogged drainage against the storm flow received from the up streams. The objectives of this experiment were,

1. to quantify the effect of floating and sunken litter particles to the resistance force generated on the water flow

2. to discover the maximum litter handling capacity or the "litter equilibrium" of the drainage

3. to identify the sensitive points where real-time overflow occurs in a clogged drainage during a rainfall event

It is intended that the correctly addressing these practical scenarios will lead to minimising operational problems in urban drainage systems of Low and Lower-Middle income countries.

3.5.3 Description of the Experimentation Variables

Laboratory replicated drainage scenarios were tested according to the experimental protocol in Table 3.3.

Table 3.2: Summary of the Experimental Conditions – Stage 01

Flow rates: Q	$0.013 m^3/s$	$0.017 m^3/s$	Q $=0.020 m^3/s$	$0.023 m^3/s$
Drainage gradients: S^0	1/200, 1/300, 1/500			

The different drainage gradients were obtained by adjusting the manual jack of the Laboratory Flume. Different upstream flow rates were acquired by adjusting the channel pump. Each experimental scenario was tested flow velocity changes and flow height changes along the channel. In addition to that, time to overflow was recorded at experimental scenario three by using a stopwatch.

Flow velocities (v) of the experimental scenarios were obtained by using a water current meter (SEBA Mini Current Meter M1 with 9mm rod). This is an electromagnetic meter which gives a velocity averaged over 30 seconds. Flow velocity measurements were taken at five points at 10cm and 20 cm height from the channel bottom as shown in Figure 3.9. At each measurement point, three readings were averaged to get the mean flow velocity. Apart from this, flow depth (D) measurements were obtained at eight positions with spacing around 1 m. This data set was used to calculate the resistance to the flow or Manning's "n" value using the below-mentioned formula.

$$n = \frac{1}{v} R^{2/3} S^{1/2} \tag{3.5}$$

Where,

n	=	Manning's roughness coefficient
v	=	flow velocity m/s
R	=	hydraulic radius
S	=	bed gradient of the drainage

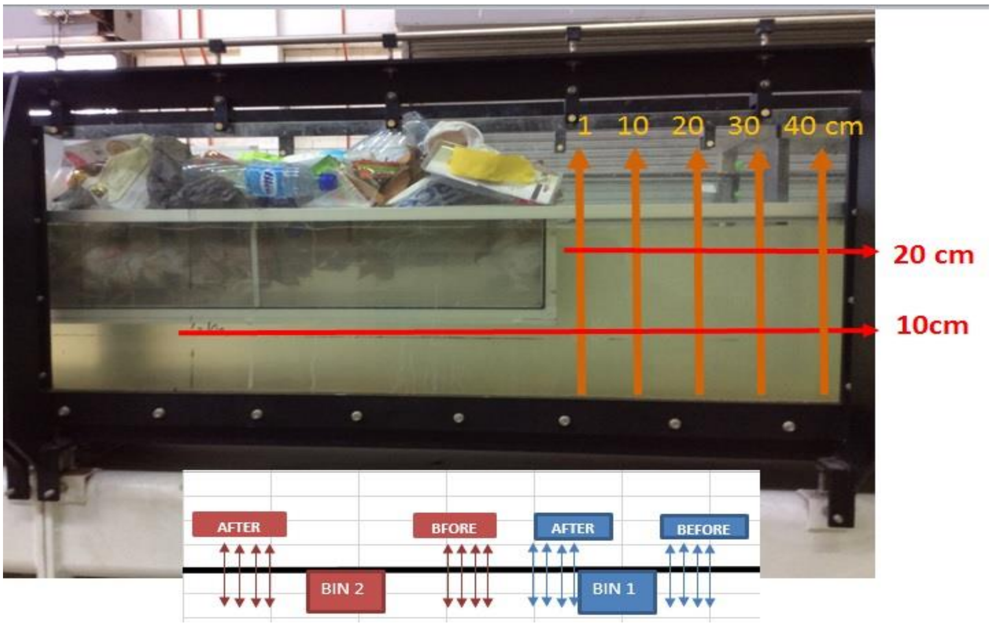


Figure 3.9: Velocity Measurement Points of the Drain

3.5.4 Independent and Dependent Variables of the Experimental Study

The three main variables deliberated in this study were the Roughness coefficient (n), flow velocity (v) and the flow depth (D) of the channel. Roughness coefficient was the independent variable that has varied and manipulated by the researcher through adding different litter amounts into the drainage. Flow depth and flow velocity were considered as the dependent variables which escalated with the obstructions to the flow in the modular channel. The experimented variables pertaining to this study were described in Table 3.4.

Table 3.3: Variables in the research

Independent	Dependent	Controlled Kept constant during the experiment
Roughness coefficient (n)	Flow velocity (v)	Slope
	Flow height (D)	

3.6 Mathematical Model and Numerical Analysis

This section describes the procedure relates to numerically assess the "litter effect" in a clogged drainage channel.

3.6.1 A Mathematical Model for Litter Distribution in a Drainage Channel

Litter in a drainage channel can be divided into two general types; sunken and floating (see Figure 3.10). Spatial distribution of these two types of litter can be described using three-dimensional distributions given by f(x,y,) and g(x,y), where x is measured across the channel and y is measured along the channel. Here, f(x,y) is defined as the height of the sunken litter load at the point (x,y) and g(x,y) is defined as the positive height of floating litter load (that is the distance to the lower point of the floating litter layer measured downwards from the water surface) at the point (x,y). In a pragmatic perspective, both floating and sunken litter distributions change with time, in particular, the floating litter. Thus, in the most general case, f and g can be regarded as functions of x,y and t.

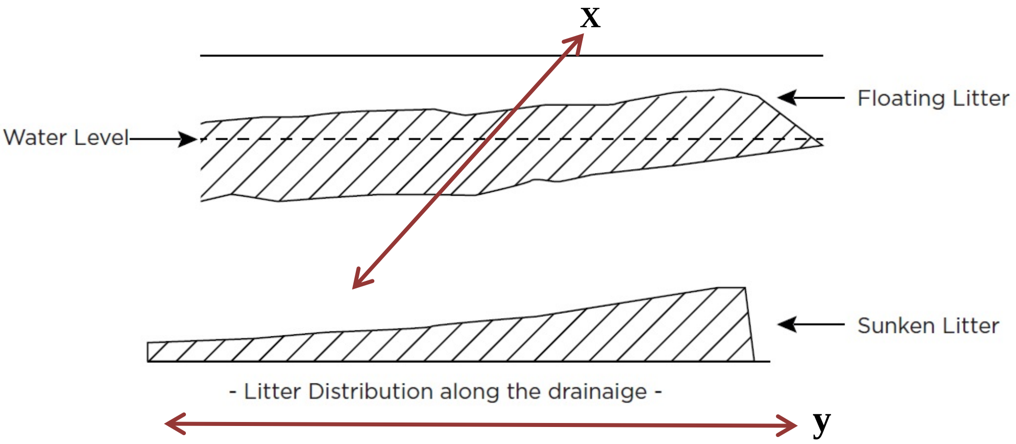


Figure 3.10: Floating and sunken litter distribution across (x) and along (y) the channel

The following section re-defines key terms used in the field of open channel hydraulics, in terms of litter distribution model introduced above.

a) Wetted perimeter (P)

Consider a cross-sectional view at length "y" as illustrated in figure 3.11;

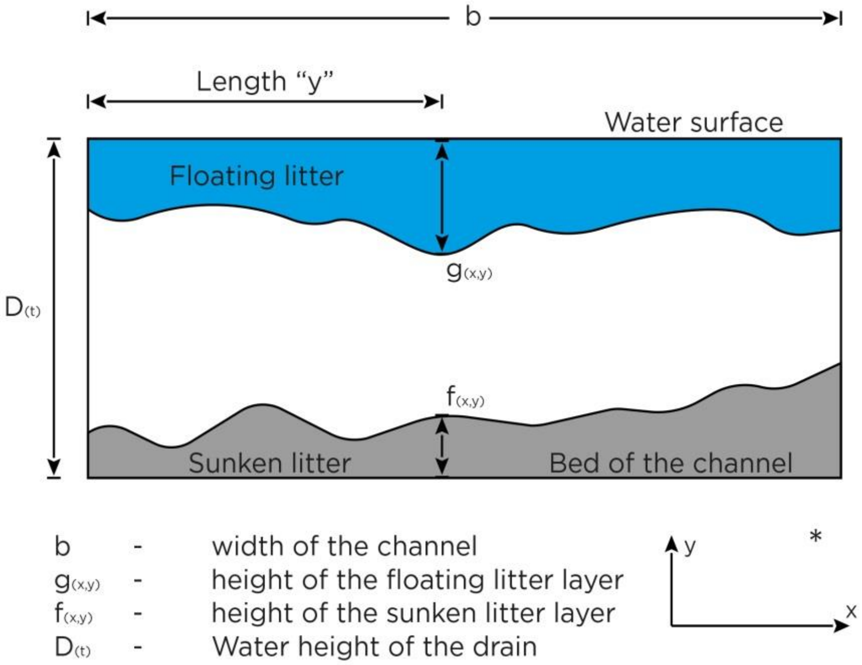


Figure 3.11: Head on cross-sectional view of a clogged drain

Wetted perimeter is defined as the perimeter of the wetted cross-sectional area of the channel and which can be obtained by summing up the hydraulic depth of both ends of the channel to the width of the channel.

The wetted perimeter at distance y at time t is the sum of the two straight line segments forming the sides of the channel and the two curved portions defining the bottom edge of the floating litter layer and the top edge of the sunken litter layer. The two vertical straight line segments at walls of the channel have lengths limited by the thicknesses of litter layers near the wall, given by; $D(t) - f(0, y, t) - g(0, y, t)$ and $D(t) - f(b, y, t) - g(b, y, t)$.

Here, the floating litter layer acts as a specific boundary at the top of water flow as shown in figure 3.12. The curved segments defined by the litter layer distributions g and f, have lengths

$\int_0^b \sqrt{1 + \left(\frac{\partial g}{\partial x}\right)^2}\, dx$ and $\int_0^b \sqrt{1 + \left(\frac{\partial f}{\partial x}\right)^2}\, dx$ respectively. Adding all these together, the total wetted perimeter can be defined as;

$$P(y, t) = 2D(t) - g(0, y, t) - g(b, y, t) - f(0, y, t) - f(b, y, t) + \int_0^b \left(\sqrt{1 + \left(\frac{\partial g}{\partial x}\right)^2} + \sqrt{1 + \left(\frac{\partial f}{\partial x}\right)^2}\right) dx \tag{3.6}$$

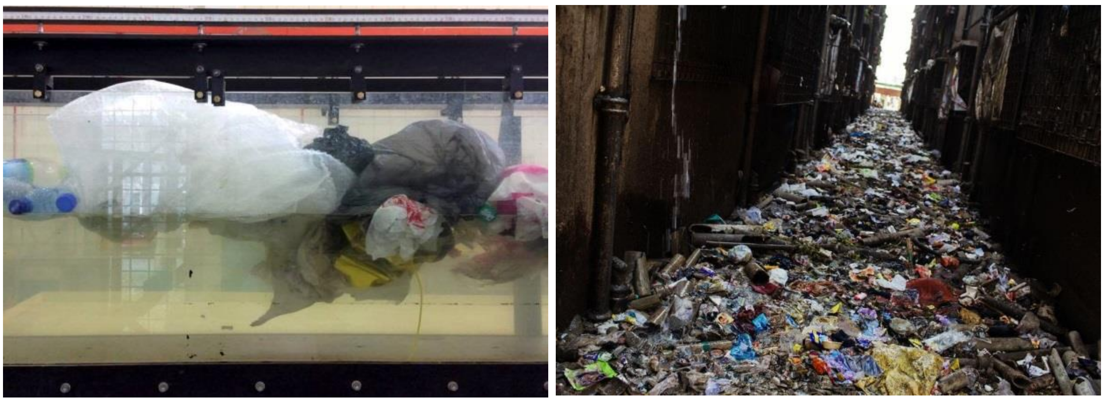


Figure 3.12: Floating litter layer

b) Hydraulic radius (R)

Hydraulic radius is defined as the area the water flows in the cross-sectional view divided by the length of the wetted perimeter. This area is the area bounded by the two vertical walls on either side and by the lower edge of the floating litter layer and the upper edge of the sunken litter layer from top and bottom. It can be expressed as the integration of the vertical distance between the two layers across the width of the channel given by;

$$A(y,t) = \int_0^b D(t) - g(x,y,t) - f(x,y,t)\,dx$$

(3.7)

Combining the expressions (3.6) and (3.7), hydraulic radius at distance y at time t

R (y,t) will be:

$$R(y,t) = \frac{\int_0^b D(t)-g(x,y,t)-f(x,y,t)dx}{2D(t)-g(0,y,t)-g(b,y,t)-f(0,y,t)-f(b,y,t)+\int_0^b\left(\sqrt{1+\left(\frac{\partial g}{\partial x}\right)^2}+\sqrt{1+\left(\frac{\partial f}{\partial x}\right)^2}\right)dx}$$

(3.8)

c) Flow velocity (vf)

Jarrett [154] defines the flow velocity of a channel in terms of friction slope and the hydraulic radius.

$$v_f = 3.14\,(sf)^{0.12}\big(R(y,t)\big)^{0.83}$$

(3.9)

Where *sf* is the friction slope of the channel and R (y,t) is the hydraulic radius.

Substitution of the expression (3.9) derived for hydraulic radius for this model results in;

$$v_f = \frac{3.14\,(sf)^{0.12}\big(A(y,t)\big)^{0.83}}{\big(P(y,t)\big)^{0.83}}$$

(3.10)

3.6.2 Modelling with the Principle of Conservation of Mass

Applying the principle of the conservation of mass, it can be stated that;

Rate water volume increases in channel = Rate water is supplied – Rate water is taken away [41, 168]

Symbolically,

$$\frac{dV(t)}{dt} = Q_{in} - A(y,t)v_{f.} \tag{3.11}$$

Where, Q_{in} is the rate water is supplied to the channel, A(y,t) the cross sectional area and vf the flow velocity.

V(t), the volume of water in the channel at time t could be expressed as the integral of area A(y,t) along the length l of the channel.

$$V(t) = \int_0^l A(y,t)dy \tag{3.12}$$

By substituting expressions 3.12 and 3.6 in 3.11, the conservation law can be restated as,

$$\frac{d}{dt}\left(\int_0^l A(y,t)dy\right) = Q_{in} - \int_0^b D(t) - g(x,y,t) - f(x,y,t)\,dx.\,v_{f.} \tag{3.13}$$

Expanding A(y,t) and vf using previously derived expressions 3.6, 3.7 and 3.10 has ended up with the relationship;

$$\frac{d}{dt}\left(\int_0^l \int_0^b D(t) - g(x,y,t) - f(x,y,t)\,dxdy\right) = Q_{in} - \frac{3.14\,(sf)^{0.12}\left(\int_0^b D(t)-g(x,y,t)-f(x,y,t)dx\right)^{1.83}}{\left(2D(t)-g(0,y,t)-g(b,y,t)-f(0,y,t)-f(b,y,t)+\int_0^b\left(\sqrt{1+\left(\frac{\partial g}{\partial x}\right)^2}+\sqrt{1+\left(\frac{\partial f}{\partial x}\right)^2}\right)dx\right)^{0.83}} \tag{3.14}$$

While seemingly complex equation 3.14 provides a relationship between water level in the channel D(t), at time t, and litter levels expressed by the time sensitive functions g and f denoting floating and sunken litter contents. Simplified expressions can be generated for specific situations, by incorporating restrictions on channel design and the behaviour of litter distributions, starting from this general relationship.

3.6.3 Development of "Mahasinghe-Chandrasena Mathematical Model" for Clogged Open Drains

This study proposed a new mathematical model to approximate the rate of spillover of a clogged drain owing to the effects generated by sunken and floating litter. Hereafter referred to as "Mahasinghe-Chandrasena Mathematical Model" for Clogged Open Drains.

Master equation of 3.14 has been derived from the principle of conservation of mass. Assuming the mass of flow entering the control volume minus the mass of flow leaving the control volume equals the change of mass within the control volume [169]. When applied to the prototype drain created in the laboratory, the difference between the volumetric flow rate entering the channel (Q_{in}) and the volumetric flow rate draining from the channel outfall (Q_{dr}) equals the volumetric flow rate stagnating in the channel (Q_{stg}). However, the Q_{in} remained constant throughout our experiments. Therefore, Q_{stg} totally depended on Q_{dr}. However, Q_{dr} was directly influenced by the "litter factor" of the drain.

In other words, the channel outfall (Q_{dr}), should be equal to Q_{out} minus the "litter effect" where Q_{out} is the outflow if there was no litter in the drain. The schematic diagram of this situation is depicted in Figure 3.13.

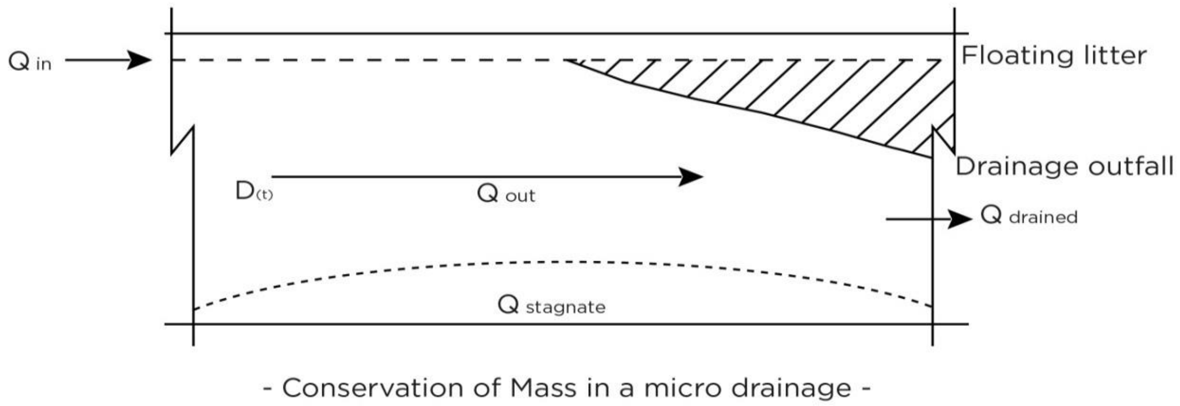


Figure 3.13: Mass balance in drainage

Where, Q_{out} is computed as = Average velocity of flow* Flow height at time t*Width of the drain

The below-mentioned equation has derived from the law of conservation of mass.

$$Q_{stg} = Q_{in} - Q_{dr} \quad (3.15)$$

But,

$$Q_{dr} = Q_{out} - Litter\ factor \quad (3.16)$$

Then,

$$Q_{stg} = Q_{in} - (Q_{out} - Litter\ factor) \quad (3.17)$$

Assuming stability of the litter distribution (time-invariant) and averaging along x and y directions we will substitute average litter gradients for ∂g/∂x & ∂f/∂x, and average heights for g & f.

