Modeling of LIDs in Context of Sustainable Urban Drainage System

A Thesis

Submitted to the Department of Civil Engineering,
CHITTAGONG UNIVERSITY OF ENGINEERING AND TECHNOLOGY,
Chattogram-4349, Bangladesh
in partial fulfillment for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

by

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2023

Dedicated to my parents, friends,
and to my respected teachers

Declaration Statement

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Date: 03-05-2023

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Acknowledgement

I wish to express my sincere gratitude and profound indebtedness to my supervisor Professor Dr. Sudip Kumar Pal for his continued encouragement, supervision, precious input, advice, contribution of new ideas and support throughout the course of this research work. His careful checking drafts, valuable comments, criticism, constructive suggestions and to debate the rationale of the ideas in it immensely contributed to the improvement of the thesis.

I would like to express my heartfelt thanks to Dr. Asiful Hoque, Dr. Aysha Akter, Dr. Mst. Farzana Rahman Zuthi, Dr. Muhammad Azizul Hoque for serving as a member of the Examination Board and also their feedback and encouragement as well as also being available, whenever I needed the guidance.

The author wishes to thank the Chittagong Development Authority (CDA), Chittagong Port Authority (CPA) and Bangladesh Meteorological Department (BMD) for assisting in necessary data collection. The author would also like to thank Directorate of Research and Extension (DRE), CUET for the financial assistance in conducting the study. I truly appreciate the constant support from the students of Port City International University for their constant support during the field work.

Lastly but importantly, the author expresses a deep sense of gratitude and indebtedness to his parents, other family members, relatives and friends for their encouragement, cooperation, companionship, and moral support throughout the tenure of the research work.

বিমূর্ত

উন্নয়নশীল দেশের শহরগুলি প্রায়ই বর্জ্যপানি নিষ্কাশন ব্যবস্থার অনুপস্থিতি উপযুক্ত বর্জ্য ব্যাবস্থাপনা না থাকায় পরিবর্তিত ভূমি ব্যবহার এবং জলবায়ু দ্বারা প্রভাবিত বিদ্যমান পানি নিষ্কাশন ব্যবস্থার কার্যকারিতা কম থাকায় শহর সমূহ অতিরিক্ত বৃষ্টির পানি প্রবাহের কারণে জলাবদ্ধতার শিকার হয়। যদিও চলমান ও প্রথাগত পানি নিষ্কাশন ব্যবস্থায় প্রবাহের পরিমাণকে সঠিকভাবে নিয়ন্ত্রণ করতে দেখা যায়, তবে প্রবাহের গুনমান এবং নান্দনিক সুবিধা সমূহ প্রায়ই উপেক্ষা করা হয়, ফলশ্রুতিতে প্রচলিত পানি নিষ্কাশন ড্রেনগুলি টেকসই স্থায়িত্বের দিকগুলিকে মোকাবেলা করতে ব্যর্থ হয়েছে, যা প্রবাহের পারিমান, গুনমান এবং নান্দনিক সুবিধাকে সমান গুরুত্ব দেয়। এই প্রেক্ষাপটে, টেকসই নিষ্কাশন ব্যবস্থা বা লো ইমপ্যাক্ট ডেভেলপমেন্ট (এলআইডি), খরচ-কার্যকারিতার সাথে উল্লেখিত সমস্ত দিকগুলিকে নিষ্কাশন ব্যবস্থার একীভূত করে। যদিও নিষ্কাশন ব্যবস্থার পরিমাণ, গুণমান এবং নান্দনিক সুবিধার বিষয়ে বেশ কয়েকটি গবেষণা পৃথকভাবে সম্পন্ন হয়েছে ,তবে ব্যয়-কার্যকর বাস্তবায়নের সাথে এই সমস্ত বিষয়গুলির একীভূতকরণ এখনও বিশদভঅবে অধ্যয়ন করা হয়নি। এই গবেষনার লক্ষ্য হল চাক্তাই-রাজাখালী খালগুলির আওতাধীস এলাকা সমূহ (যা চট্টগ্রাম শহরের উল্লেখযোগ্য বৃষ্টির পানি নিষ্কাশনের নির্গমনপথ হিসাবে কাজ করে) ব্যবহার করে বৃষ্টির পানি ব্যবস্থাপনায় বিভিন্ন জলবায়ু পরিস্থিতিতে বৃষ্টি জনিত প্রবাহের পরিমাণ, গুনমান এবং নান্দনিক সুবিধার দিকগুলি সহ এলআইডি এর উপাদানগুলির কার্যকারিতা মূল্যায়ন করা। এলআইডি কেইস ০২ঃ ভেজিটেটিভ সোয়াল; কেইস ০৩ঃ বায়োরেটেনশন, সবুজ ছাদ, ভেদযোগ্য রাস্তা, অনুপ্রবেশযোগ্য খাঁদ, এবং রেইন ব্যারেল; কেইস ০৪ (যা কেইস ০২ এবং কেইস ০৩ এর সমন্বয়ে গঠিত) হতে প্রাপ্ত বৃষ্টিপাতজনিত প্রবাহ এবং প্রবাহের গুনমানকে পরিমাপের লক্ষে পিসিএসডাব্লিউএমএম সফটওয়্যার ব্যবহার করা হয়েছিল। এসপিএসএস ভার্সন ২৩ ব্যবহার করে বিভিন্ন পরিসংখ্যান জনিত বিশ্লেষণ যেমনঃ মৌলিক পরিসংখ্যান, পারস্পরিক সম্পর্ক বিশ্লেষন এবং প্রিন্সিপাল কম্পোনেন্ট এনালাইসিস সম্পাদিত করা হয়েছে। উপরোন্তু, এসটিইপি ভার্সন ৩ (যা একটি জীবনচক্র খরচ পদ্ধতি নির্ণায়ক সফটওয়্যার) প্রস্তাবিত এলআইডি-এর জীবনচক্র মূল্য কার্যকারিতা মূল্যায়ন করতে ব্যবহার করা হয়েছে।

এ গবেষনার প্রাপ্ত ফলাফল হতে দেখা যায় যে, নিষ্কাশন ব্যবস্থায় এলআইডি এর অন্তর্ভূক্তি ১৪% থেকে ৬০% পর্যন্ত সর্বোচ্চ প্রবাহকে কমাতে সক্ষম, এবং কোনো এলআইডি না প্রয়োগের তুলনায় ৩০ থেকে ১০৫ মিনিটের একটি সময় সর্বোচ্চ প্রবাহের তৈরীতে পিছিয়ে দিতে সক্ষম। বিদ্যমান ভূমি ব্যবস্থার উপর ভিত্তি করে বিভিন্ন ভূমি ব্যবহারের ধরণ যেমনঃ আবাসিক, শিল্প, বাণিজ্যিক এবং প্রাতিষ্ঠানিক এর জন্য সার্বিক অদ্রবীভূত দ্রব্য (টিএসএস), সার্বিক নাইট্রোজেন (টিএন), সার্বিক ফসফরাস (টিপি), জিংক, বিওডি এবং সিওডি এর ইভেন্ট মিন কনসেন্ট্রেশন (ইএসসি) পর্যায়ক্রমে ২৭৫ থেকে ১০৮৫ মিলিগ্রাম/লি. ২.২০ থেকে ৭.৩ মিলিগ্রাম/লি. ০.৩৩ থেকে ১.১৪ মিলিগ্রাম/লি., ০.০২ থেকে ০.১৯ মিলিগ্রাম/লি., ২১ থেকে ৭১ মিলিগ্রাম/লি., এবং ৫৭ থেকে ২০১ মিলিগ্রাম/লি. এর মধ্যে পাওয়া যায়, যা প্রস্তাবিত এলআইডি গুলির অর্ন্তভূক্তিতে ২৩ থেকে ৮০% পর্যন্ত হ্রাস করতে সক্ষম। প্রস্তাবিত এলআইডি গুলোর স্থাপন, পরিচালনা এবং রক্ষণাবেক্ষনের সাথে সম্পর্কিত খরচ বিবেচনা করে এটি পাওয়া গেছে যে বিভিন্ন এলআইডি গুলোর জীবন চক্রের খরচ প্রকারভেদে প্রতি বর্গ মিটারের ১৫১-১২৫২ মার্কিন ডলার। গবেষনায় আরও দেখা যায় যে, একটি একক এলআইডি সম্পূর্ন সমাধান প্রদান করে না, যেমন: ভেজিটেটিভ সোয়াল), যেখানে কেইস ০৪ (যা কেইস ০২ এবং কেস ০৩ এর সমন্বয়ে গঠিত) সবচেয়ে কার্যকর বলে প্রতীয়মান। এই গবেষনার ফলাফল গুলি ভবিষ্যত পানি নিষ্কাশন ব্যবস্থায় বহুবিধ অসুবিধাগুলি মোকাবেলার জন্য টেকসই শহর নিষ্কাশন ব্যবস্থা গ্রহণের জন্য এবং কার্যকর পদ্ধতিতে বৃষ্টির পানির প্রবাহ পরিচালনা করতে সংশ্লিষ্ট প্রকৌশলীবৃন্দ, স্থাপত্যবিদ এবং নগর পরিকল্পনাবিদদের সহায়তা করবে মর্মে বিবেচনা করা যেতে পারে।

ABSTRACT

Urban cities in developing countries often suffered from water logging induced by stormwater runoff due to the underperformance of their existing drainage networks, influenced by changed land use and climate, with an inappropriate solid waste management system and the absence of wastewater networks. Although traditional drainage design is seen as accommodating runoff volume, runoff quality and drainage design amenities are often overlooked. Therefore, a drainage network constructed with conventional methods failed to address sustainability aspects that give equal importance to quantity, quality, and amenity. In this context, sustainable urban drainage systems, or low impact development (LID), open the windows of drainage design by integrating all the above aspects with cost-effectiveness. Although several studies on the quantity, quality, and amenity of drainage networks exist on separate scales, an integration of all of these along with cost-effective implementation is yet to be studied in detail. The aim of the study is to evaluate the performance of LID components, including quantity, quality, and amenity aspects, at a watershed scale under different climatic scenarios in the context of stormwater management using the Chaktai-Rajakhali watershed, which serves as significant stormwater drainage outlets for Chattogram city. The Personal Computer Storm Water Management Model (PCSWMM) software was used to simulate the rainfall-runoff and runoff quality derived from three different LID scenarios (S2-S4) addressing sources to the destination of runoff through the canal. Basic statistical analyses including principal component analysis (PCA) were performed using Statistical Package for the Social Sciences (SPSS v. 23). In addition, Sustainable Technologies Evaluation Program (STEP), a life cycle costing tool v. 3.0., has been used to evaluate the cost-effectiveness of proposed LIDs.

The study revealed that the incorporation of LIDs into drainage systems can reduce peak discharge by 14% to 60% with an increase in lag time to peak flow of 30 to 105 minutes in comparison to the scenario without LID implementation. Based on runoff quality in existing or no LIDs, the event mean concentrations (EMC) of TSS, TN, TP, Zn, BOD, and COD in various land uses such as residential, industrial, commercial, and institutional were found to range from 275–1085 mg/L, 2.2–7.3 mg/L, 0.33–1.14 mg/L, 0.02-0.19 mg/L, 21–71 mg/L, and 57–201 mg/L, respectively. Moreover, the incorporation of LID techniques, while incorporating the proposed LIDs, exhibits a substantial reduction of pollutants' amount in runoff ranging from 23 to 80%, depending on the LIDs choices. Considering the cost of installation, operation, and maintenance of proposed LIDs, it has been found that the LCA values of different LIDs vary in a wide range of 15 to 1252 US$ per square meter. While a single LID is not found to provide an effective solution (S2: vegetative swale), the S4 (combination of S2 and S4) appeared to be the most effective, followed by S2 and S3 in terms of quantity, quality, and amenity. It is hoped that the outcomes of this study can be a wakeup call to adopt sustainable urban drainage for addressing multiple benefits in future drainage design and to assist engineers, architect and city planners to manage stormwater runoff in effective ways.

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GLOSSARY OF TERMS

ARIMA	Autoregressive Integrated Moving Average
BECR	Bangladesh Environmental Conservation Rules
BIS	Bureau of Indian Standards
BMD	Bangladesh Meteorological Department
BMPs	Best Management Practices
BOD	Biochemical Oxygen Demand
ChCC	Chattogram City Corporation
CN	Curve Number
COD	Chemical Oxygen Demand
CPA	Chittagong Port Authority
DEM	Digital Elevation Model
DoE	Department of Environment
EPA	Environmental Protection Agency
GUI	Graphical user interface
IDF	Intensity Duration Frequency
LCC	Life Cycle Cost
LID	Low Impact Development
M-K	Mann–Kendall
NPV	Net Present Value
NRCS	Natural Resources Conservation Service
PCSWMM	Personal Computer Storm Water Management Model
SCS	Soil Conservation Service
SPSS	Statistical Package for Social Sciences
S-S	Sen's Slope
SUDs	Sustainable Urban Drainage
SWMM	Storm Water Management Model
TP	Total Phosphorous
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrate
TSS	Total Suspended Solids
USDA	United States Department of Agriculture
USGS	United States Geological Survey
Zn	Zinc

Chapter 1. INTRODUCTION

1.1 General

Urban drainage is a system to discharge the surface runoff and wastewater derived from a watershed or catchment with an aim of avoiding water logging and urban flooding risk (Chocat et al., 2007; Kourtis & Baltas, Tsihrintzis, 2018; Larsen & Gujer, 1997; Marlow et al., 2013; Wong & Brown, 2009). The intensifying urbanization along with the changing climate conditions is resulting in a higher occurrence of urban floods posing a substantial threat to the effective operation of drainage systems (Chen et al., 2009; Hénonin et al., 2010; Kourtis & Baltas, Tsihrintzis, 2018; Schmitt et al., 2004).

The hydrological consequences of urban growth have been well-documented, and it is widely recognized that urban streams undergo substantial changes in their natural flow patterns. These changes primarily result from the increased rate and volume of runoff, which is a direct consequence of urban development. Nevertheless, the urban flooding is a direct output of storms and is more likely to be increased in number with climate change, as reported in literature (Blair & Sanger, 2016; IPCC, 2008; Pryor & Scavia, 2014). To accommodate the increased runoff due to combined actions of urban development and climate change, there is a rising concern about the functionality of the traditional drainage system due to its adverse effect on environment (Roy et al., 2008; Stewart & Hytiris, 2008) especially with runoff quality.

It is worth noting that the traditional urban drainage system only concentrates on managing runoff volume rather than quality and amenity of the system that not only causing water quality problem for receiving water bodies but also raising growing concern from the social and economic acceptances. In developed world the urban drainage city plan has been taken to mitigate floods and improve water quality and thus amenity value (Chen et al., 2017; Yang et al., 2012). The utilization of Low Impact Development (LID) is an integral part of this plan and program, which involves an approach to land development that collaborates with the natural environment to manage stormwater in proximity to its source (Prince George's County, 1999).

Originating in North America, the concept was introduced as a land planning and engineering design strategy to control stormwater runoff. In recent years, it has gained significant traction in the fields of urban planning and water resources management due to its ability to replicate the natural hydrologic cycle of watersheds by infiltrating, filtering, storing, evaporating, and detaining runoff as close to its source as possible. These similar approaches are also seen to be exist in different name in different places, such as Sustainable Urban Drainage Systems (SUDs) highlighting runoff quality, amenity and recreational value, social and ecological protection in the UK (Cidades, 2014), Water Sensitive Urban Drainage (WSUD) (Donofrio et al., 2009) in Australia, Urban drainage in Brazil (EPA, 2018).

Low Impact Development (LID) is an approach that emphasizes the sustainable management of water at a small scale, prioritizing the preservation of water resources, protection of biological diversity, maintenance of good health, and safeguarding of natural resources (Bruijn et al., 2009; Mcdonald, 2018; Willems & Olsson, 2009; Zhou, 2014). More specifically, it is a management practices and control structures which has been designed to discharge out surface runoff in more sustained way (WBC, 2017) which results in increasing natural infiltration, collection of solid using sedimentation, increment of nutrient and hence reduction of pollutant etc.(Grimm, 2007), mimicking natural drainage system.

The LID concept can be divided into three major groups aiming to reduce the quantity of surface runoff, slowing down the velocity in order to allow infiltration and to allow water bound sediment to settle and finally providing treatment before discharge into environment (Lampe et al., 2004). The components mostly highlighted in LID are rainwater harvesting, detention and retention basins, bio-retention system, green roofing, permeable and semipermeable pavement, underground reservoir, grassed strips, attenuation storage system etc. (Reed, 1999; Zhou, 2014). Many researcher agreed LID as an important tool for addressing climate change impacts through attenuating surface runoff and the peak discharge (Willems et al., 2013; Zahmatkesh et al., 2015).

It also provides proper utilization of natural resources which promotes sustainable use of water courses of the biosphere (Butler & Parkinson, 1997). The potential impact of the components of Low Impact Development (LID) on hydrological processes is a subject of significant interest to decision-makers, planners, and designers as it may contribute to build the smart cities (Li et al., 2017). Several studies have demonstrated that incorporating Low Impact Development (LID) practices can have a significant impact on flood control and water balance, such as reducing the volume of storm runoff (Dietz & Clausen, 2008; Jennings & Jarnagin, 2002), altering the ratio of runoff to precipitation (Rushton, 2001), reducing peak flow rate (Guo & Cheng, 2008) and extending the lag time (Zimmer et al., 2007). Vegetative swales (VS), permeable pavement (PP), bio-retention (BR) pits, rainwater harvesting (RWH), and other facilities are frequently utilized in the design of Low Impact Development (LID) for urban catchments. An extensive research on these facilities and their effectiveness (e.g., Hu et al., 2017, 2018), are found to be reported from different watershed.

The phenomenon of Low Impact Developments (LIDs) is influenced by various factors, such as land use and cover changes, societal and economic aspects, and environmental conditions. To fully understand the impacts of LIDs, it is essential to conduct an integrated study that considers all three sustainability themes such as social, economic, and environmental perspectives including implementation aspects. However, such integrated studies on LIDs are limited in number and are highly dependent on the specific context of the area being studied. This means that the results of such studies cannot be generalized to other areas with different land use and cover changes, societal and economic conditions, and environmental factors. Furthermore, there is a clear lack of integrated studies of LIDs in Bangladesh, which makes it difficult to fully understand the impacts of LIDs here.

Previous studies on LIDs in Bangladesh have only focused on one or two sustainability themes, which can not provide a complete understanding of the phenomenon. Therefore, there is a need for more integrated studies on LIDs addressing sustainability themes and are specific to the context of the area being studied. A thorough comprehension of the effects of Low Impact Development (LID) is crucial in the development of effective strategies for sustainable development. Conducting research on LID can facilitate the attainment of this objective.

1.2 Rationale of the research

While the idea and implementation of LIDs are popular in developed countries, there is very limited studies and information available from developing countries. In particular to Bangladesh no such studies to date exists investigating the potential of LIDs in managing urban runoff though major cities like Dhaka and Chattogram are frequently exposed to waterlogging and flooding with moderate rainfall events. As reported in literature, Climate change has rendered Bangladesh as one of the most susceptible nations, it is therefore indeed necessary to assess city drainage system influenced by change climate and change land uses due to unplanned urbanization. Unplanned and uncontrolled urbanization leads more built-up area meaning increased runoff volume, faster peak due to smaller lag time, and end up with polluted runoff to receiving water bodies (Paule-mercado et al., 2017).

The hydrologic performance of Low Impact Development (LID) demonstrates notable variation under different precipitation scenarios (Qin et al., 2013). Pyke et al. (2011) reported that alterations in impervious areas have the greatest impact on runoff volume, followed by changes in total precipitation volume and rainfall intensity. Despite numerous reports suggesting that Low Impact Developments (LIDs) can alleviate water-related issues, their impact on water quality, amenities, and cost-effectiveness in the integrated management of built-up watersheds remains unclear. Do Low Impact Developments (LIDs) perform effectively in all types of storms, and how do changes in rainfall distribution, duration, and intensity impact the effectiveness of LIDs at the watershed scale?

Evaluating the cost-effectiveness of Low Impact Development (LID) options in city drainage construction is vital and imperative to simulate the pre-development state of the watershed ecosystem and, hence, to prevent water pollution while controlling storm water runoff quantity and quality aspects in one framework while induced runoff estimation is well explored, quality and amenity values are not studied in detail.

1.3 Research Hypothesis

The patterns of urban land use have a substantial impact on rainfall induced runoff and associated pollutants to nearby water bodies. Pollutant concentrations are likely to be greater at a site with more built-up and impervious area than at a site with more green and pervious space, considering that runoff is capable of washing off sediment bound pollutants. Furthermore, lined drains are susceptible of higher concentrations in comparison to soft measures, as suggested in LIDs, such as vegetation swales, natural soil, etc. The Life Cycle Cost (LCC) of LID components is expected to be greater than that of traditional treatment choices, however, considering environmental cost given that the efficacy of LID components in lowering water pollution levels is significantly higher with conventional drainage without any amenity value.

1.4 Objectives

The main aim of the study is to evaluate the quantity, quality, and amenity aspects of LIDs components at a watershed scale under different climatic scenarios towards future stormwater management. The specific objectives are as follows:

1. To evaluate the storm runoff quantity and quality performance of LID scenarios in stormwater networks under different hydrological attributes.
2. To quantify the life cycle cost of different LID scenarios in order to identify the most cost-effective option in drainage system.
3. To compare LID options that are cost-effective having satisfactory runoff quality improvement with drainage network amenity aspects.

1.5 Scope of the study

The study focuses on the performance of LIDs components at the watershed scale under diverse climate and land use change scenarios using a part of city drainage network. Furthermore, the cost effectiveness of LID scenarios and identifying the most suited one with recommendations are discussed in relation to sustainable urban drainage system. The following are some notes specifying the scope of this research:

- The research focused on the Chaktai-Rajakhali watershed, through which a substantial amount of stormwater runoff with dry weather flow has been discharged into the Karnaphuli river in Chattogram, Bangladesh.

- The research focused on four primary land use categories, such as residential, commercial, industrial, and institutional, based on the dominant land use types in a specific area. However, it is possible that there are additional types of land use that fall under these main categories.
- The research solely focused on the evaluation of the performance of stormwater-induced runoff. It did not consider other inflows such as dry weather flow, tidal flow, or any other types of flow.
- The study took into account return periods ranging from 2 to 100 years, which is a wider range than the typical range of 2 to 25 years used in conventional drainage design. This is because the design life of LID-induced drainage systems is expected to be longer than that of traditional drainage systems.
- The pollutants concentration in focus were limited to TSS, TN, TP, Zn, BOD and COD for the performance evaluation of different LID options.
- The study used model simulation to assess the performance of six LID options under four different scenarios only.
- In this study, the STEP Life-Cycle Costing tool (Version 3, published in December 2021) is adopted for LCC analysis. LCC costs are adjusted to Bangladesh perspectives through adjustments in unit costs based on different standard schedule rates and as appropriate assumptions were made, such as land cost, discount rate, overhead, profit, contingency, soft expenses, and so on during the Life Cycle Cost analysis for LID practices.

1.6 Limitations of the study

The study provides valuable insights into LID performance, but its limitations must be considered for a more comprehensive understanding of the topic. The following are some notes specifying the limitations of this study:

- This study solely focused on assessing the performance of LID based on meteorological factors while neglecting tidal effects in the simulation model. Additionally, the study did not account for inflows from diverse land uses such as domestic wastewater, industrial discharge, sewerage flow, and so on.

- Tidal effects and wet weather flow may affect the peak runoff in the canals, as well as water quality.
- A continuous stormwater-induced runoff collection for full duration could not be made because that may alter pollutants concentrations.
- Defining four different land use patterns is based on dominant land use types that may also affect runoff volume and quality.
- A few assumptions in the cost per square meter for LCA used in the STEP LCA cost estimation tool may alter cost values in Bangladesh.
- Additional constituents, such as heavy metals and conventional stormwater pollutants (pH, temperature, nutrients, organic matter contents, and so on), are not considered, which are also significant for urban stormwater pollution studies.
- The evaluation of LID options in the study was based solely on a simulation approach, and no practical implementation of these options was carried out.

1.7 Organization of the thesis

This thesis is presented into six chapters. The first chapter provides a brief background on the relevance of LID for urban runoff control, as well as the hypothesis, objectives, and scope of the study.

Following the introduction Chapter 1, Chapter 2 combines the findings of relevant published literature, providing insight into drainage features, current drainage systems, and various aspects of LID components. Furthermore, the research's background is described, and a knowledge gap is highlighted in Chapter 2.

Chapter 3 outlines the materials and methods used for the study, including a description of the study area, sampling locations, site investigations, experimental investigations, and modelling techniques and approaches that were used to conduct this research.

Chapters 4 portray the results and describe the performance of various LID components with their Life Cycle Cost analysis. Chapter 4 mainly focuses on the hydrological performance of various LID components in terms of runoff quantity and quality under various storms. In contrast, Chapter 4 also provides a detailed comparative assessment of the Life Cycle Cost analysis of various LID components.

Finally, Chapter 6 provides the primary conclusions and categorized conclusions based on the findings of Chapters 4 and 5, implications of this study along with suggestions and recommendations for further study.

In addition to the main text, there are a few appendices that include significant supporting data and information. Finally, references cited in the thesis's text are listed as list of references.

Chapter 2. LITERATURE REVIEW

2.1 General

Low Impact Development (LID) is a design approach in land planning and engineering that focuses on managing rainfall locally to reduce runoff and improve water quality. This method has become popular in developing countries' urban drainage systems as a solution to address the challenges posed by rapid urbanization and the effects of climate change. LID components, such as rain barrels, permeable pavement, green roofs, rainwater harvesting, infiltration trenches, and swales, imitate the natural water cycle by filtering, infiltrating, and reusing rainwater. This reduces runoff volume and improves water quality, which is crucial in urban areas where increased impermeable surfaces can lead to runoff and pollution, and where the impacts of climate change such as more intense and frequent rainfall events, are becoming increasingly evident. Despite its potential, there is still a lack of understanding about how to effectively implement LID in developing countries, particularly in regard to technical, social, and institutional obstacles. The purpose of this chapter is to examine the current understanding of LID in urban drainage systems in developing countries and to identify knowledge gaps in the context of the current study, as well as provide a brief overview of the different LID component specifications.

2.2 Climate changes and effects on urban drainage system

Climate change is expected to have a significant impact on urban drainage systems in Bangladesh. The country is in a low-lying delta region and is highly vulnerable to sea level rise and coastal flooding. The projected sea level rise of 0.5-1 meter by the end of the century will increase the frequency and severity of flooding in coastal cities (Begum & Fleming, 1997; Brammer, 2014; Kay et al., 2015) . Additionally, the frequency and intensity of extreme precipitation events is also likely to increase, putting further strain on urban drainage systems. This can cause urban flooding, waterlogging, and sewage overflow in cities and towns. The consequences of these events can be severe, leading to property damage, displacement of people, and public health risks. Urban drainage systems in Bangladesh are often inadequate and unable to handle the increased loads resulting from climate change. The existing systems are often old, poorly maintained, and not designed to handle the increased rainfall and runoff. This means that they are less able to protect urban areas from flooding and waterlogging. In addition, the increased temperatures resulting from climate change can exacerbate the impacts of poor sanitation and water pollution, particularly in low-lying and densely populated areas. To address the impacts of climate change on urban drainage systems in Bangladesh, adaptation measures are needed. These could include the construction of flood protection infrastructure such as sea walls, embankments, and stormwater management systems, as well as changes in land use and building codes to ensure new developments are more resilient to flooding. Additionally, upgrading and maintenance of existing drainage systems are crucial for their proper functioning and to reduce the risk of flooding and waterlogging.

Bangladesh is a low-lying country in south Asia, located between 20º34'N to 26º38'N latitude and 88º01'E to 92º41'E longitude, with heavy rainfall during the summer and monsoon seasons and little rainfall throughout the rest of the year. It is located on the deltas of rivers that start in the Himalayas and run through the nation. The nation is bordered on the south by the Bay of Bengal, on the east by the Assam Hills, and on the north by the Himalayas. Bangladesh is situated in the tropical monsoon season, which means it is hot and humid. Pre-monsoon (March-May), Monsoon (June-September), Post-monsoon (October-November), and Winter are the four major seasons of Bangladesh (December- February) (Hossen, Chowdhury, et al., 2021; Mullick et al., 2019). Variation of rainfall and temperature has received plenty of attention to the international community and policy makers. Observations show that climate change is causing changes in rainfall amount, intensity, frequency, and type. Temperature is rising globally, and rainfall frequency and intensity are fluctuating, according to several studies (Loo et al., 2015; Ozor, 2010; Ogutu et al., 2008). These two parameters fluctuate in different ways in different regions (Mondal et al., 2012). Variability in rainfall and temperature has a significant impact on agricultural activities (Ochieng et al., 2016). The agricultural activities of Bangladesh are also influenced by climatic factors such as rainfall and temperature. Moreover, in any region, rainfall and temperature are considered to be the most significant criteria for managing the agriculture system, productivity, food security, and crop demand (Hussain et al., 2015). Furthermore, analysis of rainfall and temperature variation trend gives useful information for water resources planning, flood control and drought management (Abeysingha et al., 2014). Trend analysis of rainfall and temperature helps to mitigate the effects of climate change (Daramola et al., 2017). Many researchers found that the temperature is increasing day by day and the rainfall pattern is shifting for the onset and cessation months (Daramola et al., 2017; Hussain et al., 2015; John & Brema, 2018) also the changing trend is statistically insignificant (Mondal et al., 2012).

Many researchers have reported a statistically significant increase in temperature in most cities around the world (Koimbori et al., 2018; Panda & Sahu, 2019). In this note, the northern part of Bangladesh is found susceptible to severe weather conditions with intense warming in the southern part (Nasher & Uddin, 2013). Many researchers used ARIMA model for forecasting and predicting climatic parameters (Graham & Mishra, 2017; Hossain et al., 2017; Rahman et al., 2016). The ARIMA model can be applied to rationalize the results from different methods in the present study as well as to justify the outcomes from other works. Mann-Kandall (MK) and Sen's slope (SS) tests are useful for trend analysis and determination of magnitude of change at verified significant level (Ahmad et al., 2015; Pal et al., 2015; Rustum et al., 2017). Bhuyan et al., (2018) predicted temperature will be increased at a rate of 1.62°C and rainfall will be decreased by 40.1 mm during the period 2040-2100 in the north-western region of Bangladesh. Using similar methods, Hossain et al., (2014) investigated the variability of rainfall in Bangladesh's southwest coastal area, finding increasing patterns. Similar type of study is in rudimentary level in the south-eastern region (e. g. Chattogram) of Bangladesh.

2.3 Traditional Versus Sustainable Urban Drainage System (SUDs)

Traditional urban drainage systems use pipes and channels to quickly move stormwater away from developed areas to prevent flooding. Sustainable Urban Drainage Systems (SUDs) on the other hand, mimic natural drainage systems by slowing down and storing stormwater close to its source through techniques like rain barrels, green roofs, permeable pavements, and detention ponds. SUDs not only reduce the risk of flooding but also improve water quality, increase biodiversity, and reduce urban heat island effect. They are more cost-effective, environmentally friendly, and adaptable to the impacts of climate change. Scientists have given much concern about the functionality of the traditional drainage system due to its adverse effect on environment (Roy et al., 2008; Stewart & Hytiris, 2008).

In traditional urban drainage system, surface runoff from impervious areas may increase the occurrences of frequent flooding also may cause sudden rise in water level and may cause poor water quality in natural water bodies. As the rainfall diverted through pipe system in traditional method, the total amount of infiltrated underground reduced which causes depletion of the ground water table (Grimm, 2007),(EA, 2007). There is also limited capacity and flexibility of traditional drainage system to adopt urbanization effect and climate vulnerability (Krebs & Larsen, 1997). Hence the concept Sustainable urban drainage (SUDs) comes to mitigate these problems. Sustainable urban drainage (SUDs) refers to management of water in small scale and facilities surface runoff in a more sustained way focusing on maintaining good health, preserving water resources and protecting biological diversity and natural resources (Bruijn et al., 2009; Mcdonald, 2018; Willems & Olsson, 2009; Zhou, 2014).