Combining these simplifications and using equation 3.14 to estimate the litter factor, we can derive the following relationship for the ordinary drainage, which greatly simplifies the application of these relationships to the prototype drain that was evaluated in the laboratory (see Figure 3.14).

$$bl\frac{D(t)}{dt} = Q_{in} - \left[Q_{out} - k\ \underbrace{\frac{(bD(t)-c)^{1.83}}{\left(2D(t)-\left(d+\int_0^b\left(\sqrt{1+(flg)^2}+\sqrt{1+(slg)^2}\right)b\right)\right)^{0.83}}}\right] \quad (3.18)$$

Litter effect

Where $k = 3.14\ (sf)^{0.12}$

Here it has been assumed that the volumetric rate of stagnation of drainage water (bl (dD(t))/dt) to be a collective function of the rate of receiving of drainage water (Q_{in}), volumentric rate of draining out of drainage water (Q_{out}) and the "litter effect" of the drainage.

Q_{in} is the rate of received of drainage water.

Q_{out} is the rate of draining out of drainage water

Q_{out} = Average flow velocity (Vf)* Unit area of flow (A)

Unit area of flow (A) = Channel width (b)* Initial height of the water flow (D_i)

c and d are constants and flg & slg stand for average floating & sunken litter gradients (see Figure 3.11 and 3.15).

If litter is distributed constantly throughout the drain,

Sunken litter average height = h_1

Floating litter average height = h_2

width of channel = b

$c=(h_1+h_2)*b$;

$d=2h_1 + 2h_2$

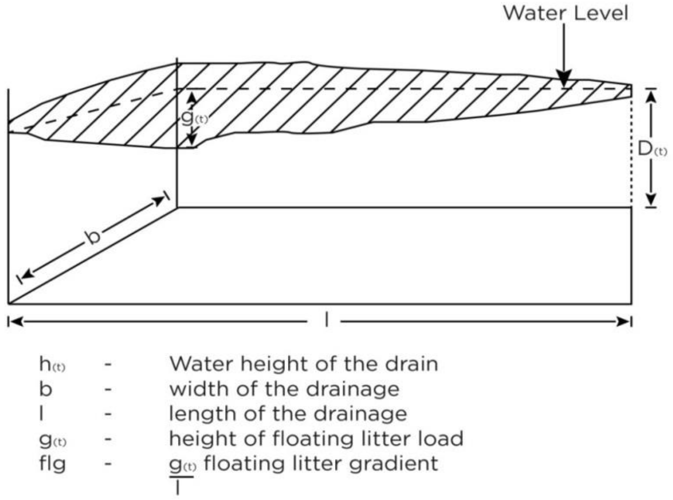


Figure 3.14: Drainage replication pertaining to equation 3.18

The key concept in the new design is to change flg & slg gradients into maximum efficient levels or the zero gradient stances. The design efficiency of the improved drainage is explained by the changes made in litter gradients.

3.6.3.1 Computation of the Time to Overflow of the Drainage

Left-hand side of the equation 3.18 represents the "Volumetric Rate of Stagnation" $bl\frac{D(t)}{dt}$. Since the "b" and "l" are known constants which represent channel width and length respectively, $\frac{D(t)}{dt}$ is considered the water infill height of the drain per unit time. Therefore, equation 3.18 has to be solved for D (t). Full height of the drain (D) divided by the value of D (t) to obtain the Time to overflow of the drainage in seconds as shown in equation 3.19.

$$Time\ to\ Overflow = \frac{\text{total height of the drain (D)}}{\text{infill water height of the drain per unit time D(t).}} \qquad (3.19)$$

3.7 Development of Solid Waste Clog Resistant Open Drain

This section described the design development and prototype testing of solid waste clog resistant open drain.

3.7.1 The Design Hypothesis

Clogged drainage channels cause travel time delays and increase the rate of stagnation of storm water. This can be corrected through an Engineering design solution that traps waste materials, provides a clear channel for storm water conveyance, and improves the hydraulic characteristics of the drain.

3.7.1.1 Effect of Litter Gradient in the Drainage Channel

The sunken (slg) and floating (flg) litter gradient of the drainage as shown in figure 3.14, has been approximated by using the following formula.

$$Litter\ gradient = \frac{Average\ height\ of\ the\ litter\ cluster}{Average\ length\ of\ the\ litter\ base} \tag{3.20}$$

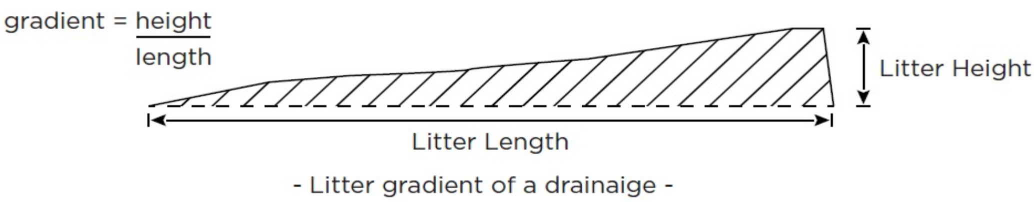


Figure 3.15: Calculate the litter gradient of a drainage

3.8 Experimental Study on Hydraulic Characteristics and Performance of the Clog Resistant Open Drain

This section presents the methodical description pertaining to the stage two of the Laboratory experimentation procedure. The laboratory Flume was partitioned with the prototype unit of Clog Resistant Open Drain as shown in figure 3.4. Hence, the channel was operated as a dual layer system which consists of a waste free bottom layer and the perforated top layer. A range of Laboratory experiments conducted to examine the hydraulic performance of the Clog Resistant Open Drain pertaining to undermentioned conditions;

(i) The control case, where the “Clog Resistant Open Drain” unit inserted into the Laboratory Flume, without adding litter particles.

(ii) The clogged drainage condition, where the “Clog Resistant Open Drain” unit inserted into the Laboratory Flume, with adding known amounts of litter particles.

Clog Resistant Open Drain was fixed to the Laboratory flume as sketched in Figure 3.16. The total length of the “Clog Resistant Open Drain” partition was 6 m. It was positioned between 2.5th and 8.5th spots of the 10m long Laboratory flume. Flow velocity measurements were obtained at 8 points along the flume, including before and after the insisted Smart Storm Drainage Unit. The total of 576 flow velocity (v) and flow height (D) readings were obtained for five different water inflow rates (Q_{in}) as shown in Table 3.5.

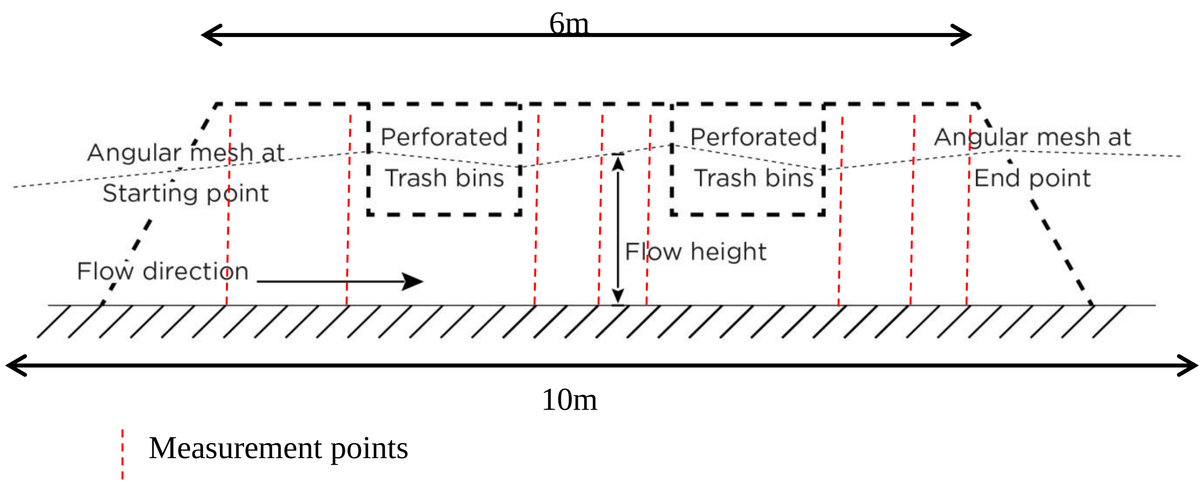


Figure 3.16: Laboratory replication of the Smart Storm Drainage

Laboratory replicated Clog Resistant Storm Drain Unit was tested according to the experimental protocol mentioned in table 3.5.

Table 3.4: Summary of the Experimental Conditions – stage 02

Flow rates: Q	0.013m^3/s	0.017m^3/s	=0.020m^3/	0.023m^3/s	0.027m^3/s
Drainage gradients: S^0	1/150,1/200, 1/300, 1/500				

To create clogged channel condition, 1-6 kg of solid matter was put into the Clog Resistant Open Drain, which consists of 1kg of plastic waste, 1kg of clothing materials, 1 kg dried leaves, 1kg of glass material, 1kg of paper waste and 1 kg of mixed organic waste.

3.8.1 Forces on the Clog Resistant Storm Drain Unit

The Clog Resistant Storm Drain Unit was designed to improve the conveyance of clogged open drains without increasing the existing drainage capacity. The conveyance of open drainage channel is given as [170];

$$K = \frac{1}{n} A R^{\frac{2}{3}} \tag{3.21}$$

Where, n is the Manning's roughness coefficient, A is the unit area of the flow and R is the hydraulic radius of the given drainage unit.

The Efficiency of a clogged drainage was improved by an engineering design solution as mentioned in the section 3.7.1, which allocates a clear channel at the bottom and allow rainwater readily infiltrate then flow with minimal disturbance. The ratio of the captured discharge by the improved drainage structure to the total discharge circulating in the area was considered the hydraulic efficiency (E) of the drainage element and it computed based on the following formula.

$$E = \frac{Q_c}{Q_r} \tag{3.22}$$

Where, Q_c is the discharge capacity of the drain and Q_r is the peak runoff at the point of the design. To obtain successful operational results, the capacity of the drain should be adequate to accommodate peak runoff rate at point of the design [70, 171]. Hence, the ratio between Q_c: Q_r should always be ≥ 1.

3.8.2 Comparative analysis of the Experimental Conditions Created in the Laboratory Flume

Data gathered during above-mentioned test conditions were used to calculate four parameters that would characterise the hydraulic performance of the Clog Resistant Open Drain.

1. Flow velocity analysis of Clog Resistant Open Drain – Velocity change along the drain

   Flow velocities along the drain, pertaining to three drainage conditions mentioned above were compared. These velocity readings were also used to calculate the Manning's roughness value based on the below-mentioned formula:

   $$n = \frac{1}{v} R^{2/3} S^{1/2} \qquad (3.23)$$

   Where n is the Manning's roughness value pertain to each test condition, v is the average velocity measured, R is the hydraulic radius obtained from the channel area divided by the wetted perimeter and S is the channel slope.

2. Flow velocity analysis of Clog Resistant Open Drain - Percentage variance of velocity

   Percentage change of velocity values between the starting point of the drainage unit and the endpoint of the drainage unit were calculated as follows:

   $$\Delta v = \frac{(v_a - v_b)}{v_a} \qquad (3.24)$$

   Where, v_a is the starting point velocity and v_b is the endpoint velocity.

3. Froude number and Specific Energy

   The Froude number value of the flow was approximated by the equation:

   $$Fr = \frac{v}{\sqrt{D\ g}} \qquad (3.25)$$

   Where, v is the average velocity, D is the depth of the flow of the channel and g is the gravitational constant.

   The Specific Energy pertains to each measurement point was calculated as:

$$E = \frac{Q^2}{2gA^2} + d \quad (3.25)$$

Where, Q is the flow rate, A is the Unit area of flow and d is the flow depth.

4. Conveyance Efficiency of the Clog Resistant Open Drain

The conveyance efficiency of the drainage was computed by:

$$ŋ = \frac{(V_r - V_S)}{V_r} \quad (3.26)$$

Where, V_(r)is the total volume received within a given time period by the drain and V_(s) is the volume stagnated during that time. Volume stagnated was defined as the total water volume present in the flume at the time of spillover. For the experimental setup, the total water volume present in the flume at the time of spill-over is equal to the total capacity of the flume. Hence, (V_(r)-V_(s)) demonstrates the total "volume drained" by the drainage.

3.9 Summary of the Research Methodology

The research methodology employed in this study consisted of five stages. In stage one; demand for storm water drainage of the case study area was computed and a simulation of the EPA SWMM version 5.0 model was carried out. The stage two estimated the effective drainage capacity and experimentally studied the uneven litter distribution along the drainage channel. Moreover, it studied the behaviour of the clogged drain during a rainfall event and numerically analysed experimental results. During the initial screening of the real-time system, a quantitative analysis of the clogging effect of open drain in case study area was carried out. Then, the observed ground situation was recreated inside the Laboratory using the modular flow channel. The behaviour of the clogged open drain was tested against five different flow rates and three drainage gradients. The final outcome of the combination of both stages was, the development of a new set of equations by incorporating litter effect in traditional engineering equations being used to describe the open-drain operation. These equations can be used for future research studies to calculate the magnitude of clogging effect on the stormwater conveyance.

Design development of the Clog Resistant Open Drain Unit and hydraulically testing its efficiency was carried out in stage three by considering the operational constraints discovered and numerical explanations developed in previous stages. Design development stage has identified the impact of floating and sunken litter particles for the variation of the hydraulic radius of the open drain. Increasing of the hydraulic radius of the drainage is considered as a crucial factor leading to a decrease in its hydraulic efficiency and increasing the risk of a spill over. Stage four experimentally studied the hydraulic characteristics and performance of the newly invented smart storm drainage unit. Stage five comparatively analysed the influence of existing and improved drainage conditions on the storm water conveyance process of case study area, using EPA SWMM 5.0 computer simulation platform.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

A range of laboratory experiments was conducted to provide the experimental justification of newly developed equation and examine the hydraulic performance of Clog Resistant Open Drain Unit. The focus, therefore, was on discovering the “litter effect” in conventional drainage and observing the reactions of water flow to the improved drainage. A total of 128 test runs were conducted in three basic drainage conditions: a normal Flume condition, a normal drainage with a conventional trash trap condition, in which downstream outfall was covered by a mesh to prevent entering solid waste particles and an improved condition, in which dual layer drainage unit inserted into the normal Flume to trap solid waste, facilitated uninterrupted storm water conveyance.

4.2 Demand for Storm Water Drainage of the Case Study Area

This section describes the results of initial numerical analysis pertaining to the case study area of this research which methodically explained in section 3.4 of Chapter Three.

4.2.1 Weighted Average Runoff Coefficient (C) of the Case Study Area

The results showed in table 4.1 expresses the weighted runoff coefficient value of the study area. As per the map depicted in figure 1.1, the weighted average runoff coefficient (C) has been calculated for 03 sub catchments with a total land area of 4.05 ha.

Table 4.1: Weighted Runoff Coefficient

Rational method Runoff coefficient calculation			
Land use	Area (ha)	runoff coefficient value C [67]	weighted C
Paved area	0.05	0.90	0.045
multiunit-attached	4.00	0.75	3.000
Total area	4.05		3.045
Weighted Runoff coefficient			0.751

The runoff coefficient values larger than 0.7 is generally imply the highly urbanised and industrialised areas that produce higher runoff volumes. The results depicted in Table 4.1 indicate the higher surface runoff generation ability of the area. Hence, a need arises for timely removal of storm water runoff during precipitation events. Therefore, uninterrupted continues storm drain conveyance is needed to achieve this purpose.

4.2.2 Peak Runoff (Q_r) of the Case Study Area

Table 4.2: Peak Runoff produced by different Rainfall Intensities in the study area

Rainfall intensity (mm/hr)	Q_r (m^3/s) Q_r =1/360 CiA	Rainfall intensity i (mm/hr)	Q_r (m^3/s) Q_r =1/360 CiA
20	0.07	10	0.03
19	0.07	9	0.03
18	0.06	8	0.03
17	0.06	7	0.02
16	0.06	6	0.02
15	0.05	5	0.02
14	0.05	**4**	**0.01**
13	0.04	**3**	**0.01**
12	0.04	**2**	**0.01**
11	0.04	**1**	**0.00**

Table 4.2 depicts the results of peak runoff produced by different rainfall intensities pertaining to the sub catchment 01 located in case study area. The total catchment area was 1.6539 ha. A 20 mm/hr rainfall will produce 0.07 m^3/s of peak runoff.

4.2.3 Total Litter Load in Drainage Channels

According to the total litter load computation mentioned in section 3.4.3, the open drainage system located in the case study area is clogged with litter and sediment for about 30% of its capacity throughout the year (see Table 4.3).

Table 4.3: Total litter load in a drain

Total litter load in the drain	5(0.2+0.5)1.6539 m^3 =5.79 m^3
Total drainage capacity	151.52m X 0.45m X 0.3m =20.45 m^3
% clogged	27%-30%

4.2.4 Effective Drainage Discharge Rates Q_c of the Case Study Area

Table 4.4: Effective drainage discharge rates Q_c of three different cases (channel gradient = 1/200)

	Description	Channel cross section area A m^2	Wetted perimeter P (m)	Hydraulic radius R (m)	Manning's n	Drainage capacity Q_c (m^3/s)
Case 01	Flume only (control case/perfect condition)	0.135	1.2	0.1125	0.014	0.16
Case 02	Flume with mesh, no waste	0.135	1.2	0.1125	0.016	0.14
Case 03	Flume with mesh, with 30% waste	0.095	0.93	0.1016	0.144	0.01

According to the results obtained in Table 4.3, the remaining capacity of drainage is computed as 70% of the total drainage capacity. Effective drainage discharge rates (Q_c) pertaining to the each case experimented is figured in table 4.4. If the drainage channel is clogged about 30% of its total capacity, its discharge rate decreased into a very low level (0.01m^3/s) due to the reduction of the effective capacity of drainage and the increase in resistance to the flow (Manning's n). As mentioned in case 01, this drain is designed to convey a peak flow rate sixteen times greater than the peak flow rate of existing drainage scenario. However, this cannot be achieved in a practical state since the unavoidable sedimentation and the clogging effects.