Therefore SUDs is a management practices and control structures which has been designed to discharge out surface runoff in more sustained way (WBC, 2017) which results in increasing natural infiltration, collection of solid using sedimentation, increment of nutrient and hence reduction of pollutant etc.(Grimm, 2007). SUDs (known in UK) is known as Low-Impact-Development (LID) in USA and Canada (Cidades, 2014), Water Sensitive Urban Drainage (Donofrio et al., 2009) in Australia, Urban drainage in Brazil (EPA, 2018). When SUDs applies to urban environment, the term may be referred to Best Management Practises (BMPs)(Charlesworth, Harkerand, & Rickard, 2015). The components mostly highlighted in SUDs are rainwater harvesting, detention and retention reservoirs, bio retention system, green roofing, permeable and semipermeable pavement, underground reservoir, grassed strips, attenuation storage system etc.(Reed, 1999; Zhou, 2014).

Surface water run off quality, Surface water run off quantity and amenity are the major issues being considered in SUDs which illustrates the wide concerns of sustainable drainage and may have valuable contribution to sustainable development (CIRIA, 2004), (Mcdonald, 2018). Thus, SUDs can be the effective solution in order to mitigate the problems associated with urban drainage. The SUDs concept can be divided into three major groups aiming to reduce the quantity of surface runoff, slowing down the velocity in order to allow infiltration and to allow settlement and finally providing treatment before discharge onto environment (Lampe et al., 2004). SUDs provide a numbers of benefits that a traditional drainage system unable to facilities. SUDs enhance water quality of a watershed and provides protection to biodiversity in urban water bodies besides it gives protection to people and property from frequent flooding. SUDs protect the water bodies from different type of contamination from both local pollutant as well as from accidental pollution. It also provides proper utilization of natural resources which promotes sustainable use of water courses of the biosphere (Butler & Parkinson, 1997).

Sustainable Urban Drainage Systems (SUDs) are an alternative approach to traditional urban drainage systems that aim to mimic natural drainage systems by slowing down and storing stormwater close to its source. Each type of SUDs has its own unique set of benefits and drawbacks as stated by many researchers (Charlesworth, harkerand & Rickard, 2015; Harker, 2001; Jefferies, Aitken, McLean, Macdonald & McKissock, 1999). Wetland SUDs such as retention ponds and vegetation-based systems have high pollutant removal capacity, large capacity and can operate over a large range of soil types and sizes. They reduce stormwater discharges and have water-quality benefits; however, they can contribute to thermal pollution, cause downstream warming, have high investment and maintenance costs, and may flood wildlife areas. Above-ground SUDs such as permeable surfaces, grass swales, and dry ponds have low investment costs, reduce runoff and minor storms, and have pollution reduction and groundwater recharge benefits. However, they can have high failure rates unless maintained regularly and are only sustainable for small areas. Underground SUDs such as infiltration trenches, filter drains, and soakaways have runoff reduction of minor storms, groundwater recharge, and pollution reduction benefits.

They also take little land from other uses. However, they have high investment costs, can be restricted by soil type, have maintenance costs, and often have a short lifespan. While SUDs have many benefits, their implementation and operation can be challenging. Some of these challenges include issues with modelling and predicting the performance of SUDs, understanding the interactions between SUDs and other water bodies, uncertainty about population growth and costs, and a lack of funding. Despite these challenges, SUDs are widely recognized as an important tool for addressing climate change, as they can help to reduce surface runoff and peak discharge. Many researchers have identified SUDs as an effective means of mitigating the impacts of climate change (Willems et al., 2013; Zahmatkesh et al., 2015).

2.4 LIDs in Sustainable Urban Drainage System (SUDs)

Low Impact Development (LID) is a set of design principles and best management practices that focus on mimicking the natural water cycle by slowing down, spreading out, and infiltrating rainwater close to its source. LID practices include rain barrels, green roofs, bio swales, and permeable pavements. These practices are an essential component of Sustainable Urban Drainage Systems (SUDs) as they help to reduce the amount of stormwater runoff, recharge groundwater, and improve water quality. LID practices can also help to reduce the risk of flooding and erosion, create wildlife habitats, and improve air quality. LID practices are also able to address the impact of climate change by reducing the volume of water that needs to be conveyed and treated, and by reducing the frequency and volume of combined sewer overflow (CSO) events. Additionally, LID approach can be cost-effective as it reduces the need for costly stormwater infrastructure and can even provide additional benefits such as improved aesthetics and increased property values. However, LID practices require proper design, construction, maintenance, and monitoring to ensure their long-term performance and effectiveness. There are several types of Low Impact Development (LID) practices that can be used to manage stormwater runoff and improve water quality. Some of the most common types of LIDs include:

2.4.1 Vegetative Swale

Channels or depressions with sloping sides known as "vegetative swales" are covered in grass and other vegetation (see figure 2.1). They reduce the amount of runoff that is transported and give it more time to saturate the underlying native soil (Rossman, 1975). Vegetated swale (open channel) systems include systems designed to convey and treat either shallow flow (swales) or sheet flow (filter strips) runoff. These practices are explicitly designed to capture and treat the full water quality volume within dry or wet cells formed by check dams or other means (Iastate, 2009).

(a) **(b)**

Figure 2.1 Pictures showing vegetative swale (a) grass swale, (b) dry swale (adopted from Logan Simpson et al., 2015).

Grass Swale

In essence, grass swales (see figure 2.2 and figure 2.3) are standard drainage ditches. They often have softer longitudinal and side slopes than their equivalents with vegetation. Swales with shorter and denser vegetation are typically more expensive than swales with grass. They do, however, offer much less options for infiltration and pollution disposal. Only as a pre-treatment for other structural BMPs, grass swales are to be employed. Grass swales are frequently designed based on rates. Grassed swales are preferable over catch basins and pipes when applicable because they can lower the rate of flow across a place (Pennsylvania DEP, 2006).

Dry swale

The dry swale, also known as a bio-swale, is made up of an open channel that has been modified to improve its capacity to treat water quality by adding a filtering medium made of a dirt bed with an underdrain system (Curry, 1999; Iastate, 2009). The dry swale system is designed to accommodate the entire water quality, allowing it to filter through the treatment medium and/or penetrate through the swale's bottom. The dry swale system is made to drain down in about a day between storm occurrences. This method is preferred for residential applications since it is often dry. The water quality remediation procedures are comparable to bio-retention techniques, but since just a grass cover is present, the pollutant uptake is probably more constrained (Iastate, 2009).

Wet Swales

Linear wetland cells are essentially what wet swales are. They frequently have persistent shallow lakes or marshy areas that can support wetland flora, which might possibly remove a lot of pollutants. Wet swales require either soils with a high-water table or soils with poor drainage. Wet swales have the disadvantage that the shallow standing water may encourage mosquito breeding, at least in residential or commercial environments (follow additional guidance under Constructed Wetland for reducing mosquito population). If water is present for a long time, there is very little infiltration.

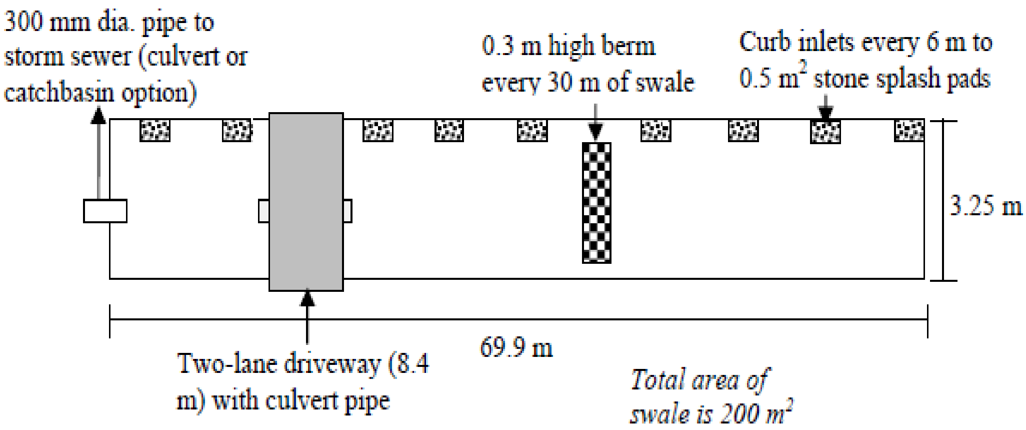


Figure 2.2 Plan view of vegetative swale (Drainage area is 2000 m^2) (adopted from Seters et al., 2013).

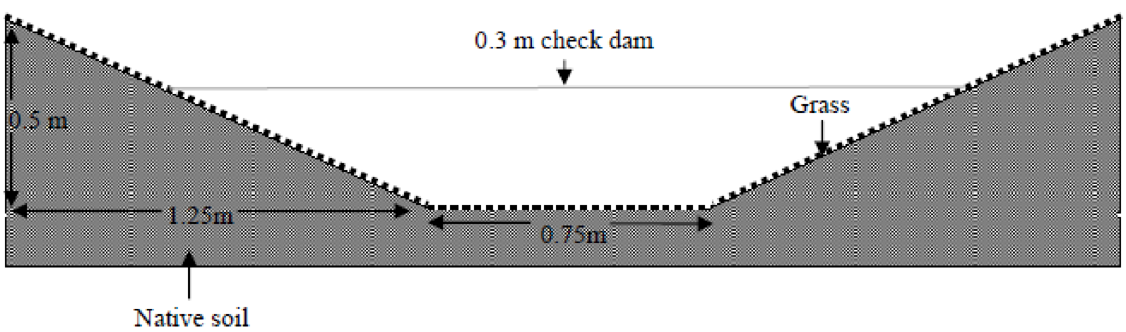


Figure 2.3 Cross section of vegetative swale (adopted from Seters et al., 2013).

Design Consideration

To encourage water infiltration, reduce erosion, and care needs, deep-rooted native plants are ideal. The soil quality at the site should check. More than one-half inch per hour should be the ideal pace for soil infiltration. It could be necessary to amend the soil to get the best infiltration rates. A meandering or linear alignment with side slopes under 4:1 is desirable. Slopes near sidewalks or easily accessible hardscape areas shouldn't be greater than 6:1 (Leaflet, 2020). Grass is planted in the swale, and check dams are placed every 30 meters. The drainage area is one eighth the size of the footprint of the swale (Seters et al., 2013).

A meandering installation should be employed in suburban settings. Urban settings are ideal for linear installations. To find out the greatest depths permitted without a guard rail need, consult the building codes. Any vertical drop greater than 30 inches will need the installation of a guard rail. All swales that hold stormwater must comply with current engineering standards. To guarantee that they transmit stormwater while avoiding erosion damage, channel alignments and side slopes must be built in close collaboration with civil engineers. Use channel stabilization and erosion control strategies to promote long-term establishment of upland and riparian plants (Leaflet, 2020).

Table 2:1 Specifications for the design variables for vegetative swales used in the SWMM model in various studies by researchers worldwide.

Properties	Parameters	Units	(Rossman, 1975)	(Gülbaz & Kazezyilmaz-Alhan, 2014)	(Baek et al., 2015)	(Bai et al., 2019)
Surface	**Berm Height**	mm	0	500	1.97	200
	Vegetation Volume Fraction	n/a	0	0.2	0	0.1
	Surface Roughness	Manning’s n	0.1	0.24	0.24	0.13
	Surface Slope	%	1	1	0.5-4	0.8
	Swale Side Slope	run/rise	5	1	1.0-3	-

Table 2.1 provides an overview of the vegetative swale parameters added in SWMM's Default LID Editor as well as the values used by different studies around the world

(Baek et al., 2015; Bai et al., 2019; Gülbaz & Kazezyilmaz-Alhan, 2014) to characterize the systems (Jato-Espino et al., 2016). These components are mainly Berm Height, Vegetation Volume Fraction, Surface Roughness, Surface Slope, Swale Side Slope, which define surface layer properties (Gülbaz & Kazezyilmaz-Alhan, 2014). Table 2.1 shows that the values of berm height ranges from (0-500); vegetation volume fraction ranges from (0-0.2), where SWMM and (Baek et al., 2015) proposes similar value; surface roughness ranges from (0.1-0.24), where (Gülbaz & Kazezyilmaz-Alhan, 2014) and (Baek et al., 2015) gives similar values; surface slope ranges from (0.5-1), where SWMM and (Gülbaz & Kazezyilmaz-Alhan, 2014) suggest similar values; swale side slope ranges from (1-5), where authors shows distinction. Comparing these values with the values of Table 2.1, berm height is 2.5 times, vegetation volume fraction is 2 times, surface roughness is 15 times, swale side slope is 1.67 times greater than; on the other hand, surface slope is 50% less than the used values in this study (Table 2.1)

2.4.2 Green Roof

Green Roof (see Figure 2.4) is called one type of bio-retention cell, which has a soil layer on top of a particular drainage mat material that drains extra percolated rainfall from the roof (Chung, 2017).

Figure 2.4 Pictures showing typical installed Green Roof system (adopted from LiveRoof, 2022).

Green roofs have been successfully employed in other countries for decades to reduce runoff volume and peak runoff (Li et al., 2017), it enhances the quality of the air and water, and encourage energy conservation (Shafique & Kim, 2015). Above the roofing membrane, a green roof assembly typically consists of the following elements: a root-resistant layer to prevent root damage to the membrane; a drainage layer to remove excess water from the drainage medium; a filter fabric to prevent fine particles from the growing medium from clogging the drainage layer; a growing medium to support healthy plant growth; and plants chosen for their adaptability to the local climate (see Figures 2.5 & 2.6).

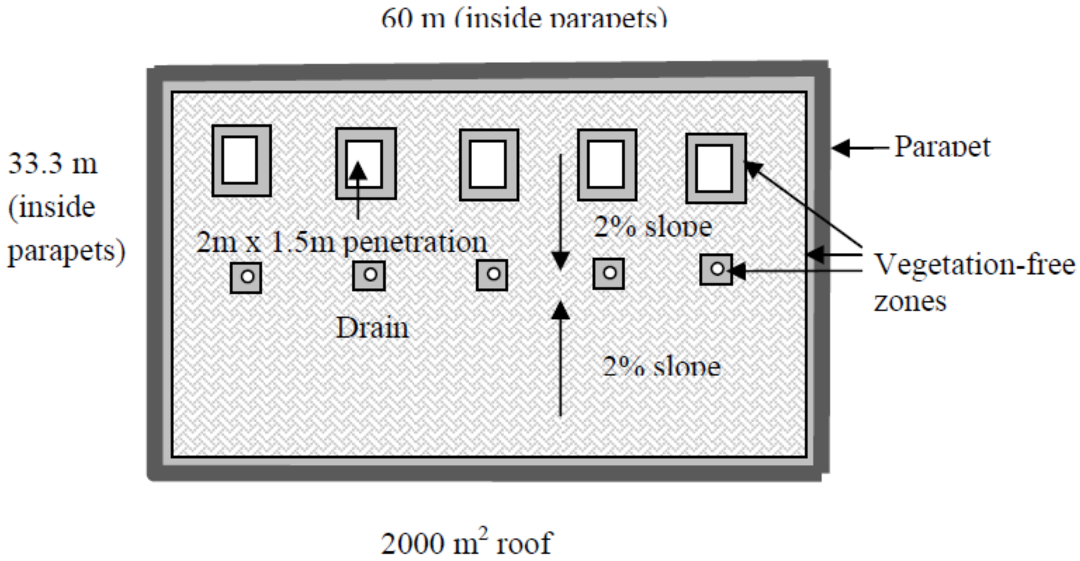


Figure 2.5 Plan view of green roof design (adopted from Seters et al., 2013).

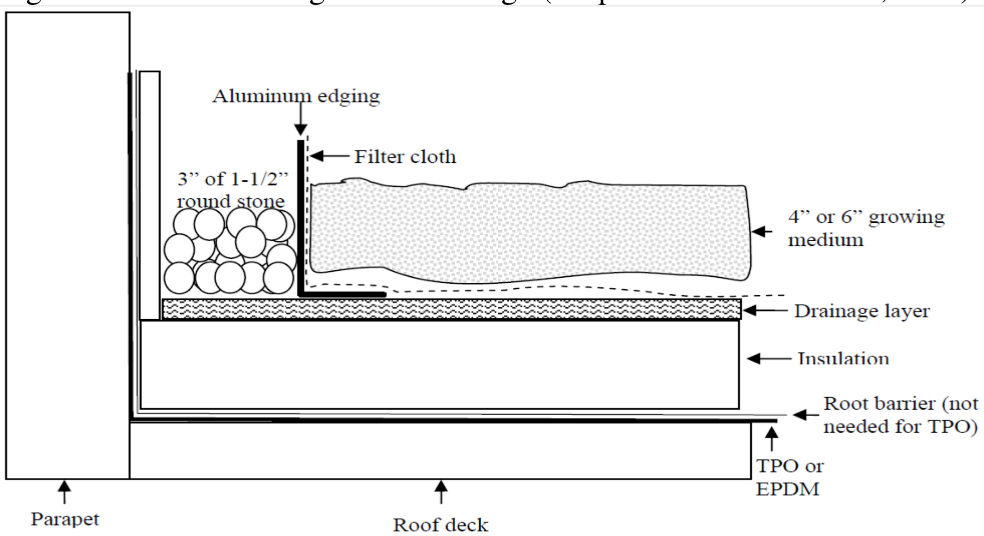


Figure 2.6 Cross section of green roof design (adopted from Seters et al., 2013)

Depending on the chosen plant species, an appropriate irrigation system is required. Green roofs are often divided into two categories: (i) extensive and (ii) intensive. Extensive green roofs have substrate depths of 5 to 15 cm and accommodate low-growing plants. A green roof is often considered intensive if the substrate is deeper than 15 cm (Seters et al., 2013).

Design Consideration

Green roofs are typically built using 2% roof slope is assumed. The green roof is presumably placed as part of the initial new building design, as is the case with other techniques. Considering cost, green roof designs come in two variations, cheap and expensive. The cheap method is done by a sedum cutting system with a 10 cm growing media on a structure for no taller than five stories, which makes it simpler to place the plants and other components for a green roof on the roof. There are no pathways, fences, or other accessibility-enhancing elements in this environment. The water leakage test is a less complex and pricey test than the more complex ones.

It uses a TPO (thermoplastic polyolefin) waterproof membrane. In this case, a complex water leakage test is conducted, the building is over five storeys tall, and the waterproof membrane is more expensive. It also comes with a 15 cm growing media, an irrigation system, more expensive edging, and a root barrier. Sedum mats, which are far more expensive than sedum plugs or cuttings, are where the plants are found (Figure 2.3). In this instance, a more costly EPDM (Ethylene Propylene Diene Monomer) waterproof membrane was utilized (Seters et al., 2013).

Green roof's parameters including surface, soil, drainage mat layers are listed in table 2.2 (Gülbaz & Kazezyilmaz-Alhan, 2014), which are used further analysis in SWMM model. These parameters' values are taken from different literatures (Abualfaraj et al., 2018; Baek et al., 2015; Chui et al., 2016; Jato-Espino et al., 2016; Kourtis & Baltas, Vassilios Tsihrintzis, 2018; Leimgruber et al., 2018; Wu et al., 2018) around the world . Baek et al. (2015), Chui et al. (2016) and Wu et al. (2018)) reported similarity in case of surface slope for surface properties and porosity, field capacity for Soil properties. Kourtis & Baltas, Tsihrintzis (2018) and Kourtis & Baltas, Tsihrintzis, (2018) suggested same value for soil thickness, wilting point and conductivity slope and Chui et al. (2016) and Wu et al. (2018) proposed same value for void fraction and roughness parameter for drainage mat properties.

Table 2:2 Specifications for the design variables for green roofs used in the SWMM model in various studies by researchers worldwide

Properties	Parameters	Units	**(Rossman, 1975)**	**(Martin-Mikle et al., 2015)**	(W. Yang et al., 2020)	**(Baek et al., 2015)**	**(Abualfaraj et al., 2018)**	**(Leimgruber et al., 2018)**	**(Kourtis & Baltas, Vassilios A. Tsihrintzis, 2018)**	**(Jato-Espino et al., 2016)**
Surface	Berm Height	mm	3	25mm	12.4-24.8(mm)	3mm	-	0-80	100	-
	Vegetation Volume Fraction	-	0.2	0.1	0	0.1	0.9	0-0.2	0.2	0.5
	Surface Roughness	Manning's n	0.1	0.1	0.1	0.017	0.035	.04-.35	0.25	0.15
	Surface Slope	%	1	1	1	1	1.5	2-100	1	
Soil	Thickness	mm	6	Variable	74.9-149.8	100	25.5	40-200	200	100
	Porosity	-	0.5	0.5	0.5	0.5	0.4139	0.36-0.65	0.5	0.5
	Field Capacity	-	0.2	0.2	0.2	0.2	0.371	0.1-0.35	0.4	0.2
	Wilting Point	-	0.1	0.1	0.1	0.024	0.12	0	0.1	0.1
	Conductivity	mm/hr	0.5	750	0.5	30	381	18-100	1000	12.7
	Conductivity Slope	-	10	10	10	5	--	30-55	10	10
	Suction Head	mm	3.5	87.5	3.5	60	-	50-100	50	88.9
Drainage Mat	Thickness	mm	1	75	-	3	76.2	13-50	100	10
	Void Fraction	-	0.5	0.5	-	0.5	0.75	0.2-0.4	0.3	0.75
	Roughness	Manning's n	0	0.1	-	0.1	0.05	0.01-0.03	0.015	0.03

Table 2.2 also shows that authors define surface properties, soil properties and drainage mat properties by berm height, conductivity & suction head and thickness respectively by different value. Abualfaraj et al., (2018), Leimgruber et al. (2018) and Kourtis & Baltas, Vassilios Tsihrintzis (2018) shows distinction for Berm Height, Vegetation Volume Fraction, Surface Roughness, Surface Slope of surface properties; Thickness, Porosity, Field Capacity, Wilting Point, Conductivity, Conductivity Slope,

Suction Head of soil properties; Thickness, Void Fraction, Roughness of drainage mat. Comparing with the value of Table 2.2, surface roughness is 2.33 times, surface slope is 100 times, soil conductivity is 10 times, soil suction head is 1.67 times, drainage thickness is 1.33 times higher than. Conversely, in comparison to table 2.2 values, the values of surface berm height are 88%, soil thickness is 94%, soil porosity is 28%, wilting point for soil is 76%, void fraction for drainage mat is 60%, drainage roughness is 90% less than the used values in this study (Table 2.2).

2.4.3 Permeable Pavement

Permeable pavement, as presented in Figure 2.7, are places that have been excavated, filled with gravel, and resurfaced with porous concrete or asphalt mixture, stabilized aggregate, structural grid, permeable pavers (Chung, 2017; Logan Simpson et al., 2015).

Figure 2.7 Pictures showing permeable pavement (adopted from Rossman, 1975).

In a typical scenario, all precipitation will quickly flow through the pavement and into the gravel storage layer beneath it, where it might gradually seep into the native soil of the site (Rossman, 1975). Stabilized aggregate permits surface water to permeate the subgrade, minimizing (or eliminating) runoff and offering large storage volume. Porous asphalt and porous concrete can reduce pollutants in runoff before it is discharged into storm sewer systems and can decrease the velocity and volume of stormwater runoff transported into those systems. Structural Grid Systems allow water to permeate through sizable gaps filled with aggregate stone, topsoil, or turf grass (Logan Simpson et al., 2015).

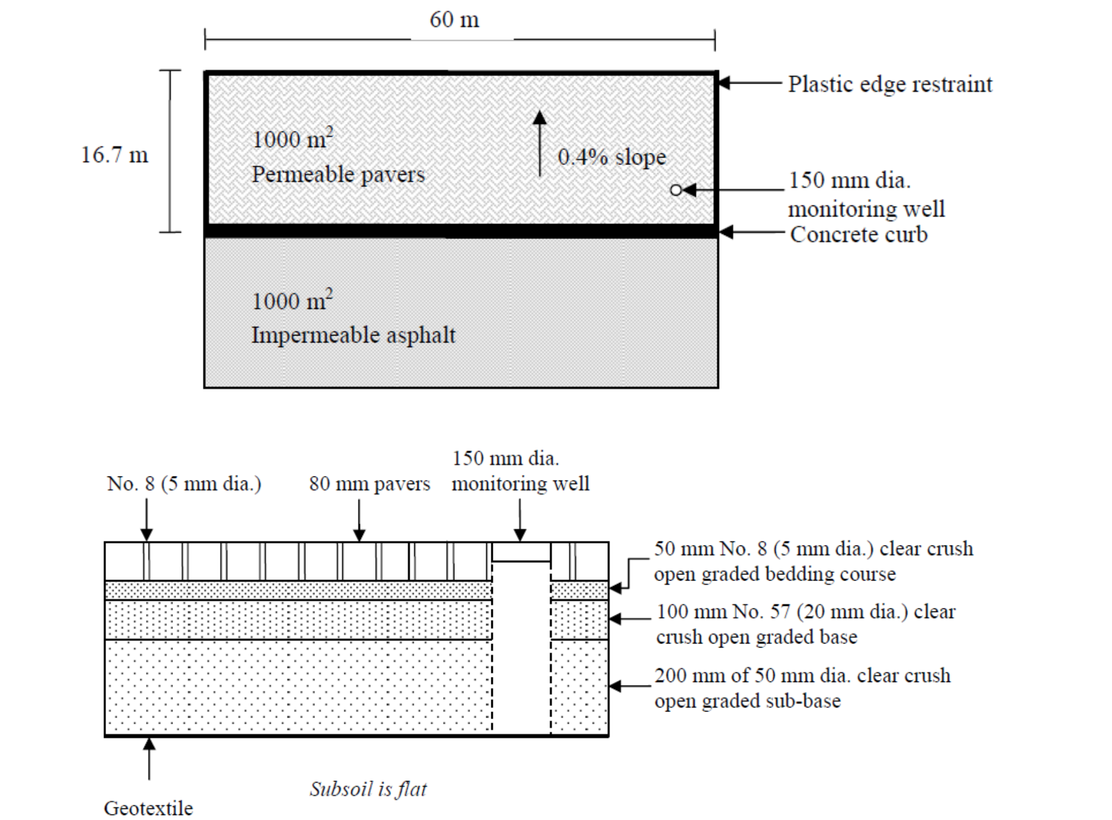
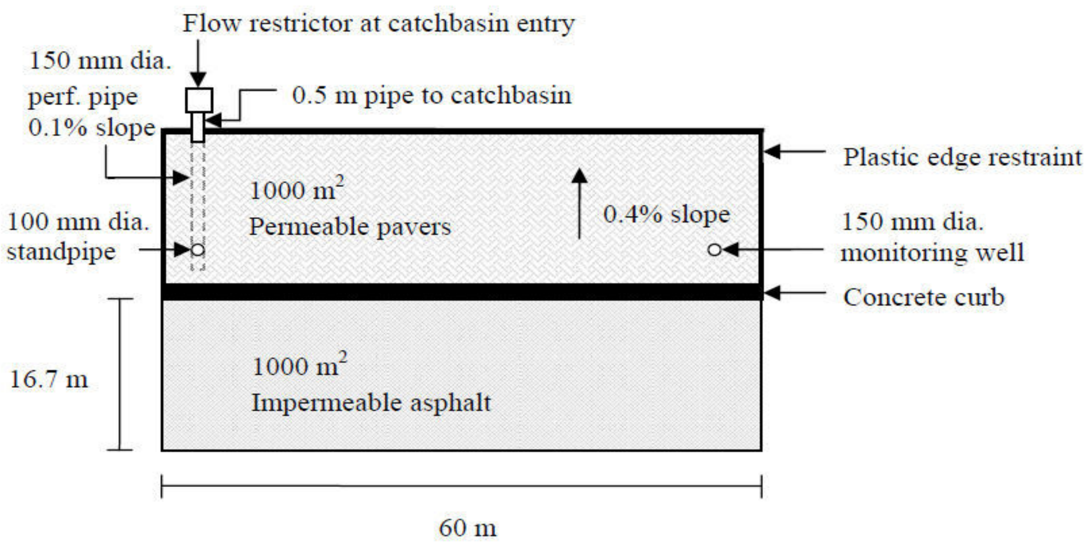


Figure 2.8 Permeable pavement full infiltration design illustrating plan view (top) and cross section (bottom) (adopted from Seters et al., 2013).



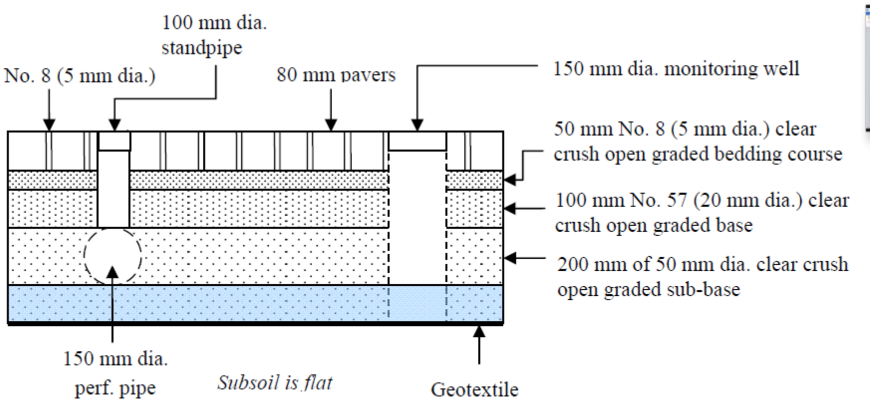


Figure 2.9 Permeable pavement showing partial infiltration design plan view (top) and cross section(bottom) (Seters et al., 2013).

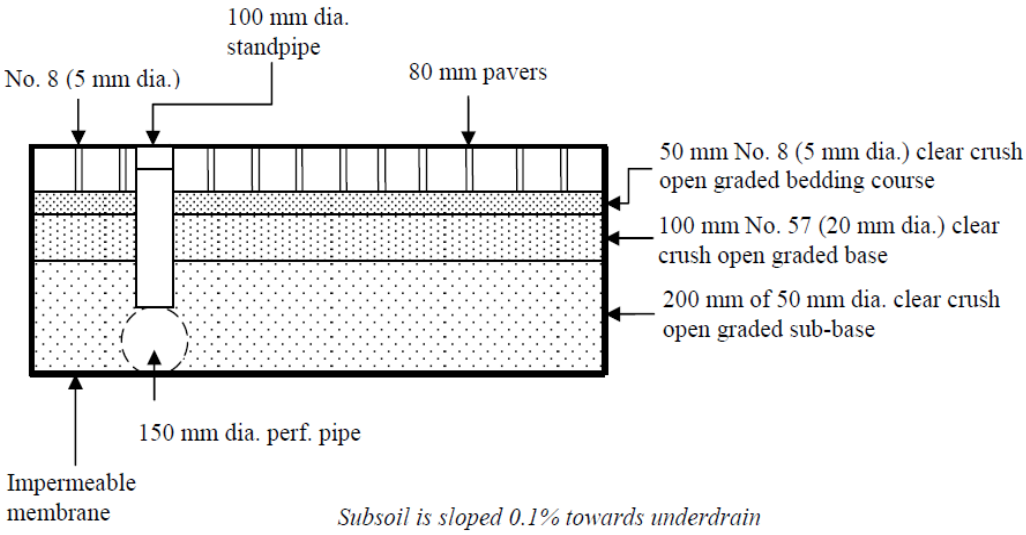


Figure 2.10 Permeable pavement no infiltration design. Plan view (top); cross section (bottom) (adopted from Seters et al., 2013).