Table 4.2 presents the changes of the peak runoff rates with the average rainfall intensity values recorded throughout the year. For timely and proper conveyance of storm water, the capacity of the drain should be adequate to accommodate peak runoff. Hence, the estimated values for the discharge capacity of the drain should be equal or larger than the peak runoff. However, the numerical approximations obtained from equation 3.3 have confirmed the drainage channels situated in the case study area carried litter about 30% of its total capacity throughout the year. Hence, the estimated value for the drainage discharge capacity pertaining to the existing conditions of the case study area is reduced to 0.01 m^3/s. Therefore, it is clear that the open drains situated in the case study area cannot handle the runoff generated by rainfall intensities greater than 5 mm/hr since it exceeds the present carrying capacity of the drain.

Due to this situation, open drains tend to overflow easily even after a mild precipitation event which brings 5mm/hr rain. If the case study area receives a rainfall greater than this intensity (5mm/hr), it may result in an intense flash flood caused by drain spill overs.

4.3 Laboratory Experimental Results of Stage 01

Table 4.5: Changes in hydraulic features of the drainage channel with the amount of litter added (channel gradient =1/200, water inflow rate = 0.023 m^3/s)

Flow Depth D (m)	Unit area of flow A (m^2)	Wetted Perimeter P (m)	Hydraulic Radius R (m)	Manning's coefficient (n)	velocity (m/s)	% of litter
0.133	0.0399	0.566	0.070	0.016	0.73	0
0.161	0.0483	0.622	0.078	0.021	0.61	7%
0.199	0.0597	0.698	0.086	0.030	0.46	15%
0.244	0.0732	0.788	0.093	0.144	0.10	24%
Prototype channel demonstrated overflow						25%

The representative results in Table 4.5 used to approximate the "Rate of stagnation of water" and "Time to overflow" of the clogged drain using "Mahasinghe-Chandrasena mathematical formulae" described in equation 3.18 and 3.19 respectively. The estimated values for time to overflow of clogged drainage are shown in Table 4.6.

4.3.1 Estimated Values for Time to Overflow of Clogged Drainage

Table 4.6: Time to overflow of clogged drainage (channel gradient = 1/200, water inflow rate = 0.023 m^3/s)

Litter amount As a % of drainage capacity	Rate of stagnation of water (m^3/s)	Time to overflow (s)
05%	-0.187	NO OVERFLOW
10%	-0.008	
20%	-0.006	
25%	0.001	1585.00
30%	0.006	148.59
35%	0.062	15.26
40%	0.092	10.33
45%	0.122	7.81

Litter amount As a % of drainage capacity	Rate of stagnation of water (m^3/s)	Time to overflow (s)
50%	0.151	6.28
55%	0.181	5.25
60%	0.211	4.51
65%	0.241	3.95
70%	0.270	3.52
75%	0.300	3.17
80%	0.330	2.88
85%	0.359	2.65
90%	0.389	2.44
95%	0.419	2.27
	Equilibrium break	

Table 4.6 showed the numerically computed results obtained for the equation 3.19 which determined the rate of stagnation of water in a clogged drainage channel. The representative results showed that the prototype drainage created for this experiment has been able to manage its equilibrium until 20% of litter presence in the channel. Then, the drain attained an unstable equilibrium level as it started stagnation of water (see figure 4.1). This has occurred when the amount of litter in the drainage was higher than 20% but less than 24%. Finally, it has confirmed that the prototype drain was actually been capable of handling less than 24% of litter capacity. If the amount of litter exceeds that point, the litter equilibrium broke and stagnation started.

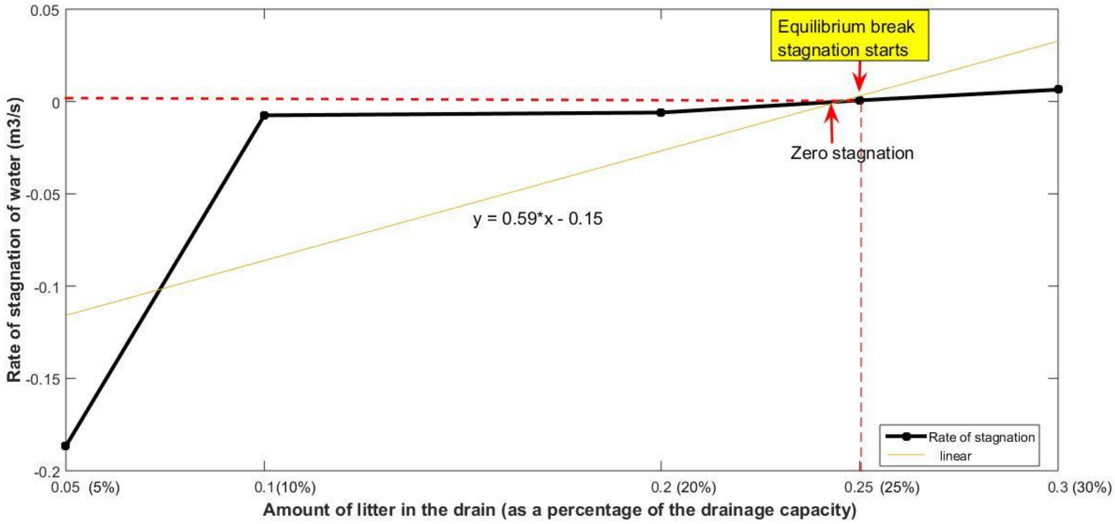


Figure 4.1: Litter equilibrium of the prototype drainage

Before attaining the "litter equilibrium break point" or the "litter threshold of the drain" the flow was "steady non-uniform". It flows constantly through the duct of non-uniform cross-sections and does not change with respect to time. Inflow rate < outflow rate since the outfall is clear as shown in figure 4.2. The flow not accumulates in the duct, hence no stagnation happens.

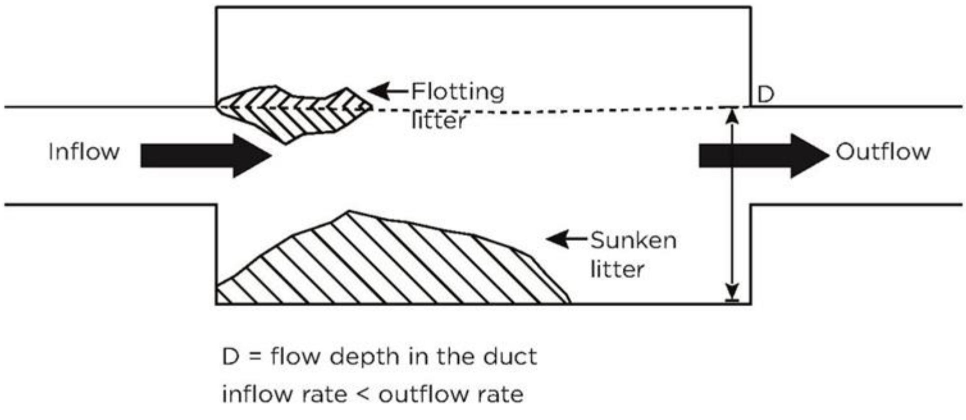


Figure 4.2: Steady-Non uniform state

After breaking litter equilibrium point, the flow becomes "unsteady non-uniform". Flow at a varying rate through a duct of non-uniform cross-sections. Flow depth (D) and velocity (v) change with time. Inflow rate > outflow rate since the outfall blocked with litter as shown in figure 4.3. The flow starts accumulating in the duct and tends to spill over at the end.

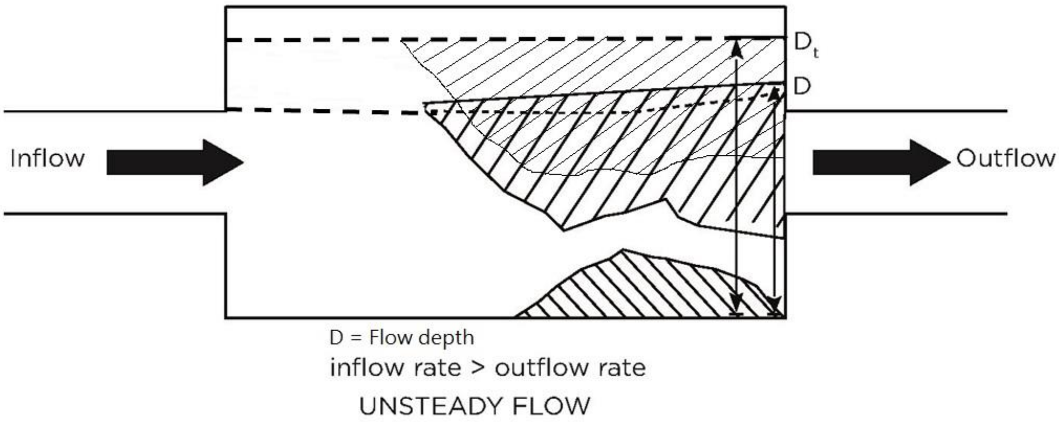


Figure 4.3: Unsteady Non-uniform state

4.3.2 Validation of Experimental and Numerical Findings in Stage 01

As explained in subsection 3.4.1, a conventional drainage has been prototyped in the laboratory modular channel, and fed with different amount of litter and observed for time to overflow. Overflow timing was also computed by using new mathematical model represented by equation 3.19 that explained in chapter three. The obtained results from the experimental and numerical methods have been validated through the linear regression analysis and coefficient of determination R^2 values expressed in Table 4.7.

A high correlation of more than 0.89 was obtained for four different scenarios compared under this section. It is confirmed that the capability of the new mathematical model (represented in equation 3.19) in determining the rate of stagnation of water in a clogged drainage channel.

Table 4.7: Regression Analysis in Predicting the Time to overflow for a Clogged Drainage

Input Flow Rate m^3/s	Observed overflow time (s)	Predicted overflow time (s)	Coefficient of Determination (R^2)
0.023	64	95	0.8967
0.020	71	103	
0.017	109	134	
0.013	145	255	
Slope = 1/200			

4.4 Clog Resistant Open Drain Unit

This section describes the design and novelty features of the newly invented Clog Resistant Open Drain Unit.

4.4.1 Detailed Design Description

Use of a suitable litter filtering screen over the opening of the drain was the first approach considered. This would prevent litter from entering the drain and also from accumulating within the flow path which would lead to eventual clogging of the drain.

The final improved design consists of two stacked channels separated by suitably perforated middle layer into which perforated steel containers are incorporated at suitable intervals. Removable perforated steel containers equipped with wireless sensor technology. Wireless sensors measure and forecast the fill level of the waste container. Once the perforated container is full, it will automatically generate text messages to responsible parties like Municipal garbage collectors. Moreover, it alerts the neighbouring community via social media updates. Collected solid waste is easily removed by lifting the perforated container out of the pit.

This middle layer collects and prevents solids from entering the bottom channel. The bottom channel, therefore, is always maintained free of any solids or debris, thereby maintaining an adequate capacity to carry runoff during an excessive rainfall event, preventing unnecessary spillovers. The drain could be made of concrete, the usual material of construction for drains. The perforated middle layer could be made of anti-corrosive materials like stainless-steel wire mesh with a range of 0.5mm to 5mm sieve size which depends on the distribution of the size of the solids in the area. The collection and removal of accumulated solid waste is accomplished via removable perforated steel containers that are to be placed at suitable intervals along the length of the drain. The height of the container extends ¾ of the height of the bottom channel, thereby creating an open channel along the bottom of the drain.

Much of the waste will be collected on the floor of the top layer of the channel, but Municipal Garbage Collectors or members of the surrounding community can easily use a rake or a broom to sweep this waste and debris from the top layer of the storm drain to the waste container. During heavy rain, increased water flow in the top channel will automatically move the accumulated waste and debris into the collection container.

Collected solid waste and debris is easily removed by lifting the perforated container out of the pit and emptying into a suitable secondary container to be transported to a disposal site. The detailed design of the Clog Resistant Open Drain is depicted in figure 4.4, 4.5 and 4.6 respectively.

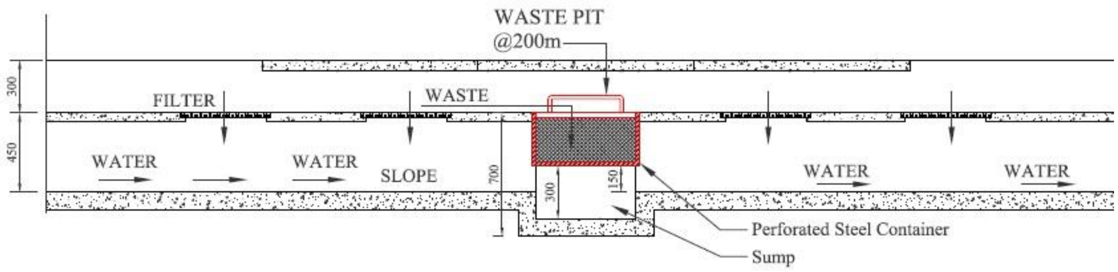


Figure 4.4: Partial section along the Drain

Figure 4.5: Top Plan of Clog Resistant Open Drain

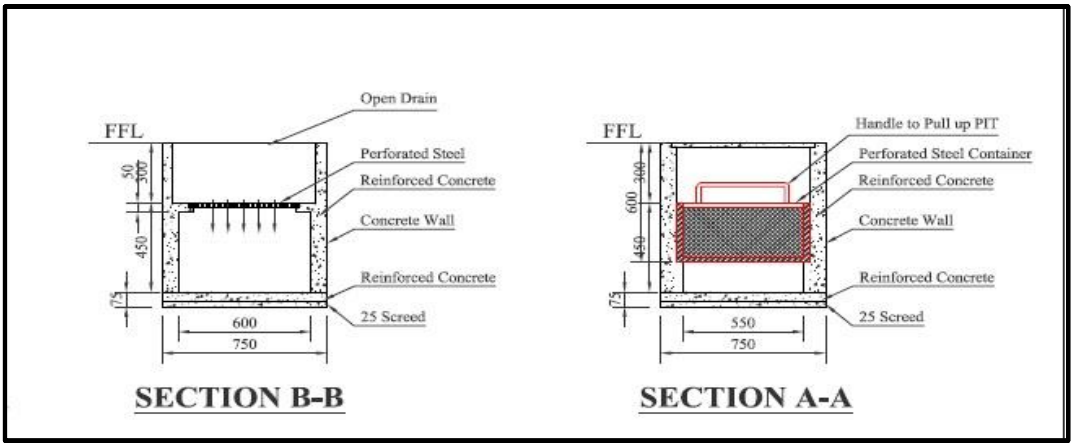


Figure 4.6: Cross section along the Drain

4.4.2 Novelty of the Design

Almost all of litter capturing mechanisms that have been tested or implemented in the past have depended on capturing and storing of litter at specific points of the drain [166]. The main result of this would be retaining of litter items that can clog the drain much more hastily compared to individual pieces of litter. The design proposed from this study implements a distributed collection mechanism that would prevent a large volume of solid waste agglomerating together and becoming a source of clogging itself. Distributed collection that would create low volumes of litter accumulating at a given point will simplify the collection and removal efforts too. In fact, collection and removal functions in the proposed drain could be easily passed on to inhabitants of the area if desired. At the same time, it allows a waste collection removal process that could be easily tied to an electronic monitoring system capable of sending timely alarms to Municipal workers, speeding up the entire waste collection process.

In conventional clogged drains, litter distribution positions change with respect to time. This may cause crucial point clogging as mentioned shown in Figure 4.7.

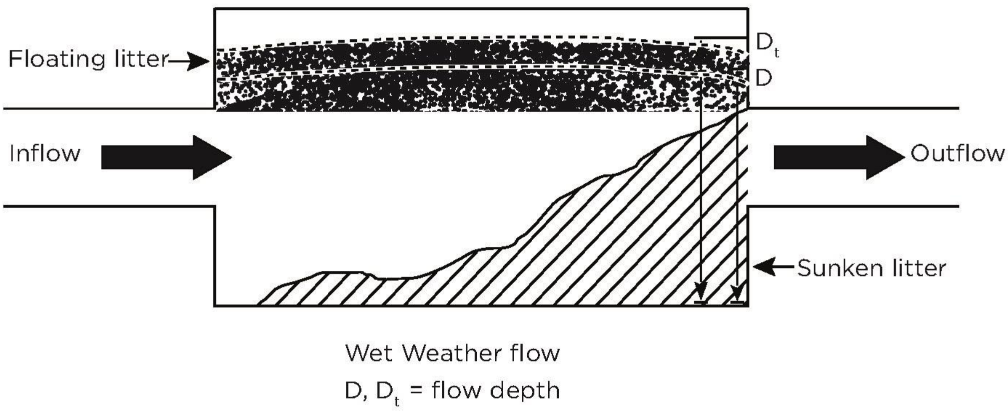


Figure 4.7: Conventional clogged drain

In clog-resistant open drains, litter distributed within the demarcated perforated boundary and it never tends crucial point clogging. Water readily infiltrates to the bottom layer and flow with little or no disturbance as shown in Figure 4.8.

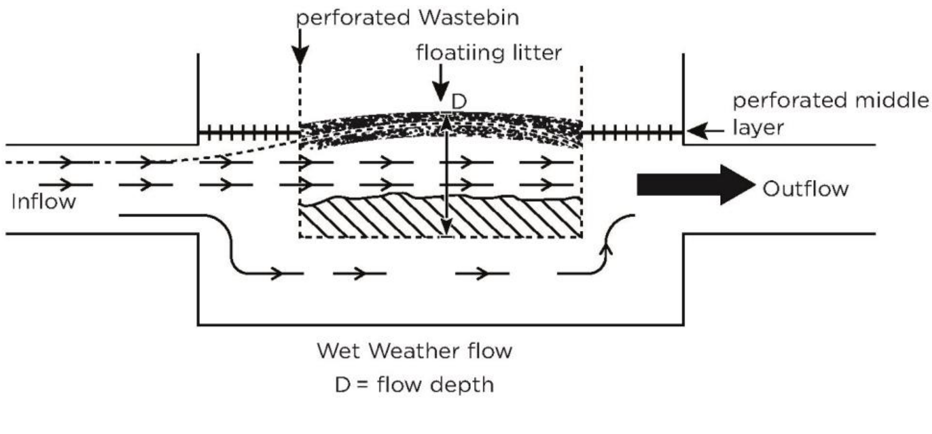


Figure 4.8: Clog-resistant open drain

4.4.3 Preventing System Breakdown by Preserving the Litter Equilibrium of a Drainage

The Clog Resistant Open Drain has been invented to secure the runoff conveyance process of a clogged drain while preserving "litter equilibrium". Numerically computed results obtained for the equation 3.19 pertaining to the prototype Clog Resistant Open Drain is shown in table 4.8.

The following conditions have been imposed on the master equation to obtain practical numerical solutions.

4.4.3.1 Assumptions

- No sunken litter presence since all litter particles trapped in the upper channel of the drainage.
- The maximum height of floating litter layer (h_2) is equal to the height of the upper channel of the drainage. This considered the extremely clogged situation since it represented 50% of the total drainage capacity.
- Sunken litter gradient (slg) and floating litter gradient (flg) is non-considerable because the improved design has rearranged litter gradients into the most effective positions.
- The average height of the drainage water flow (D_t) remains constant over the period.

4.5 The Influence of the Hydraulic Radius

There are two factors determine the hydraulic radius in a cross-section of a channel: the width and the depth of water flow. Since the channel width was a constant value throughout this experiment, hydraulic radius depended only on flow depth of the channel. As mentioned in literature, the hydraulic radius is directly proportionate to flow velocity. According to Baker and Freeze [171, 172], higher hydraulic radius generates more efficiency in the storm flow profiles. Alternatively, lower flow heights could reserve more space for emergency conveyance in an intense storm event. Therefore, a channel with higher hydraulic radius will have higher flow velocity. However, the results as shown in Table 4.8 have opposed the above relationship. It was observed that the prototype channel in case 03, with the higher hydraulic radius, was recorded the lower flow velocity. The flow depth and the hydraulic radius in this channel increased due to water stagnation caused by clogged litter. Hence, it is confirmed that the hydraulic radius in a channel implies its maximum efficiency only for an obstruction free flow. Therefore, a clogged drain with a higher hydraulic radius will not produce a higher flow velocity.

Table 4.8: Hydraulic Radius and flow velocity in different drainage scenarios (channel gradient= 1/200, water inflow rate=0.023m^3/s)

	Description	Flow Depth D (m)	Hydraulic Radius R (m)	Manning's n	Flow Velocity (m/s)
Case 01	Flume only (control case/perfect condition)	0.131	0.070	0.014	0.88
Case 02	Flume with mesh, no waste	0.133	0.070	0.016	0.73
Case 03	Flume with mesh, 7 kg litter	0.244	0.093	0.144	0.10
Case 04	Clog Resistant Open Drain, No litter	0.196	0.085	0.020	0.70
Case 05	Clog Resistant Open Drain, 7 kg litter	0.205	0.087	0.020	0.70

4.5.1 Satisfying the Design Hypothesis of Clog Resistant Open Drain

The different litter distribution positions have resulted in higher litter gradient values (flg and slg) hence finally increased the hydraulic radius (R) of the drainage channel, as numerically explained in equation 3.8 and 3.14 respectively.

Litter distribution pattern along the channel was the only possible parameter to be changed to reduce stagnation of water and obtain an efficient conveyance value as mentioned in the equation 3.14 and 3.18. Considering this, the improved design has re-positioned these original litter distributions to a separate layer in the channel (see Figure 4.5). As a result, the change in hydraulic radius (dR) in Clog Resistant Open Drain became independent from the amount of litter added to the channel. The hydraulic radius is a measure of channel flow efficiency [173, 174]. The lower flow depth (D) is more efficient in hydraulically since it is able to convey a higher volume of flow when it is necessary. Therefore, if clogged with a similar amount of litter and subjected to the same inflow rate, the Solid Waste Clog Resistant Open Drain with lower flow depths can operate more efficiently than conventional existing open drains with higher flow depths.

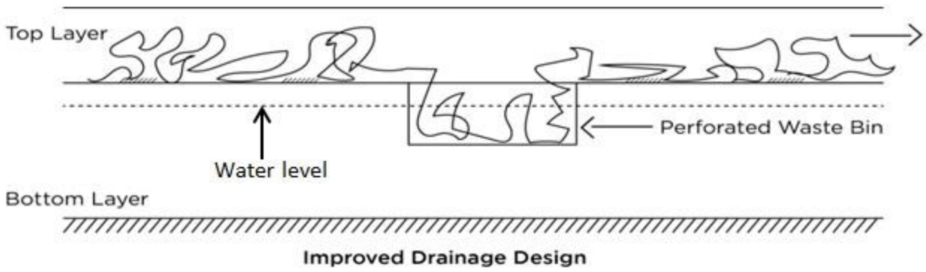


Figure 4.9: Litter distribution stance in the SolidWaste Clog Resistant Open Drainage

4.5.2 Estimated values for Time to Overflow of Clogged Drainage

The detailed results of the laboratory experiments in stage 02 as shown in figure 4.6 to 4.13 were used to approximate the "Rate of stagnation water" and "Time to overflow" of the clogged drain using new mathematical formulae described in equation 3.18 and 3.19 respectively.

The results obtained for "Time to overflow" of the clogged drain are shown in Table 4.9.

Table 4.9: Time to overflow of Clog Resistant Open Drain

Input rate of water (m^3/s)	Rate of stagnation (m^3/s)	Time to overflow (s)
0.023	-0.0190	NO OVERFLOW
0.020	-0.0175	
0.017	-0.0166	
0.013	-0.0146	

The Solid Waste Clog Resistant Open Drain never tends to overflow during the test runs conducted for both litter-free and clogged conditions. Moreover, the experimental results confirmed that there was a very minimal tendency of increasing the “flow depth” and “stagnated volume” during the whole operation process in the improved drain. These flow escalations caused due to unsteadiness of the inflow received through the flume, but that was non-considerable when it compared with the flow escalation measured during the operation of existing conventional clogged drain. Thus, the improved drainage condition has maintained a stable equilibrium by keeping the “litter effect” minimum and a higher output rate (rate of drained) than the input rate (rate of received) of water. It happens because of the channel outfall is free from clogging.

4.6 Hydraulic Characteristics and Performances of Different Drainage Scenarios

This section presents the laboratory experimental results pertaining to the hydraulic characteristics and performances of newly invented Clog Resistant Open Drain and comparatively analyses the findings with different drainage scenarios mentioned in the research methodology.

4.6.1 Hydraulic Conveyance (K) and Drainage Efficiency pertaining ($\eta_{hydraulic}$) to Different Drainage Scenarios

The representative results in Table 4.10 describe the hydraulic conveyance pertaining to five different drainage scenarios. These values were derived from the numerical calculation pertaining to the equation 3.21 of stormwater conveyance in open drains. Case 01 or the Flume only condition acted as the control case of this experiment. It maintains uniform flow and no clogging or backwater effect reported. It has maintained the highest conveyance value or the highest carrying capacity. The rest drainage conditions were compared as a percentage of the control case. Case 02 or the Flume with mesh is the perfect condition in the real world, but it is hard to achieve the represented conveyance value due to the regular sedimentation and litter clogging. Flume with mesh and waste is the worst condition. If the drainage channel gets clogged, its carrying capacity and conveyance decreased into very lower levels as represented in Case 03. However, the Clog Resistant Open Drain with the same amount of litter that represented in Case 05 was able to improve this situation seven times better than the worst scenario represented in Case 03.

Table 4.10: Hydraulic Conveyance pertaining to different drainage scenarios

	Description	Conveyance of the drainage K (m^3)	As a percentage of the perfect condition In case 01
Case 01	Flume only (control case/perfect condition)	2.23	
Case 02	Flume with mesh, no waste	1.95	87.50%
Case 03	Flume with mesh, with 30% waste	0.14	6.36%
Case 04	Smart Storm Drainage, no waste	1.56	70.00%
Case 05	Smart Storm Drainage, with 30% waste	1.02	45.77%

Results shown in Table 4.11 describe the hydraulic efficiency pertaining to five different scenarios of existing conventional drain and Clog Resistant Open Drain. These values derived from the numerical calculation pertaining to the equation 3.22 of the hydraulic efficiency of open drains. To obtain successful operational results, the capacity of the drain (Q_c) should adequate to accommodate peak runoff rate (Q_r) at the point of the design. Hence, the ratio between Q_c:Q_r should always be ≥ 1. It shows four drainage scenarios: Case 01, Case 02, Case 04 and Case 05 respectively are able to fully accommodate the peak runoff generated from the desired sub-catchment. The existing conventional clogged drain represented in Case 03 is unable to fully accommodate the peak runoff due to extremely low cross sectional capacity. However, the Clog Resistant Open Drain with same amount of waste is able to fully accommodate the peak runoff as shown in Case 05. Regular cleaning of the waste bins in Clog Resistant Open Drain can increase the hydraulic efficiency by allocating more cross-sectional capacity.

Table 4.11: Hydraulic Efficiency values pertaining to different drainage scenarios

	Description	Discharge capacity Q_c pertains to each case (m^3/s)	Peak runoff rate of the catchment Q_r pertains to each case (m^3/s)	$\eta_{hydraulic}$ Q_c:Q_r
Case 01	Flume only (control case/perfect condition)	0.16	Catchment area = 1.6539 ha Runoff coefficient = 0.75 *i* = 20 mm/hr **0.07 m^3/s**	2.15
Case 02	Flume with mesh, no waste	0.14		1.88
Case 03	Flume with mesh, with 30% waste	**0.01**		0.14
Case 04	Clog Resistant Open Drain, no waste	0.11		1.51
Case 05	Clog Resistant Open Drain, with 30% waste	0.07		0.99

4.6.2 Experimental Results of the Hydraulic Characteristics and Performance of the Solid Waste Clog Resistant Open Drain with 30% of Waste

This section presents and discusses the laboratory experimental results of newly invented Clog Resistant Open Drain pertaining to research methodology stated in subsection 3.8.2.

1. **Flow velocity analysis of Solid Waste Clog Resistant Open Drain with 30% of waste - Velocity change along the drain**

Average flow velocity fluctuation along the Clog Resistant Open Drain was tested and illustrated in Figures 4.10, 4.11, 4.12 and 4.13.

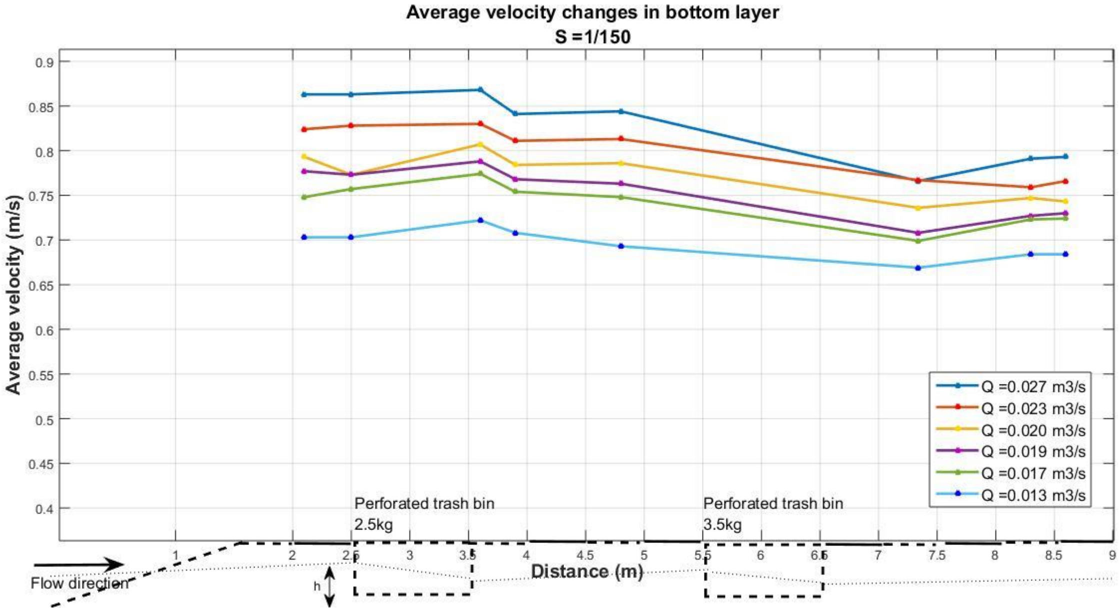


Figure 4.10: Velocity changes in Clog Resistant Open Drainage flow drainage gradient = 1/150

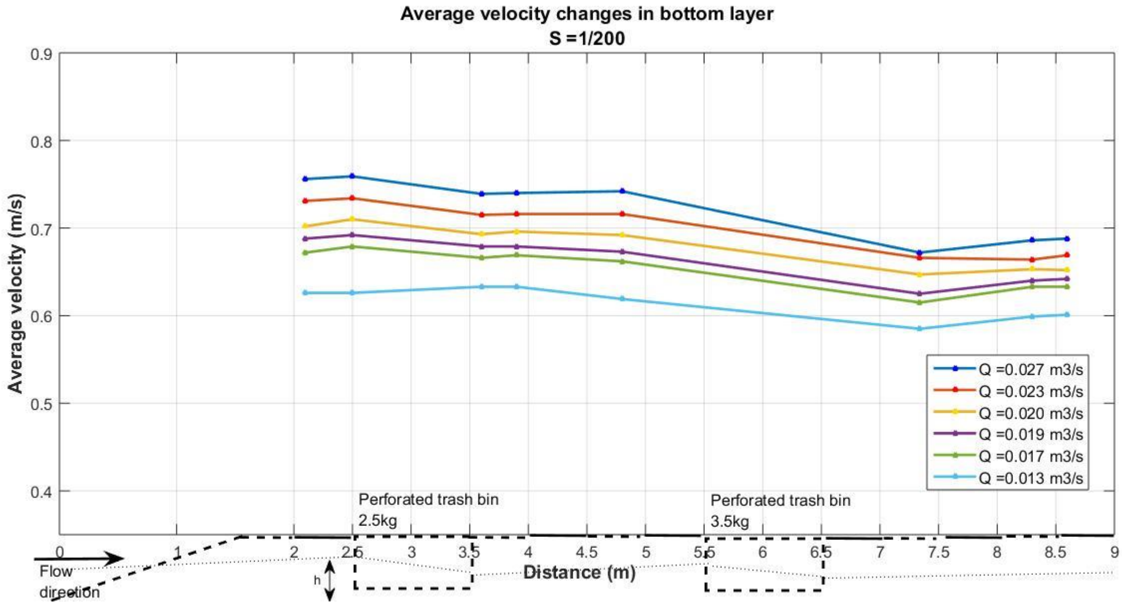


Figure 4.11: Velocity changes in Clog Resistant Open Drainage flow drainage gradient = 1/200

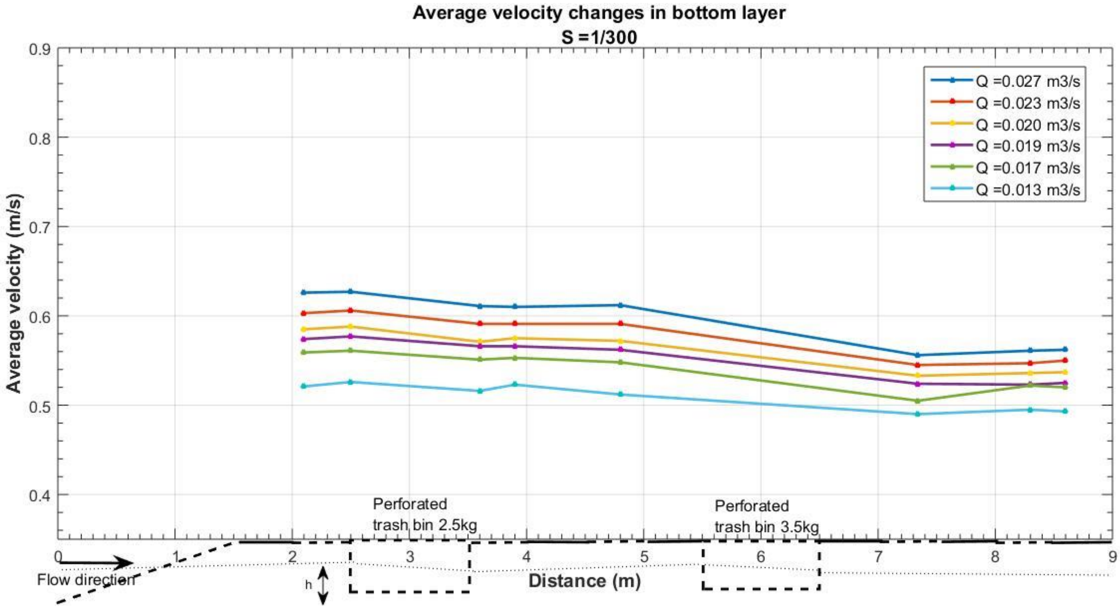


Figure 4.13: Velocity changes in Clog Resistant Open Drainage flow drainage gradient = 1/300

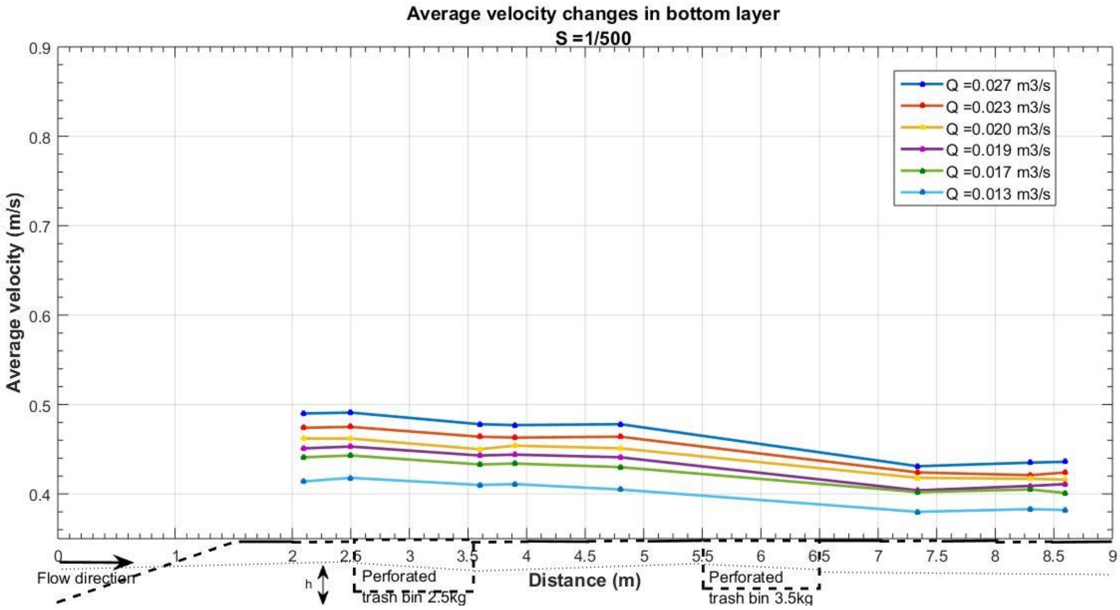


Figure 4.12: Velocity changes in Clog Resistant Open Drainage flow drainage gradient = 1/500

Flow velocity decreases and escalations are commonly seen throughout the drainage as the results depicted in all four figures. However, the flow velocity did not change with respect to time; hence the flow remained at steady state. The difference in flow velocity readings has caused by following reasons.