Design Consideration

Full infiltration

The pavement may be constructed for full infiltration after compaction, if the subsurface beneath the pavement has a permeability of at least 15 mm/h. Without underdrains, the 350 mm-deep base granular reservoir can hold the runoff from a 61 mm rain event across the catchment area (Figures 2.7 to 2.10). A monitoring well is incorporated for inspection purposes, and plastic edge restraints are utilized to stop paver drooping around the edges (Seters et al., 2013).

Partial infiltration

Where the post-compaction permeability of the native subsoil is less than 15 mm/h, a partial infiltration method is used. The system is equally deep as the full infiltration system, but it also incorporates an underdrain to ensure complete drainage in between downpours (Figures 2.7 to 2.10). To permit some infiltration, the perforated pipe in this instance is elevated by about 50 mm above the surrounding subsoil. A flow restrictor is occasionally used to keep water in the base above the perforated underdrain and thus encourage higher infiltration because the depth below the underdrain can only store runoff from a 9 mm event. The price of this feature has not been factored in because these restrictors are optional and reasonably priced (Seters et al., 2013).

No infiltration

When infiltration is undesirable, no infiltration systems are used. In this scenario, the pavement structure would aid in filtration of toxins, but runoff would not be decreased. The impermeable liner that encloses the pavement base and sidewalls is the main extra feature (Figures 2.7 to 2.10) (Seters et al., 2013). Table 2.3 lists the parameters of permeable pavement for surface, pavement, storage and underdrain properties, which are used for further study in the SWMM model. The values of these parameters are obtained from several international literatures (Abualfaraj et al., 2018; Baek et al., 2015; Chui et al., 2016; Jato-Espino et al., 2016; Kourtis & Baltas, Tsihrintzis, 2018; Leimgruber et al., 2018; Wu et al., 2018).

Table 2.3 shows that the values of surface berm height ranges from (0-2), where Wu et al., (2018) reported surface roughness ranges from (0.012-0.1), where SWMM, Jato-Espino et al., (2016) and Wu et al., (2018) showed similarity; surface slope ranges from (0.5-2). Whereas Baek et al., (2015), Chui et al., (2016), Wu et al., (2018) and Kourtis & Baltas, Tsihrintzis, (2018) give similar value; pavement thickness ranges from (0-3084.92), where (Wu et al., 2018) and (Jato-Espino et al., 2016) give similar value; void ratio ranges from (0.12-0.25), where (Chui et al., 2016) and (Kourtis &

Baltas, Tsihrintzis, 2018) give similar value; pavement permeability ranges from (6.6-500), where (Chui et al., 2016; Kourtis & Baltas, Tsihrintzis, 2018) and (Wu et al., 2018) give similar value; storage thickness ranges from (12-2286 mm).

Table 2:3 Specifications for the design variables for permeable pavements used in the SWMM model in various studies by researchers worldwide.

Properties	Parameters	Units	**(Rossman, 1975)**	**(Chui et al., 2016)**	**(Baek et al., 2015)**	**(Wu et al., 2018)**	**(Zahmatkesh et al., 2014)**	**(Kourtis & Baltas, Tsihrintzis, 2018)**	**(Jato-Espino et al., 2016)**
Surface	Berm Height	mm	1	-	-	2	-	-	-
	Vegetation Volume Fraction	-	0.1	-	-	-	-	-	-
	Surface Roughness	Mannings n	0.02	0.012	0.1	0.014	0.03	0.015	0.02
	Surface Slope	%	2	1	1	1	0.5	1	-
Pavement	Thickness	mm	8	Variable	0-3084.92	100	158.75	150	100
	Void Ratio	voids/solids	0.15	0.15	0.12	0.25	0	0.15	0.2
	Impervious Surface Fraction	-	-	-	-	-	-	-	-
	Permeability	mm/hr	100	500	Over 6.6	250	0	500	254
	Clogging Factor	-	-	-	9179	-	-	-	-
	Regeneration Interval	days	-	-	-	-	-	-	-
	Regeneration Fraction	-	-	-	-	-	-	-	-
Storage	Thickness	mm	12	300	149.8-449.8	150	2286	400	300
	Void Ratio	voids/solids	0.75	0.4	0.5-0.75	0.4	0.5	0.3	0.6
	Seepage Rate	mm/hr	0.2	750	10	1.2	1905	750	3.3
	Clogging Factor	-	-	-	7042	-	-	-	-
Underdrain	Flow Coefficient	mm/hr	-	0.5	-	-	6.35	-	-
	Flow Exponent	-	0.5	0.5	0.5	-	0.5	-	-
	Offset Height	mm	-	100	-	-	-	-	-
	Open Level	mm	-	-	-	-	-	-	-
	Closed Level	mm	-	-	-	-	-	-	-

Storage void ratio ranges from (0.3-0.75), where Chui et al. (2016) and Wu et al. (2018) give similar value; storage seepage ratio ranges from (1.2-1905), where Chui et al. (2016), Kourtis & Baltas, Tsihrintzis (2018) and Wu et al. (2018) give similar value. Comparing these values with the values of Table 2.3, it can be seen that surface roughness is 2.5 times, pavement thickness is 30.85 times, pavement permeability is 2 times, storage thickness is 15.24 times, void ratio is 1.87 times, seepage rate is 1587.5 times higher than the used values in this study. Conversely, in comparison to table 2.3 values, the values of berm height are 50%, surface slope is 50%, pavement void ratio is 52% lower (Table 2.3).

2.4.4 Bio-Retention Cell

Bioretention cells are small depressions lined with plants that are tailored to the soil and climate of the area and a specially designed soil mixture that is layered over a gravel drainage bed (Chung, 2017; Logan Simpson et al., 2015).

Figure 2.11 Pictures showing Bio-Retention Cells (adopted from Logan Simpson et al., 2015).

The most prevalent elements of bio retention cell practices are a shallow, excavated depression with layers of stone, prepared soil mix, mulch, and specifically chosen native plant that is tolerant of road salt and periodic inundation (Seters et al., 2013). These are utilized in areas that are more urbanized and where the subsoil is permeable and allows for penetration into the subgrade (Logan Simpson et al., 2015). Bio-retention utilizes the inherent qualities of soils, plants, and associated microbial activity to infiltrate water and filter pollutants out of storm water runoff (Seters et al., 2013). Depending on the project's scope and the underlying soil permeability, bio-retention can be implemented with full, partial, or no infiltration (Seters et al., 2013).

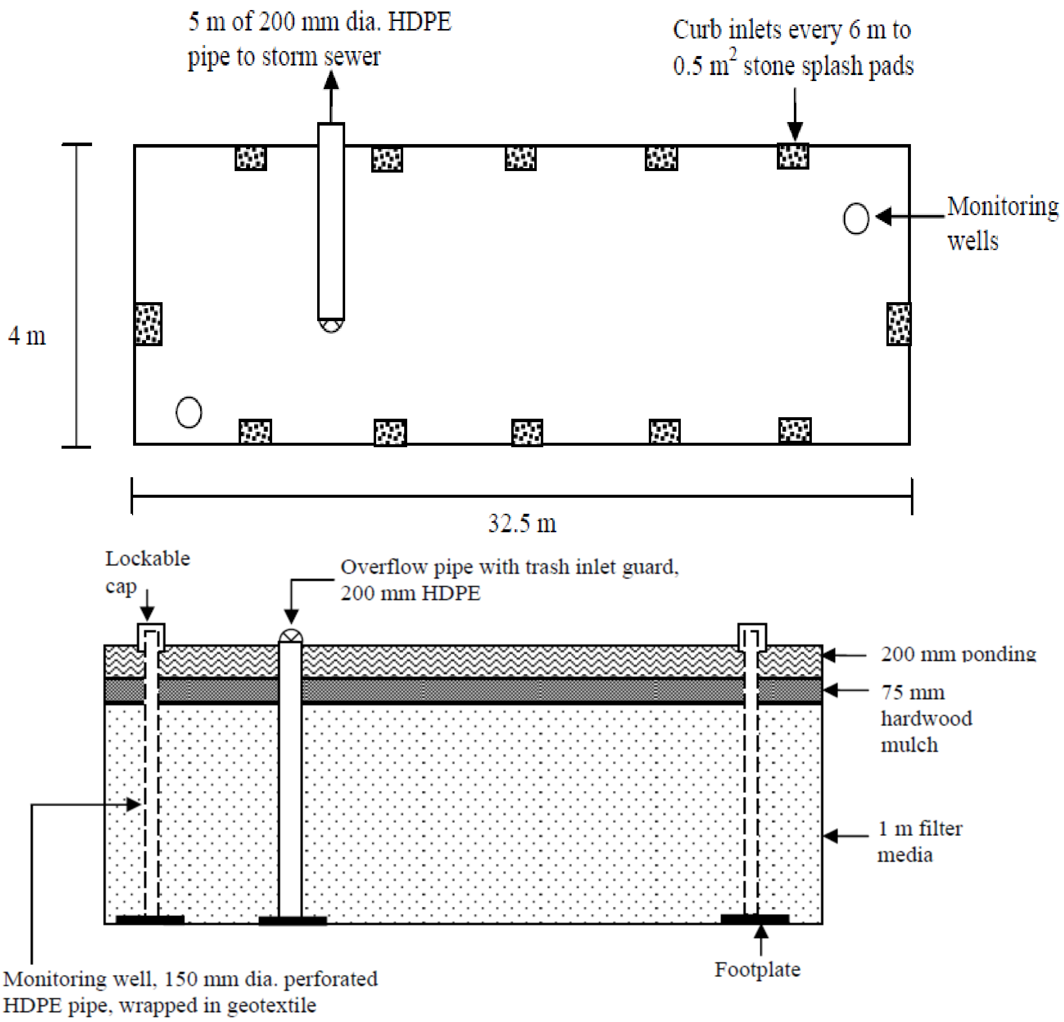


Figure 2.12 Typical Bio-retention full infiltration design. Plan view (top) and cross section (bottom) (Seters et al., 2013).

Figure 2.12 represents bio-retention full infiltration design through plan view and cross section view. Where the native soils are comparatively permeable (>15 mm/h), bio-retention areas designed for full infiltration are created without underdrains. In the basic layout that was used for pricing (see Figure 2.12), runoff from a 2000 m^2 parking lot drains into a 130 m^2 system through curb inlets that are 6 m apart and include splash pads to reduce the force of the flowing water. In relation to the facility's footprint, the drainage area is approximately 15 times larger (Seters et al., 2013).

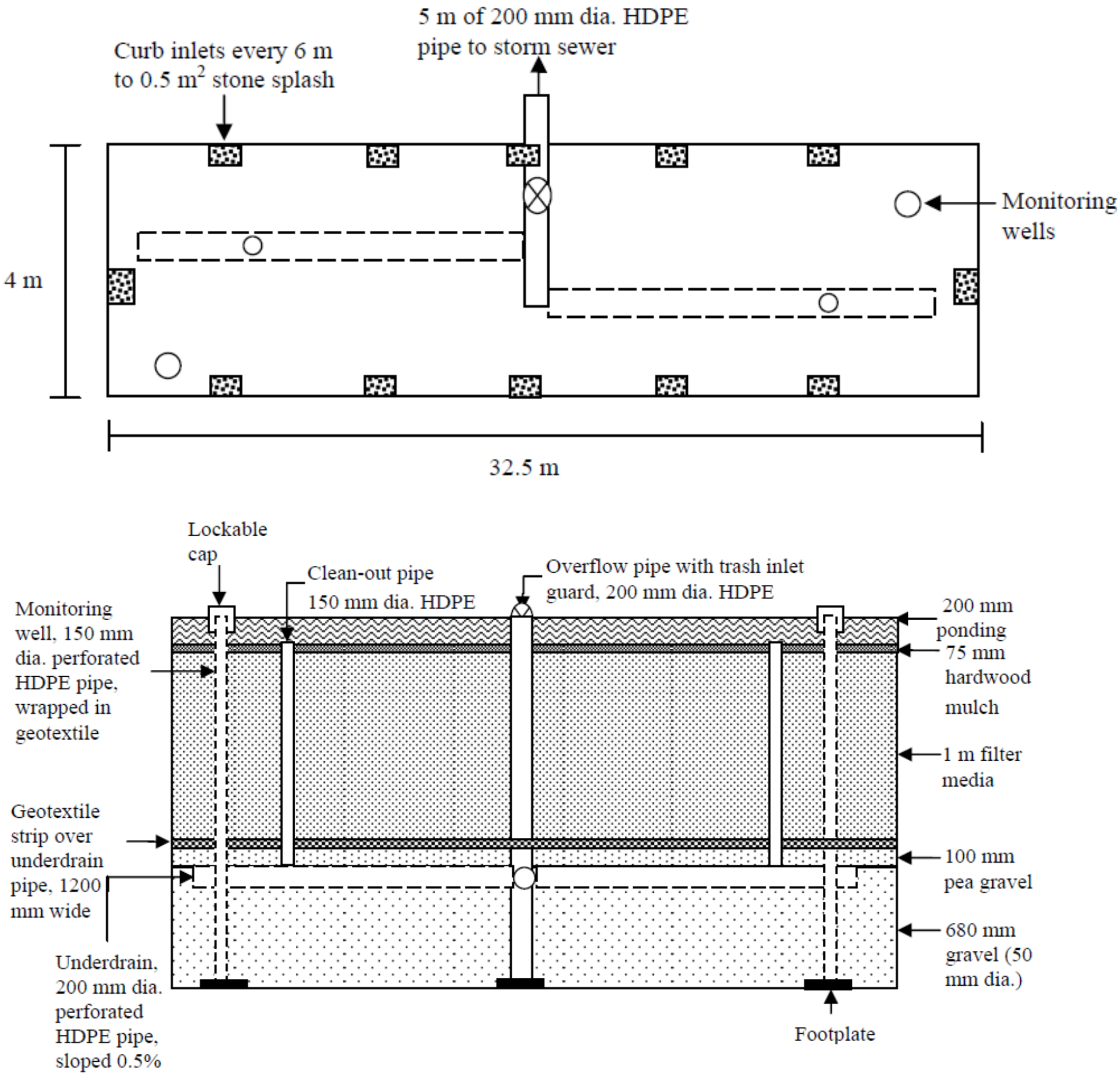


Figure 2.13 Typical Bio-retention partial infiltration design. Plan view (top); cross section (bottom) (Seters et al., 2013).

The partial infiltration system seen in Figure 2.13 is comparable to the full infiltration system, but it also has a raised underdrain and a granular storage reservoir, resulting in an increase in depth from 1.28m in the full infiltration example to just over 2 m. The amount of granular material below the underdrain was designed to hold and allow infiltration of runoff from a 25 mm event across the drainage region, excluding moisture retention in the soils above (Seters et al., 2013).

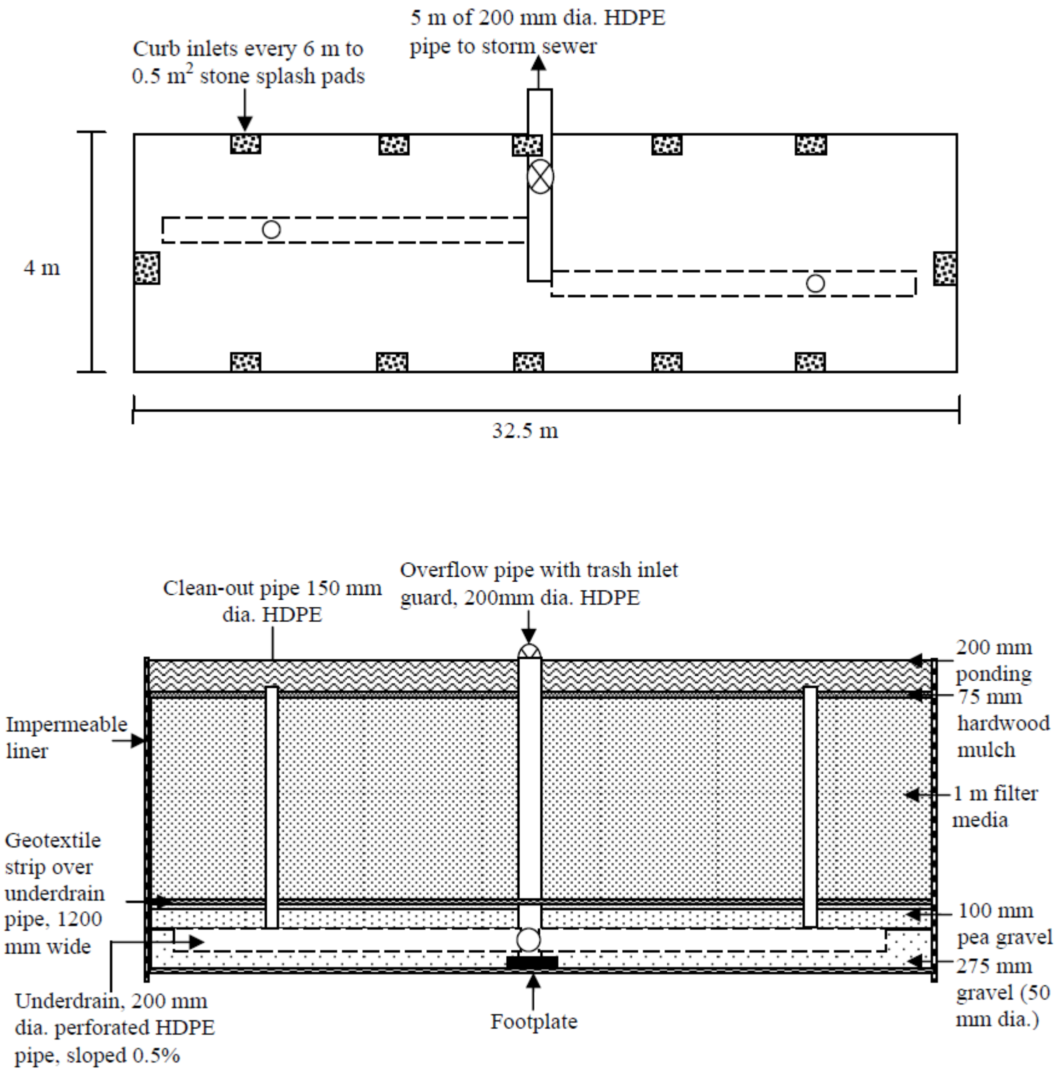


Figure 2.14 Bio-retention (no infiltration) design. Plan view (top); cross section (bottom) (Seters et al., 2013).

Figure 2.14 represents bio-retention no infiltration design through plan view and cross section view. The least popular design is one that forbids infiltration; it is only used in situations where infiltration is prohibited. The granular reservoir has an impermeable liner and is 40 cm shallower in the no infiltration model design than the partial infiltration model design (Figure 2.14). It mostly serves as a filtering system to improve the quality of the water, with some runoff being reduced by plant evapotranspiration.

Table 2.4 gives a summary of the bio-retention cell parameters included in SWMM's default LID editor as well as the values adopted by other research internationally (Baek et al., 2015; Chaosakul et al., 2013; Chui et al., 2016; Leimgruber et al., 2018) to characterize the systems (Jato-Espino et al., 2016).

Table 2:4 Specifications for the design variables for Bio-retention cells used in the SWMM model in various studies by researchers worldwide.

Properties	Parameters	Units	**(Rossman, 1975)**	**(Chui et al., 2016)**	**(Baek et al., 2015)**	**(Chaosakul et al., 2013)**	**(Leimgruber et al., 2018)**
Surface	Berm Height	mm	6	150	Below 151.8	200	150-300
	Vegetation Volume Fraction	-	0	0.1	0	0.7	0-0.2
	Surface Roughness	Manning's n	0.2	0.1	0.1	0.3	0.04-0.35
	Surface Slope	%	0	1	1	0	0-10
Soil	Thickness	mm	12	Variable	449.8 - 899.9	1075	300-2000
	Porosity	-	0.5	0.5	0.5	0.5	0.3-0.55
	Field Capacity	-	0.2	0.2	0.2	0.3	0.01-0.2
	Wilting Point	-	0.1	0.1	0.1	0.1	0
	Conductivity	mm/hr	0.5	250	0.5	10.9	50-140
	Conductivity Slope	-	10	10	10	10	30-55
	Suction Head	mm	3.5	87.5	3.5	110.1	50-100
Storage	Thickness	mm	12	500	149.8 - 449.8	400	150-1500
	Void Ratio	-	0.5	0.75	0.5-0.75	0.75	0.2-0.4
	Seepage Rate	mm/hr	0.5	750	10	6	7.2-72
	Clogging Factor	-	0.2	0	7042	-	-
Underdrain	Flow Coefficient	mm/hr	0	0.5	0	-	-
	Flow Exponent	-	1	0.5	0.5	-	-
	Offset Height	mm	0.5	150	0	-	-
	Open Level	mm	-	-	-	-	-
	Closed Level	mm	-	-	-	-	-

These parameters are mainly Berm Height, Vegetation Volume Fraction, Surface Roughness, Surface Slope; Thickness, Porosity, Field Capacity, Wilting Point, Conductivity, Conductivity Slope, Suction Head; Thickness, Void Ratio, Seepage Rate, Clogging Factor; Flow Coefficient, Flow Exponent, Offset Height, Open Level, Closed Level; which define surface, soil, storage, underdrain properties respectively (Gülbaz & Kazezyilmaz-Alhan, 2014).

Table 2.4 also illustrates that the values of berm height ranges from (6-300); Vegetation Volume Fraction ranges from (0-0.7); Surface Roughness ranges from (0.05-0.35), where (Chui et al., 2016) and (Baek et al., 2015) give similar value; Surface Slope ranges from (0-10); soil thickness ranges from (12-2000); soil porosity ranges from (0.3-0.55), where Baek et al., (2015), Chaosakul et al., (2013), Chui et al., (2016) give similar value; soil conductivity ranges from (0.5-250), where SWMM and (Baek et al., 2015) give same value; soil suction head ranges from (3.5-110.1); storage thickness ranges from (12-1500); storage void ratio ranges from (0.2-0.75), where (Baek et al., 2015; Chaosakul et al., 2013; Chui et al., 2016) give similar value; storage seepage rate ranges from (0.5-750).

Comparing these values with the values in table 2.4, surface berm height is 2 times, Vegetation Volume Fraction is 7 times, surface roughness is 3.5 times, surface slope is 10 times, soil thickness is 4 times, conductivity is 500 times, suction head is 31.45 times higher than the used values in this study. On the other hand, storage thickness is 97.6%, storage void ratio is 73.33%, storage seepage rate is 95% less than the used values in this study (table 2.4).

2.4.5 Infiltration Trench

Infiltration trenches (see figure 2.15) are small gravel-filled ditches that intercept rainwater from upslope impermeable regions (Chung, 2017). Rectangular excavations with finely ground stone constitute infiltration trenches. A perforated pipe allows runoff from roads or roofs to enter the system, carrying the water to a trench where it can seep into the subsoil. This component are frequently utilized in confined places where surface portions are either unavailable or reserved for other purposes (Seters et al., 2013).

Figure 2.15 Pictures showing typical Infiltration trench (Wales, 2022)

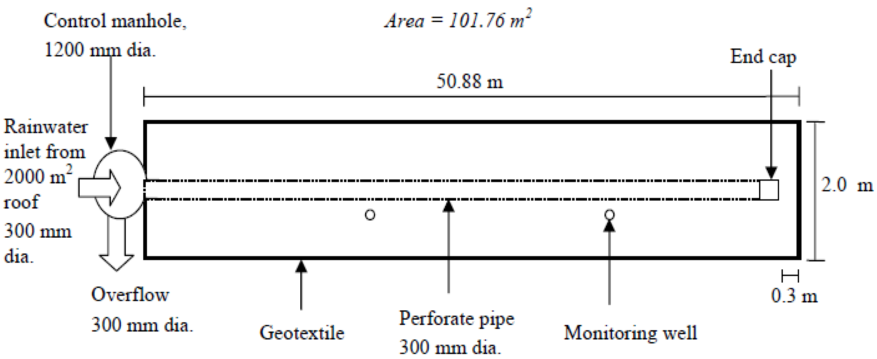


Figure 2.16 Plan view of the infiltration trench receiving roof runoff only (adopted from Seters et al., 2013).

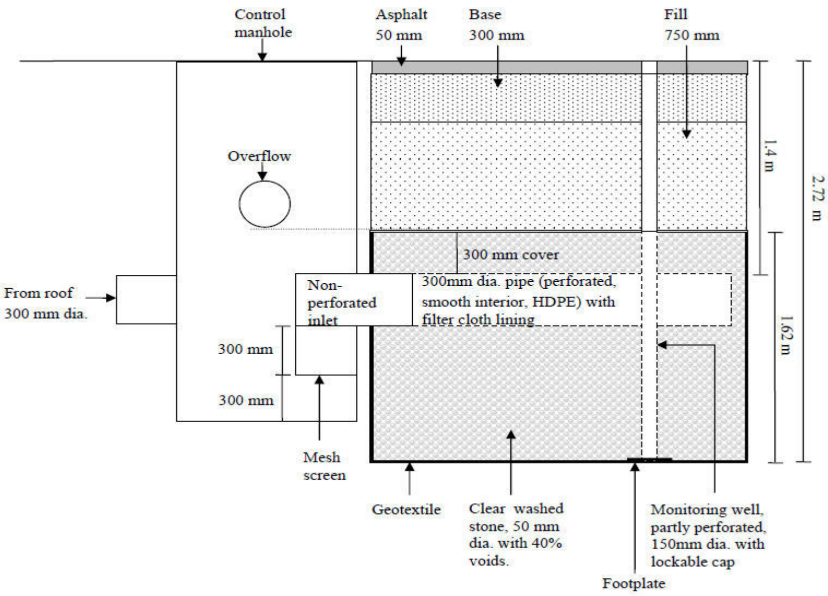


Figure 2.17 Cross section of infiltration trench receiving roof runoff only (Seters et al., 2013).

Figures 2.16 & 2.17 represent plan view and cross section view of infiltration trench receiving roof runoff only. In this case, runoff from a 2000 m^2 industrial or commercial roof drains into a 2 x 51 m trench via a control manhole (see figures 2.16 & 2.17). The building's footprint is around one twentieth the size of the roof.

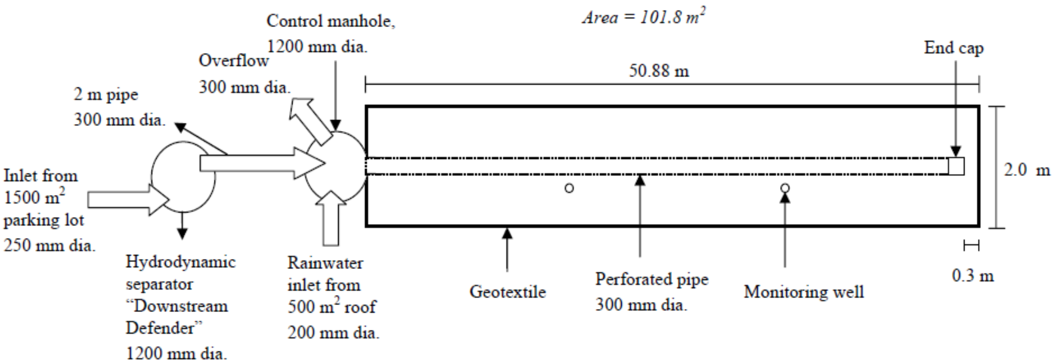


Figure 2.18 Typical plan view of the infiltration trench receiving road (1500 m^2) and roof runoff (500 m^2) (Seters et al., 2013).

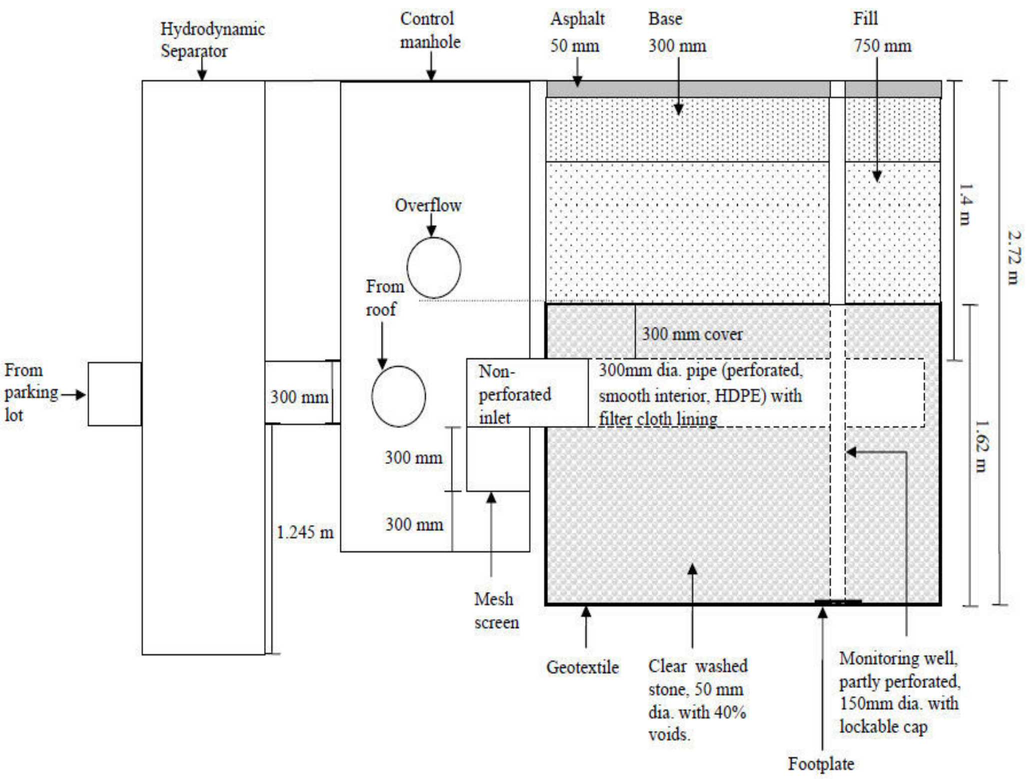


Figure 2.19 Typical cross section of the infiltration trench receiving road (1500 m^2) and roof runoff (500 m^2) (Seters et al., 2013).

The system, which has a 1.62 m depth, can hold runoff from a 29 mm rain event. Storm sewer pipes that contribute provide additional storage. To avoid freezing, the overflow's invert is 1.2 meters below the surface. There is no pre-treatment other than a slump in the manhole, which enables some settling of bigger materials. Monitoring wells are offered to make inspections easier.

Figures 2.18 & 2.19 represent plan view and cross section view of infiltration trench receiving road and roof runoff. The drainage region in this case is made up of both road runoff and roof runoff, with the road runoff component receiving pre-treatment through a hydrodynamic separator. Without any pre-treatment, the roof runoff part pours directly into the control manhole. The hydrodynamic separation would need to be larger if the road and roof runoff were merged in one sewer.

Table 2:5 Specifications for the design variables for infiltration trench used in the SWMM model in various studies by researchers worldwide

Properties	Parameters	Units	**(Rossman, 1975)**	**(Baek et al., 2015)**	**(Leimgruber et al., 2018)**
Surface	Berm Height	Mm	0	0	0-300
	Vegetation Volume Fraction	-	0	0	0
	Surface Roughness	Manning's n	0.24	0.1	0.012-0.03
	Surface Slope	%	0.4	1	0-10
Storage	Thickness	Mm	36	149.8-449.8	900-3650
	Void Ratio	-	0.4	0.5-0.75	0.2-0.4
	Seepage Rate	mm/hr	0.2	10	7.2-72
	Clogging Factor	-	0	2817	-
Underdrain	Flow Coefficient	-	0	0	-
	Flow Exponent	-	0.5	0.5	-
	Offset Height	Mm	0	0	-
	Open Level	Mm	-	-	-
	Closed Level	Mm	-	-	-

Table 2.5 lists the parameters of infiltration trench for surface, storage, and underdrain properties, which are used for further study in the SWMM model. These parameters are mainly Berm Height, Vegetation Volume Fraction, Surface Roughness, Surface Slope; Thickness, Void Ratio, Seepage Rate, Clogging Factor; Flow Coefficient, Flow Exponent, Offset Height, Open Level, Closed Level; which define surface, storage,

underdrain properties respectively (Gülbaz & Kazezyilmaz-Alhan, 2014). These values are taken from different literatures (Baek et al., 2015; Leimgruber et al., 2018) around the world (Chui et al., 2016). Table 2.5 shows that the values of Berm Height ranges from (0-300); Surface Roughness ranges from (0.012-0.24); Surface Slope ranges from (0.4-10); storage thickness ranges from (36-3650); storage void ratio ranges from (0.2-0.75); storage seepage rate ranges from (0.2-72). Comparing these values with table 2.5, it can be seen that the berm height is 3 times, storage thickness is 7.3 times, storage seepage ratio is 7.2 times higher than the typically used values (Table 2.5). Conversely, in comparison to table 2.5 values, the values of surface roughness is 95%, surface slope is 86.67%, storage void ratio is 73.33% which are found smaller than the used values.

2.4.6 Rain Barrels

The term "rainwater harvesting" (RWH) refers to the old practice of gathering rainwater from roofs or other impermeable surfaces to be used in the future to meet daily water demands. A RWH system typically comprises of three fundamental components: a collection system (such a roof), a conveyance system (infrastructure that conveys the water), and a storage system (such as rain barrel) (Seters et al., 2013). Rain barrels are vessels that catch runoff from roofs during storms and can either discharge or reuse the water during dry seasons (Logan Simpson et al., 2015).

Figure 2.20 Picture showing typical Rain Barrel (adopted from Nebraska, 2022).

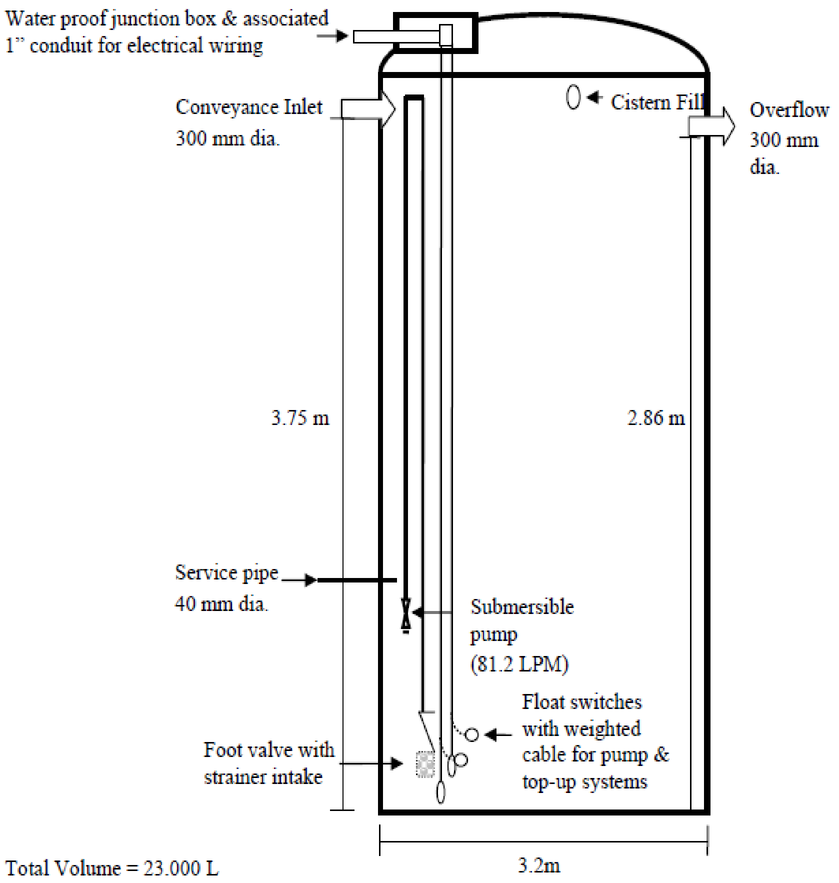


Figure 2.21 Plastic tank design for RWH (adopted from Seters et al., 2013).

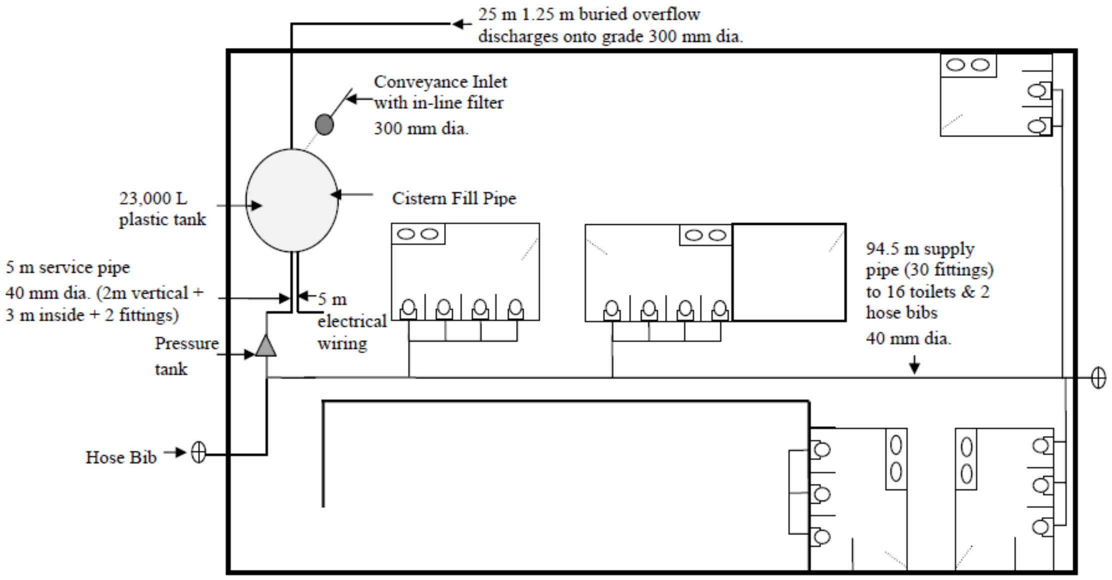


Figure 2.22 Site design for indoor plastic tank (adopted Seters et al., 2013).

Table 2.6 Specifications for the design variables for Rain Barrels used in the SWMM model in various studies by researchers worldwide.

Properties	Parameter	(Rossman, 1975)	(Baek et al., 2015)	(Chaosakul et al., 2013)
Surface	Berm Height	48	-	**3.15**
Underdrain	Flow Coefficient	1	0	**0**
	Flow Exponent	0.5	0.5	**0**
	Offset Height	0	0	**0**
	Drain Delay	6	6	**96**

Rain barrel's parameters including in surface and drain properties are listed in table 2.6, which are used further analysis in SWMM model. These parameters are berm height, flow co-efficient, flow exponent, offset height, drain delay, which values are taken from different literature (Baek et al., 2015; Chaosakul et al., 2013). It can be seen from table 2.6 that the values of berm height ranges from (3.15-48); underdrain flow co-efficient value is 1; flow exponent value is 0.5, where SWMM and (Baek et al., 2015) give similar value; drain delay values ranges from (6-96). Comparing these value with table 2.6, it can be seen that (Chaosakul et al., 2013) shows berm height is 93.44% less and drain delay is 16 times higher than the used value in this study.

2.5 Stormwater induced runoff quality

Urban stormwater runoff is considered as one of the major contributors to nonpoint sources that contributes to the pollution of all water resources in the surrounding environment. Pollutant concentrations of urban stormwater runoff are directly or indirectly linked with land use types in a catchment that is quite different in different places, and hence, site-specific studies are necessary, unless otherwise the modelling of runoff quality using modelling tools may not be rationally reflected the actual field scenarios. The understanding of urban runoff quality and quantity is essential for designing and adopting socially, economically, and environmentally viable urban drainage systems towards greener cities. The built-up area in cities, particularly in developing countries, is expanding rapidly due to the increased growth of the population and the intensive development of urban cities for their inhabitants (Ajjur & Al-Ghamdi, 2022; Uduporuwa, 2020; Yang & Lee, 2021). Increased unplanned built-up areas are inexorably leading to a significant loss of urban green spaces and, therefore, a subsequent rise in rainfall induced runoff containing a range of hazardous pollutants (Du, 2016; Güneralp et al., 2020; Hoffmann, 2021). As a result of unplanned urbanization, deterioration of water quality, degradation of stream habitats, and an increased frequency of flash floods are exacerbated (Khatun et al., 2014), which results in pollutants accumulation during dry periods through natural and anthropogenic activities and discharged through runoff events or road cleaning activities (Song et al., 2019) to the nearby water bodies harming life under water.

2.5.1 Factors influencing runoff quality

In general, the catchment characteristics (including, size and shape of the area, elevation, types of land use etc.), anthropogenic activities (road traffic, construction activities, commercial and industrial activities), drainage surfaces and precipitation factors (e.g., intensity, antecedent dry days, duration, frequency, and magnitude) have a substantial influence on the pollutants concentrations in surface runoff (Müller et al., 2020; Rodriguez-Hernandez et al., 2013). Nevertheless, it has been revealed that nutrients, pathogens, suspended solids, etc., originated from residential land use (LU) and hydrocarbons, heavy metals, PAHs and sediments derived from the road traffic environment along with the presence of industrial and commercial LU in urban areas influence the stormwater runoff quality of a catchment (Camara et al., 2019). Runoff quality parameters such as EC, pH, alkalinity, P, Ca, Na, Cl-, SO_4^-, and Pb are seen to have a significant correlation ($\rho<0.001$) with urban LU areas as reported (Liu et al., 2009), while many researchers argued that the surface runoff of a catchment-largely depends on the land use pattern of that particular watershed (Camara et al., 2019; Khatun et al., 2014; Liu et al., 2013; Liu et al., 2009; Sarukkalige, 2011) indicates the site-specific influences that necessitates local studies.

Factors affecting pollutants in surface runoff are linked to a wide variety of variables including geology, geomorphology, catchment topography, soil characteristics, degree of saturation, precipitation patterns, surface gradient, and land use types (Kirkby et al., 2002; Meng et al., 2021). Atmospheric deposition caused by air pollution may have contributed to the increased pollutant concentrations in the sampling sites highlighting the site specific characteristics of given sample locations within the same catchment boundary or intra boundaries (Gunawardena et al., 2013; Wicke et al., 2012). Afed Ullah et al. (2018) and Stein et al. (2018) noted the contribution of diverse land use patterns highlighting the influence of site-specific characteristics of various land-use patterns on specific water quality parameters. Another study by Fernando & Rathnayake (2018) noted that the rapid change from the pervious to impervious nature of cities causes increased runoff volume with a shorter time of concentration and varying degrees of pollutants. Stormwater runoff data, such as pollutant loading from different LU types, are considered important parameters for calibrating watershed models, particularly those applied in the field of water quality (Arabi et al., 2006; Stein et al., 2018). In addition, these datasets, such as the established relationship between LU and runoff water quality, may be effectively used to anticipate pollutant concentrations for an unmonitored catchment, despite the fact that pollutant loading monitoring on specific LU is most often expensive and time-consuming (Afed Ullah et al., 2018).

Since stormwater quality is not well explicated by the typical urban wash off and build up models, local runoff quality data based on different LU types has become a vital factor in performing the statistical analysis of worldwide runoff data (Song et al., 2019). Hence, to characterize the pollutant loading and to select the appropriate water treatment options, the evaluation of the physicochemical properties of urban surface runoff with respect to different land use types is needed and that is currently not studied in depth and even unexplored in many mega cities. Furthermore, developing a relationship between stormwater runoff and LU characteristics particularly for a developing country like Bangladesh, can be a denting task since the LU zones are not well defined. For example, a residential land use area in Bangladesh, for instance, could be affected by a few other land use activities, showing that it does not always correspond to the same land use characteristics as a residential area in a developed country. Therefore, resulting stormwater runoff is often found with unwanted pollutants like inorganic, trace metals and toxic micro-chemicals that supposed not be in their compositions.

2.5.2 Rationale of runoff quality assessment in Chattogram city

Chattogram City, the second largest after capital Dhaka and the financial hub housing the major sea port, is situated in the south-eastern region of Bangladesh (Figure 1). Similar to other major cities in Bangladesh, Chattogram is also going through the process of rapid urbanization over the last few decades that has ultimately resulted in increased impervious land areas. City dwellers, who number almost 73 million, are reliant on both surface and groundwater. The frequency of waterlogging, those associated with flash flooding, has become more acute in recent years, mostly due to poor drainage networks, heavy rainfall, and waste management systems. To cite an example, most parts of the city remain waterlogged at a depth of 0.2-2.1 m with 48-72 hours of inundation, which typically occurs 8-15 times per year (Masum & Hossesn, 2018; Mohit & Akter, 2014). Population growth is the primary driver of urban growth in Chattogram city, accounting for 51.33% of the city's physical growth between 2001 and 2011, while unplanned urban growth accounts for 48.46% of the city's growth (Samad, 2015). The situation has been worsened due to the absence of a proper stormwater management system within the city. Consequently, there is a chance that the stormwater runoff from various LU areas throughout the city will contain significant levels of physical and chemical pollutants.

While there has been a significant amount of research performed on stormwater quality, water logging and stormwater harvesting (Akter et al., 2020; Akter & Ahmed, 2015; Hossen et al., 2021; Hossen et al., 2021), the influence of land use types on stormwater runoff quality in this region is not well documented though the issue is crucial in its merits. The runoff quality aspects are increasing concerns for today and future drainage design towards green cities, addressing urban diffuse pollution aspects. It is further highlighted in recent studies (Bell et al., 2020; Simpson et al., 2022) that a significant variability of runoff quality and pollutants exists among different land use patterns within a city landscape and on a regional and global scale. Furthermore, the site-specific nature of land-use-induced runoff pollutants, particularly in unplanned cities, like Chattogram, shows that replication of studies elsewhere may not be directly applicable and that local studies are required. This research gap has been addressed in this study by evaluating the physicochemical characteristics of stormwater runoff from four different LU types (i.e., residential, commercial, institutional, and industrial). The variation of stormwater quality in different monitored land uses developed in the previous two decades (i.e., the developing period of the city) is also investigated and compared with data available in the literature. Pollutant concentrations in stormwater runoff of Chattogram city are investigated for the first time in this study. The relationship among varieties of pollutants with land use patterns is also evaluated. The data and information generated from this study could be useful in developing and/or enhancing the city's stormwater drainage master plan. For example, prioritizing the use of urban land based on its stormwater runoff pollution and correlation with the water quality parameters would help to identify the pollution sources and therefore develop an efficient management strategy for the concerned area.

2.6 The Urbanization-Waterbody Nexus

With the ongoing growth of rapid urbanization, likewise surface water in many developing countries, surface water resources in Bangladesh are also being polluted day by day from various anthropogenic sources in terms of water quality. Water is a fundamental natural resource which is deemed necessary for the existence of all living species, including human, as well as food production and economic development. The demand for water in commercial uses is increasing substantially from the typical use for agricultural purposes worldwide though the pattern is found erratic in country scale (Mannan & Al-Ghamdi, 2020). To meet the water demand, the availability of surface and groundwater are mostly drive by the monsoon climate and topography of the country that influences storage and preservation of water bodies (Melesse et al., 2013; Moeck et al., 2020). In the context of Bangladesh, urbanization has had a significant impact on water quality in nearby water bodies. The rapid expansion of cities, coupled with poor infrastructure and inadequate sanitation systems, has led to increased pollution and degradation of water resources. The large number of impervious surfaces, such as roads and buildings, in urban areas has led to increased runoff and erosion, which has contributed to sedimentation and pollution in nearby streams and rivers. Additionally, the lack of proper wastewater treatment in many urban areas has led to increased inputs of nutrients, chemicals, and pathogens into nearby water bodies, leading to eutrophication and the growth of harmful algal blooms, and also posing health risks to the people who are dependent on these water bodies. Climate change and sea level rise also exacerbates these impacts in Bangladesh, as it is a low-lying deltaic country. Unplanned urbanization and industrilaization and in absences of wastewater treatment plants, in general, most of the South Asian cities are facing problem with polluted water (Prakash, 2013) with a significant concern. Unlike other countries in Sotheast Asia, the uses of water for country's socio-economic growth has been found to increase dramatically and in turn produces unaccpetable quality of a significant volume received in environment (Bhattacharjee et al., 2019). Regarding quality, the surface water of the country is susceptible to pollution from untreated industrial effluents and municipal wastewater, washout of chemical fertilizers and pesticides from agricultural fields, and oil and grease leakage from the operation of sea and river ports in the coastal area (Bhuyan & Islam, 2017; Hasan et al., 2019; Uddin & Jeong, 2021).

The city Chattogram is one of the important commercial hubs of Bangladesh housing approximately 6 million people along with the countries largest sea port, a significant number of industries, factories, housings, offices. Karnafully river is the largest and one of the most significant river in Chattogram providing water to every stakeholders. The availability and quality of water encourages industrial, agricultural, fishing, domestic, and navigational infrastructure growth along its bank. In the last few years, unregulated industrial expansion, migration of people to city from village and ineffective implementation of environmental rules and regulations have all been put negative impacts on surface water qualities by receiving wasterwater from the interconnecting canals (Bhuyan & Islam, 2017; Hossain et al., 2017). It has been seen that the domestic and sanitary sewage is often discharge to a drain that is connected to a nearby canal. In addition, effluent from industries is discharged into canals across the city that is with unaccepatble form of treatment. In absence of sweage treatment facilities, all these wastewater along with runoff from rain ultimately reaches to the river and poses significant risk of pollution to aquatic and river health environment. Chaktai and Rajakhali are the two most important canals among the thirty six canals of Chattogram city, through which the city's water flows to the Karnafully River. These two canals cover the maximum watershed area of Chattogram city. Several studies have been performed about the water quality of Karnafully river (Ali et al., 2016; Hasan et al., 2021; Hossen et al., 2019; Islam et al., 2017; Karim et al., 2018; Roy et al., 2020). Authors noted that the water quality of Rajakhali river is polluted mainly due to the discharge of industrial and domestic effluents. There exists few stduies to evaluate the water quality of the indivudual canal discharging to the river Karnaphuli to understand the adoption of onsite or so called decentralized measures towards improvement of wastewater quality while trasporting long way prior discharging into the river.

2.7 Intensity-duration-frequency (IDF) curve in stormwater system design

An intensity-duration-frequency (IDF) curve is a graphical representation of the relationship between rainfall intensity, duration, and frequency for a specific location. The curve is typically created using historical rainfall data and is specific to a particular location. It is used in hydrology and civil engineering to design infrastructure that can handle the expected rainfall in a specific area, such as stormwater management systems, drainage systems, and water treatment facilities. The curve shows the average maximum rainfall intensity that can be expected for different durations and frequencies. IDF curve is useful for designing the drainage and irrigation systems, culverts, bridges, and other hydraulic structures. It is also used to estimate the design stormwater runoff and to calculate the required capacity of detention basins and other stormwater management facilities. It is important to note that IDF curves are created based on historical data and are approximate and should not be used for design in areas with a high likelihood of extreme events.

In this sequence, IDF relationships requires historical data of good quality and continues for long term, which is normally not available in most countries. Although, many studies have been done to develop the IDF relationships in various regions (Ewea et al., 2017; Hadadin, 2005)and few studies have been conducted in for local or regional scale. With climate change, one of the anticipated impacts is an increase in the intensity and frequency of extreme rainfall which further increase the region's flood catastrophes, human casualties, and economic loss. The site control or regional control/ mitigation measures can be effective only when stormwater systems are designed using rainfall Intensity-Duration-Frequency (IDF) curves derived from a long and good quality rainfall data available at sites. Developing IDF curves for the future climate can be even more challenging especially for ungauged sites. The current practice to derive current climate's IDF curves for ungauged sites is, for example, to 'borrow' or 'interpolate' data from regions of climatologically similar characteristics.

Bangladesh is the biggest shop of different climatic extreme events as compared with the other countries of the world. Every year it appearances frequent flooding, high intensity rainfall, drought, cyclone, water logging and other natural as man-made disasters.

Therefore, design of urban drainage, hydraulic structures (bridges, culverts, dams, polders etc.) and other water sensitive configurations becomes problematic as the inconsistency of these climatic extreme events are quite ambiguous (Afrin et al., 2015; Rimi & Matin, 2016). water falls within a catchment area for a certain period. IDF curves are extensively used for the calculation of basin area, time of concentration, imminent rainfall intensity, runoff coefficient, peak runoff rate, irrigation scheme capacity, capacity of hydraulic structures etc.(Namitha & Vinothkumar, 2019; Wambua, 2019).

Various researchers attempt to develop IDF curves in different regions of Bangladesh are seen to exist (Afrin et al., 2015; Akter & Alam, 2019; Rasel & Hossain, 2015; Rasel et al., 2016; Rasel & Chowdhury, 2015; Rimi & Matin, 2016). These studies are in general based on daily rainfall data record with the prediction of the relatively small scale (1-hr, 2-hr, 3-hr, 5-hr, 8-hr, 12-hr) rainfall intensity from daily rainfall data using an empirical formula suggested by the Indian Meteorological Department. Point to be noted that the derivation of such curves may subjected to inaccuracy as most of the values are prophesied without validation with a very short period of rainfall events. Consequently, this study aims to construct IDF curves using long term available records for Chattogram city, for which such studies are not found. The study hope to address the uncertainty involved with existing IDF curves from the short-term short period rainfall records to provide an effective and optimum guidelines for design rainfall selections for Chattogram city.

2.8 Drainage model development and SWMM

A stormwater drainage model is a computer simulation used to predict the amount and rate of stormwater runoff from a particular site. It helps engineers and designers understand how stormwater will flow through a system of pipes, channels, and other structures, and identify potential flooding or erosion issues. The model typically takes into account factors such as the size and shape of the site, the type and number of impervious surfaces, the slope of the land, and the local climate and weather patterns. The model's output can be used to design and size stormwater management systems, such as retention ponds and detention basins that can effectively control and manage the runoff. The development of a stormwater drainage model involves creating a computer simulation to predict the amount and rate of stormwater runoff from a specific site. It is important to note that the development of a stormwater drainage model can be a complex and time-consuming process requiring specialized expertise in hydrology, hydraulic engineering, and computer modeling.

The empirical formula may be established considering these effects for the development of the hydrologic models (Wang et al., 2012). The simplest rational method considering “runoff coefficient” have already been introduced to determine the total runoff. This been done multiplying the coefficient with total rainfall (Zekai and Altunkaynak, 2006). Then imperviousness along with other factors such as time of concentration, soil properties, land use conditions of a catchment have been converted into a regression formulation or tabulated values to have more accurate prediction about runoff. A black box based conceptual modelling approach has also been proposed to formulate linear or nonlinear rainfall runoff transformation with calibration. But this approach fails to evaluate the nonlinear dynamics transformation between rainfall and runoff. Recently artificial neural networks (ANN) based on training process from previous measured data has brought attraction. The process is very easy and simple as it doesn’t require the explicit data of physics. Fuzzy Logic (FL) another black-box approach for rainfall runoff simulation incorporates the linguistic variable instead of numerical values. Time varying runoff parameters can’t be handled using this approach. Hydrologic models have been popular to predict the effects of the land use and climatic conditions on storm water runoff. These models are calibrated and validated with their characteristics parameters which lead to less uncertainty. The most popular and worldwide used hydrologic models for engineering applications are HEC- Hydrologic Modelling System (HEC-HMS) model developed by U.S. Army crop of Engineers, Storm Water Management Model (SWMM) developed by U.S. EPA, MIKE, MOUSE, , Watershed Management System (WMS) developed by Danish Hydrologic Institute etc. (Walega, 2013, Wang et al., 2012).

Many of the models have GIS interface which allows spatial analysis too make it easy to validate data as appropriate.

2.8.1 Storm Water Management Model (SWMM)

The Storm Water Management Model (SWMM) developed by the United States Environmental Protection Agency (USEPA) is a dynamic, distributed, comprehensive, hydro-meteorological and surface runoff (quantity & quality) simulation model used for making plans, investigating, and designing related to stormwater runoff, sewers (both combined and sanitary), and other related drainage systems primarily in urban areas around the world for single or long-term (continuous) events (Anand, 2014; Gülbaz, Kazezyılmaz-Alhan, et al., 2019; Rossman, 1975). Monitoring stormwater pollution in urban catchments is not only critical, but it also takes a lot of time in order to characterize the quality of stormwater runoff and develop an effective pollution management plan for a specific watershed with a particular set of characteristics. The SWMM model is able to track the flow rate, flow depth, and quality of water with the concentration of selected pollutants for all conduits or reaches, sub-catchments, junctions, and outfalls over a simulation period consisting of several time steps (Hossain et al., 2019; Niazi et al., 2017).

2.8.2 Development history of SWMM

Figure 2.23 depicts the historical context and step-by-step development of SWMM. In a cooperative initiative including the USEPA, University of Florida (UF), and Water Resources Engineers, the initial version of SWMM (SWMM 1.0), which was built in FORTAN programming language, was created in 1971 (Metcalf & Eddy, 1971). SWMM 1.0 was divided into many blocks (Executive Components, Stormwater Runoff, Runoff Transport, Water Storage, and Receiving Water); however, the runoff block was only capable of simulating infiltration using Horton's equations. Additionally, continuity equations were applied for simulating overland flow. SWMM 1.0 applications could only cover a range of 4 to 2,023 hectors (Metcalf & Eddy, 1971; Niazi et al., 2017). In 1975, the combined block was introduced to the model's second iteration (SWMM 2.0), enabling it to be used in bigger watersheds than in its first iteration. Additionally, this version included modeling capabilities for pollutants (BOD_5, TN, and PO_4) and erosion prediction (Huber et al., 1975).

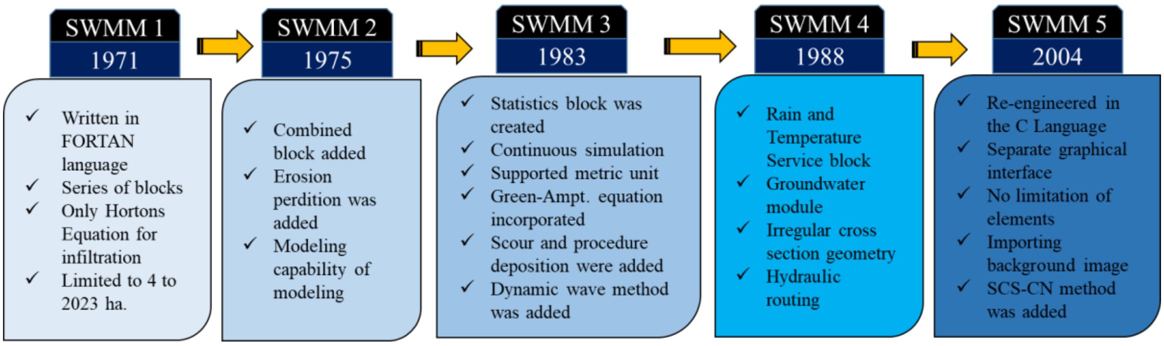


Figure 2.23 Flow diagram showing the historical development of SWMM model (1971-2004).

A short while later, the third version was released in 1983. This version featured statistics and graph blocks that enabled frequency analysis and the generation of other hydrological graph layouts (hydrographs and pollute-graphs). Continuous simulations of a specific model on a monthly and yearly scale became possible with SWMM 3.0. The introduction of the metric unit for the first time in many blocks was the most advantageous feature of this edition. In addition, SWMM 3.0 included the Green-Ampt equation for infiltration modeling, scour and deposition procedures for transporting sediment, and a comprehensive dynamic wave approach for flow routing. (Niazi et al., 2017). The groundwater and irregular cross sectional geometry modules are included in the fourth edition of SWMM (SWMM 4.0), which resolves the convergence problems. Additionally, a block for temperature and precipitation was included, allowing the model to accept long-term input of continuous temperature and precipitation data.

The model's engine was fully redesigned in C programming language for the model's fifth and final version, SWMM 5.0, which was launched in 2005 (Niazi et al., 2017; Rossman & Huber, 2016; Wu et al., 2013). The restriction on using limited elements was removed with the release of SWMM 5.0. The introduction of an advanced graphic user interface (GUI) has made it possible for users to access all features and options as well as create new maps within the interface. Nevertheless, SWMM 5.0 can simulate Low Impact Development (LID) and Best Management Practices (BMPs). The Soil Conservation Service-Curve Number (SCS-CN) approach was also introduced for the estimation of infiltration loss. SWMM 5.2.2, the most recent version, was released on December 1st, 2022. The most recent SWMM 5.2.2 has four main input components. The first one is the atmospheric and climatological data, which allows for the entry of various climatic data (temperature, evaporation, wind speed, rainfall, snowmelt, etc.). Urban hydrology, the second input component, defines the sub catchment's many properties, including area, slope, percent impervious, percent zero impervious, N-impervious, N-pervious, storage characteristics, etc. Additionally, LID component characteristics are defined. The hydraulics component includes a map of the reach network's layout that includes information on the junctions, nodes, and conduits. When defining the types of land use patterns and the quality parameters for stormwater runoff, this component also considers the characteristics of each.

The Personal Computer Storm Water Management Model (PCSWMM) which was released in 2007 (Version 0.0.001.026), is a comprehensive 2D model software with EPA SWMM integration and a GUI that lets users construct, edit, and visualize any hydrologic component (PCSWMM, 2022). PCSWMM models dynamic storm events with high spatial and temporal resolution, enabling engineers and planners to assess, synthesize, and develop urban storm water systems and make informed decisions (Surwase & Manjusree, 2019). The few examples of applications that PCSWMM can perform are Low-Impact Development (LID) design, integrated catchment watershed modeling, water quality modeling, detention pond design, combined drainage system design, sanitary sewer system design, stormwater management and sewer remediation, flood forecasting, floodplain mapping, and risk analysis (CHI, 2022).

2.8.3 SWMM modelling processes

The numerical methods used by SWMM models to simulate runoff quantity and quality are shown in figure 2.24. Additionally, it demonstrates the linkages between the components. In this study, the highlighted operations are considered. First, rain or precipitation is brought from the atmosphere into a particular watershed. Some portion evaporates to atmosphere, infiltrates into sub-surface soil (initial abstraction by rainfall interception, evaporation, percolation, and infiltration into groundwater layers) and the excess water flows as overland surface runoff. Low Impact Development (LID) controls effectively capture significant amounts of runoff or rainfall that infiltrate and evaporate. Pollutants accumulate over time in dry conditions across a variety of land uses.