1. The uniform water flow, which was flowing from the upstream, was interrupted by the elements of the new drainage unit.

2. Perforated trash bins of Clog Resistant Open Drain when fully stacked with 30% of waste generated additional resistance against the flow.

When consider about the flow velocity changes represented in figure 4.6 to 4.9, it is clear that the flow velocity was improving after the fully stacked trash bins with 6 kg of waste. However, the flow velocity dropped again as the flow had met the second trash bin. Moreover, a velocity drops at 7.5^{th} meter spot onwards since the Flume outfall was vertically covered by a wired mesh. In comparison, the existing conventional clogged drain demonstrated spillover within minutes followed by a rapid stagnation of water due to diminishing flow velocity. This scenario has observed in experimental Stage 01 of this research. However, the Clog Resistant Open Drain Unit clogged with a similar amount of litter, did not demonstrate spillover during the whole experimental process. Channel flow was in "steady, non-uniform state" throughout the experiment. It is hence confirmed that the non-uniform state of flow velocity in Clog Resistant Open Drain not affected for its conveyance process.

These results show that the Clog Resistant Open Drain is able to maintain the average flow velocity at a considerable level throughout its length, the under tested operating conditions. As recommended by widely used drainage manuals, drainage channels should maintain a minimum velocity of 0.7 m/s to achieve optimal operational results [69, 89, 175-177]. Therefore, the drains should be properly sloped. As shown in Figure 4.6 and 4.7, the efficient flow velocity can be obtained through drainage gradients greater than 1/200 with the gravitational support.

2. Percentage variance of velocity

Percentage variance of the velocity was calculated in order to find out the newly inserted design's influence on the "steady, uniform" water flow received from upstream. The results are shown in Table 4.12. The maximum velocity drop reported throughout the experiments was 10.55 percent.

Table 4.12: Percentage variance of velocity- fully stocked Smart Storm Drainage

Flow rate Q (m^3/s)	Percentage variance of velocity [at tested gradients]			
	1/500	1/300	1/200	1/150
0.023	**10.55**	9.67	9.19	7.58
0.020	9.96	9.01	7.61	6.7
0.019	8.91	9.38	7.27	6.39
0.017	9	7.42	6.3	3.29
0.013	7.62	5.8	4.18	**2.77**

The percentage variance of velocity between the start and end point of the drainage channel was fall between 2.77 percent to 10.55 percent. It was observed that this velocity variance decreased with increasing drainage gradient. When the conventional existing drain was fed with the same amount of litter, it tends to overflow within minutes due to diminishing flow velocity caused by a crucial point clog. However, the flow velocity in Clog Resistant Open Drain unit did not change with respect to time and preserves "steady state" throughout the whole experiment. Therefore, the Clog Resistant Open Drain unit with fully stocked trash bins has the ability to maintain a steady flow than a conventional existing drain. The reason behind this steadiness is that the proper placement of litter items in the drain. The "litter distribution positions" in Clog Resistant Open Drain did not change with respect to time.

3. Froude Number and Specific Energy analysis

Froude number classifies the flow profile based on the relationship between velocity and flow depth [93, 178]. These two hydraulic parameters have a significant influence on the carrying capacity and the efficiency of storm drainage.

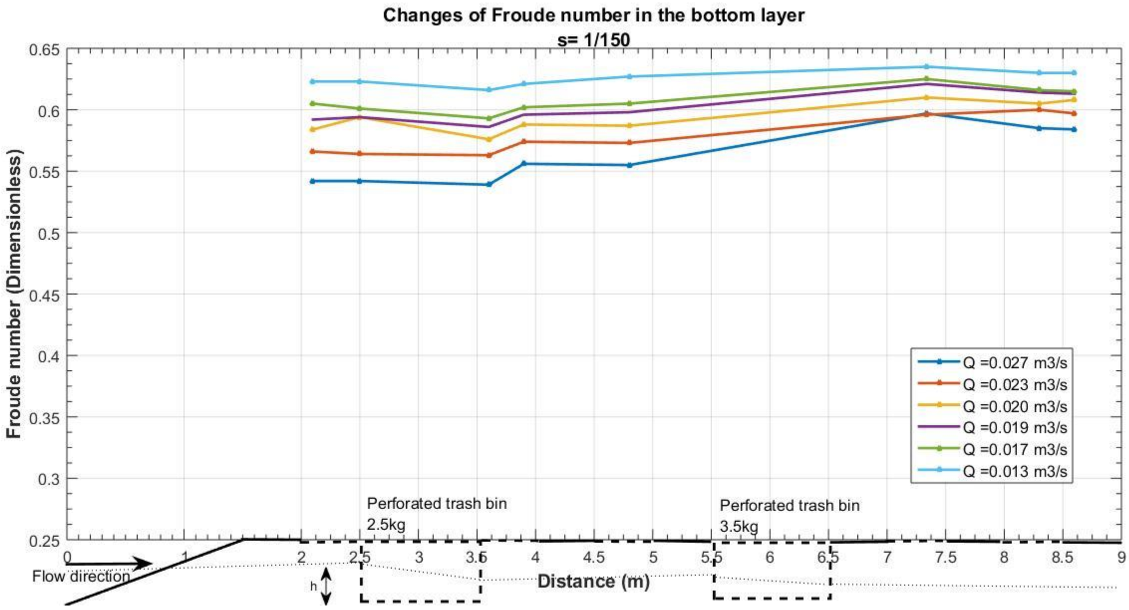


Figure 4.15: Changes of Froude number with different flow rates, drainage gradient= 1/150

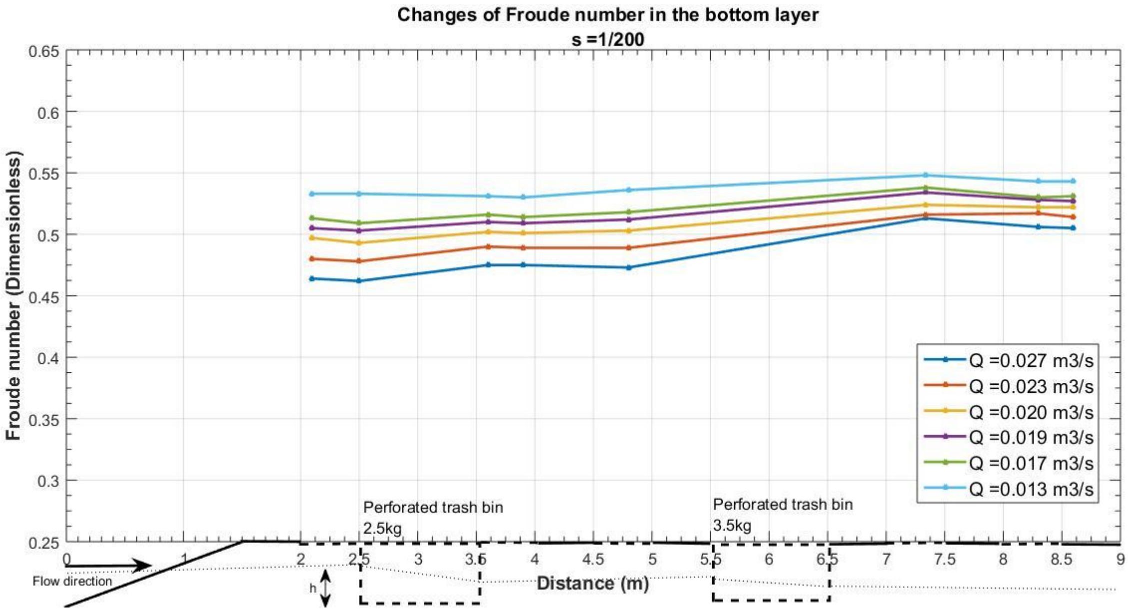


Figure 4.145: Changes of Froude number with different flow rates, drainage gradient= 1/200

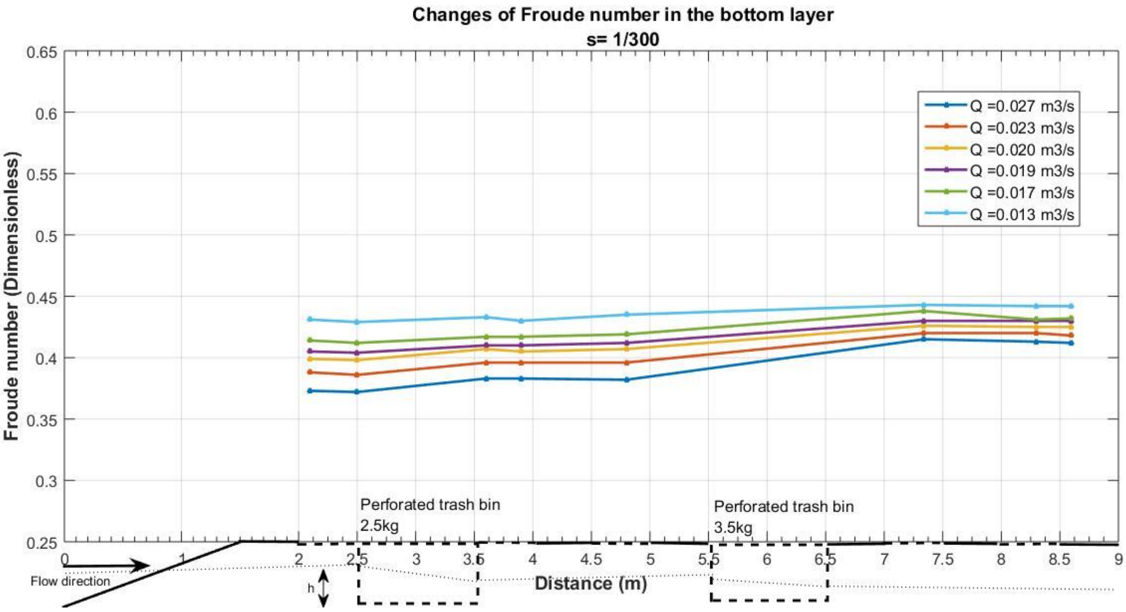


Figure 4.16: Changes of Froude number with different flow rates, drainage gradient =1/300

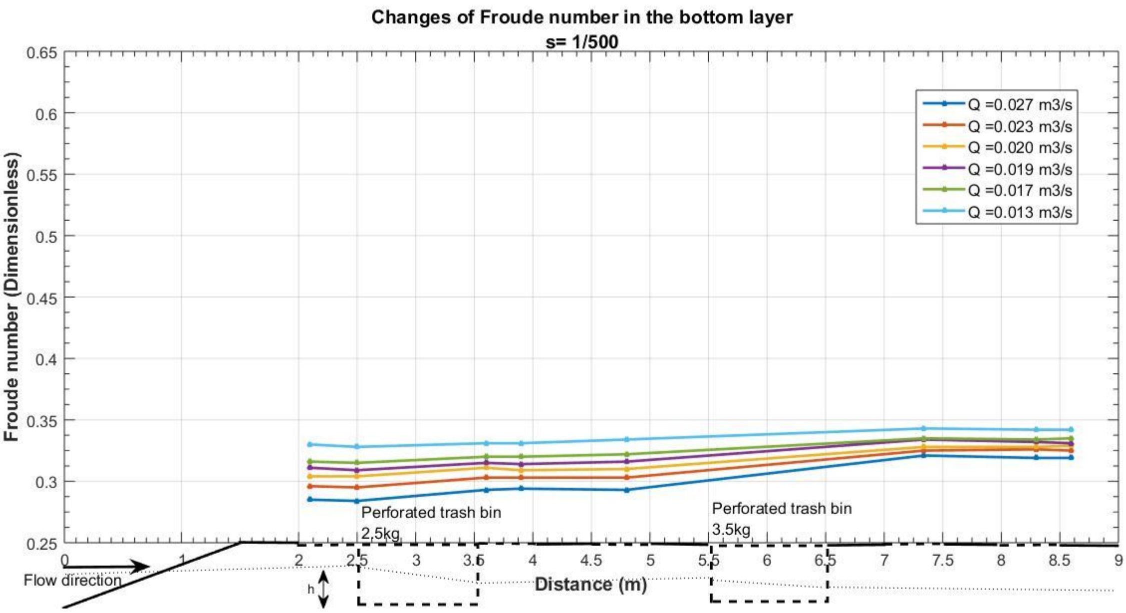


Figure 4.17: Changes of Froude number with different flow rates, drainage gradient = 1/500

Figures 4.14, 4.15, 4.16 and 4.17 presents the observed Froude number changes in the bottom layer of Clog Resistant Open Drain. According to the results obtained, the Froude number value recorded was less than one (Fr <1) for all experiments conducted in stage two with improved Clog Resistant Open Drain.

It was found that the Clog Resistant Open Drain has maintained a sub-critical flow throughout the set of experiments even at higher flow rates. According to widely recognised drainage manuals, storm drainage should maintain sub-critical flow throughout its operation to prevent unnecessary situations, such as hydraulic jumps [67, 89]. It confirms that the Clog Resistant Open Drain is distinctly efficient in handling higher flow rates even when the trash bins are completely stacked.

As illustrated in above figures, an increase in the Froude number was recorded at perforated trash bins, especially between the 2.5 to 3.6 and 5.5 to 6.5 spots. All cases investigated for this experiment were conducted under "fully stacked trash bins" condition. When the Clog Resistant Open Drain operates under fully stacked conditions; lower density trash items trapped in perforated bins tend to float around the bin area. This situation has naturally created some space for water to move through the perforated trash bins. As a result of this, a significant flow velocity difference manifests between before and after trash bins. This can be seen in the average velocity readings presented in Figures 4.10 to 4.13. This velocity difference results in a clearly observed visual flow depth variation before and after the trash bins as shown in the schematic drawing in Figure 4.18.

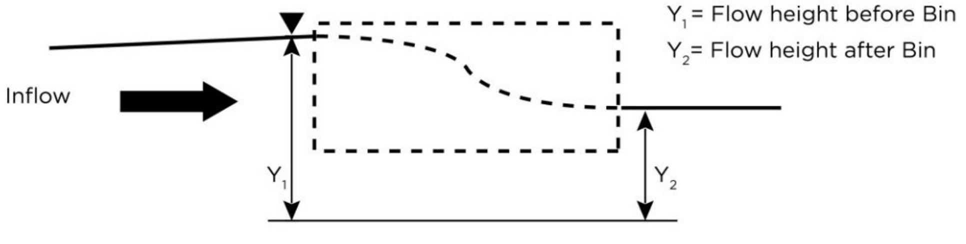


Figure 4.18: Schematic representation of flow height changes before and after the perforated trash bin

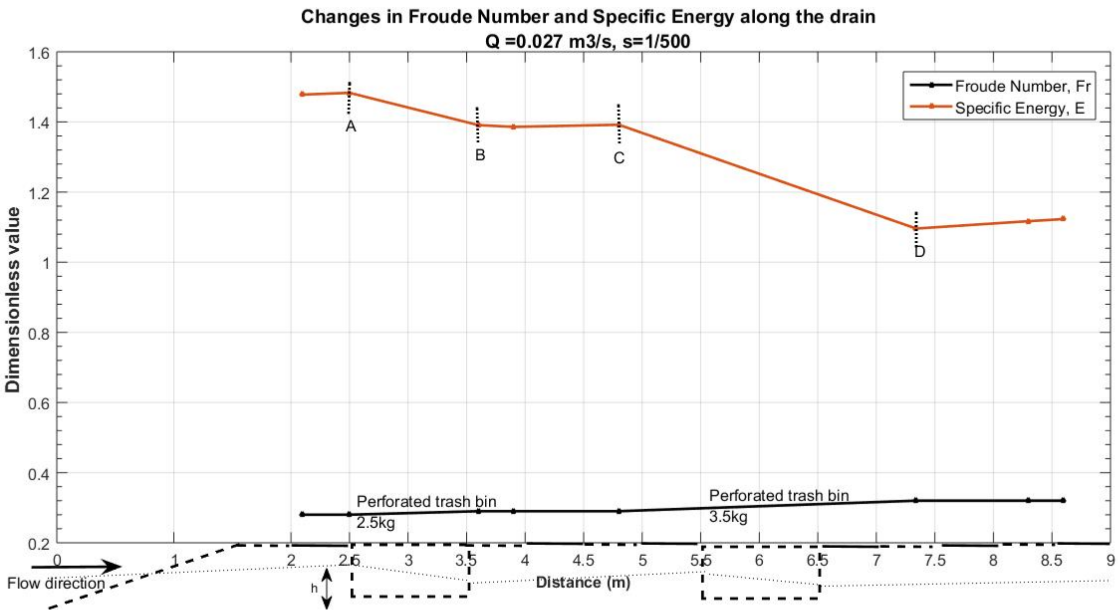


Figure 4.19: Changes in Froude number and Specific Energy value

Observed flow depth variations at trash bins were used with flow velocity values to calculate specific energy (E) value along the channel. As demonstrated in Figure 4.15, for the specific case of Q=0.027 m^3/s and S=1/500, there was a considerable decrease in specific energy at the perforated trash bins (A-B and C-D sections). This energy conversion happens in the watercourse just before and after the trash bins. Before entering the perforated trash bin area, the flow depth of the watercourse was considerably higher indicating the accumulation of potential energy in the watercourse at the very point. A drastic decrease in the flow height immediately passing through the perforated bin indicated the conversion of potential energy into kinetic energy. As a result of this energy conversion, the Froude number value tends to increase, but it again decreased to the normal level as the watercourse get stabilised and moved on.