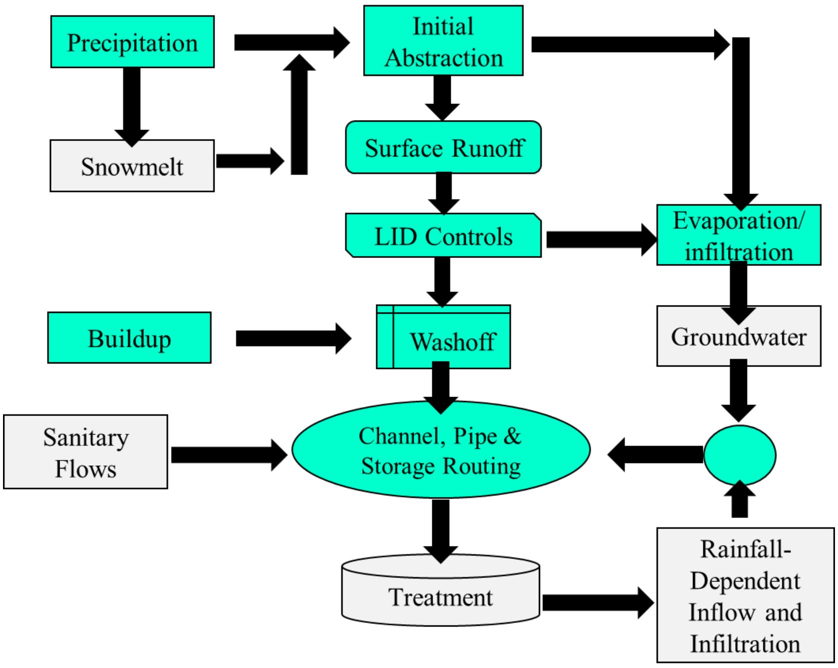


Figure 2.24 Conceptual framework and Step by step hydrological processes considered in the SWMM model (Adopted from (adopted from Rossman & Huber, 2016)

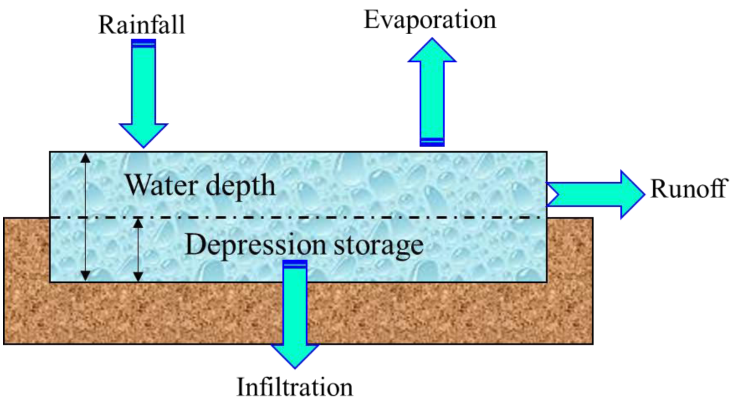


Figure 2.25 Figure showing the conceptual non-linear reservoir model of a sub-catchment considered in SWMM.

The contaminants are washed-off from the designated land usage regions during storm occurrences. The contaminants then combine with other surface runoff and move through an open channel or piping system. Finally, the concentration of pollutants is lowered using a variety of treatment techniques by a few treatment units or by natural processes.

The theoretical framework for surface runoff modeling considered by SWMM is shown in Figure 2.24 as follows. The surface of each sub catchment is considered a nonlinear reservoir. Inflow comes from precipitation, which flows from upstream to downstream sub-catchments. Infiltration, evaporation, and surface runoff are only a few of the hydrological processes that are involved in the routing processes (outflows). The maximum depression storage for this reservoir—i.e., the maximum surface storage provided by ponding, surface wetting, and interception—is specified as its capacity. Only then does surface runoff per unit area, Q, begin, when the water depth in the "reservoir" is greater than the maximum depression storage, ds. The depth of the water over the sub catchment can be determined by numerically solving a water balance equation over the sub catchment.

2.9 Financial aspects of LIDs in SUDs

In the context of Bangladesh, the financial aspect of low impact development (LID) practices is particularly important due to the limited budget available for infrastructure projects and the need to maximize the benefits of limited resources. When evaluating the financial aspects of LID practices in Bangladesh, it's important to exclude factors that may not be relevant to the specific context. For example, some LID practices, such as green roofs or solar-powered systems, may have energy costs associated with them, which would not be relevant in Bangladesh as the country has abundant solar power. Life cycle cost analysis (LCCA) is an important tool for evaluating the financial aspects of low impact development (LID) practices in sustainable urban development (SUD). LID practices are designed to manage stormwater runoff in a way that mimics natural systems, rather than relying on traditional grey infrastructure such as concrete pipes and retention ponds. When evaluating the financial aspects of LID practices, it's important to consider all of the costs associated with the project over its entire life span. This includes the initial costs of design, construction, and installation, as well as the ongoing costs of operation, maintenance, and eventual decommissioning. One of the key benefits of LCCA is that it allows for a comprehensive comparison of the costs and benefits of different LID options. By considering all the costs and benefits over the life of the project, LCCA can help identify the most cost-effective solution for a specific project. The financial aspect of LID practices is necessary in the context of Bangladesh because it allows decision-makers to evaluate the costs and benefits of different options and identify the most cost-effective solution for a specific project. This is particularly important in a country where resources are limited and maximizing the benefits of limited resources is crucial.

Various studies have been conducted to determine the most cost-effective low impact development (LID) practices for urban watershed management. The results of these studies suggest that combined LID techniques can be more cost-effective than individual LID components (Xu et al., 2017). A study conducted in Phoenix, Arizona, USA, and found that the implementation of Low Impact Development (LID) practices, such as combining Green Roofs (GR) and Permeable Pavements (GR + PP), in urban watersheds can offer a sustainable and economical alternative to traditional drainage systems and the combination of LID practices reduced the Life Cycle Cost (LCC) by 27.2% and 18.7% over 50 and 25 year evaluation periods, respectively (Zhang & Ariaratnam, 2021). A study conducted by Xu et al. (2017) in China reported that the LCC sequence was found to be vegetative swales < permeable pavement < bio-retention < infiltration trench < constructed wetlands, while the environmental impact sequence was found to be vegetative swales < permeable pavement < constructed wetlands < bio-retention < infiltration trench. Another study in Hong Kong and Seattle found that green roofs were the most cost-efficient solution, followed by bio-retention and permeable pavements (Xu et al., 2017).

Similar study was conducted in Hong Kong, China and Seattle, U.S. and the LCC was found as GR (0.02-0.03 $L/10^3$ US$)> BR (0.15-0.29 $L/10^3$ US$)> PP (0.93-1.58 $L/10^3$ US$) (Chui et al., 2016). In London, Ontario, a study found that infiltration trench and infiltration trench in combination with green roof were the most cost-efficient solutions among eleven (11) LID techniques for runoff reduction (Joksimovic & Alam, 2014). Similarly, a study conducted by Zeng et al. (2020) in Xuhui District, Shanghai, China concluded that a combination of bio-retention cell and permeable pavement would be the best choice for runoff reduction, as they are most cost-effective and have maximum runoff reduction efficiency (Zeng et al., 2020). Finally, a study by

Garbanzos & Maniquiz-Redillas (2022) in Bacoor, Cavite, Philippines found that the combination of infiltration trench and permeable pavement (IT + PP) was the least expensive option for both the expectant and pessimistic scenarios among three individual LID practices (bio-retention, infiltration trench, permeable pavement) and four combined LID scenarios (Garbanzos & Maniquiz-Redillas, 2022). Overall, the most cost-effective LID practice can be determined through a detailed evaluation of local conditions and LID techniques.

2.10 Rainfall runoff studies on local scale

A few studies, as tabulated in table 2.7, were conducted in two major cities (Dhaka and Chattogram) of Bangladesh, and the results show that reduction rates varied, with rain barrels being found effective in reducing flooding and runoff in Mirpur (Abdullah-al-masum et al., 2021), while 15 locations in Chattogram were identified to have high flood risk with varying runoff volumes from 1755 m^3 to 8835 m^3 (Alam, 2018). The same study simulated the total suspended solids (TSS) concentration in the runoff, which varied from 175 to 475 mg/L with an R^2 value of 0.5937 (Alam, 2018). It has also been identified that nearly half of the city suffered from water logging with a 0.2 to 2.1 m overland water depth, causing a lot of subsequent issues and inconveniences, while areas remained drowned for about 48-72 hours (Akter et al., 2017). Chattogram City has undergone notable changes in its groundwater levels, which have been investigated through a few studies.

A reduction rate of about 4.75 meters per year in the city's central region was identified, and five out of the twenty two wards (21% of the wards) experienced a significant drop in groundwater levels (Akter & Ahmed, 2021). Another study (Akter, Uddin, et al., 2020) also revealed that 5.5% of the city's overall area had a high potential for groundwater recharge (GWR), while 11% to 48% of the area showed medium to high potential. On the other hand, around 20% of the area was determined to have low potential for GWR.

Table 2:7 Various studies regarding sustainable water and drainage management in Bangladesh, with a focus on implementing LID solutions.

Study area	Time span	Consideration	Results	Reference
Mirpur, Bangladesh	2020	This study aims to model stormwater using SWMM and assess the impact of LID structures on the drainage system	The SWMM model showed high levels of flooding and surface runoff in the study area, but implementing LID through the use of a rain barrel reduced flooding, flooding time, and runoff, making it a recommended solution for minimizing flood frequency and amount.	(Abdullah-al-masum et al., 2021)
22 Wards of Chattogram City, Bangladesh	2009-2020	The research endeavor aimed to analyze fluctuations in the groundwater level by employing the widely acknowledged MODFLOW-2005 model.	The results of the study revealed that there was a reduction rate of approximately 4.75 meters per year in the central area of the city, with 21% of the wards (five out of a total of 22 wards) experiencing a significant decrease in groundwater levels.	(Akter & Ahmed, 2021)
Chattogram City, Bangladesh	2019-2020	The study assessed the possibilities for Groundwater Recharge (GWR) using geospatial techniques in conjunction with Multi-Criteria Decision Analysis (MCDA).	The findings of the study demonstrated that 5.5% of the overall area possessed a high potential for Groundwater Recharge (GWR), while 11% to 48% of the area was identified as having medium to high potential. Additionally, around 20% of the area was considered to have low potential for GWR.	(Akter, Uddin, et al., 2020)
Chattogram, Bangladesh	2018	The primary objective of this study was to investigate the surface runoff's implications on Chattogram city, with particular attention to the hazards it poses in terms of flood risk and water pollution.	Fifteen locations in Chattogram city were identified as having a substantial risk of flooding, with surface runoff volumes ranging from 1755 m^3 to 8835 m^3,	(Alam, 2018)
South Agrabad, Chittagong, Bangladesh	2015	This study sought to evaluate the potential of RWH systems in an area with the typical annual precipitation amounts to 3000 mm.	The study's results indicate that RWH systems could potentially decrease stagnant stormwater by a maximum of 26% and provide an annual supplement of up to 20 liters of water per person to the city's water supply.	(Akter & Ahmed, 2015b)
Chattogram, Bangladesh	2013-2014	This study investigates the impact of LID on urban flooding by analyzing the flooded area and depth in a specific area in	The study found that implementing LID measures in SWMM can result in a reduction of the flooded area by about 30%. Additionally, the research demonstrated that an	(Akter, Tanim and Isalm, 2020)

		Chittagong, and explores the potential of implementing distributed rain barrel RWH systems to mitigate flash flooding in a highly urbanized area.	impervious surface covering between 10% to 60% of the sub-catchment area can yield a monthly rainwater harvesting potential of 0.04 to 0.45 m3 per square meter of rooftop area.	
Chattogram, Bangladesh	2013-2014	The objective is to use HEC-HMS hydrological model to predict urban storm water-logging events in Chittagong city.	It has been identified that nearly half of the city suffered from water logging with a 0.2 to 2.1 m overland water depth, causing a lot of subsequent issues and inconveniences, while areas remained drowned for about 48-72 hours	(Akter et al., 2017)

A few studies conducted in the Chittagong area of Bangladesh investigated the potential of rainwater harvesting (RWH) systems to mitigate urban flooding and supplement the city's water supply. Akter & Ahmed (2015) evaluated the potential of RWH systems in South Agrabad of Chattogram City, where the annual precipitation was 3000 mm. The study found that RWH systems could potentially reduce stagnant stormwater by up to 26% and provide an annual supplement of up to 20 liters of water per person to the city's water supply. Another study (Akter, Tanim and Isalm, 2020) conducted in Chattogram analyzed the impact of low impact development (LID) on urban flooding and explored the potential of implementing distributed rain barrel RWH systems to mitigate flash flooding in a highly urbanized area. The study found that implementing LID measures in SWMM could reduce the flooded area by about 30%. Additionally, the study demonstrated that an impervious surface covering between 10% to 60% of the sub-catchment area can yield a monthly rainwater harvesting potential of 0.04 to 0.45 m^3 per square meter of rooftop area.

Several studies have examined sustainable water and drainage systems in Dhaka and Chattogram cities in Bangladesh. However, these studies only focused on evaluating rainwater harvesting (RWH) as a low-impact development (LID) component for these systems. Additionally, Low Impact Development (LID) is not yet extensively studied in Bangladesh and requires further exploration in various cities with distinct rainfall characteristics. Additionally, the researchers did not assess the reduction rates for peak flow or volume of LID options, nor did the researchers evaluate the effectiveness of LIDs in reducing other parameters of runoff quality aside from total suspended solids

(TSS). Furthermore, the economic cost is a crucial consideration for the widespread implementation of LIDs, as different types of LIDs have varying hydrologic efficacy and costs. No studies in Bangladesh considered the life cycle cost analysis (LCCA) for different LID options or investigated the cost-effectiveness of these options.

2.11 Conclusion

Climate change and land use changes have a complex relationship with each other, and both can have significant impacts on urban systems. Climate change can lead to more extreme weather events such as heavy precipitation, heat waves, and droughts, which can have negative effects on water management, air quality, and biodiversity. Land use changes, such as urbanization, can also have negative effects on these areas by increasing the amount of impervious surfaces and reducing the amount of green space. Low Impact Development (LID) components can help mitigate the impacts of climate change and land use changes by reducing stormwater runoff and improving water quality.

LID components such as green roofs, rain barrels, and permeable pavements can help to absorb and filter rainwater, reducing the amount of runoff and improving the quality of water that enters local streams and rivers. They also help to reduce the urban heat island effect, by absorbing less heat and release more moisture than traditional surface. The Storm Water Management Model (SWMM) is a software tool that can be used to simulate the performance of LID components in each urban setting. This can be useful for evaluating the potential benefits of different LID components and for making decisions about where to locate them. The software can also be used to model the effects of climate change and land use changes on urban systems, providing insight into how these factors may impact water management and other aspects of urban systems in the future.

Life cycle cost analysis (LCCA) is a method for evaluating the economic feasibility of LID components, considering not only initial installation costs but also long-term maintenance and replacement costs. This can be useful for determining the overall cost-effectiveness of different LID components and for determining which components may be the most cost-effective in a given urban setting. Overall, in the context of sustainable urban systems, LID components and LCCA can be important tools for promoting sustainable land use, managing the impacts of climate change, and ensuring that urban systems are economically viable in the long term.

Chapter 3. METHODOLOGY

3.1 General

The hydrologic performance of LIDs in the context of SUDs is a crucial area of investigation. Chapter 2 has recognized the need for a thorough examination of the hydrological performance of Low Impact Development (LIDs) in the context of Stormwater Utilization and Detention (SUD) systems. The steps and overall outline involved in the study are shown in Figure 3.1. This section has been divided into two parts to provide a comprehensive investigation of the topic.

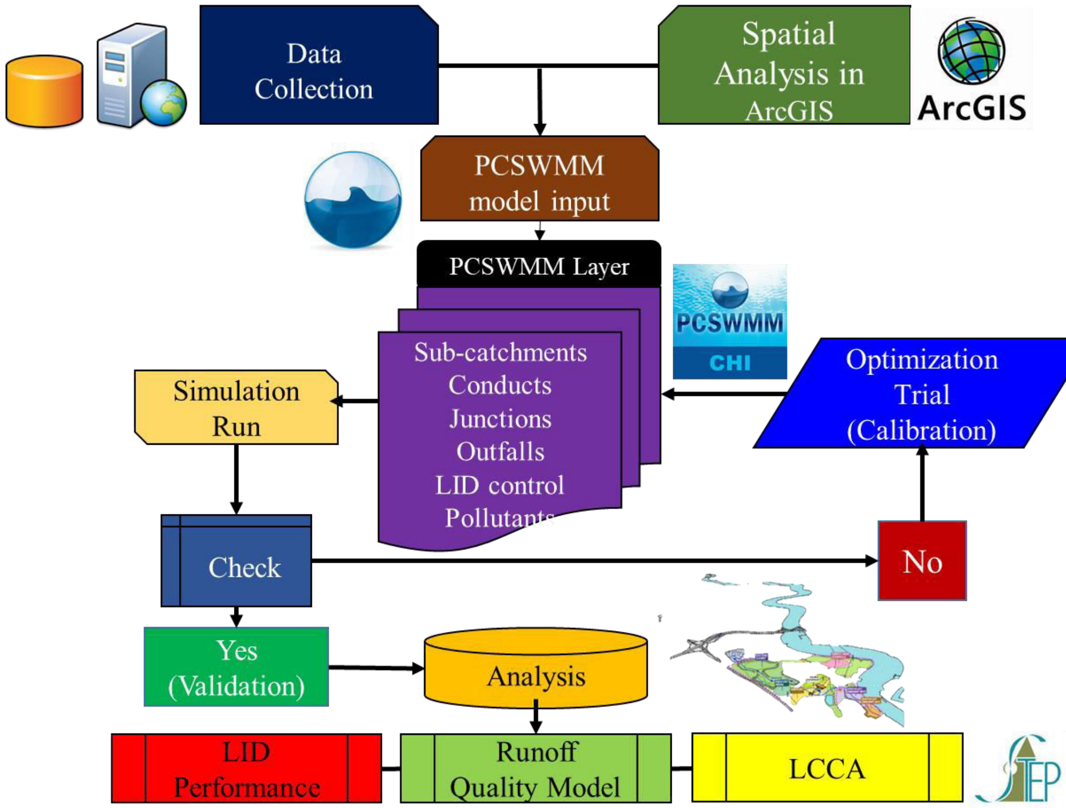


Figure 3.1 Step by step procedure adopted for this study.

The first part of the section outlines the procedures and techniques used for field sampling and laboratory experiments, as well as the spatial techniques utilized in ArcGIS to determine the different parameters needed for PCSWMM modeling. The field sampling involved collecting data from the study area, and the laboratory experiments were performed to gather information about the hydrological characteristics of the study area. The spatial techniques applied in ArcGIS were used to analyze the data collected and to determine the parameters required for modeling in PCSWMM. The second part of the section describes the methods used in the study to evaluate the performance of urban watersheds. The aim of this study was to determine how well the LIDs in context of SUDs are functioning in the urban watersheds. The steps involved in the study are presented in Figure 3.1, which provides a visual representation of the process and helps to understand the overall methodology of the study.

3.2 Study Area

Chaktai- Rajakhali watershed (as seen in Figure 3.2) in Chattogram city has been chosen as study area. The area is situated on the right bank of the river Karnaphuli between 22°14´ and 22°24´30´´ North Latitude and between 91°46´ and 91°53´ East Longitude is found to occupy the area of about 11.45 km^2 with a slope of 15.45±17.61%. The average elevation of the study area is about 10.46±6.34 m with a maximum value of 56m and minimum value is about 1m. The study area is further classified into 09 sub-catchments or drainage sub-basin based on land use patterns. The land use patterns belong to residential and commercial categories comprising 26% of the total area covered up by vegetation, 4% is water body, while 49% is to built-up area and 21% is it's bare land. Total length of Chaktai- Rajakhali canal is found as 14.64 km. Both canals collect the natural flow along with water draining from sub-basin areas at the upstream and finally discharges into the river Karnaphuli in two outlets. The average rainfall received by the watershed is about 3378 mm that is substantially higher than country's annual average of 2300 mm and rainfall is mostly occurs between May to October (BMD, 2019). Furthermore, it is noted that in July, the precipitation reaches its peak, with an average of 743 mm (BMD, 2019).

The study focuses on assessment of storm runoff quantity and quality of the existing drainage channel network of the Chattogram urban area, mainly Chaktai and Rajakhali canals and their branches which carry water from the south eastern parts of Chattogram city. This case study deals with a systematic approach for the estimation of urban runoff quality and quantity from the catchment area of these canals considering LID-BMPs alternatives.

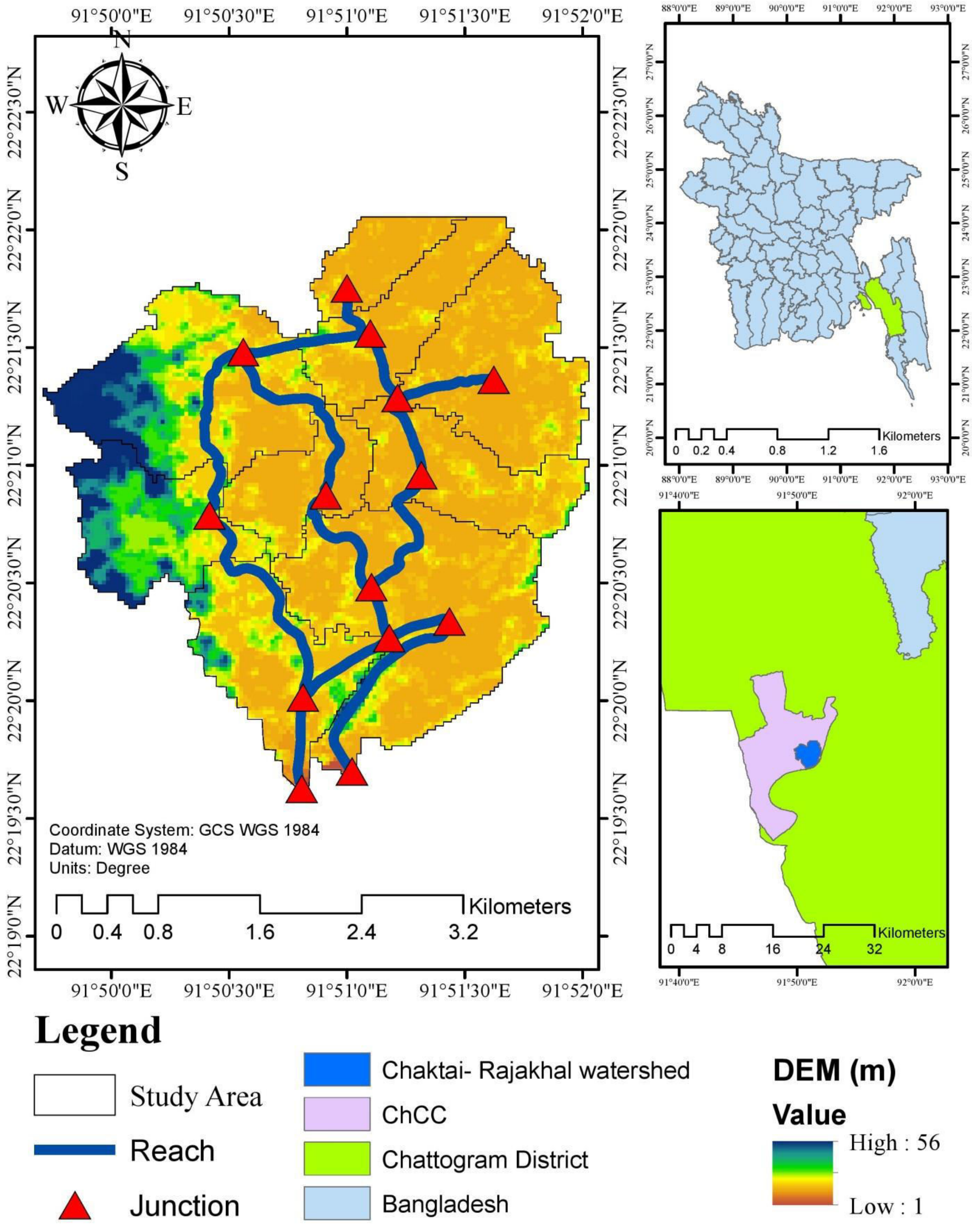


Figure 3.2 Chaktai- Rajakhal watershed in Chattogram, Bangladesh

3.2.1 Characteristics of Sub-catchment

The information provided describes nine (9) sub-catchments in Chittagong City, Bangladesh. Each sub-catchment is described with its area in hectares, percentage of improved area, slope, and the name of the wards covered. The sub-catchments are found with the varying levels of area, slope, and impervious (developed) areas. The area of the sub-catchments ranges from 47.29 ha in SC5 to 252.73 ha in SC9. The sub-catchments also have different levels of slope, with SC1 having the highest slope at 11.12%, and SC5 having the lowest at 2.64%. The percentage of impervious (developed) area in the sub-catchments also varies, with SC1 having the highest at 89.09% and SC7 having the lowest at 33.86%. The area and slope of the sub-catchments can affect the availability of open and green spaces, as well as the potential for flooding and erosion. The higher the slope, the greater the potential for erosion and landslides.

The larger area of the sub-catchment, the greater the potential for development, which can lead to a decrease in open and green spaces. The higher the percentage of impervious area, the greater the potential for runoff and flooding. The sub-catchments are primarily located in the wards of Baxir Bazar, Patharghat, South Bakalia, Dewan bazar, Jamal Khan, Andarkilla, East Sholashahar, Chawk bazar, and West Bakalia. The highest Improved area percentage can be found in SC1 (89.09%) and the lowest in SC7 (33.86%). The highest slope percentage can be found in SC1 (11.12%) and the lowest in SC5 (2.64%). Additionally, each sub-catchment has specific characteristics, such as primarily being a commercial or residential area, the presence of open green spaces, the type of materials used for the roof surfaces of buildings, and the availability of local and regional roads. The sub-catchments vary in terms of population density, the presence of water bodies, and the amount of green and open spaces.

Most of the sub-catchments are primarily residential, but some are with commercial activity as well. Many of the buildings in these sub-catchments have roof surfaces made of either concrete or tin-sheds, but the proportion of each type of roof surface vary from catchment to catchment. Overall, in terms of area, residential area is found in 79.01% of the total area and commercial area is found in 20.99% of the total area. Typically, surface is concrete in nature.

Table 3:1 Sub-catchment characteristics for Chaktai-Rajakhali drainage watershed

Sub-catchments	Area (ha)	Imprv. area (%)	Slope (%)	Name of the wards covered in ChCC	Catchment characteristics
SC1	126.31	89.09	11.12	The majority of the region is in Baxir Bazar, but a small amount is in Patharghat and other sections are in South Bakalia.	✓ Primarily a commercial area with some residential areas. Nearly impenetrable terrain. ✓ There are some patches of open, green ground with short grass, but no forest sites. ✓ Local roads of a medium density are only present on one stretch of the regional road. ✓ Concrete and tin-shed are the major materials used to make the roof surfaces of the existing buildings.
SC2	109.89	58.76	18.3	The majority of the area is in Dewan bazar. Other areas include Bakalia in the south and west, Jamal Khan, and Andarkilla.	✓ Mostly residential with a large slum area. Additionally, there are mountainous areas with big trees and a tiny amount of arid ground. ✓ Regional route with high density and few local roads are available. ✓ The majority of the structures' roof surfaces are made of concrete.
SC3	191.92	66.07	14.85	The majority of the region is in East Sholashahar, Chawk bazar, and West Bakalia.	✓ Primarily a residential and commercial region, with some hilly terrain. ✓ There is a limited amount of open and green space. ✓ Local and regional routes with high densities. ✓ This sub-catchment includes both concrete-made and tin-roof sheds.
SC4	71.75	82.83	5.12	The majority of the region is in East and South Bakalia, with only a little amount in West Bakalia.	✓ There are some green and open spaces accessible in this primarily residential region with some business activity. ✓ There is no hill and barren plain. Susceptible to flooding region. ✓ Not many local roads. ✓ Most of the roof surfaces of the buildings are tin-shed with some being concrete roof surfaces.
SC5	47.29	70.93	2.64	The majority lies in East Sholashahar, only a small	✓ Here, there are water bodies and green open spaces with bare soil. The density of buildings is average.

				portion in West Bakalia.	✓ There is a national highway that runs through the region. Such a little local road cannot be found. ✓ The majority of the buildings in this area have roof surfaces made of tin sheds, while some others have roof surfaces made of concrete.
SC6	92.09	65.89	4.42	The catchment is in East Sholashahar and west Bakalia	✓ The upper portion (East Sholashahar) has green open space with some barren terrain and low-density buildings while the bottom section (West Bakalia) has high density construction with little green open space. ✓ The region has one national highway crossing through it, along with other low traffic local roads. ✓ Available buildings include a blend of concrete and tin-shed roof surfaces.
SC7	146.58	33.86	3.97	East Bakalia makes up the majority of the region, with only a little amount located in East Sholashahar and West Bakalia.	✓ There are mostly grassy open spaces and a few low-density buildings. The region is still being developed. ✓ Here, there are not many waterbodies. ✓ Local roads are few and have relatively low density. ✓ The majority of roof surfaces of buildings are built of concrete, with a few tin-shed structures.
SC8	104.52	44.91	5.37	The sub catchment is situated in East bakalia.	✓ Moderately densely populated areas, green spaces, and some barren terrain. ✓ Local roads are few and have relatively low density. ✓ The large proportion of buildings are made of tin, and just a small number have concrete roof surfaces.
SC9	252.73	67.05	7.2	The area is mainly in Boxir bazar and East bakalia	✓ Buildings with a moderate to high density, commercial and residential activity, some green and barren area, and a limited number of water bodies. ✓ Two low-density local roads and one national route. ✓ In this catchment, half of the buildings are built of tin-sheds, while the other half (which is under construction) has buildings made of concrete.

The sub-catchments also have different characteristics in terms of terrain, such as mountainous or hilly areas, susceptibility to flooding, and presence of barren or arid ground. SC1 is described as having nearly impenetrable terrain and no forest sites, while SC2 has a large slum area and mountainous areas with big trees. SC4 is described as a region with no hill and barren plain, but susceptible to flooding. SC5 has water bodies and green open spaces with bare soil. SC7 is described as mostly grassy open spaces and a region that is yet to be developed. Furthermore, the availability of local and regional roads also varies among the sub-catchments.

Some sub-catchments, such as SC1, have only one stretch of regional road with medium density local roads, while others, such as SC2 and SC3, have regional routes with high density and more local roads available. In SC4, SC7 and SC8, there exists typical local roads for communication. SC5 has only a national highway that runs through the region. SC6 has one national highway crossing through it along with other low traffic local roads. SC9 has two low-density local roads and one national route. Overall, the sub-catchments in Chittagong City have unique characteristics in terms of population density, type of terrain, availability of local and regional roads, and the presence of commercial and residential areas. The information provided herewith can be useful for urban planning, flood management, and infrastructure development in the region.

3.2.2 The coefficients used in this study

"N-impervious" and "N-pervious" coefficients are used to estimate the percentage of rainfall that will become runoff on impervious and pervious surfaces, respectively. These coefficients are dimensionless numbers typically between 0 and 1, with values closer to 0 indicating low runoff potential and values closer to 1 indicating high runoff potential. The N-impervious coefficient is used to estimate runoff from surfaces such as pavement, roofs and other surfaces that do not allow water to infiltrate. The N-pervious coefficient is used to estimate runoff from surfaces such as grass, soil, and other surfaces that allow water to infiltrate. The "D-impervious" and "D-pervious" parameters are used to estimate the amount of water that can be temporarily stored on a surface before runoff or infiltration occurs.

Table 3:2 Different coefficients used in SWMM by different researcher around the world.