In this study, it was found that the Froude number value varies between 0.4 to 0.7 at the tested drainage gradients, especially 1/200 and 1/150. According to the widely recognised drainage manuals, Froude number value of an efficient flow falls within the range of 0.7 to 0.8 [89, 170, 175, 179, 180]. However, the obtained Froude number values for Clog Resistant Open Drain can be increased to achieve maximum efficiency levels with design alternation or using a construction material which generates low resistant force against the flow such as hard PVC.

Numerical analysis carried out for the flow in Clog Resistant Open Drain has discovered a significant relationship between the flow rate and the Froude number value. It was confirmed that lower flow rates generate higher Froude number values.

As presented in Table 4.13, when the flow rate increased while the other parameters were kept unchanged, the average flow height increased. The increased flow rates produced higher flow volumes.

Table 4.13: Average flow Depth changes with Drainage Gradient

Flow rate m^3/s	Average flow depth at each gradient (m)			
	s=1/500	s=1/300	s=1/200	s=1/150
0.027	0.25	0.24	0.23	0.22
0.023	0.22	0.21	0.21	0.2
0.020	0.2	0.19	0.18	0.17
0.019	0.19	0.18	0.17	0.16
0.017	0.17	0.17	0.16	0.15
0.013	0.15	0.14	0.13	0.13
Percentage variance (Vertical)	40.00%	41.67%	43.48%	40.91%

The results represented in Table 4.14 shows a linear relationship with average flow velocity and flow rate. The higher flow rates generated higher flow velocities. As a result of that, storm water conveyance in the drainage channel becomes faster. In this study, it was found that the percentage variance of flow velocity escalation pertaining to each gradient was distributed between 15% and 18.57%.

Table 4.14: Average flow velocity at each drainage gradient

Flow rate m3/s	Average flow velocity at each gradient (m/s)			
	s=1/500	s=1/300	s=1/200	s=1/150
0.027	0.46	0.60	0.72	0.83
0.023	0.45	0.58	0.70	0.80
0.020	0.44	0.56	0.68	0.77
0.019	0.43	0.55	0.66	0.75
0.017	0.43	0.54	0.65	0.74
0.013	0.40	0.51	0.62	0.70
Percentage variance (Vertical)	15.00%	17.65%	16.13%	18.57%

The value of Froude number is inversely proportional to the flow depth (D) and directly proportional to the flow velocity (v) as expressed in following equations [93, 178].

$$Fr \propto \frac{1}{D} \tag{4.1}$$

$$Fr \propto v \tag{4.2}$$

Technically, if the flow depth increased, the Froude number is decreased. Moreover, if the flow velocity is increased, the Froude number increased accordingly. As the numerical analysis presented in Table 4.12 and Table 4.13 confirmed that the flow depth changes in an open drain are more critical than flow velocity changes. It was found that the percentage variance of flow height escalation (40% to 43.48%) of this drain is nearly a two times higher than the flow velocity magnification (15% to 18.57%). Finally, it was found that a significant influence on the Froude number value was generated by the changes in flow heights of the drainage channel.

4. **The Comparative Analysis of Conveyance Efficiency of a Clogged Drains**

When a drainage channel is clogged, the conveyance efficiency most likely decreases with increasing flow rates. Moreover, the conveyance efficiency also decreases with the increase of the drainage gradient. Even when a drain is clogged with a minimal amount of litter, its efficiency tends to decrease rapidly. This happened merely because the crucial point clogging of a drain. Laboratory experiments have proved that at the flow rate of 0.013 m^3/s the drains are barely able to handle this situation as the efficiency is only between 40% to 50 %. During the experiment, the conventional existing drainage was unable to handle higher flow rates greater than 0.020 m^3/s ($Q >$ 0.020 m^3/s) without spillover. This was caused by following reasons.

a) If the downstream end or a crucial point of the drainage channel is clogged, the watercourse tends to stagnate around the clogged object. Although, the higher flow rates always produce large water volumes. As large water volumes are continuously received from the upstream especially in the monsoon period, it increased stagnation of water inside the channel especially, at litter accumulated points. Therefore, a clogged drainage tends to overflow shortly at higher flow rates. Therefore, it is clear that the clogged drainages cannot efficiently handle the higher runoff received especially in monsoon periods

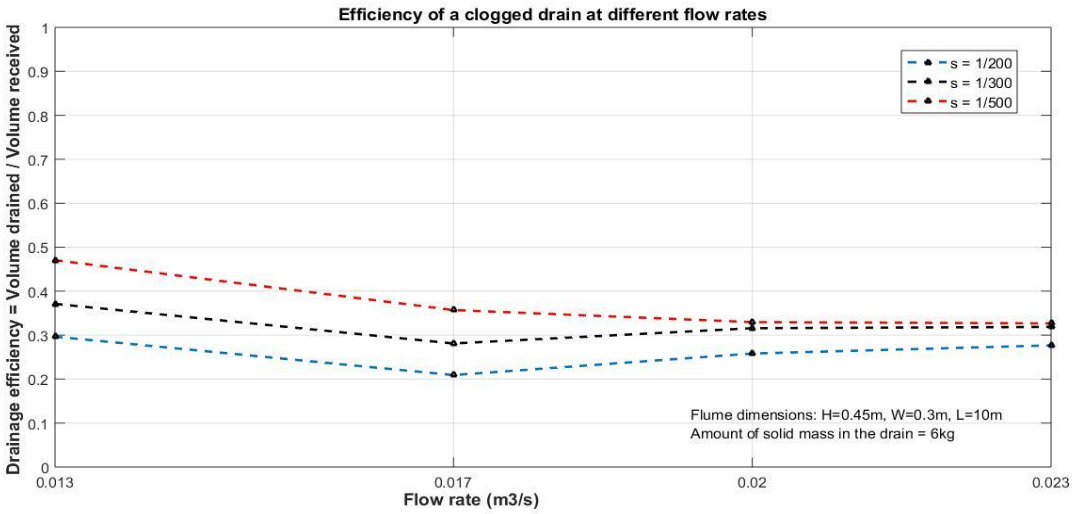
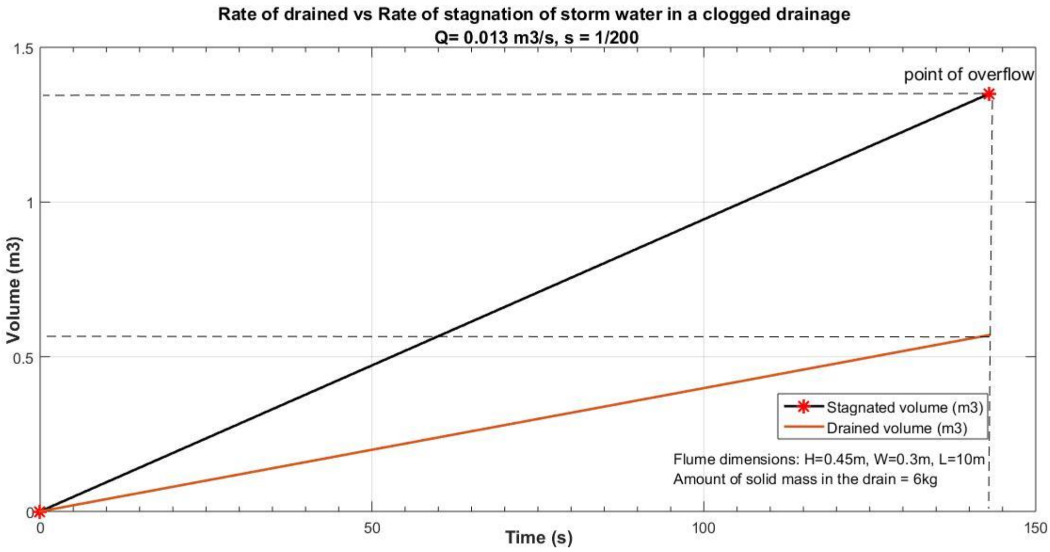


Figure 4.20: Efficiency of a conventional drainage

(see Figure 4.20).

b) Any drainage network works efficiently if the rate of draining exceeds the rate of receiving water (see Figure 4.21). If a crucial point at the drainage network gets clogged, the rate of draining gets decreases and water start accumulating inside the channel. Apparently, the rate of stagnation of water rapidly increases. When drainage attains to this situation, the whole system gets



unstabilised. It ultimately leads to the sudden spillover of the drain.

Figure 4.21: Rate of drained and rate of stagnation of storm water in a clogged drainage

Widely recognised drainage manuals, for example, Singapore, Malaysia, USA etc., highly recommend selecting a proper drainage gradient above 0.005 to achieve an efficient flow velocity [29, 67, 69, 175]. The experiment results have proved that the conveyance efficiency rapidly decreases with increasing the drainage gradient if the channel was clogged (see figure 4.20). It is clear that the clogged drains cannot achieve the effective outcomes of a good drainage design if it is clogged.

This experiment used a 7 kg mass of solid waste. When compared to the experimental drainage capacity (1.35m^3), the amount of waste presence in the drainage was technically insignificant. However, it generated a considerable influence on the flow efficiency of the drain. Once this channel was free from solid waste, it never demonstrated overflow and achieved full efficiency throughout each of the experimental flow rates and drainage gradients (Q = 0.013m^3/s, Q = 0.017m^3/s, Q = 0.020m^3/s, Q = 0.023m^3/s and S=1/200, S=1/300, S=1/500). However, once the conventional drainage channel fed with 7kg of litter, the flow efficiency reduced to a range between 46 percent and 20 percent. This figure was extremely lower at higher drainage gradients (see Figure 4.20).

If the macro litter items fall into open drains, it barely transported through narrow drainage channels. These litter items gradually accumulate at drainage channels situated in agglomeration points of the city, such as hospitals, schools, transport terminals etc., and make physical obstruction against the flow [138]. Following a high-intensity rainfall which creates larger runoff, the narrow sections or crucial points like drain intersects leads to spillover since the water flow cannot move forward due to physical obstructions.

Considering the all other factors that have an influence on the drainage efficiency such as, evaporation rate, infiltration rate, soil type, soil water content, soil porosity, etc. remained constant during this experiment, it is clear that the drainage efficiency was solely influenced by 7kg of litter that presence in the drain. Due to the effect caused by sunken and floating litter items in the conventional existing drain replicated by Case 03, its hydraulic efficiency was decreased by thirteen times compared to results depicted in Case 02 of Table 4.11. As a result, the conventional drainage designs have failed for decades in the handling of clogged solid mass and higher flow rates it receives, especially in the monsoon periods.

Lastly, it is concluded that the Clog Resistant Open Drain is significantly more efficient in handling clogged litter and higher flow rates than the conventional drainage designs. The results will enable planners and engineers to implement simple design solutions to solve complicated storm water management issues that arise.

4.7 Comparison of Existing and Improved Drainage Conveyance (K)

Table 4.15: existing and improved drainage conveyance (K)

Hydraulic feature	Channel Conveyance	
	Existing	Improved
Manning's n	0.144	0.020
Effective cross-sectional area of flow (A) m^2	0.095	0.095
Hydraulic Radius (R.)	0.1016	0.1016
Conveyance (K)	**0.14**	**1.02**

The experimental values pertaining to existing and improved drainage conveyance (K) is represented in Table 4.15. It is confirmed that the new drainage design will be able to accommodate urban runoff thirteen times greater than the existing conventional drains. Herewith it proves the ability of new design to improve the channel conveyance without expanding physical capacity.

4.8 Computer Model Simulation with EPA SWMM 5.0

This section discussed the results of the EPA SWMM 5.0 simulation model for all five drainage conditions replicated in the experimental procedure of this research. The model simulation summary reports are enclosed at the end of this report under the Appendix A.

4.8.1 Analysis of EPA SWMM 5.0 Model Simulation for Existing and Improved Drainage Conditions

On 15-16 May 2016, a 276mm rain fell in 24 hours at the case study area located in Colombo 15, Sri Lanka. An intense flood event occurred as a result of this massive rainfall. It recorded as the highest rainfall received for Colombo district in last 25 years. EPA SWMM 5.0 simulation model was developed for the catchment of 4.05 hectare by using the time series pertain to the rainfall record of 15-16 May 2016. Manning’s n values apply to each drainage condition was obtained from the laboratory experiments mentioned in subsection 3.3.5.

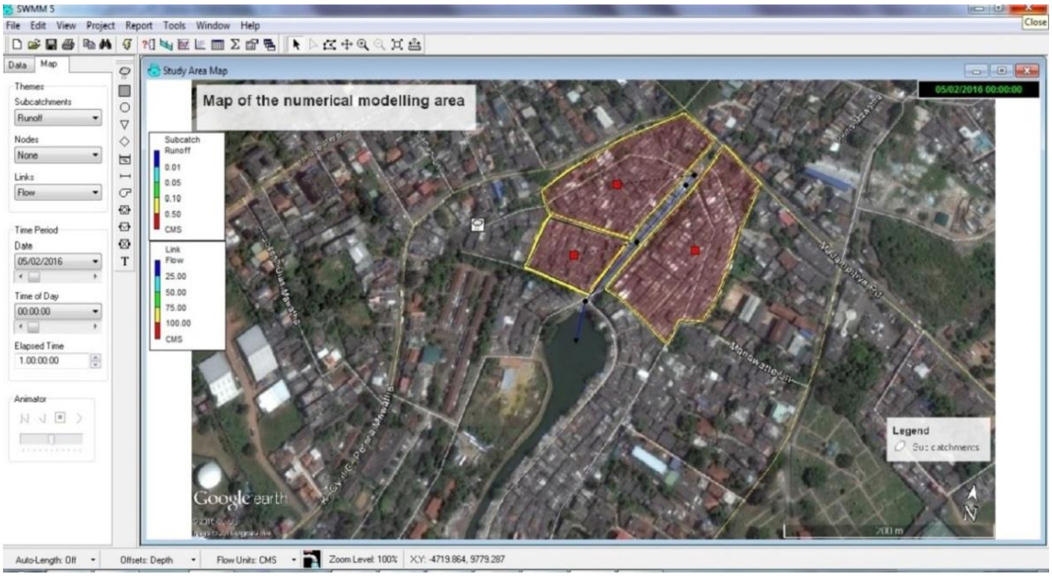


Figure 4.22: Numerical Model Building Interface for Case Study Area

Table 4.16: EPA SWMM Model Results obtained for each Experimental Case

Drainage scenario	Description	Manning's n	Total flood volume during 24 hrs (m^3)
case 01	control case Flume only	0.014	2408
case 02	0% clogged Outfall covered by mesh	0.046	7195
case 03	30% clogged Outfall covered by mesh	0.132	**9228**
case 04	0% clogged Improved design insisted	0.020	3996
case 05	30% clogged Improved design insisted	0.021	**4320**

4.8.1.1 Conventional drainage control case

This represents the "perfect drainage scenario" replicated for this study. It has been used as the control case but is not possible to occur in the real situation due to regular sedimentation and waste clogging that happens in the open drainage system. The only resistance force applied to this drainage condition was the channel bed roughness. As per the simulation model results depicted in Table 4.16, the perfect drainage scenario replicated by the control case 01 has been flooded (2408m^3 of flood) during the above-mentioned rainfall event.

4.8.1.2 Conventional drainage clogged with 0% of waste

This scenario represents a "perfect drainage condition with a trash barrier" which is well maintained and is free of solid waste and hence no blockage was reported in the drains. However, the nodes of the existing conventional drainage system have been flooded (71958m^3 of flood volume) as a result of the unprecedented rainfall received on 15-16 May 2016.

4.8.1.3 Conventional drainage clogged with 30% of waste

As specified in table 4.15, this replicated the "existing conventional drainage system" in the case study area that is usually clogged with 30% of solid waste. It could not handle the unprecedented rainfall received on 15-16 May 2016. This is evident from the drainage node flooding about 9228m^3 of total flood volume and this was recorded as the highest flood amount occurred among all five drainage scenarios.

4.8.1.4 Improved drainage without clogging

This was considered as a "perfect drainage condition" with regard to the improved engineering design. It replicated the well-maintained litter free Clog Resistant Open Drain. The nodes of this drainage system tend to spillover with 3996m^3 of flood volume as a result of the unprecedented rainfall received. It represents the second lowest flood volume recorded among all five drainage scenarios. Hence, this result has also been able to assert that the improved design is effectively catering to the storm water conveyance requirements of the case study area through the greater level of development of the hydraulic capacity of the drainage system.

4.8.1.5 Improved drainage clogged with 30% of litter

The "improved drainage which carried the same amount of litter" as mentioned in Case 03, was able to handle this massive runoff generated to a significant level. However, the improved clogged drainage also affected with 4320m^3 flood resulted by the said rain event. As depicted in Table 4.16 the improved drainage was successfully able to convey more than 50% of flood water when compared to the conventional drainage which clogged with the same amount of waste. However, the improved drainage was not able to fully eliminate the flood attack due to following reasons.

a) The flood event strike on 15-16th May 2016 was a result of 276mm/24hr rainfall which considered as the highest amount of 24-hour rainfall recorded in past 25 years in the case study area. It was not a practicable task for any open drainage system to completely handle such a massive overland flow volume.

b) The level of flood risk can be diminished and controlled by a proper engineering design. According to the researchers, any flood risk cannot be fully eliminated, and there is always a residual risk [11, 181-183].