Parameters	Values	Study sites	Year of study	References
N-pervious	0.278-0.645	Chaktai, Rajakhali watershed, Chattogram, Bangladeah	2022	This study
	0.400	Lijia Mountain, Nanjing, China	2022	(Yuan et al., 2022)
	0.150	Tehran, Iran	2022	(Zakizadeh et al., 2022)
	0.092	Ayamama watershed, Istanbul, Turkey	2021	(Ekmekcioğlu et al., 2021)
	0.250-0.300	McClelland Basin, For Collins, Colorado, USA	2021	(Dell et al., 2021)
	0.075-0.125	Mawson Lakes, Australia	2020	(Hidayat & Soekarno, 2020)
	0.050-0.800	Beijing Normal University, Chaina	2016	(Li et al., 2016)
	0.161-0.582	Lathi, Finland	2014	(Krebs et al., 2014)
	0.180-0.500	headwater stream watersheds, Iowa, USA	2013	(Wu et al., 2013)
	0.020-0.400	Taapelipolku, Lathi, Finlad	2013	(Krebs et al., 2013)
N-impervious	0.045-0.124	Chaktai, Rajakhali watershed, Chattogram, Bangladeah	2022	This study
	0.013	Lijia Mountain, Nanjing, China	2022	(Yuan et al., 2022)
	0.023	Tehran, Iran	2022	(Zakizadeh et al., 2022)
	0.046	Ayamama watershed, Istanbul, Turkey	2021	(Ekmekcioğlu et al., 2021)
	0.010-0.016	McClelland Basin, For Collins, Colorado, USA	2021	(Dell et al., 2021)
	0.0075-0.0125	Mawson Lakes, Australia	2020	(Hidayat & Soekarno, 2020)
	0.011-0.150	Beijing Normal University, Chaina	2016	(Li et al., 2016)
	0.014-0.021	Lathi, Finland	2014	(Krebs et al., 2014)
	0.017-0.050	headwater stream watersheds, Iowa, USA	2013	(Wu et al., 2013)
	0.110-0.400	Taapelipolku, Lathi, Finlad	2013	(Krebs et al., 2013)
D-storage pervious	1.77-4.57	Chaktai, Rajakhali watershed, Chattogram, Bangladeah	2022	This study
	3.80	Tehran, Iran	2022	(Zakizadeh et al., 2022)
	5.08-7.62	McClelland Basin, For Collins, Colorado, USA	2021	(Dell et al., 2021)
	0.0375-0.0625	Mawson Lakes, Australia	2020	(Hidayat & Soekarno, 2020)
	2.54-7.62	Beijing Normal University, Chaina	2016	(Li et al., 2016)
	3.41-6.49	Lathi, Finland	2014	(Krebs et al., 2014)
	2.00-5.08	Taapelipolku, Lathi, Finlad	2013	(Krebs et al., 2013)

D-storage impervious	0.75-2.13	Chaktai, Rajakhali watershed, Chattogram, Bangladeah	2022	This study
	1.35	Tehran, Iran	2022	(Zakizadeh et al., 2022)
	1.27-2.54	McClelland Basin, For Collins, Colorado, USA	2021	(Dell et al., 2021)
	0.0375-0.0625	Mawson Lakes, Australia	2020	(Hidayat & Soekarno, 2020)
	1.27-2.54	Beijing Normal University, Chaina	2016	(Li et al., 2016)
	0.45-1.75	Lathi, Finland	2014	(Krebs et al., 2014)
	1.27-2.00	Taapelipolku, Lathi, Finlad	2013	(Krebs et al., 2013)

These parameters are typically measured in inches and represent the maximum depth of water that can accumulate on the surface before it starts to runoff or infiltrate. The D-impervious parameter is used to estimate the depression storage on surfaces such as pavement, roofs, and other surfaces that do not allow water to infiltrate. The D-pervious parameter is used to estimate the depression storage on surfaces such as grass, soil, and other surfaces that allow water to infiltrate. The values for N-impervious, N-pervious, D-impervious, and D-pervious can be set by the user. It is important to note that the values of these parameters can vary significantly depending on the specific conditions at a site, and it's important to use site-specific data where possible.

The table 3.2 presents the different coefficients used in the Storm Water Management Model (SWMM) by various researchers around the world. The table includes four different parameters: N-pervious, N-impervious, D-storage pervious, and D-storage impervious. It has been seen that, the values of these parameters vary among different study sites and in temporal scale of study. The N-pervious parameter, which represents the ratio of pervious area to total area, ranges from 0.020 to 0.645, with the highest value found in the Chaktai and Rajakhali watershed in Chattogram, Bangladesh in 2022. This value is relatively high compared to other study sites such as Lijia Mountain in Nanjing, China, where the N-pervious value is 0.400 (Yuan et al., 2022). Similarly, the N-impervious parameter, which represents the ratio of impervious area to total area, ranges from 0.0075 to 0.124, with the highest value found in the Chaktai and Rajakhali watershed in Chattogram, Bangladesh in 2022. This value is relatively low compared to other study sites such as Lijia Mountain in Nanjing, China, where the N-impervious value is 0.013 (Yuan et al., 2022). The D-storage pervious parameter, which represents the depression storage depth on pervious area, ranges from 0.0375 to 7.62, with the highest value found in the McClelland Basin in Fort Collins, Colorado, USA in 2021 (Dell et al., 2021). This value is relatively high compared to other study sites such as Mawson Lakes in Australia, where the D-storage pervious value ranges from 0.0375 to 0.0625 (Hidayat & Soekarno, 2020). Similarly, the D-storage impervious parameter, which represents the depression storage depth on impervious area, ranges from 0.0375 to 2.54, with the highest value found in the McClelland Basin in Fort Collins, Colorado, USA in 2021 (Dell et al., 2021).

This value is relatively low compared to other study sites such as Lathi, Finland, where the D-storage impervious value ranges from 0.45 to 1.75 (Krebs et al., 2014). It is worth noting that the coefficients used in the SWMM model may vary based on the specific characteristics of the study site, such as climatic conditions, land use, and topography. Additionally, the results of this table indicate that the values of the coefficients used in SWMM model in different regions of the world vary greatly. This variation in coefficient values can be attributed to several factors.

Table 3:3 Information regarding the coefficients used (after calibration and validation) for each sub-catchments

SCs	Slope (%)	Imprv. area (%)	N-impervious	N-pervious	D-impervious	D-pervious
SC1	11.12	89.09	0.058	0.351	2.26	0.95
SC2	18.3	58.76	0.062	0.378	1.77	0.75
SC3	14.85	66.07	0.075	0.451	1.96	0.85
SC4	5.12	82.83	0.055	0.332	3.30	1.45
SC5	2.64	70.93	0.067	0.411	4.57	2.13
SC6	4.42	65.89	0.093	0.568	3.55	1.45
SC7	3.97	33.86	0.104	0.624	3.74	1.68
SC8	5.37	44.91	0.124	0.645	3.23	1.32
SC9	7.2	67.05	0.045	0.278	2.80	1.15

One possible reason is the difference in the physical characteristics of the study sites. For example, the Chaktai and Rajakhali watershed has a higher percentage of pervious area compared to Lijia Mountain, which would result in a higher N-pervious coefficient. Additionally, the variation may be due to differences in the methods and data used by the researchers. For example, the study conducted by Dell et al. (2021) in McClelland Basin, Colorado, USA used remote sensing data to estimate the coefficient values, while the study conducted by Hidayat and Soekarno (2020) in Mawson Lakes, Australia used field data. Noteworthy to mention, it is anticipated that the coefficients are dynamic in nature and the values must have changed over time and may have different values for the current date.

The table 3.3 provides information on the coefficients used in a study of sub-catchments. The sub-catchments (SCs) are identified by a number, and the table lists the slope (%) and percentage of improved area for each sub-catchment. Additionally, the table provides values for the coefficients of N-impervious, N-pervious, D-impervious, and D-pervious for each sub-catchment. Upon analyzing data presented in the table, it can be observed that there is a variation in the coefficients among the sub-catchments. For example, the slope percentage varies from 2.64% to 18.3% among the sub-catchments. Similarly, the percentage of improved area also varies significantly among the sub-catchments, ranging from 33.86% to 89.09%. When comparing the values of N-impervious, which refers to the percentage of impervious area in a sub-catchment that is not connected to a drainage system, there is a variation among the sub-catchments. SC1 has the lowest value at 0.058, while SC5 has the highest value at 0.067. Similarly, when comparing the values of N-pervious, which refers to the percentage of pervious area in a sub-catchment that is not connected to a drainage system, there is also a variation among the sub-catchments. SC1 has the lowest value at 0.351, while SC5 has the highest value at 0.411. When comparing the values of D-impervious, which refers to the percentage of impervious area in a sub-catchment that is connected to a drainage system, there is a variation among the sub-catchments. SC7 has the lowest value at 1.68, while SC4 has the highest value at 3.30. Similarly, when comparing the values of D-pervious, which refers to the percentage of pervious area in a sub-catchment that is connected to a drainage system, there is also a variation among the sub-catchments. SC7 has the lowest value at 0.104, while SC4 has the highest value at 0.332.

The possible reasons for this variation could be the differences in land use, topography, and soil characteristics among the sub-catchments. For example, sub-catchments with steeper slopes may have a higher percentage of impervious surfaces, while sub-catchments with flatter terrain may have a higher percentage of pervious surfaces. Similarly, sub-catchments with a higher percentage of urban development may have a higher percentage of impervious surfaces and a lower percentage of pervious surfaces. It is important to note that the coefficients used in this study are based on the specific conditions of the sub-catchments studied. While these coefficients may be useful for similar sub-catchments, it is important to calibrate and validate the coefficients for any specific sub-catchment before using them in a study. Additionally, it would be beneficial to compare these coefficients with references from similar studies to determine the accuracy and relevance of the coefficients for this study.

3.3 Data Collection

3.3.1 Cross-sectional data collection

To collect data for the study, cross sections of the canal were taken manually at 14 selected points along its length (see for details in Appendix A). The width of the canal's bottom was divided into several sections, and the depth of the bottom was measured using a rope with a weight attached. The length of the canal was determined using ArcGIS 10.4 and then verified by the field measurements. The average slope of the canal's bottom was determined using GPS and adjusted with data from HEC-GeoRAS. Field investigations were also conducted to examine the physical materials of the canal's bottom for determining Manning's n values, which is a coefficient used in the calculation of open channel flow and is dependent on the roughness of the channel's bottom. In addition to physical measurements, field land use and cover data was recorded in various locations for the purpose of assessing the accuracy of a land use map prepared from a DEM using ArcGIS 10.4. This information can be used to understand how land use and cover changes may be impacting the flow and overall functioning of the canal. Additionally, an opinion survey was conducted to identify any problems and gather information about the flow patterns and causes of overflow in the canal. This survey included questions about the flow patterns, causes of overflow, and other issues that may be impacting the canal's performance and function.

3.3.2 Stormwater Runoff sample collection

The Chaktai-Rajakhali watershed will undergo a runoff quality assessment, which will involve examining four distinct land use types: residential, commercial, industrial, and institutional. While residential, commercial, and industrial land uses are the most studied (Mohammed et al., 2022, Rezaei et al., 2019, Shrestha & He, 2017, Chow et al., 2012, Hossain et al., 2012, Gülbaz & Kazezyilmaz-Alhan, 2012, Temprano et al., 2006 and Barco et al., 2000). This study will also consider educational institutions. Institutional land use is important for the runoff quality assessment of the Chaktai-Rajakhali watershed for several reasons. Educational institutions may generate different types and amounts of pollutants compared to other land uses.

This type of land use has been evaluated for campus based LID performance by many researchers in different educational institutions of the world, such as in Turkey (Gülbaz, Yıldırım, et al., 2019), USA (Crowl, 2017; DiGiovanni et al., 2010), China (Jia et al., 2015; Rong et al., 2021) and Philippines (Frias & Maniquiz-Redillas, 2021). Moreover, educational institutions occupy 5.10% of the total area and are present in SC2, SC3, and SC8 sub-catchments, accounting for 31.47%, 10.18%, and 4.02% of their respective areas, totalling 58.32 ha. In addition, a more comprehensive understanding of the sources and patterns of pollutants in the watershed can be achieved by including institutional land use in the assessment. This information are critical for developing effective management strategies to reduce the impact of runoff on water quality. Finally, the outcomes of this assessment can inform the implementation of appropriate LID options to mitigate the impact of institutional land use on runoff quality.

Four (04) representative land uses were sampled to address the variability of rain-induced runoff from each of the land use patterns. In total, sixteen (16) sampling points from four distinct land uses were selected to capture runoff samples from a typical rain event lasting an hour or more which was used as training sample. Furthermore, nine (09) stormwater runoff samples were also collected from the outlets of each sub catchment which were considered as validation sample that were used for runoff quality model validation. Therefore, runoff samples were collected at the inlet point of the drain using a previously cleaned plastic bucket of 5L volume at every 3-to-5-minute intervals. Then Event Mean Concentration (EMC) were determined from the data. Stormwater induced runoff samples were collected from four different LU types within the CCC area by using sheet flow and grab sampling techniques (Harmel et al., 2010; Kalkhajeh et al., 2019; Martin et al., 1992; USEPA, 2009) at sixteen (16) distinct sampling points (see figure 3.3) separately.

The stormwater induced runoff samples were collected from the specific LU types at the point just before they mixed with the stream/canal water in order to reflect the pollution contribution from a specific LU only (see figure 3.3). It is worth noting that the institutional sites' runoff passes over relatively grassed land in contrast to paved surfaces in industrial and commercial areas, while in residential areas a mixture of paved and grassland surfaces is encountered. Collected samples were labelled and were further processed separately for elemental analysis in the Environmental Engineering Laboratory.

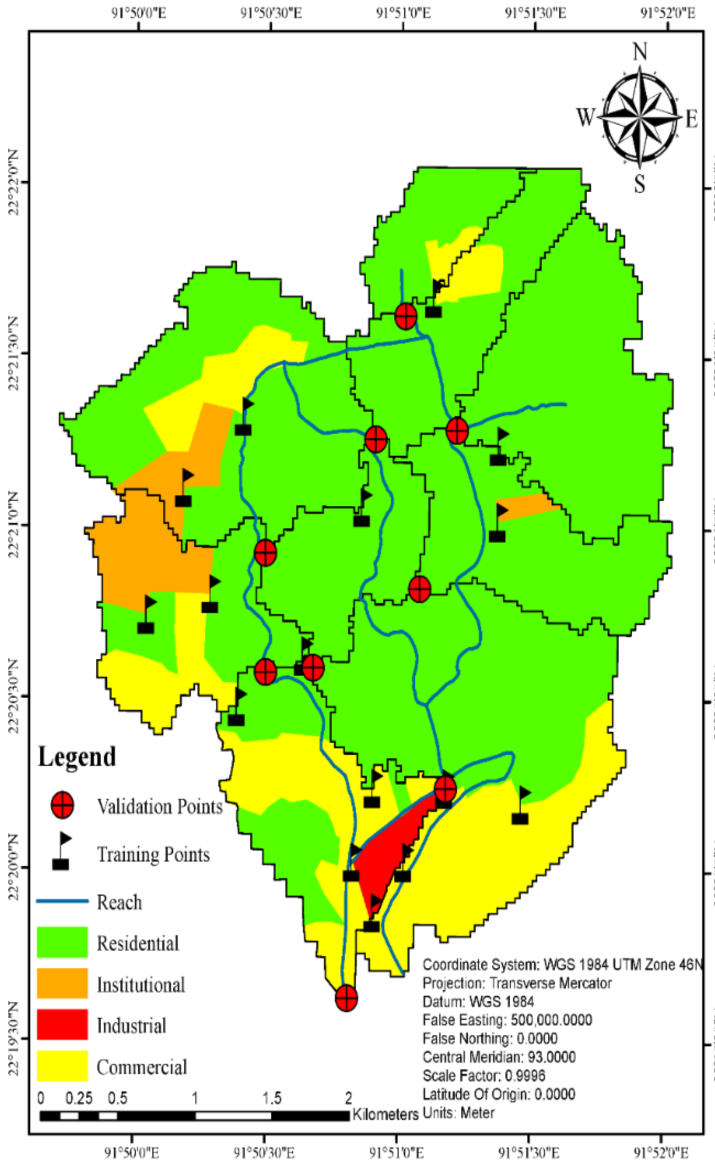


Figure 3.3 Soil Map of studied area indicating Training and Validation sampling locations.

Table 3:4 Technical specification of the devices and methods used for the laboratory tests

Parameters	Name of the Instrument/ Methods	Range	Accuracy	Runoff or Surface water quality standards (mg/L)			
				BDS[a]	BIS[b]	CWP[c]	EPA[d]
TSS	Standard Methods provided by APHA			--	--	78.4	180-548
TN	HI801	10-150 mg/L	± 4.0%	--	--	2.39	--
TP	HI801	0.00 to 32.6 mg/L	± 4.0%	--	--	0.32	0.42-0.88
Zn	HI801	0.0-3.00 mg/L	± 3.0%	--	--	0.162	0.202-0.633
BOD_5	Standard Methods provided by APHA			< 6	< 3	14.1	12-19
COD	Standard Methods provided by APHA			--	--	52.8	82-178

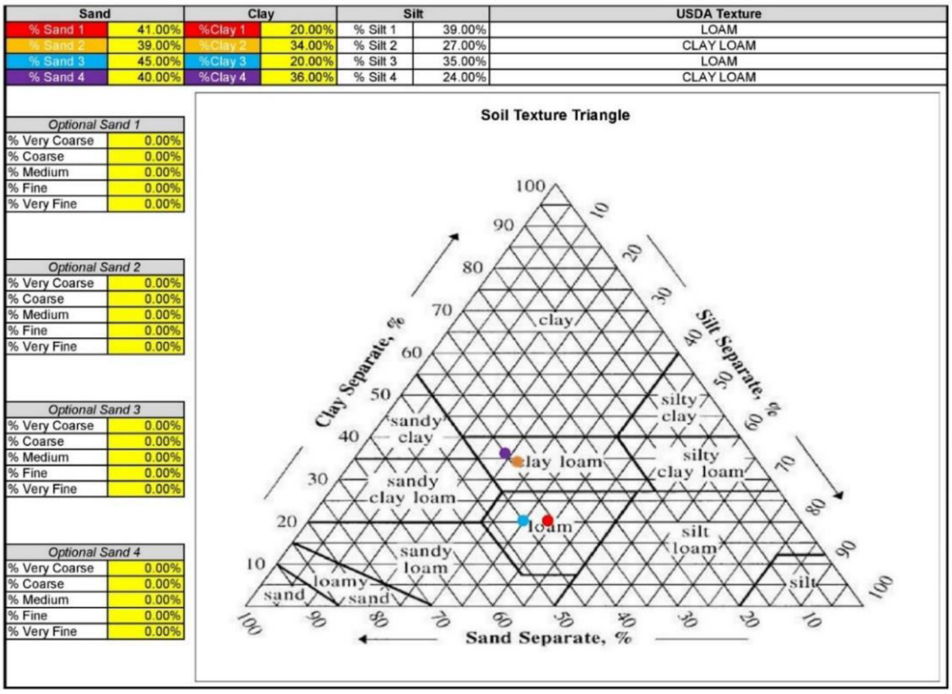
Note: Surface water quality used for aquatic life
[a]BDS: Bangladesh Standards (BECR, 1997)
[b]BIS: Bureau of Indian Standards (BIS, 1991)
[c]CWP: Center for Watershed Protection (CWP, 2003)
[d]EPA: Environmental Protection Agency (EPA, 1983)

Each of the collected water samples was analysed to measure the crucial physical and chemical parameters, including total suspended solids (TSS), Total Nitrogn (TN), Total Phosphorus (TP), biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) and Zinc (Zn). Tests were carried out within 24 hours of data collection with the use of standard water quality control and test procedures as specified in Standard Methods for the Examination of Water and Wastewater by the American Public Health Association (APHA) and various water quality testing devices (see Table 3.4).

3.3.3 Soil sample collection and determination of HSG

In order to determine the Hydrologic Soil Group (HSG) of the study area, a soil textural classification method was employed. This method involves collecting soil samples from various locations within the watershed and analyzing them in a laboratory setting. In this study, soil samples were collected from 30 locations (detail is in Appendix B) and taken to the Geotechnical Engineering Laboratory at Chittagong University of Engineering and Technology (CUET) for analysis. Additionally, land-use information was also collected for all sampled locations. The soil samples were collected using appropriate tools and methods, and were then air-dried, sieved, and homogenized to prepare them for analysis.

The analysis consisted of two methods, sieve analysis and hydrometer analysis. Sieve analysis involves passing a dry soil sample through a set of sieves of decreasing mesh size to separate the soil particles by size. The weight of the soil retained on each sieve is then used to calculate the particle size distribution of the soil and classify it as sand, silt, and clay. Hydrometer analysis is also used to classify the soil texture, which involves suspending a dry soil sample in water (passing through a #200 sieve) and then measuring the time it takes for the soil particles to settle. The rate of settling is then used to calculate the particle size distribution of the soil and classify it as sand, silt, or clay.



Sand		Clay		Silt		USDA Texture
% Sand 1	41.00%	%Clay 1	20.00%	% Silt 1	39.00%	LOAM
% Sand 2	39.00%	%Clay 2	34.00%	% Silt 2	27.00%	CLAY LOAM
% Sand 3	45.00%	%Clay 3	20.00%	% Silt 3	35.00%	LOAM
% Sand 4	40.00%	%Clay 4	36.00%	% Silt 4	24.00%	CLAY LOAM

Optional Sand 1	
% Very Coarse	0.00%
% Coarse	0.00%
% Medium	0.00%
% Fine	0.00%
% Very Fine	0.00%

Optional Sand 2	
% Very Coarse	0.00%
% Coarse	0.00%
% Medium	0.00%
% Fine	0.00%
% Very Fine	0.00%

Optional Sand 3	
% Very Coarse	0.00%
% Coarse	0.00%
% Medium	0.00%
% Fine	0.00%
% Very Fine	0.00%

Optional Sand 4	
% Very Coarse	0.00%
% Coarse	0.00%
% Medium	0.00%
% Fine	0.00%
% Very Fine	0.00%

Figure 3.4 Soil Texture Triangle (USDA, 2018)

After the analysis, the soil samples were classified into one of the 12 textural classes such as sandy loam, clay loam etc. based on the relative proportions of sand, silt and clay using the USDA Soil Texture Triangle (USDA, 2018) (see Figure 3.4). This method is widely used because it is simple, inexpensive, and widely available. In addition, it has been found to be a reliable method for determining the HSG in many different types of soils and environments.

The Hydrologic Soil Group (HSG) and the Curve Number (CN) are related concepts used in assessing the hydrological characteristics of soils. The HSG is a soil classification system that is used to determine the infiltration rate and runoff potential of soils, while the CN is a method used to estimate the amount of runoff that will occur from a specific area of land given a certain amount of precipitation. It was developed by the USDA Natural Resources Conservation Service (NRCS) to identify soil's ability to infiltrate water, and thus it's potential for runoff.

Table 3:5 Hydrological Soil Group Table given by USDA-NRCS (USDA-NRCS, 2020)

HSG	Runoff Potential	Soil Textural classification	Infiltration Rate (mm/hr)
A	Low	Sandy, Loamy sand, sandy loam	8-12
B	Moderately Low	Silt or Loam	4-8
C	Moderately high	Sand, Clay, Loam	1-4
D	High	Clay loam, silty clay loam, sandy clay, silty clay or clay	0-1

It classifies soils into four groups: A, B, C, and D (as shown in Table 3.5), where group A soils have the highest infiltration rates and the lowest runoff potential, group B soils have moderate infiltration rates and moderate runoff potential, group C soils have low infiltration rates and high runoff potential, and group D soils have the lowest infiltration rates and the highest runoff potential. Soil textural classification was used for the determination of HSG of the study area.

Each textural class has a corresponding Hydrologic Soil Group (A, B, C, or D) based on its infiltration rate and runoff potential. For example, soils that are classified as sandy loam or loamy sand are typically classified as Group A soils, which have the highest infiltration rates and the lowest runoff potential. On the other hand, soils that are classified as clay or clay loam are typically classified as Group C or D soils, which have the lowest infiltration rates and the highest runoff potential. Soil textural classification is a widely used method for determining the HSG because it is relatively simple, inexpensive, and widely available. In addition, it has been found to be a reliable method for determining the HSG in many different types of soils and environments.

3.3.4 Secondary Data Collection

Table 3.6 shows the necessary data Sources of the Study provides a list of data sources that are required for the study. The table includes information on the data source, the organization or agency providing the data, the resolution or period of the data, and the links to access the data. The data sources listed include a Digital Elevation Model (DEM) from the United States Geological Survey (USGS) with a resolution of 30m x 30 m that can be used for terrain analysis, flood modeling and infrastructure planning.

Table 3:6 Necessary data sources of the study

Data	**Source**	**Sources**	**Resolution /Periods /Others**
DEM	United States geological Survey (USGS)	https://earthexplorer.usgs.gov/	30m X 30m
Landsat Data	United States geological Survey (USGS)	https://earthexplorer.usgs.gov/	Landsat 4,5,7,6
Land Use Map	GlobeCover	http://due.esrin.esa.int/page_globcover.php	n/a
Soil Data Map	Food and Agricultural Organization (FAO)	http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116	1000m
Precipitation	National Aeronautics and Space Administration (NASA) Bangladesh meteorological department (BMD)	https://earthdata.nasa.gov/ www.bmd.gov.bd	1990-2020
Water tide table	Chittagong Port Authority (CPA) Bangladesh Navy Hydrographic & Oceanographic Centre (BNHOC)	http://www.cpa.gov.bd/site/view/commondoc/Tide%20Table/ http://bnhoc.navy.mil.bd/?pageid=77	2010-2020
Discharge	Bangladesh Water Development Board (BWDB)	https://www.bwdb.gov.bd/	2020
CN Values	Washington State Department of Transportation	https://wsdot.wa.gov/	2019

Source: BMD, 2022; BNHOC, 2018; BWDB, 2018; CPA, 2018; ESRIN, 2018; FAO, 2018; NASA, 2018; USGS, 2018.

The Landsat data from the USGS, which includes Landsat 4, 5, 7, and 8, is a collection of satellite imagery that covers the entire Earth's surface, useful for monitoring land cover changes, vegetation analysis and natural resource management. The Land use map from Globe Cover provides information on the different types of land cover present in an area, such as urban areas, forests and agricultural land that can be used for land use planning, biodiversity conservation and natural resource management.

The Soil data map from the Food and Agricultural Organization (FAO) provides information on the different types of soil present in an area, including their texture, structure and fertility that can be used for crop suitability analysis, soil conservation and land use planning.

Precipitation data from the National Aeronautics and Space Administration (NASA) and the Bangladesh Meteorological Department (BMD) provides information on the amount and distribution of rainfall in an area for the period of 1990-2020 that can be used for water resource management, flood forecasting and drought monitoring. Water tide table data from the Chittagong Port Authority (CPA) and the Bangladesh Navy Hydrographic & Oceanographic Centre (BNHOC) provide information on the tidal patterns and changes in an area for the period of 2010-2020 that can be used for coastal zone management, navigation, and coastal engineering. Discharge data from the Bangladesh Water Development Board (BWDB) provide information on the flow of water in a particular area for 2020 that can be used for water resource management, flood forecasting and hydroelectric power generation. CN Values from the Washington State Department of Transportation provides information on the runoff characteristics of a particular area for 2019 that can be used for stormwater management, flood forecasting and land use planning.

3.4 Validation of the model

Validation of a hydrologic model in SWMM involves comparing the results of the model with observed data from the study area. The process starts with data collection and setting up the model with accurate input parameters. The model is then calibrated by adjusting the parameters until the results match observed data. Validation is performed by comparing the model results with the observed data and evaluating the model's performance using metrics such R, R^2, Adjusted R^2, Mean Absolute Deviation (MAD), Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) as shown in Eqs. (3.1-3.7). The validation process is iterative and may require multiple rounds of calibration and validation until an acceptable level of accuracy is achieved. The model can then be refined as necessary based on the results of the validation.

$$R = \sqrt{\frac{\sum_{t=1}^{n}(O_t - S_t)^2}{\sum_{t=1}^{n}(O_t - \bar{O})^2}} \qquad \text{Eq. (3.1)}$$

$$R^2 = \frac{\sum_{t=1}^{n}(O_t - S_t)^2}{\sum_{t=1}^{n}(O_t - \bar{O})^2} \qquad \text{Eq. (3.2)}$$

$$Adjusted\ R^2 = \frac{\frac{\sum_{t=1}^{n}(O_t - S_t)^2}{n-k}}{\frac{\sum_{t=1}^{n}(O_t - \bar{O})^2}{n-1}} \qquad \text{Eq. (3.3)}$$

$$MAD = \frac{\sum_{t=1}^{n}|O_t - S_t|}{n} \qquad \text{Eq. (3.4)}$$

$$MSE = \frac{\sum_{t=1}^{n}(O_t - S_t)^2}{n} \qquad \text{Eq. (3.5)}$$

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(O_t - S_t)^2}{n}} \qquad \text{Eq. (3.6)}$$

$$MAPE = \frac{\sum_{t=1}^{n}\left|\frac{O_t - S_t}{O_t}\right|}{n} \times 100 \qquad \text{Eq. (3.7)}$$

O_t, S_t, $\bar{O}$, k, n (t = 1, 2,…..n) O_t, S_t, $\bar{O}$, k, n (t = 1, 2,……..n) represents the observed values, Simulated values, and average values. In addition, K represents the number of parameters fit by the regression and nos. of observation points, respectively.

The validation of the rainfall-runoff model at the two outlets (O1 and O2) of the Chaktai Rajakhali watershed was performed using ground truthing method. The comparison was made between the modeled data and actual measurements of water depth taken during multiple events from August 15 to August 25, 2020. The ground truthing method used in this validation process involves comparing the modeled data with actual measurements taken in the field. In this case, the water level and runoff quality data were collected from different sampling locations within the Chaktai Rajakhali watershed. This data was then used to validate the accuracy of the rainfall-runoff model. In addition to rainfall runoff model, the runoff quality model validation was also conducted. This was done by determining the Event Mean Concentration (EMC) at the outlets of each sub-catchment. The EMC provides a measure of the concentration of pollutants or substances in the runoff water. The comparison of the modeled EMC values with the actual measurements allows for a more comprehensive evaluation of the runoff quality model and its ability to accurately predict runoff quality.

3.5 Data processing and key framework development

PCSWMM is developed version of SWMM has been used as modeling software for watershed analysis around the world. The software basically used for drainage and green infrastructure design, floodplain delineation, water quality and integrated catchment analysis. In this study all the parameters (i.e., land uses, soil types, flow paths, surface elevations and rainfall data) and shape files of sub-catchments will be given as input in PCSWMM. The existing situation of the channel drainage for rainfall runoff, infiltration and runoff depth will be estimated using PCSWMM hydrologic model for different return periods of rainfall. Again, storm depths will be chosen from generated IDF curve based on time of concentration. SCS curve number method was selected for runoff estimation in PCSWMM 2D, Then, different return periods of rainfall intensity/ design flow will be used to simulate the surface runoff.

The runoff from storms will be tested for total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) using accepted methods for various types of land usage. Four scenarios will be evaluated for Low Impact Development Best Management Practices (LID-BMPs) options, including:

1. S1 (No LIDs): Business as usual
2. S2 (vegetative swale): The runoff from storms to be analyzed using the current situation and the addition of a vegetative swale.
3. S3 (Bio-retention cells, Rain barrels, Infiltration trenches, Permeable pavements): The runoff from storms to be assessed using the current situation and the addition of Bio-retention cells, Rain barrels, Infiltration trenches, and Permeable pavements.

4. S4 (S2 and S3): The runoff from storms are to be analyzed using both the current situation with the addition of a vegetative swale and the addition of Bio-retention cells, Rain barrels, Infiltration trenches, and Permeable pavements.

Cost effectiveness for mention four scenarios will also be evaluated using Life Cycle Cost (LCC) method to find out the most suitable and economically viable LID options for the urban area. The study will also identify possible optimized options towards arriving at appropriate planning decisions for the improvement of city drainage system along with detention pond design.

3.6 Spatial analysis and Watershed Preparation

In this study, hydrological analysis for canal performance was carried out using ArcGIS 10.4 and the HEC-HMS model. The analysis included extracting various components such as flow direction, flow accumulation, watershed delineation, and stream networks. The methodology adopted for the preparation of a spatial database using ArcGIS 10.4 is shown in the figure provided. The first step in the process was to prepare the watershed of the study area that would be used in the model. This was done by acquiring digital elevation model (DEM) data and using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (USGS, 2018) radar data to create a DEM with a 30 m x 30 m resolution.

This data was collected in 2020 and was used to determine different hydrographic parameters. The first step in the preparation of the watershed was to create a fill DEM. This is essential because the drainage network is built to the flow path of every cell, eventually off the edge of the grid. If cells do not drain off the edge of the grid, they may attempt to drain into each other, leading to an endless processing loop. The Hydrology toolbar was selected from the search window bar and the fill tool was selected. The raw DEM was selected as the input surface and the output surface raster was also specified. After processing, the fill DEM was prepared and ready for further use. For all spatial analysis, both the raw DEM and the watershed boundary needed to be added to ArcGIS.

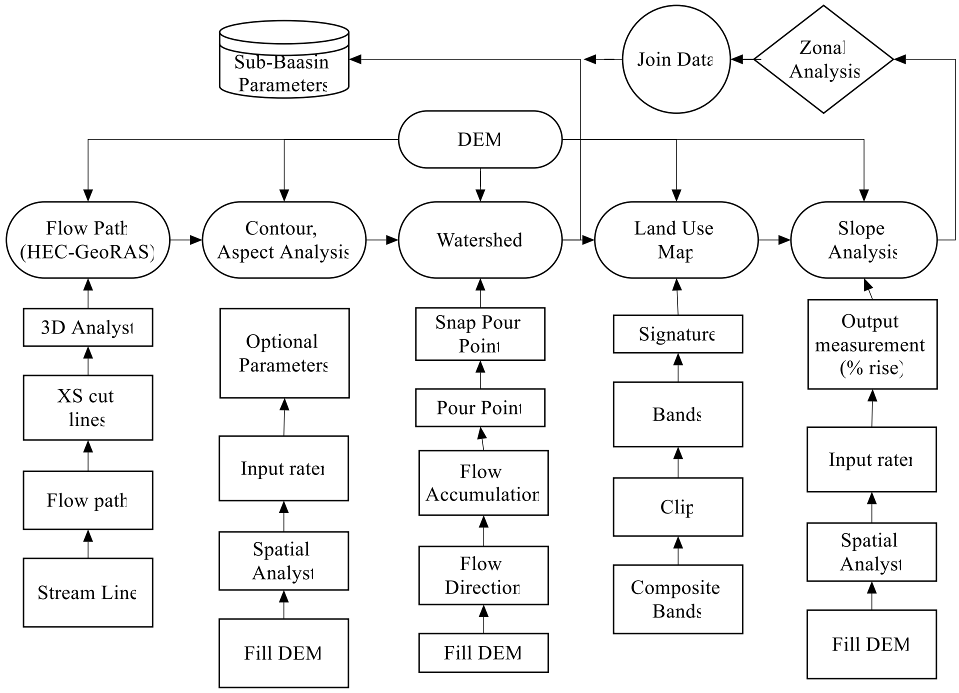


Figure 3.5 Spatial database preparation procedure using ArcGIS 10.4

The fill tool (Spatial Analysis) in the search window was selected and then the output directory was specified. The process took 2-3 minutes, but the time may be extended depending on the PC configuration. Contour lines indicate lines on a map joining points of equal height above or below sea level. Information about the shape of the land (hilly, flat, etc.) can be found from the contour map. To create the contour map for the study area, the contour tool (Spatial Analyst) in the search window was selected. After specifying the output directory and contour interval, sometime was allowed for processing, and the final contour map for the study area was obtained.

The slope of an area indicates the rise or fall of the land surface, in other words, the steepness or the degree of incline of a surface. To analyze the slope for the study area, the slope (Spatial Analyst) tool in the search window was selected. The input raster (Fill DEM), output directory, and output measurement (Degree/Percent Rise) were specified for the slope analysis of the study area. Aspect is the orientation of the slope, measured clockwise in degrees from 0 to 360, where 0 is north-facing, 90 is east-facing, 180 is south-facing, and 270 is west-facing. To analyze the aspect for the study area, the Aspect (Spatial Analyst) tool in the search window was selected. The input raster (Fill DEM) and output directory were specified for the aspect analysis. The stream order indicates numerical designations that give information about where in a certain stream segment lies in the watershed drainage system. This was done using the 'Stream Order' tools under 'Hydrology' tools in the 'Search' window. The Fill DEM and flow direction raster were added, and thereafter, the stream order for the study area was created. Flow direction is determined for landscape drains. This is accomplished with the selection of the Flow Direction menu choice. The ArcGIS grid processor finds the direction of steepest downward descent for every cell in the surface grid.

Flow accumulation is a process used to identify the path of water flow on a landscape. This is achieved by using the 'Flow Accumulation' tool in the 'Hydrology' section of ArcGIS and specifying a surface raster file. The next step is to identify the pour points, which are the locations where water exits in the watershed. This is done using the 'Snap Pour Point' tool in the 'Hydrology' section, and manually selecting the highest flow accumulation pixel. The process of identifying pour points is typically done through an iterative approach, moving upstream, and creating smaller and smaller sub-basins until the desired objective is reached. The pour points, flow accumulation, and flow direction information is then used by the grid processor to create the watershed. ArcGIS can create a watershed for each identified pour point, and the resulting raster watershed can be converted into a polygon using the 'Raster to Polygon' converter.

3.7 Maximum Likelihood Classification for Land use Land Cover Mapping

Maximum Likelihood Classification is a method used in remote sensing and GIS to analyze land use and land cover. This method is particularly useful for mapping large land areas with high accuracy and at low cost. The process begins by obtaining a Landsat-8 OLI image with a spatial resolution of 30m x 30m, which can be found on the USGS website (http://earth explorer.usgs.gov). The image classification process can be divided into two types: supervised and unsupervised. In this study, supervised image classification was used.

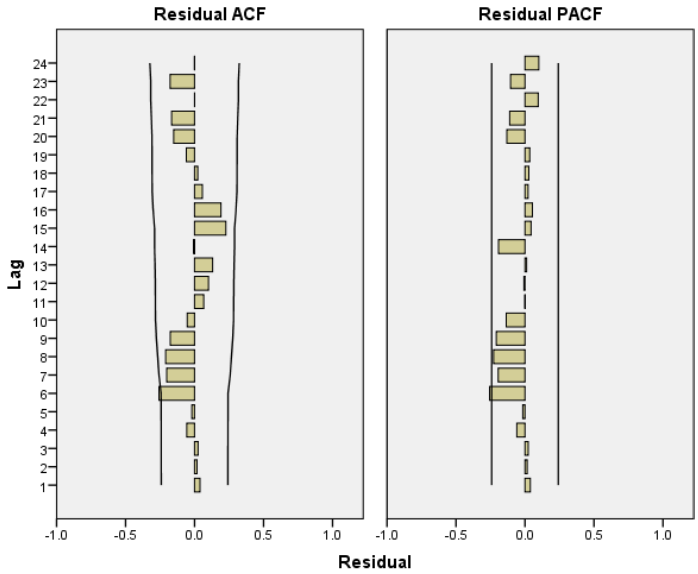
The first step in the image classification process is to open ArcGIS and import the raster bands of the LANDSAT images along with the boundary shape file. The next step is to select the desired boundary area from the full DEM images using the 'Clip' tool. The image classification toolbar is then used to generalize patches of pixels with the same attribute/quality. Different types of bands with a common characteristic are available for different LANDSAT images. The next step is to identify "training sites" which are areas that are known to be representative of a particular land cover type. This is done by picking up specific signatures and merging similar classes. The materials can be distinguished from one another by examining which portions of the spectrum they reflect and absorb. Zonal statistics is then used to analyze statistical parameters such as mean, max, standard deviation, and sum of a zone.

In this study, zonal statistics were only done for slope analysis. The final step is to join the field to the watershed attribute table and incorporate the zonal statistics results in the field. The Zonal table is selected as the input table, and OBJECTID is used as the input join field. The required parameters are checked and processed, and finally, the parameters are added to the watershed attribute table.

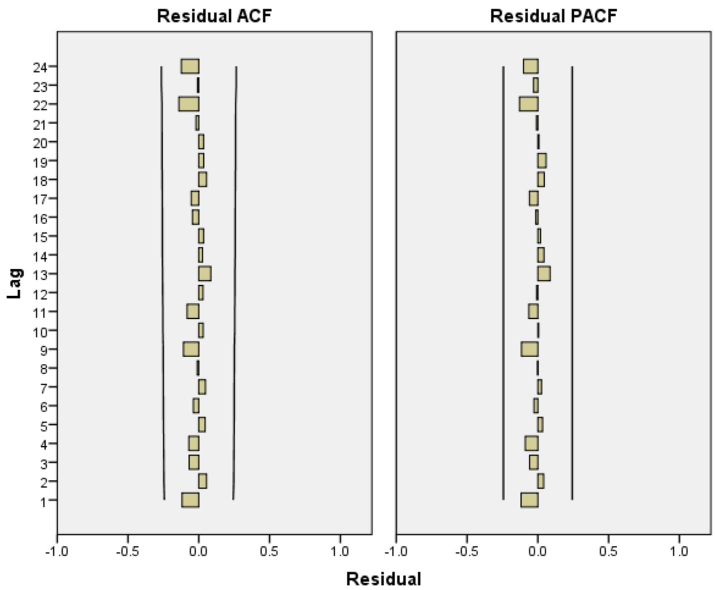
3.8 Prediction and forecasting of rainfall using ARIMA model

Monthly data of rainfall and temperature collected for the duration of 1953 to 2020 from Patenga, Chattogram (22.35°N and 91.817°E) station of Bangladesh Meteorological Department (BMD). The Prediction and forecasting of rainfall and temperature is done using the ARIMA model in SPSS v.20. The Prediction is done for the period of 2021 to 2070. Winter (December- February), Pre-monsoon (March-May), Monsoon (June-September), Post- Monsoon (October-November) seasons are considered to evaluate the changes of seasonal variation of rainfall and temperature. Total time series is divided in four phase (1953-1990, 1991-2020, 2021-2050, 2051-2070). Trend analysis and significance test have been done using Mann-Kendall (MK) analysis and magnitude of change is determined using Sen's slope (SS) estimator. Moreover, correlation analysis between rainfall and temperature is done using Spearman's rank correlation method. Finally, the study is concluded with comparative variation of rainfall and temperature in different seasons.

The Auto Regressive Integrated Moving Average (ARIMA) Model was used to forecast rainfall and temperature trends. The model is simple and effective, demonstrating a stochastic time series model that may be used to anticipate future events using present data. The three essential elements of the ARIMA model are autoregressive, integrated, and moving average, which drive the evaluation and selection of coefficients in an iterative and recursive manner. Because data stationarity is required, stationarity tests were initially performed using monthly data for the period of the research by displaying Auto Correlation Function (ACF) and Partial Auto Correlation Function (PACF) as shown in figure 3.6.



(a)



(b)

Figure 3.6 ACF and PACF before (a) and after (b) calibration

The monthly data has been found to be inconsistent and nonstationary in character, as seen in figure 3.6(a), with spikes crossing the upper and lower border levels. The ARIMA model was created using IBM-SPSS version 20 and Box-Jenkins' algorithm methods. As previously stated, the ARIMA (p, d, q) model uses three predictor variables to predict and forecast data, where p refers to the number of autoregressive orders, d to the order of differencing applied to the series, and q (0) to the number of moving average orders of the data series. Prior to future prediction, the various ACF and PACF have been assessed as acquired from several trials for various p, d, and q values until the spikes in ACF and PACF fall between upper and lower boundary limits. Figure 3.6(b) depicts the final trial in this sequence. In addition, the predicting of future rainfall (Figure 3.7) was done using the current trend ARIMA (28~30, 0, 0) model. For each example, several statistical metrics such as stationary R squared (R^2) and R squared (R^2) were employed to assess the model's accuracy. The average stationary R squared (R^2) and R squared (R^2) for rainfall prediction was 0.952 according to this study.

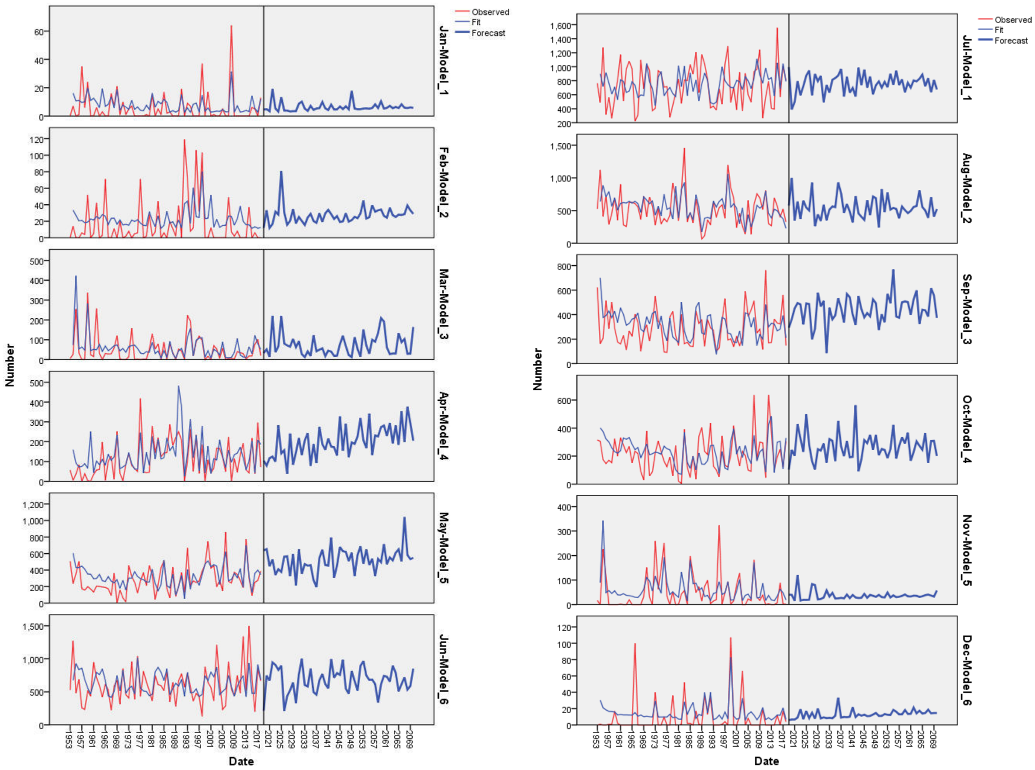


Figure 3.7 Forecasting and prediction of rainfall pattern using ARIMA model

3.9 Generation of IDF Curve

3-hourly rainfall data from (2003-2019) and daily (24- hourly) rainfall data (1953-2019) were collected from BMD for Chattogram Station (22.35°N and 91.82°E) . Based on long term rainfall records, it is seen that the average rainfall received by the ChCC area is about 3378 mm that is substantially greater than country's annual average of rainfall of 2300 mm. Analyzing the rainfall records, it has also been revealed that the rainfall is mostly confined between May to October in a calendar year. Furthermore, it is noted that the highest precipitation with an average of 743 mm generally found in the month of July (BMD, 2019).

Reviewing studies in Chattogram, it has been identified that nearly half of the city suffered by water jam with a 0.2 to 2.1 m overland water depth causing lot of subsequent issues and inconveniences while areas remained drowned about 48-72 hours (Masum & Hossesn, 2018; Mohit & Akter, 2014). 3-hourly rainfall depth data were arranged as descending order based on their magnitude. The successive rainfall depth records were studied for predicting possible rainfall amount in different return periods probability.

Moreover, the extreme rainfall distributions were done following standard protocols. For the daily rainfall data were analyzed with different probability using Weibull's equation as mentioned in Eq. (3.8).

$$P = \frac{m}{N+1} \qquad \text{Eq. (3.8)}$$

Where, P refers the probability of occurrence, m indicates the successive ranking observed rainfall value after arranging them with order and N is the total number of years of rainfall record.

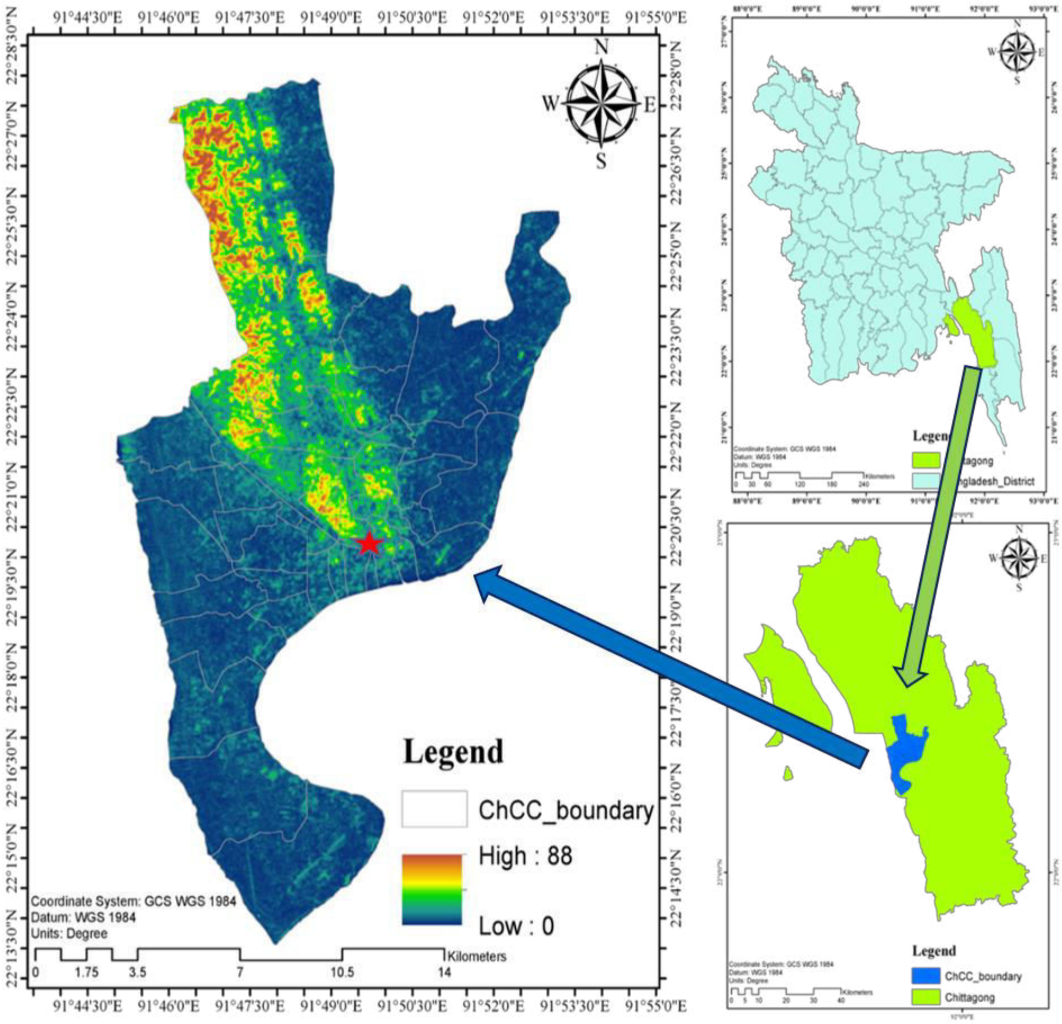


Figure 3.8 Map showing the geograpgical location of the BMD (Potenga) station in Chattogram.

In this study IDF curves were developed for Chattogram City for 1, 2, 5, 10, 15, 25, 50, 100 years return period. Firstly, rainfall depths were determined for 3, 6, 12, 24, 48, 72 hours for 1, 2, 5, 10 and 15 years of return period using 3-hourly data (2003-2019). Because of measured data records of 17 consecutive years, return period beyond 15 years are derived using nonlinear multiple regression method for selected rainfall durations of 3, 6, 12, 24, 48, 72 hours, as presented in Table 3.7. The equations derived were checked using R^2 statistic, and it has been seen that the values ranging between 0.8344 - 0.9814, illustrating a reasonably good fit. The necessary biased, errors, outliers were also checked using SPSS and Excel made spreadsheet. All the primary rainfall records used here were collected from the Bangladesh Meteorological Department (BMD).

Table 3:7 Relationships between rainfall depth (mm) and return periods (year)

Return duration	Derived Equations	R^2 value
3 hour	P_1=84.245 $T_1^{0.0675}$	0.8344
6 hour	P_1=103.65$T_1^{0.1409}$	0.9789
12 hour	P_1=136.81$T_1^{0.1102}$	0.8378
24 hour	P_1=184.39$T_1^{0.1678}$	0.9171
48 hour	P_1=265.41$T_1^{0.1593}$	0.9814
72 hour	P_1=310.14$T_1^{0.2313}$	0.9563

Where, T is the return periods (year) and P is the rainfall depth (mm).

Following on, the rainfall depths are determined further for 25, 50 and 100 years return period using the derived relationships that was not found from the record. Similarly, the rainfall depths are estimated for 24, 48 and 72 hours with 1, 2, 5, 10, 15, 25, 50 years of return period using daily (24-hourly) dataset from 1953 to 2019 (67 years). Cross validation was done between rainfall intensity for 24, 48, 72 hours duration of the 1, 2, 5, 10 and 15 years of return period for 3-hourly and 24-hourly datasets. In addition, the relationship between rainfall depths (mm) and duration (hr.) is developed using nonlinear multiple regression method for different return periods (1, 2, 5, 10, 15, 25, 50, 100 years). Thereafter, following standard procedure, rainfall intensity (I), rainfall volume (P) and duration (D), the IDF curves are constructed graphically showing the variation of intensity (I) versus duration (D) for a different return period.

3.10 Rainfall induced runoff estimation

Rainfall and runoff are the two essential hydrological variables and understanding the interrelationships between, may help planners, engineers, and policymakers make decisions for integrated water resources and watershed management in urban contexts (Kumar et al., 2021; Viji et al., 2015). Precipitation is an important component of water cycle which is defined as almost all condensed air vapor that falls as rain, hail, snow, dew and frost as a result of gravitational force (Odiji et al. 2020; Kumari et al. 2019).

Whereas, stormwater induced runoff is the portion of excess rainfall flows over surface of watershed and ultimately transferred to the nearby waterbodies after being lost mainly by the infiltration and evaporation (Kumari et al. 2019; Gupta and Dixit 2022).

In the subsequent decades, freshwater availability might be drastically reduced as a result of urbanization, air and water pollution, population growth, and climate variability (Caletka et al., 2020; Kumar et al., 2021). The SCS-CN is a widely used statistical method for estimating the direct surface runoff in a watershed for a certain rainfall event (Wang et al., 2015). The curve number (CN), which aggregates the hydrological impacts of various types of soil, is the only requirement of the SCS-CN method. Since it is simple, well-reflected, and only needs one set of data as input parameters, this method is well-liked for hydrological prediction and forecasting, especially for ungauged watersheds (Mishra & Singh, 2003; Wang et al., 2015). The USDA Natural Resources Conservation Service (NRCS) method previous known as SCS method is most widely used for the computation of storm water runoff rates, volumes and hydrograph. The NRCS Curve Number (CN) is the key component of NRCS method which depends on soil permeability, surface cover, hydrologic condition etc. The most commonly used are the June, 1986 Technical release 55 – Urban Hydrology for small watershed (TR-55) (USDA, 1986). The empirical equations used in defining the partitioning of rainfall into infiltration and runoff are shown in below (Mishra & Singh, 2003).

The water-balance equation as given below (Eq. 3.9) is the foundation of the SCS-CN approach.

$$P = I_a + F + Q \qquad \text{Eq. (3.9)}$$

The equal proportions hypothesis is defined in terms of the ratios of surface-induced runoff and precipitation (rainfall) to cumulative infiltration and likely maximum retention. Two underlying presumptions of the proportional equality hypothesis are given below (Eq. 3.10).

$$\frac{Q}{P - I_a} = \frac{F}{S} \qquad \text{Eq. (3.10)}$$

The following equation (Eq. 3.11) is an example of how to express the initial abstraction assumption (Ia), which demonstrates the connection between initial abstraction and the theoretical maximum retention (S) (see Eq. 3.13).

$I_a = \lambda S$ Eq. (3.11)

$CN\ composite = \frac{\sum A_i \times CN_i}{A}$ Eq. (3.12)

$S = \frac{25400}{CN} - 254$ Eq. (3.13)

Ia = 0.2S Eq. (3.14)

$Q = \frac{(P-Ia)^2}{(P-Ia)+S}$ Eq. (3.15)

Where,

Q (m^3/sec) = Direct Runoff

F (mm) = Cumulative infiltration

P (mm) = Precipitation (Rainfall)

S = Potential Maximum retention

= Ability of a watershed to abstract and retain storm precipitation

Ia (mm) = Initial abstraction

λ = Parameters dependent on geological and climatic factors ($0.1 \leq \lambda \leq 0.3$)

CN = Runoff curve Number

CN_i = $CN_1+CN_2+CN_3+\ldots\ldots+CN_n$

A_i = $A_1+A_2+A_3+\ldots\ldots+A_n$

A = Total Area of the watershed

The CN values generally varies from 0 to 100. While CN value 100 indicates that all rain will always be flown as runoff and that the smallest amount of infiltration will occur, CN value 0 indicates that no rain will ever turn into runoff and that the highest amount of infiltration will occur (Kauser & Akther, 2022; Odiji et al., 2020).

3.11 Generation of CN Grid

The generation of a CN grid in HEC-GeoHMS within ArcGIS was an important step in the methodology of this study. The process of generating a CN grid within HEC-

GeoHMS in ArcGIS was illustrated in figure 3.9, which displayed the step-by-step procedure. The figure 3.9 demonstrated the different steps involved in generating the CN grid, starting with the collection of necessary input data on land use, soil characteristics, precipitation and evapotranspiration, to the final step of using the generated CN grid. The figure 3.9 also highlighted the use of the HEC-GeoHMS software tool for processing the input data and generating the CN grid. It also illustrates how the software tool was utilized to generate a raster dataset, which represents the CN grid and how it was used to estimate the amount of runoff that will occur in the study area. The CN grid is used to estimate the amount of runoff that will occur in each area, based on the land use and soil characteristics of that area. This is done by using the CN method, which uses a standard set of CN values for different land use and land cover (LULC) and soil conditions as mentioned in Table 3.8.

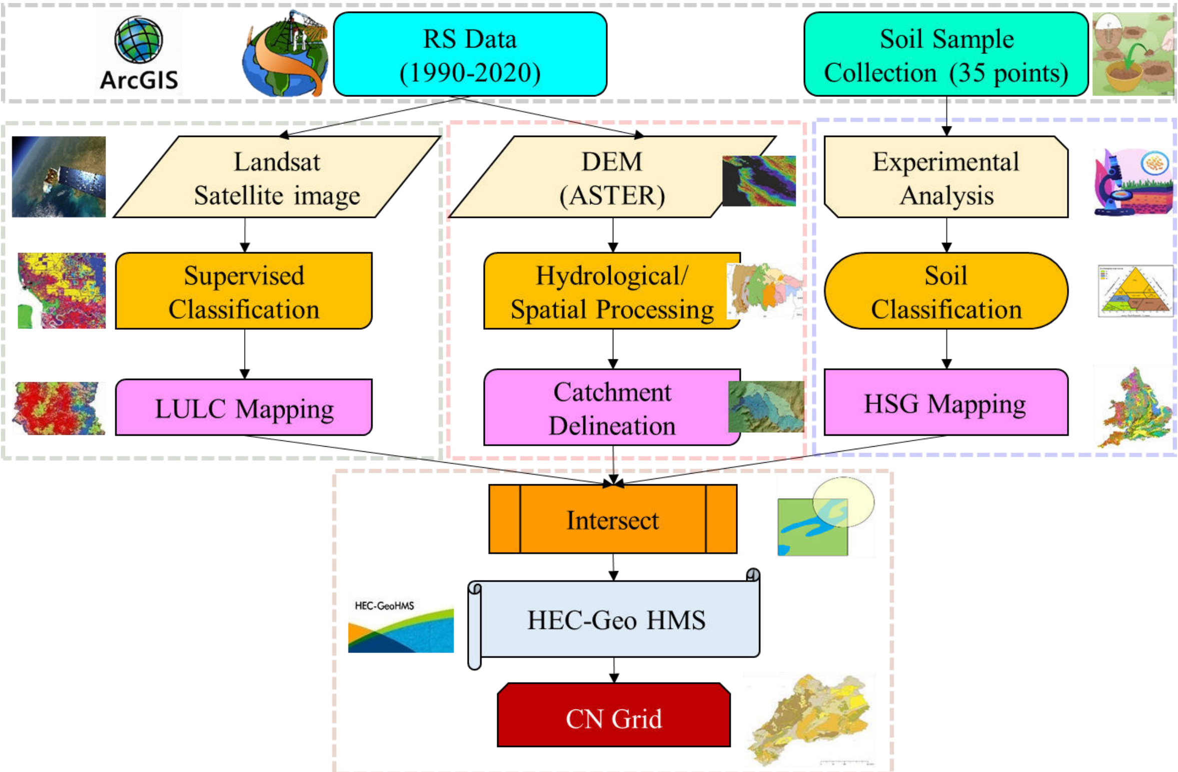


Figure 3.9 Flow diagram showing the step-by-step procedure for the generation of CN Grid

The CN values are used to calculate the initial abstraction, which is the amount of water that is retained in the soil before it becomes runoff. The higher the CN value, the less runoff is expected, and vice versa. To generate the CN grid, the first step was to gather the necessary input data, which included information on land use and soil characteristics of the study area, as well as any other relevant data such as precipitation and evapotranspiration. The land use and soil information were used to assign appropriate CN values to each grid cell in the study area. The other data, such as precipitation and evapotranspiration, were used to calculate the actual runoff that occurred in the study area.

Table 3:8 Standard Curve Number (CN) values for different LULC and soil conditions (Al-Ghobari et al., 2020; WSDOT, 2014).

LULC Classification	Description	A	B	C	D
Waterbody	River, canal, pond, lake, Reservoir etc.	98	98	98	98
Vegetation	Agricultural field, forest, gardens, green parks and fields etc.	26	40	58	61
Built up	Urban LU, settlements, roads, utilities etc.	77	85	90	92
Bare land	Open land, uncultivated land, excavation sites etc.	72	82	87	89

The input data was then imported into HEC-GeoHMS, a software tool developed by the U.S. Army Corps of Engineers Hydrologic Engineering Centre (HEC), which allows for the processing of spatial data in ArcGIS. The software tool was used to generate a raster dataset, which represented the CN grid. The generated CN grid was then used to estimate the amount of runoff that will occur in the study area. The estimated runoff values were compared with the actual runoff values, calculated using the other input data, to verify the accuracy of the CN grid. The generated CN grid was then used in the analysis and interpretation of the research objective. It was used to identify areas with high or low runoff potential, and to understand the relationship between land use, soil, and runoff. It is important to note that the CN grid is only an estimation of the runoff, and it might not be accurate in certain conditions, also the CN method is based on statistical data and it might not reflect the actual runoff in a specific area. Therefore, it is essential to validate the results by comparing them with the actual runoff data, and to take into consideration the limitations of the CN method.

3.12 Hydrologic performance assessment

In this study, the rainfall-runoff model was used to evaluate the hydraulic performance of the watershed over a period of 25 years, from 1995 to 2020 for the selected rainfall events as shown in Table 3.9 (for details see Appendix C). The Figure 3.10 illustrates the step-by-step procedure that was adopted for evaluating the hydraulic performance of the watershed. The procedure starts with the collection of the necessary input data, including information on precipitation, evapotranspiration, land use, and soil characteristics of the study area. The performance was evaluated at five-year intervals, to understand the changes in the hydraulic performance over time. The model was designed to simulate the hydrological response of the watershed to different rainfall events.

The selection of rainfall events for the model was based on two criteria: maximum rainfall amount and duration of the event (it should last for more than one day). The rainfall-runoff model was run using the PCSWMM software, which is widely used for simulating the runoff, infiltration, and routing process in urban and small watersheds. The model was calibrated and validated using the available data. The model was then used to simulate the runoff and infiltration process, and a variety of hydrologic parameters, such as total runoff, runoff rate, total infiltration, and infiltration rate, were determined.