4.9 Conclusions

Increased flow velocity is considered a factor to be controlled in stormwater management. However, maintaining an effective flow velocity is a challenge for the storm drainage operation in low and lower-middle income countries. Drainage capacity losses are identified as a major cause for floods in these countries. Haphazardly dumped litter items and sediment particles obstruct the free flow of storm water in open drains. Clogged drains cause travel time delays and increase the rate of stagnation of storm water. Very slow and shallow storm water flow causes operational problems in drains. This was modified by the Clog Resistant Open Drain Unit. The Clog Resistant Open Drain unit traps waste materials along the drain and provides a clear channel for stormwater conveyance, thus by improving the hydraulic characteristics of the flow.

CHAPTER 5

CONCLUSION

5.1 Summary of Research Activities

Based on peer literature, it is clear that inadequate and poorly functioning urban drainage system to be a major contributor to frequent flood events in urban areas of low and lower-middle income countries of the world. At the same time, poor financial capabilities and the escalating population density of urban areas have prevented the much-needed overhaul of improving drainage infrastructure of these countries.

This research project was aimed at finding ways to resolve operational deficiencies in open storm drains of low and lower-middle income countries, through improved design solutions. It included following specific research objectives.

a) To assess litter holding capacity of a drainage using analytical and numerical approaches

b) To design a clog resistant open drain unit for uninterrupted storm water conveyance

a) To optimise the performance of Clog Resistant Open Drain unit through experimental and numerical approaches

An analytical approach derived from detailed literature reviews, site observations, and unstructured interviews have been carried out to identify the operational deficiencies of open storm drains in the urban areas of low and lower-middle-income countries. Drainage capacity losses caused by the presence of litter items in open drains are considered the prime contributor to frequent interruptions in the continuous stormwater conveyance. Centuries old drainage infrastructure dating back to colonial days as well as haphazard, unplanned development activities to accommodate the spiralling population increase has compounded the problem of clogged drains. Clogged drains cause travel time delays and increase the rate of stagnation of storm water. Very slow and shallow storm water flow causes operational problems in drains. The conclusion of the analytical approach was that clogged drains cause intense spillovers, which lead to flash floods if the drainage capacity is not adequate for proper conveyance. However, a conventional drainage is capable of handling 24% of waste compared to its capacity whereas the channel outfall and the crucial points are free from clogging.

The research methodology employed in this comprised five stages. In Stage One, the real-time storm water demand of the case study area computed, and initial screening carried out using EPA SWMM 5.0 computer simulation platform. Stage Two estimated the effective hydraulic capacity of existing conventional open drains in case study area and experimentally observed the uneven litter distribution through a prototype open drain. Moreover, it studied the behaviour of a clogged open drain during a rainfall event and numerically analysed experimental results. The outcome of the combination of Stage One and Two were, the development of a new mathematical model for the approximate the rate of spill over of a clogged drain by incorporating the effects of floating and sunken litter in traditional engineering equations being used to describe an open-drain operation. This mathematical model can be used for future research to compute the magnitude of clogging effect on the stormwater conveyance.

Design development of the Solid Waste Clog Resistant Open Drain and testing it for hydraulic efficiency was explained in Stage Three by considering the operational constraints discovered through the analytical approach and mathematical approximations developed in the previous segments. Design development stage identified the impact of floating and sunken litter items on the variation of the hydraulic radius of the open storm drain. Increasing the hydraulic radius of the drainage was found as a crucial factor leading to a decrease in its hydraulic efficiency and increasing the risk of a spillover. Stage Four experimentally studied the hydraulic characteristics and performance of the newly invented clog resistant open drain unit. Stage Five comparatively analysed the influence of existing and improved drainage conditions on the storm water conveyance process of case study area, using EPA SWMM 5.0 computer simulation platform.

Analysis of laboratory experimental results of clog resistant open drain confirmed its ability to circumvent this problem by trapping clogged litter along the drain and providing a clear channel for stormwater conveyance, thus by improving the hydraulic characteristics of the flow. This design will minimise spill overs by increasing the flow velocity in open drains and decreasing the travel time of the flow.

5.2 Overall Conclusions

All three objectives defined at the beginning of this research activity were achieved successfully via activities completed during the study.

- To approximate spillover time of a clogged drainage using analytical and numerical approaches

  A new mathematical model was formulated for the approximation of spillover rate of a clogged drainage considering the effects of sunken and floating litter.

- To design a clog resistant open drain unit for expediting storm water conveyance

  A novel drainage design that is capable of trapping and temporarily retaining litter items falling into the drainage was developed.

- To optimise the performance of clog resistant open drain unit through experimental and numerical approaches

A laboratory scale prototype of the improved Clog Resistant Open Drain unit and an existing conventional drain unit were tested for hydraulic efficiency under a range of flow rates of $0.013m^3/s$ to $0.027m^3/s$. The existing conventional clogged drain demonstrated spillover at a flow rate of $0.013m^3/s$ in minutes while the improved Clog Resistant Open Drain unit did not spill over even at a flow rate of $0.027m^3/s$.

Numerical comparison of existing and improved drainage conditions was done using EPA SWMM 5.0 computer simulation platform to examine the flood flow handling abilities.

The improved clog resistant drain unit was able to reduce flood volumes by half compared to existing conventional drain in the case study area. In other words, the improved drain unit was capable of handling storm water volumes with a double efficiency than the conventional drain.

5.3 Proposed Future Work

Following specific areas were identified for further development activities in the future.

a) Expanding and further relationships developed for incorporate litter effects into open channel hydraulics

b) Supplementary ground studies to gather data on the behaviour of urban litter in drainage channels. There is a lack of quantitative evaluations of litter effects other than recognising the fact that litter should be an important consideration in designing urban drainage systems for many cities.

c) Further research into developing the novel drainage design invented and tested

    a. Investigating incorporation of new materials, eg. permeable concrete

b. Investigating incorporation of advances in sensors and electronics to take advantage of ‘internet of things’ eg. Solar-powered wireless communication to speed up emptying of litter traps

APPENDIX A

SWMM MODEL SIMULATION

Numerical model of the study area

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

Numerical model of the study area

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

****************
Analysis Options
****************
Flow Units ............... CMS
Process Models:
  Rainfall/Runoff ........ YES
  Snowmelt ............... NO
  Groundwater ............ NO
  Flow Routing ........... YES
  Ponding Allowed ........ NO
  Water Quality .......... NO
Infiltration Method ...... HORTON
Flow Routing Method ...... KINWAVE
Starting Date ............ MAY-15-2016 00:00:00
Ending Date .............. MAY-16-2016 00:00:00
Antecedent Dry Days ...... 0.0
Report Time Step ......... 00:30:00
Wet Time Step ............ 00:05:00
Dry Time Step ............ 00:00:00
Routing Time Step ........ 5.00 sec


*************
Element Count
*************
Number of rain gages ...... 1
Number of subcatchments ... 3
Number of nodes ........... 5
Number of links ........... 4
Number of pollutants ...... 0
Number of land uses ....... 0


****************
Raingage Summary
****************
```

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

Numerical model of the study area

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

****************
Analysis Options
****************
Flow Units ............... CMS
Process Models:
  Rainfall/Runoff ........ YES
  Snowmelt ............... NO
  Groundwater ............ NO
  Flow Routing ........... YES
  Ponding Allowed ........ NO
  Water Quality .......... NO
Infiltration Method ...... HORTON
Flow Routing Method ...... KINWAVE
Starting Date ............ MAY-15-2016 00:00:00
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Antecedent Dry Days ...... 0.0
Report Time Step ......... 00:30:00
Wet Time Step ............ 00:05:00
Dry Time Step ............ 00:00:00
Routing Time Step ........ 5.00 sec


*************
Element Count
*************
Number of rain gages ...... 1
Number of subcatchments ... 3
Number of nodes ........... 5
Number of links ........... 4
Number of pollutants ...... 0
Number of land uses ....... 0


****************
Raingage Summary
****************
```

```
C3              RECT_OPEN          0.45     0.13     0.11     0.30     1          0.02
C4              RECT_OPEN          0.45     0.13     0.11     0.30     1          0.05


*********************
Control Actions Taken
*********************


**************************        Volume         Depth
Runoff Quantity Continuity     hectare-m            mm
**************************     ---------       -------
Total Precipitation ......         1.091       269.125
Evaporation Loss .........         0.000         0.000
Infiltration Loss ........         0.010         2.591
Surface Runoff ...........         1.052       259.567
Final Surface Storage ....         0.030         7.464
Continuity Error (%) .....        -0.185


**************************        Volume        Volume
Flow Routing Continuity        hectare-m      10^6 ltr
**************************     ---------     ---------
Dry Weather Inflow .......         0.000         0.000
Wet Weather Inflow .......         1.047        10.469
Groundwater Inflow .......         0.000         0.000
RDII Inflow ..............         0.000         0.000
External Inflow ..........         0.000         0.000
External Outflow .........         0.120         1.204
Internal Outflow .........         0.923         9.228
Storage Losses ...........         0.000         0.000
Initial Stored Volume ....         0.000         0.000
Final Stored Volume ......         0.006         0.061
Continuity Error (%) .....        -0.245


*********************************
Highest Flow Instability Indexes
*********************************
All links are stable.


*************************
Routing Time Step Summary
*************************
Minimum Time Step           :      5.00 sec
Average Time Step           :      5.00 sec
```

```
Maximum Time Step          :     5.00 sec
Percent in Steady State    :     0.00
Average Iterations per Step :    1.01
```

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

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff CMS	Runoff Coeff
W1	269.13	0.00	0.00	2.26	259.78	4.30	0.20	0.965
W2	269.12	0.00	0.00	2.82	262.25	1.67	0.08	0.974
W3	269.12	0.00	0.00	2.82	258.39	4.55	0.21	0.960

```
******************
Node Depth Summary
******************
```

Node	Type	Average Depth Meters	Maximum Depth Meters	Maximum HGL Meters	Time of Max Occurrence days hr:min
N4	JUNCTION	0.35	0.45	10.45	0 03:16
N5	JUNCTION	0.38	0.45	8.45	0 03:14
N6	JUNCTION	0.39	0.45	7.45	0 03:10
N7	JUNCTION	0.39	0.45	6.45	0 03:23
O1	OUTFALL	0.15	0.17	5.17	0 03:38

```
*******************
Node Inflow Summary
*******************
```

Node	Type	Maximum Lateral Inflow CMS	Maximum Total Inflow CMS	Time of Max Occurrence days hr:min	Lateral Inflow Volume 10^6 ltr	Total Inflow Volume 10^6 ltr
N4	JUNCTION	0.200	0.200	0 05:00	4.276	4.276
N5	JUNCTION	0.209	0.237	0 05:00	4.530	6.332
N6	JUNCTION	0.078	0.105	0 05:00	1.663	3.634

```
N7                  JUNCTION     0.000     0.016     0  03:23       0.000       1.205
O1                  OUTFALL      0.000     0.016     0  03:38       0.000       1.204


**********************
Node Surcharge Summary
**********************

Surcharging occurs when water rises above the top of the highest conduit.
---------------------------------------------------------------------
                                           Max. Height   Min. Depth
                                Hours      Above Crown    Below Rim
Node                Type      Surcharged        Meters       Meters
---------------------------------------------------------------------
N4                  JUNCTION       15.27         0.000        0.000
N5                  JUNCTION       18.58         0.000        0.000
N6                  JUNCTION       20.83         0.000        0.000
N7                  JUNCTION       20.62         0.000        0.000


*********************
Node Flooding Summary
*********************

Flooding refers to all water that overflows a node, whether it ponds or not.
--------------------------------------------------------------------------
                                                           Total   Maximum
                                 Maximum   Time of Max     Flood    Ponded
                      Hours         Rate    Occurrence    Volume    Volume
Node                 Flooded         CMS   days hr:min  10^6 ltr   1000 m3
--------------------------------------------------------------------------
N4                     15.27       0.172      0  05:00     2.459     0.000
N5                     18.58       0.210      0  05:00     4.352     0.000
N6                     20.83       0.089      0  05:00     2.417     0.000


***********************
Outfall Loading Summary
***********************

-----------------------------------------------------------
                      Flow       Avg.       Max.      Total
                      Freq.      Flow       Flow     Volume
Outfall Node          Pcnt.       CMS        CMS   10^6 ltr
-----------------------------------------------------------
O1                    86.66      0.016      0.016      1.204
-----------------------------------------------------------
System                86.66      0.016      0.016      1.204
```

```
********************
Link Flow Summary
********************

-----------------------------------------------------------------------------
                               Maximum  Time of Max   Maximum    Max/    Max/
                                |Flow|   Occurrence   |Veloc|    Full    Full
Link                 Type          CMS  days hr:min    m/sec    Flow   Depth
-----------------------------------------------------------------------------
C1                   CONDUIT     0.027     0  03:25     0.22    1.00    1.00
C2                   CONDUIT     0.027     0  03:18     0.20    1.00    1.00
C3                   CONDUIT     0.016     0  03:23     0.12    1.00    1.00
C4                   CONDUIT     0.016     0  03:38     0.31    0.30    0.38


*************************
Conduit Surcharge Summary
*************************

----------------------------------------------------------------------------
                                                           Hours        Hours
                      --------- Hours Full --------   Above Full   Capacity
Conduit               Both Ends  Upstream  Dnstream   Normal Flow   Limited
----------------------------------------------------------------------------
C1                        14.87     15.27     15.01        0.01       15.27
C2                        18.39     18.58     18.46       18.46       18.58
C3                        20.62     20.83     20.62       20.62       20.83


Analysis begun on:  Fri May 27 21:43:11 2016
Analysis ended on:  Fri May 27 21:43:11 2016
Total elapsed time: < 1 sec
```

APPENDIX B

SSD TECHNICAL DETAILS

INDRA Smart Drainage Unit

Industrial Design protection Registration Number; 14-01505-0101
Date of registration – 05/12/2014

I. *ABSTRACT*; A method of constructing a drain by adding an upper layer with a suitably perforated bottom to collect and separate solid wastes disposed into the drain. Thus, by ensuring storm water handling capacity during excessive precipitation events to provide adequate draining of storm water to prevent street flooding. Solid waste collection layer is equipped with removable perforated bins to ;

II. (a) collect and trap solid waste

III. (b) function as manual collection points of solid waste, facilitating frequent cleaning.

IV.

V. Field of Invention

The present invention relates to preventing blockages of surface drains which leads to street floods. In compact cities, where indecisive disposal of solid waste and debris has become a problem in maintaining adequate drainage capacity to handle storm events.

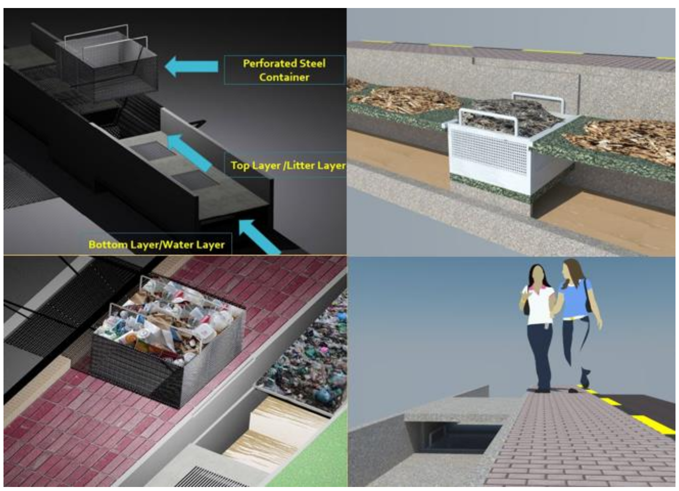


Fig. 1. Solid waste resistant duel layer drainage unit

VI. Description of Relevant Art

Current urban drainage design practices assume drain to receive runoff from precipitation events only. As such these designs are not equipped to handle solid waste and debris accumulations in the drain. Which will result in serious clogging and leading to street floods or even flash floods under excessive precipitation events.

VII. Objectives

The objectives of this invention is to;

A. *To maintain a clear channel for the transportation of storm water all the time*

B. *To separate and trap solid waste and debris, preventing those from getting mobilized during a storm event, thereby preventing clogging and blocking of the drain*

VIII. Brief Explanation

The invention comprises of two stacked channels separated by a suitably perforated bottom layer. It leads to separation of solid waste and debris from storm water. The bottom channel, therefore is always maintained free of any solids or debris thereby maintaining an adequate capacity to carry runoff preventing flooding during an excessive precipitation event.

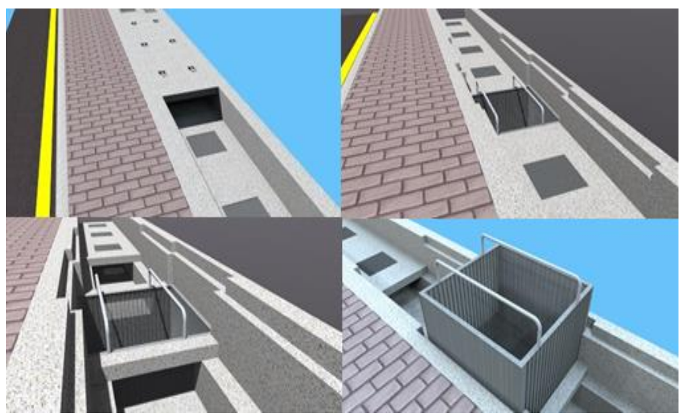


Fig. 2. Top plan of solid waste resistant duel layer drainage unit

IX. Detailed Description

The invention consists of an upper drain channel with suitable perforations on the bottom at suitable intervals (1-2m) along the length of the channel. It stacked over a second drain channel as shown in Fig. 3.

Perforations in the bottom layer of the top channel allow storm water to seep the bottom channel leaving solid waste and debris to accumulate in the top channel.

Storm water is free to flow in the bottom channel, which least receives any solid waste and debris directly, thereby maintaining the required drainage capacity all the time.

Removable perforated steel container are to be placed at suitable intervals along the length of the drain.

The height of the container extends up to the bottom layer of the upper channel, thereby creating a dump trap for any solid waste or debris being moved along the bottom of the upper channel by the runoff flow.

Municipal Garbage Collectors or surrounding community can easily use rake or broom to sweep waste and debris from the top later of storm drain to waste container.

Collected solid waste and debris is easily removed by lifting the perforated container out of the pit and emptying into a suitable secondary container to be transported to a disposal site.

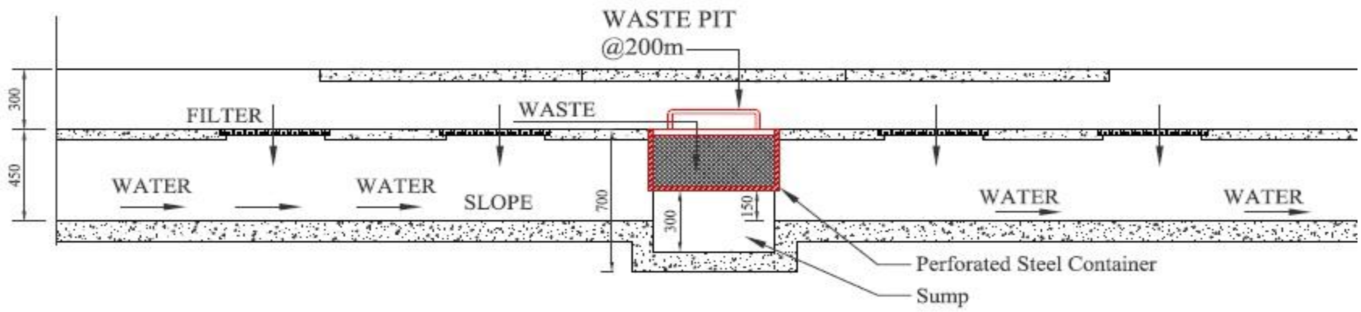


Fig. 3. Partial section along the drain

A top view of the upper channel is shown as Figure 4, which shows the placement of filter spaces for draining of liquid into the lower channel and the placement of the pit and waste collection container.

Cross sectional details at two points A-A and B-B along the length of the drain is shown in Figure 5. Section A-A shows the cross sectional view at a point a filter is placed on the bottom of the top channel. Section B-B shows the cross sectional view at the pit and the waste collection container.

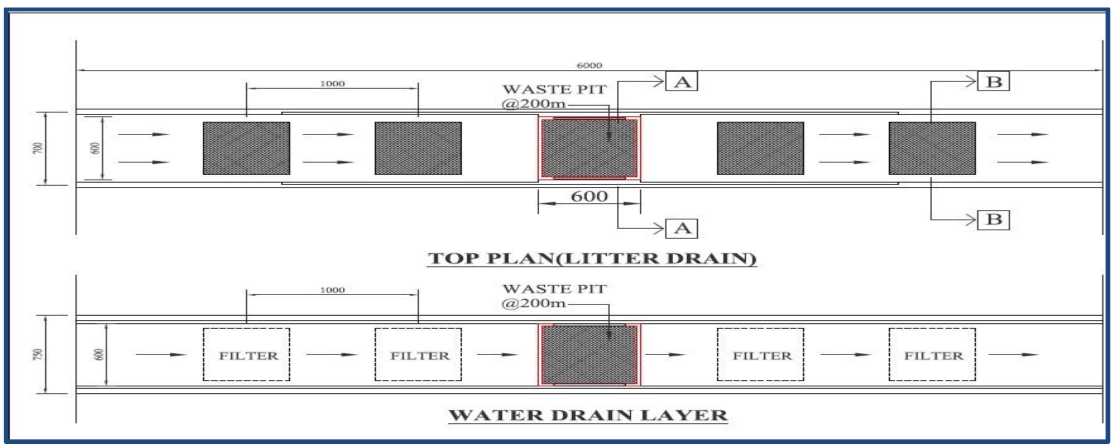


Fig. 4. Partial section along the drain

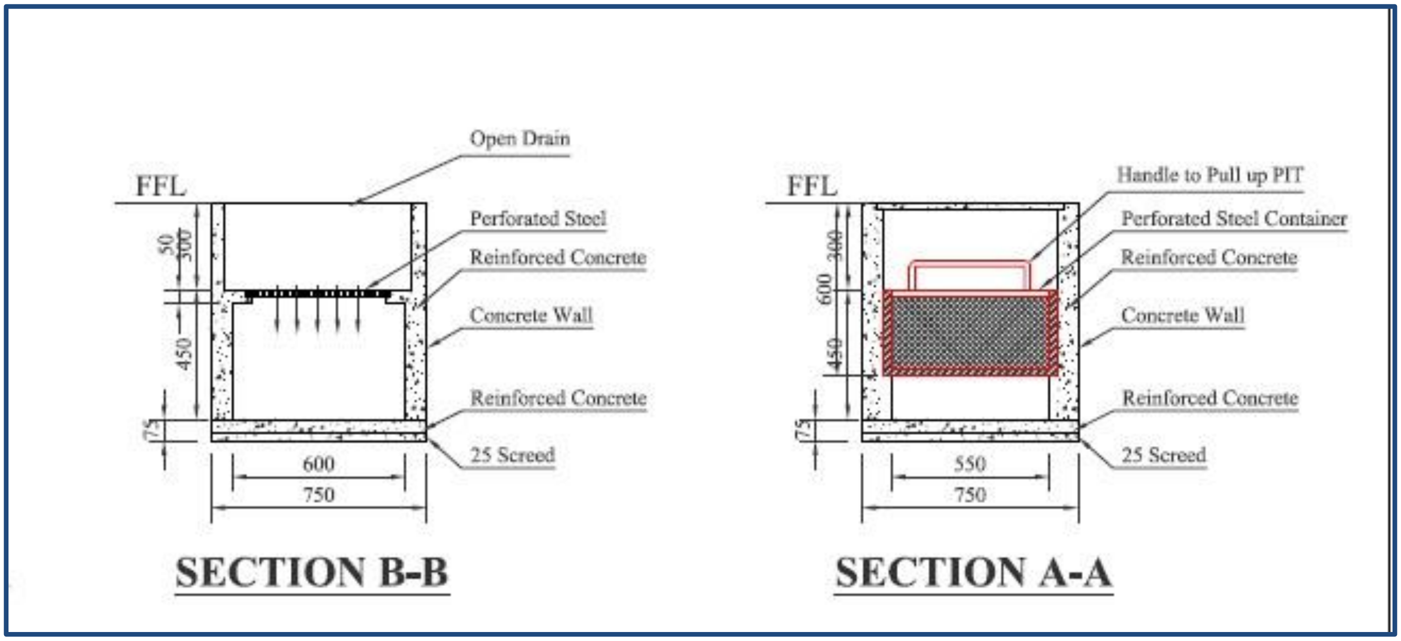


Fig. 5. Partial section along the drain

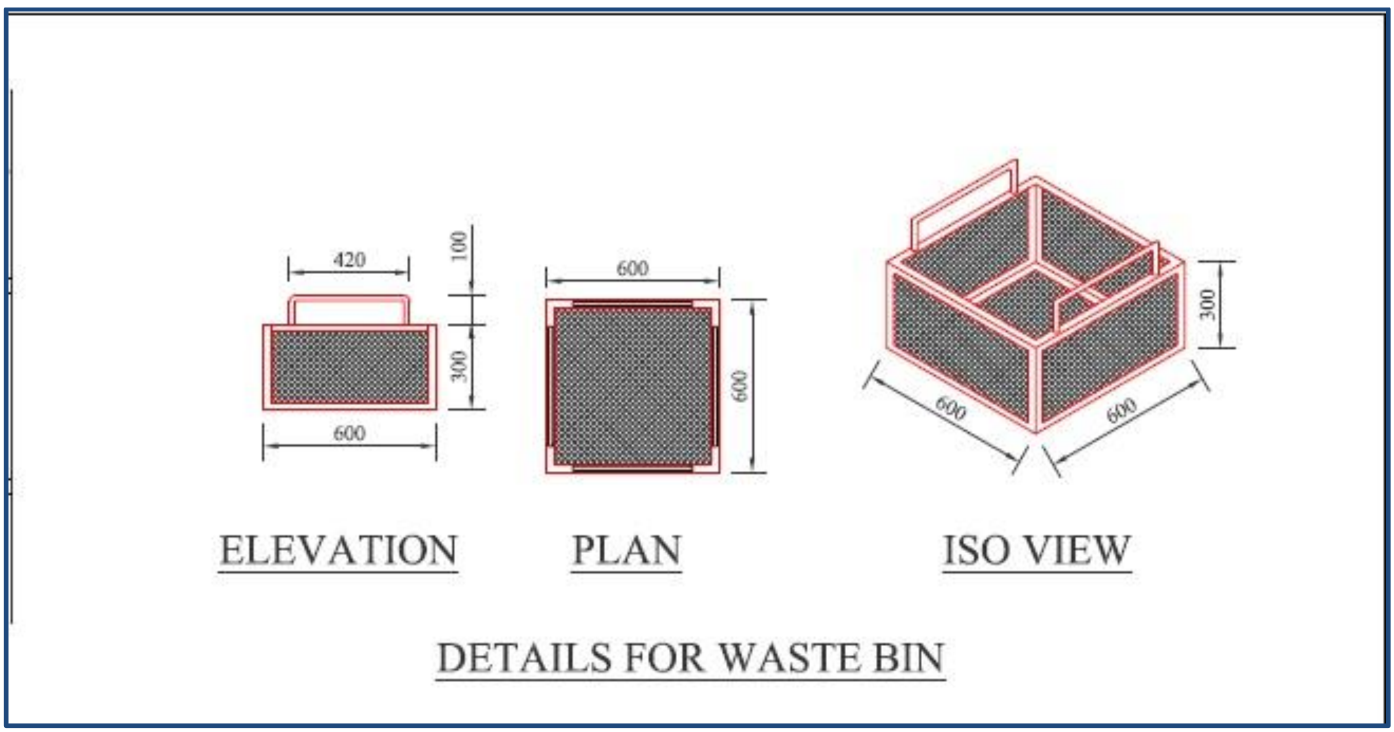
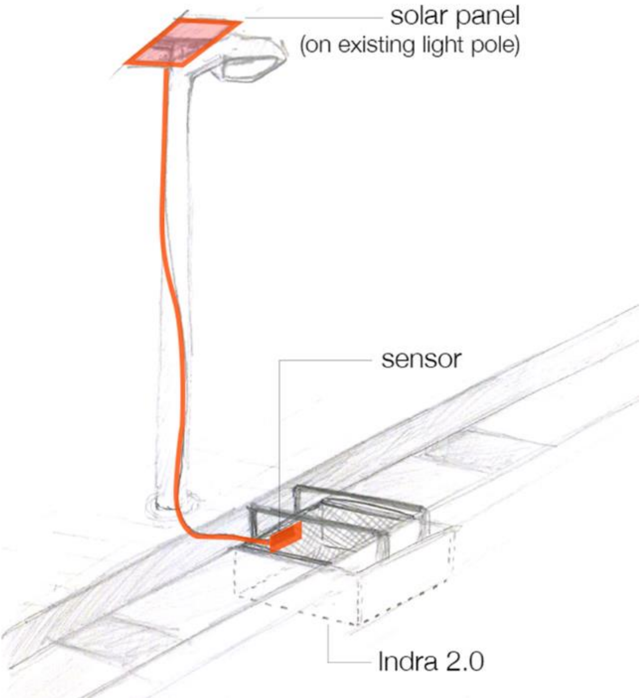


Fig. 6. The dimensions of perforated waste container.

Fig. 7. Smart waste container unit



X. INDRA SMART WASTE CONTAINER

This is a removable and fully perforated bin which placed in the drain. It carries a wireless sensor on the topmost surface of the container. The main objective of the wireless sensor is to measure and forecast the fill-level of waste container. Once the perforated container is filed, it will automatically generate text messages to responsible bodies (e.g: Garbage collector, Municipal work services wing) Moreover, it alerts the neighboring community via social media updates (e.g: twitter)

INDRA Smart Drainage Unit consists with numbers of INDRA Smart Waste Containers placed along the drainage. Distance between two waste containers depend on the location specific conditions such as; type of the locality, demographic data, floating population.

XI. CLAIMS

1) Duel layer drain which separated with a bottom fitted filtering elements to trap and collect solid waste and debris directly in the upper channel.
2) Use of a lower channel to maintain adequate storm water handling capacity of the drain to prevent overflowing and street flooding in an excessive precipitation event.
3) Use of waste collection pits at suitable intervals (200m -300m) along the length of the drain, to capture and retain solid waste and debris.
4) Use of a removable perforated container that will allow water to pass through unhindered, the same time act as an aid to conveniently collect and remove solid waste and debris from the drain.
5) Sensor based waste management entity and neighborhood alert system

XII. MATERIALS AND ALTERNATE DESIGN IDEAS

The main element of the INDRA Smart Drainage Unit is the duel layer, waste resistant drain. Two alternative designs can apply to construct this drainage so far.

1) Construct the bottom surface of top drainage layer with suitable perforated materials. As such conditions it is expected to use “higher gauge mesh” put in regular intervals (1-2 m) along the drain.

2) Construct the bottom surface of top drainage layer by permeable concrete (perforated concrete) slab.

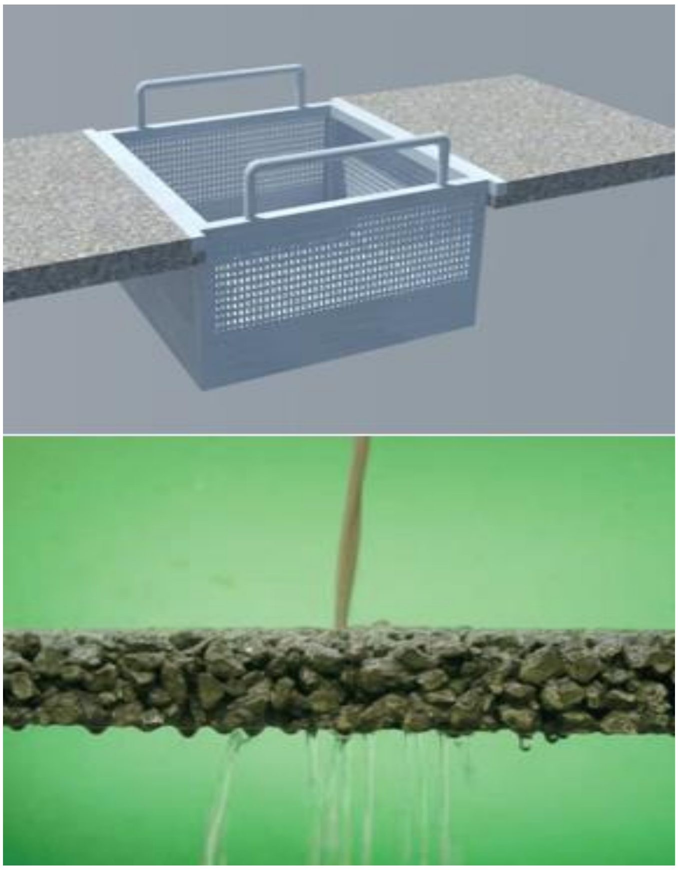


Fig. 8. Permeable concrete layer.

APPENDIX C

MATLAB CODE

MATLAB Code for Simplified Equation 3.19

```
clear all
close all
clc


syms x

prompt1 = 'h1 =    ';
prompt2 = 'h2 =    ';
prompt3 = 'fig =    ';
prompt4 = 'slg =    ';
prompt5 = 'Vin =    ';
prompt9 = 'Vout =   ';
prompt6 = 'k =    ';
prompt7 = 'D(t) =    ';
prompt8 = 'b =     ';

h1 = input(prompt1)
h2 = input(prompt2)
fig = input(prompt3)
slg = input(prompt4)
Vin = input(prompt5)
k = input(prompt6)
Dt = input(prompt7)
b = input(prompt8)
Vout = input(prompt9)
c = (h1 + h2)*a
d =2*(h1+h2)
up = (b*Dt- c)^1.83

flgq = ((sqrt(1+ (fig)^2) + sqrt(1+ (slg)^2))*b)
inte = int(flgq,x,0,b)

down = (2*Dt - (d + inte))^0.83
Final = Vin - (Vout - (k*((up)/(down))))
double (Final)
```

GLOSSARY

Colonized Countries

The countries or colonies located in Asia, Africa Oceania and Latin America has administratively occupied by Western European countries including Portugal, Netherlands, United Kingdom, Spain and France in the beginning of 18th century [184].

Low and Lower Middle income countries

According to the World Bank 2017 fiscal year classifications, the countries with per capita Gross National Index (GNI) less than US Dollars 1025 are defined as Low Income economies. The Lower Middle income economies are defined as the countries with per capita Gross National Index (GNI) between US Dollar 1025 and US Dollar 4035 [1].

Separate Sewer System

The usage of separate drainage lines for conveyance of storm water runoff and Municipal gray water [185].

Urban Litter

Alternatively called trash, solid waste, floatables, gross pollutants etc. which are disposed waste matter made out of polythene, plastics, PVC, glass, timber or paper. It accumulates in public areas especially on congesting points like schools, hospitals, play grounds and public transportation terminals. If someone does not manually remove, it can get transported by wind, overland flow and finally end up in nearby water bodies [138].

Sunken Litter

These are the deposited waste matter in the drainage channels. It may tend to move with the higher flow rates receive from the upstream. However, in general these are the heavy waste particles with a higher tendency of deposition for example, glass disposals, wood particles, construction debris.

Floating Litter

Unsettled and floating (moving) waste matter in a drainage channel; for example, plastic waste, dry leaves clothing and paper waste.

Conventional Drainage

Traditional drainage designs which only cater to the needs of storm water conveyance.

Micro Drainage

Secondary drainage channels constructed for conveyance of overland flow. These channels are generally concrete lined and connected to primary drainage lines and ends up at a receiving water body.

Conveyance system

"Mechanism" of transporting water between drainage channels

Litter Effect

The combined effect generated on the output rate of water from the sunken and floating litter particles in drainage channel.

Input Rate of Water

The volume of water which per unit time a natural drainage line receives from upstream sources.

Output Rate of Water

The volume of water per unit time which conveys through the drainage channel.

Rate of Drained

The volume of water per unit time which leaves the drainage channel.

Rate of stagnation

The rate of increase in the volume of water per unit time retained in the drainage channel as a result of accumulation of litter in the drainage (litter effect).

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