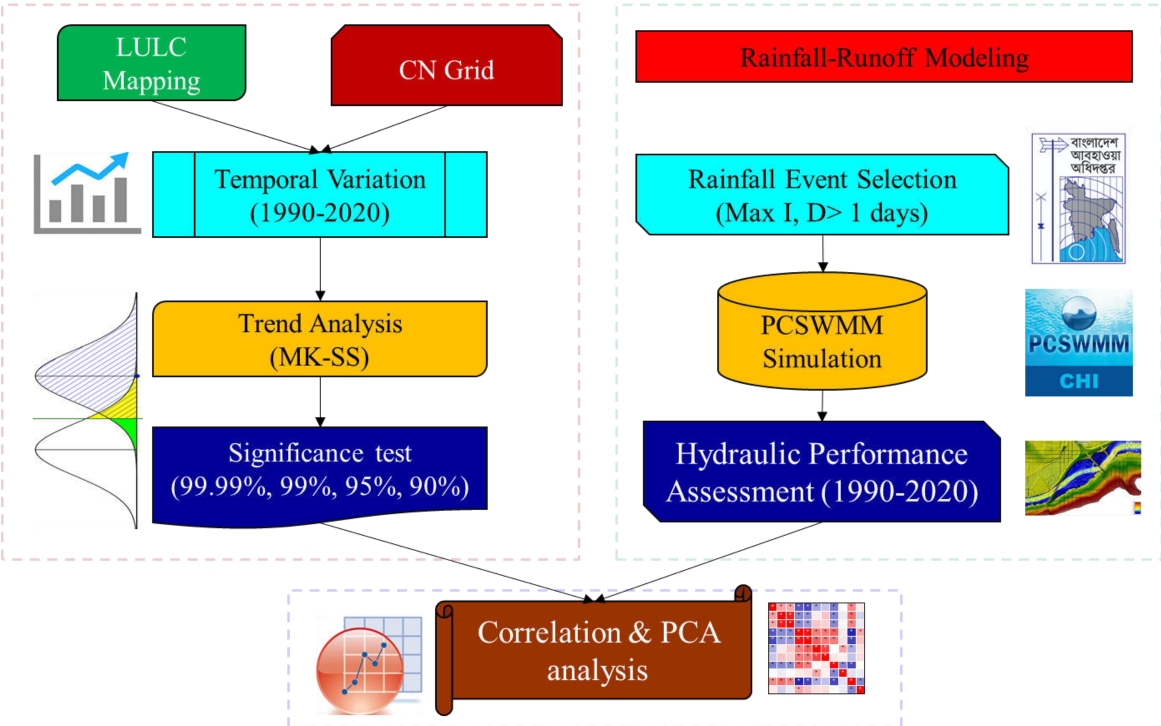


Figure 3.10 Flow diagram showing the working steps for the evaluation of hydraulic performance.

Table 3:9 Selected rainfall events (1995-2020) for hydrological performance evaluation.

Events	Years	Duratuion From (Date and time) (mm/dd/yyyy, hh:mm)	Duratuion To (Date and time) (mm/dd/yyyy, hh:mm)	Total storm depth (mm)
Event 1	1995	07/11/1995, 03:00	07/16/1995, 21:00	558.81
Event 2	2000	06/02/2000, 00:00	06/06/2000, 03:00	594.13
Event 3	2005	08/02/2005, 06:00	08/09/2005, 09:00	245.00
Event 4	2010	06/12/2010, 09:00	06/16/2010, 12:00	359.20
Event 5	2015	07/17/2015, 00:00	07/20/2015, 21:00	391.00
Event 6	2020	10/21/2020, 03:00	10/24/2020, 06:00	254.40

These parameters were then correlated with different climatic factors, CN values, and land use types of each sub-catchment. The correlation helped to understand the relationship between the hydrological parameters and the different sub-catchment characteristics and thus to evaluate the overall performance of the watershed. It is important to note that the simulation results assume that the watershed has a homogeneous soil, land use, and hydrologic properties, which may not reflect the actual conditions of the watershed.

3.13 Data Analysis Methods

3.13.1 Descriptive statistics

Descriptive statistics (Mean, Median, Coefficient of Variation, Standard Deviation, Minimum, Maximum, Range, Interquartile *Range,* Skewness, and Kurtosis) were used within this study to illustrate the basic characteristics of the measured runoff quality parameters using the Statistical Package for the Social Sciences (SPSS v.23). The Coefficient of Variation (CV) represents the ratio of the standard deviation to the mean, which is used for comparing the degree of variation from one data series to another. The range is the difference between the maximum value and the minimum value of any dataset where the Interquartile *range indicates the* difference between the 75^{th} and 25^{th} percentiles.

Skewness is a measure of the probability distribution's asymmetry, and Kurtosis is a measure of whether the data are heavy-tailed or light-tailed in comparison to a normal distribution. In order to assess the variability in water quality parameters among different land uses, the experimental investigation's runoff water quality data were classified into four land use types (residential, commercial, institutional, and industrial). Experimental water quality datasets extracted from different land use types were evaluated with nonparametric arithmetic methods and represented in a violin plot with whiskers box plot in Origin Pro 2021b. The violin plot illustrates the median with a white dot, the interquartile range (IQR) with a thick black bar, and the remaining distribution as a thin black line that uses a function that is 1.5 times the IQR. Different colours are used for different water quality parameters. A kernel density estimation was placed on either side of the black line to depict the data distribution shape. The wider region of the violin plot corresponds to a higher likelihood of data, whereas its narrower region has fewer data points.

3.13.2 Statistical Method for trend analysis

Trend analysis of various factors such as rainfall, land use changes, and CN value changes were conducted using the Mann-Kendall (MK) analysis. The purpose of this analysis is to identify any significant trends in these factors over time. The magnitude of the changes was then calculated using Sen's Slope (SS) estimator. This method provides an estimate of the rate of change of a particular factor, allowing for a more detailed understanding of the changes that have occurred in the study area over time. The results of this trend analysis were then used to inform further analysis and interpretation of the study's findings. In Mann-Kendall analysis, the number of sequential values in studied data series is denoted by n. If n is 9 or less, the absolute value of S is compared directly to the theoretical distribution of S derived by Mann and Kendall (Gilbert, 1987). The Mann-Kendall test statistic S is calculated by using Eq. (3.16).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \qquad \text{Eq. (3.16)}$$

Where,

$$sgn\ \delta(x_j - x_k) = \begin{cases} 1 & if\ x_j - x_k > 0 \\ 0 & if\ x_j - x_k = 0 \\ -1 & if\ x_j - x_k < 0 \end{cases}$$

x_j and x_k are the sequential data values. When S bears a positive value, it indicates an upward or increasing trend and if the value is negative, it indicates downward trend or decreasing trend. If n is at least 10 or more than 10, the test follows a normal distribution and hence normal approximation test is used with expectation (E) and variance of S VAR(S) as using Eq. (3.17).

$$VAR\ (S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right] \qquad \text{Eq. (3.17)}$$

Here, q is the number of tied groups and t_p is the number of data points in the p^{th} tied group in the dataset. The standardized test statistic (Z) is calculated using Eq. (3.18).

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if\ S < 0 \end{cases} \qquad \text{Eq. (3.18)}$$

Where the value of Z is the Mann-Kendall test statistic which follows a standard normal distribution with mean being 0 and variance being 1. In this study, confidence intervals of 90%, 95%, 99%, 99.99% ($p < 0.10$, $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively) were taken to classify the significance of positive and negative temperature and precipitation trends.

Sen's slope estimator is known as the slope of the linear trend has been estimated using the Theil–Sen estimator (Sen, 1968). It is a nonparametric method used to determine the true slope of an existing trend where the trend can be assumed linear (as change per time). The slope (Q) estimates of N pairs of data are first computed by Eq. (3.19).

$$Q_i = \frac{x_j - x_k}{j-k}\ ; For\ i = 1, 2, 3 \ldots\ldots\ldots N \qquad \text{Eq. (3.19)}$$

Where x_j and x_k are data values at times j and k ($j > k$), respectively. The median of these N values of Q is the Sen's estimator of the slope.

3.13.3 Correlation analysis

Spearman's rank correlation coefficient (r_s) is a method to determine the correlation between variables that are not normally distributed using a monotonic function. The coefficient can be determined using Eq. (3.20).

$$r_s = 1 - 6\frac{\sum {d_i}^2}{n(n^2 - 1)} \quad \text{Eq. (3.20)}$$

Where, n indicates the number of alternatives, and d_i represents the difference between the ranks of two parameters. In this study, confidence intervals of 95% and 99% ($p < 0.05$, $p < 0.01$) were taken for the analysis.

3.13.4 Principal Component Analysis (PCA) method

Principal Component Analysis (PCA), a multivariate statistical data analysis method, was carried out in order to filter raw data sets based on their component loadings that identify the clusters between the considered objects and variables with similar characteristics (Arora & Reddy, 2013). Principal component analysis (PCA) is a statistical technique used to reduce the dimensionality of a dataset while retaining as much information as possible.

It is a method of identifying patterns in data, and expressing the data in such a way that most of the variation is retained in the first few principal components. The principal components are linear combinations of the original variables, which are ordered by the amount of variance they explain. In PCA, the first principal component explains the most variance, and each subsequent component explains less variance. Once the principal components are determined, they can be used to summarize the data, or as new variables for further analysis.

PCA transforms the observed parameters into new, orthogonal variables named principal components (PCs). It provides the parameters of similar nature and origin, considering total variations with the minimum possible number of factor loadings. The loadings, one of the outcomes of PCA, are the values that represent the contribution of each variable to any particular principal component (Rahman Zuthi et al., 2022). Large loadings (positive or negative) stipulate that a particular variable has a strong association to a particular principal component. The interpretation of PCA was based on loadings and grouping of selected variables, with loading values close to -1 or +1 indicating that the PC has a strong influence on the variables, and loading values close to 0 indicating a weak influence on the variables. Nevertheless, some variables may also illustrate high loadings on a few PCs.

3.14 Performance evaluation of LIDs

Low Impact Development (LID) is a stormwater management strategy that aims to mimic natural hydrological processes by using a variety of techniques, such as rain barrels, green roofs, and permeable pavements, to reduce the volume and velocity of stormwater runoff. The peak flow reduction efficiency of LID refers to the extent to which the LID techniques can reduce the peak flow of stormwater runoff. The investigation focuses on evaluating the effectiveness of LID scenarios for assessment periods ranging from 2 to 100 years. The lifespan of a drainage system and Low Impact Development (LID) practices refer to the duration of time that the system or practice functions effectively, whereas the design life refers to the intended or planned duration of time that the system or practice is expected to function effectively based on its design and construction. The design life of a drainage system incorporating LID techniques can vary widely, ranging from as little as 5 years to over 25 years and the specific duration of the design life will depend on a variety of factors, including the type of drainage system and LID techniques used, prevailing environmental conditions, the quality of materials and installation, and the level of maintenance and inspection (Aranda et al., 2021; Ezugwu & Eze, 2022; Hossain et al., 2016; LGED, 2018).

Many researchers have also assessed the effectiveness of drainage systems for a range of return periods, spanning from 2 to 100 years (Abduljaleel & Demissie, 2021; Abdullah-al-masum et al., 2021; Hossain et al., 2016; Li et al., 2017; Tansar et al., 2022). However, it is crucial to evaluate the performance of LID systems for return periods exceeding 25 years to ensure that these systems can withstand severe weather events, continue functioning effectively over extended periods, and safeguard public safety and the economy. Additionally, analyzing the performance of individual components of LID options across various return periods can aid in determining the optimal return periods for drainage design.

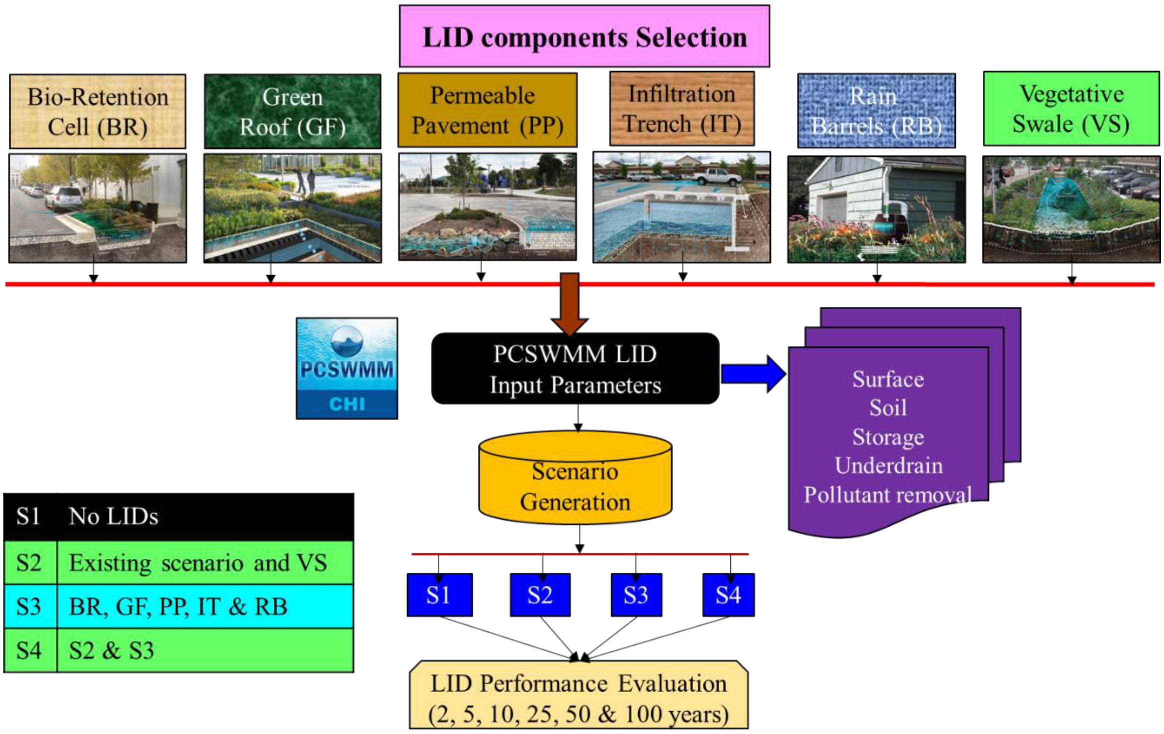


Figure 3.11 Flow diagram showing the step-by-step procedure for the performance assessment of the proposed LIDs.

Table 3:10 Proportion of LID practices considered in each sub-catchment of Chaktai-Rajakhali watershed.

Parameters	BB	GR	IT	PP	RB	Total
SC1	1%	4%	6%	5%	4%	20%
SC2	2%	3%	6%	5%	4%	20%
SC3	3%	3%	6%	5%	3%	20%
SC4	2%	5%	4%	3%	6%	20%
SC5	3%	3%	5%	5%	4%	20%
SC6	4%	4%	3%	4%	5%	20%
SC7	4%	5%	3%	3%	5%	20%
SC8	4%	6%	2%	2%	6%	20%
SC9	3%	4%	5%	4%	4%	20%

The peak flow reduction efficiency of LID with lag time differences can vary depending on the specific scenario and factors such as the type of LID technique used, the site conditions, the size of the area being treated, and the intensity and duration of the storm. LID techniques with longer lag time may have a higher peak flow reduction efficiency than those with shorter lag times.

The flow diagram in the figure 3.11 illustrates the step-by-step process for evaluating the effectiveness of the proposed four scenarios of Low Impact Development (LID) techniques for different return periods (2-10 years). The process begins with collecting data on the site conditions and properties of LID components. The table provides important information on the distribution of Land and Water Conservation (LID) practices in the watershed. The different parameters such as BB, GR, IT, PP, and RB represent the different types of LID techniques that are being proposed for the site, such as rain barrels, green roofs, or permeable pavements. It is significant to note that a total of 20% of LID area (see table 3.10) has been considered for each sub-catchment, meaning that a portion of the land in each sub-catchment is dedicated to LID practices as suggested by different literature (Jafrin & Beza, 2018; Padeco, 2014; Syed & Haider, 2022). This data is critical in understanding the conservation efforts being made in the Chaktai-Rajakhali watershed. By allocating a portion of the land for LID practices, the community is taking steps to improve the water quality and reduce the amount of stormwater runoff.

Additionally, these LID practices have numerous environmental and social benefits, such as promoting biodiversity, mitigating the heat island effect, and providing green spaces for the community. The next step is to simulate the hydrological performance of the proposed LID techniques using computer models. This allows for the prediction of the amount of stormwater runoff that would be generated by the site under different rainfall conditions, as well as the volume and velocity of the runoff. Then, the peak flow reduction efficiency of the proposed LID techniques is calculated based on the simulated data. The lag time, or the time delay between the start of precipitation and the peak flow of runoff, is also considered in this step. Finally, the results of the simulation are analyzed, and recommendations are made based on the effectiveness of the proposed LID techniques in reducing peak flows and overall stormwater runoff. The process is completed by implement the selected LID techniques and monitoring their performance over time.

Table 3:11 Technical specification of different properties of various LID components

LID components	Properties	Parameters	Values	Units	Remarks
Vegetative Swale	**Surface**	Berm Height	200	mm	**Each Unit information:** Area:230 m^2 Length:69.9 m Width:3.25 m % imp:0.1 %
		Vegetation Volume Fraction	0.1	-	
		Surface Roughness	0.016	Manning's n	
		Surface Slope	1	%	
		Swale Side Slope	3	run/rise	
Green Roof	**Surface**	Berm Height	25	mm	**Each Unit information:** Area:2000 m^2 Length:60 m Width:33.3 m % imp:0.184%
		Vegetation Volume Fraction	0.1	-	
		Surface Roughness	0.15	Manning's n	
		Surface Slope	1	%	
	Soil	Thickness	100	mm	
		Porosity	0.5	-	
		Field Capacity	0.2	-	
		Wilting Point	0.1	-	
		Conductivity	100	mm/hr	
		Conductivity Slope	10	-	
		Suction Head	60	mm	
	Drainage Mat	Thickness	75	mm	
		Void Fraction	0.5	-	
		Roughness	0.1	Manning's n	
Permeable Pavement	**Surface**	Berm Height	2	mm	**Each Unit information:** Area:2000 m^2 Length:60 m Width:16.4 m % imp:0.3 %
		Vegetation Volume Fraction	0.1	-	
		Surface Roughness	0.012	Manning's n	
		Surface Slope	1	%	
	Pavement	Thickness	100	mm	
		Void Ratio	0.25	voids/solids	
		Impervious Surface Fraction	0	-	
		Permeability	250	mm/hr	
		Clogging Factor	0	-	
		Regeneration Interval	0	days	
		Regeneration Fraction	0	-	
	Storage	Thickness	150	mm	
		Void Ratio	0.4	voids/solids	
		Seepage Rate	1.2	mm/hr	
		Clogging Factor	0	-	
	Underdrain	Flow Coefficient	0.5	mm/hr	
		Flow Exponent	0.5	-	
		Offset Height	100	mm	
		Open Level	0	mm	
		Closed Level	0	mm	
Bio-Retention Cell	**Surface**	Berm Height	150	mm	
		Vegetation Volume Fraction	0.1	-	

		Surface Roughness	0.1	Manning's n	
		Surface Slope	1	%	
	Soil	Thickness	500	mm	
		Porosity	o.5	-	
		Field Capacity	0.2	-	**Each Unit information:** Area:130 m^2 Length:32.5 m Width:4 m % imp:10 %
		Wilting Point	0.1	-	
		Conductivity	0.5	mm/hr	
		Conductivity Slope	10	-	
		Suction Head	3.5	mm	
	Storage	Thickness	500	mm	
		Void Ratio	0.75	-	
		Seepage Rate	10	mm/hr	
		Clogging Factor	0	-	
	Underdrain	Flow Coefficient	0.5	mm/hr	
		Flow Exponent	0.5	-	
		Offset Height	150	mm	
		Open Level	0	mm	
		Closed Level	0	mm	
Infiltration Trench	**Surface**	Berm Height	100	mm	
		Vegetation Volume Fraction	0	-	
		Surface Roughness	0.24	Manning's n	**Each Unit information:** Area:101.76 m^2 Length:50.88 m Width:2 m % imp:40 %
		Surface Slope	3	%	
	Storage	Thickness	500	mm	
		Void Ratio	0.75		
		Seepage Rate	10	mm/hr	
		Clogging Factor	0	-	
	Underdrain	Flow Coefficient	0	-	
		Flow Exponent	0.5	-	
		Offset Height	0.5	mm	
		Open Level	0	mm	
		Closed Level	0	mm	
Rain Barrels	**Storage**	Berm Height	48	mm	
	Underdrain	Flow Coefficient	1	-	**Each Unit information:** Area:100 m^2 Length: - m Width:0 m % imp:4 %
		Flow Exponent	0.5	-	
		Offset Height	0	mm	
		Drain Delay	6	hrs	
		Open Level	0	mm	
		Closed Level	0	mm	

This table 3.11 appears to be listing various properties and parameters of different Low Impact Development (LID) components, such as vegetative swales, green roofs, permeable pavements, bio-retention cells, infiltration trenches, and rain barrels. These parameters are used in PCSWMM software to analyze and evaluate the performance of the LID components. Some of the parameters listed include berm height, vegetation volume fraction, surface roughness, surface slope, thickness, porosity, field capacity, wilting point, conductivity, void ratio, permeability, clogging factor, regeneration interval, regeneration fraction, seepage rate, flow coefficient, flow exponent, offset height, open level, and closed level. Each LID component has a set of properties that are described by a set of parameters and associated values, units, and remarks. For example, the vegetative swale has a surface property with a berm height of 200 mm, an area of 230 square meters, a length of 69.9 meters, and a width of 3.25 meters.

3.15 Performance evaluation of LIDs in reduction of runoff quality

3.15.1 Build-up and Wash-off coefficient

In the context of water quality modeling, build up refers to the accumulation of pollutants on the ground surface over time due to dry weather conditions. This accumulation will be available for wash-off during a runoff event, which is triggered by precipitation. The rate of build up for a specific pollutant and land use is determined by the build up function, which can be represented using one of the three options offered by SWMM (Figure 3.12): the power function, exponential function, and saturation function. These functions describe the relationship between the pollutant build up rate and various environmental factors, such as temperature, rainfall intensity, and land use.

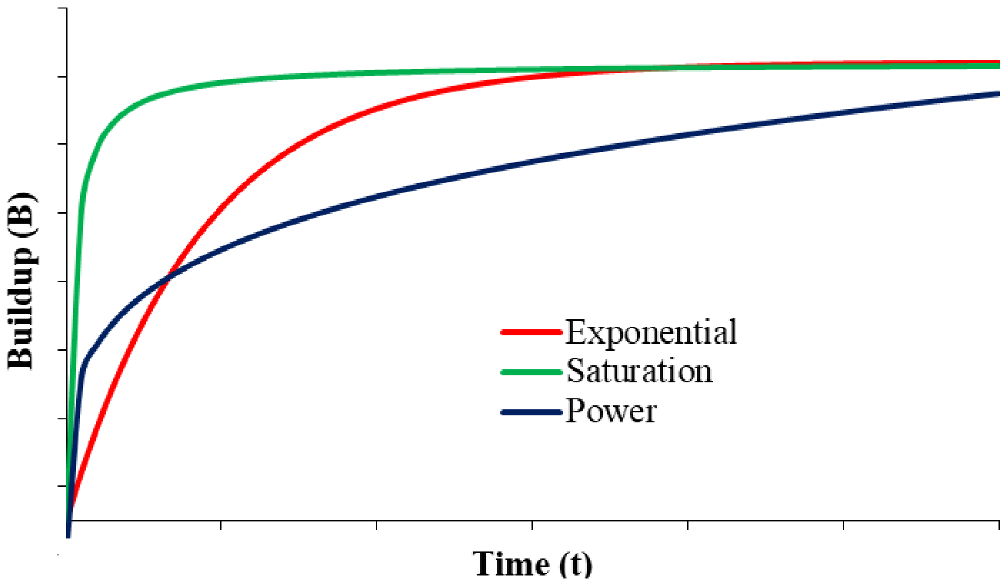


Figure 3.12 Rating curve of different mathematical functions used in SWMM model

The build up function is used to calculate the total build up of pollutants within a sub-catchment, which can be expressed in terms of mass per unit area or length. To quantify the build up of pollutants within a specific land use category, a mass per unit area of the sub-catchment is used. In US units, this mass is expressed in pounds, and in metric units, in kilograms. To calculate the build up, one of the following functions can be used, which considers the number of dry weather days prior to the calculation: the power function, exponential function, or saturation function. The choice of function will depend on the specific conditions and factors affecting the build up of pollutants in the sub-catchment.

Power Function

Before a maximum limit is reached, the pollutant build-up (B) increases according to time (t) raised to a certain power (see Eq. 3.21):

$$B = Min\ (C_1, C_2 t^{C_3}) \qquad \text{Eq. (3.21)}$$

Where, C_1 is the maximum build-up possible (mass per unit of area), C_2 is the build-up rate constant, C_3 is the time exponent, and t is antecedent dry days

Exponential Function

A maximum limit is asymptotically approached by the pollutant buildup (B), which follows an exponential growth curve (see Eq. 3.22):

$$B = C_1\ (1 - e^{-C_2 t}) \qquad \text{Eq. (3.22)}$$

Where, C_1 is the maximum build-up possible (mass per unit of area), C_2 is the build-up rate constant, and t is antecedent dry days

Saturation Function

The pollutant build-up (B) starts at a linear rate and gradually slows down until it reaches a saturation value (see Eq. 3.23):

$$B = \frac{C_1 t}{C_2 + t} \qquad \text{Eq. (3.23)}$$

Where, C_1 is the maximum build-up possible (mass per unit of area), C_2 is the half-saturation constant (days to reach half of the maximum build-up) and t is antecedent dry days.

External Time Series

With this choice, it is possible to utilize a Time Series to express the rate of build up every day as function of time. The time series values would be expressed in units of mass per unit area (or curb length) every day. With this option, it is also possible to enter a maximum build up (mass per unit area or curb length) as well as a scaling factor which multiplies the time series data.

Pollutant Wash-off

Wash-off refers to the process of pollutants being eroded, mobilized, or dissolved from the ground surface during wet weather events. This can result in an increase in the concentration of pollutants in the runoff water. SWMM provides three options for representing the wash-off process for each pollutant and land use: event mean concentrations (EMCs), rating curves, and exponential functions. Event mean concentrations (EMCs) represent the average concentration of a pollutant in runoff water for a given event.

Rating curves are used to describe the relationship between runoff volume and pollutant concentration. The exponential function is used to model the wash-off process as a function of time and other environmental factors, such as rainfall intensity and land use. These wash-off models are used to predict the concentration of pollutants in runoff water, which is an important factor in water quality management and assessment. Pollutant wash-off from a land use happens during wet weather seasons and can be computed with one of the following functions:

Exponential Wash-off

The product of runoff elevated to some power and the quantity of build up still present determines the wash-off load (W), expressed in mass per hour (see Eq. 3.24):

$$W = C_3 q^{C_4} B \qquad \text{Eq. (3.24)}$$

Where, C_3 is the wash-off coefficient, C_4 is the wash-off exponent, q is the runoff rate per unit area and B is the pollutant build-up in mass units

The build-up in this context refers to the total mass, not the mass per unit of area, and the units used to represent the build-up and wash-off mass are the same as those for the pollutant's concentration.

Rating Curve Wash-off

The runoff rate increased to some power determines the rate of wash-off W, measured in mass per second (see Eq. 3.25):

$$W = C_3 Q^{C_4} \qquad \text{Eq. (3.25)}$$

Where, C_3 is the wash-off coefficient, C_4 is the wash-off exponent, Q is the runoff rate in user-defined flow units and B is the pollutant build-up in mass units

Event Mean Concentration

This is a unique instance of the Rating Curve Wash-off, where the exponent is 1.0 and the coefficient C1 denotes the concentration of wash-off pollutants in mass per litre.

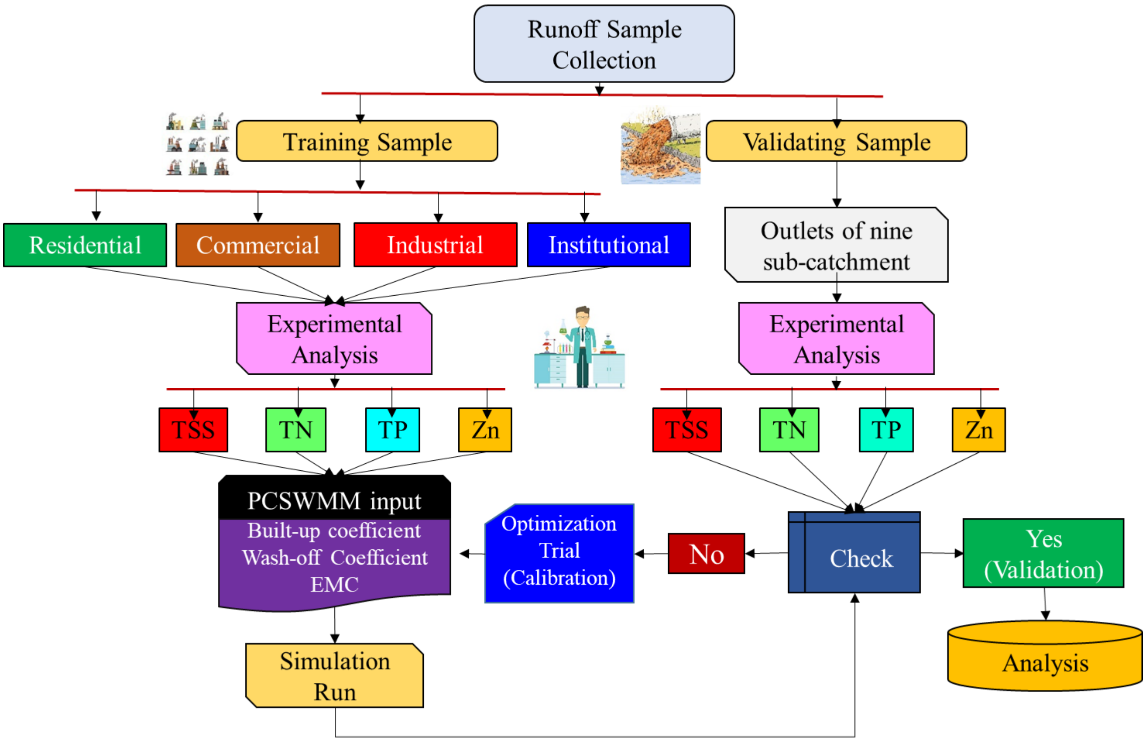


Figure 3.13 Step by step procedure adopted for the runoff quality assessment

The build up and wash-off parameters listed in table 3.12 play a crucial role in estimating the impact of pollutants on receiving waters in urban drainage systems.

Accurate determination of these coefficients is important for ensuring compliance with water quality regulations and assessing the potential impact of pollutants on receiving waters. The build up and wash-off parameters C1 to C4 in Table 3.12 play a significant role in the SWMM (Storm Water Management Model) software, which is widely used to model water and pollutant movement in urban drainage systems.

These parameters are used to estimate the accumulation of pollutants on a surface (build up coefficient, C1 and C2) and the amount washed off during a storm event (wash-off coefficient, C3 and C4). Accurate determination of these coefficients is crucial for assessing the impact of pollutants on receiving waters and ensuring compliance with water quality regulations. The values of these coefficients vary based on local factors such as population density, land use patterns, and climate, as well as the characteristics of the area such as traffic volume, drainage system configuration, rainfall pattern, and preceding dry days. Build up parameter C1 represents the maximum build up possible, with unit of kg/ha if area is used as the normalizer and kg/m curb if curb length is used as the normalizer. C1 values for various pollutants, such as TSS, TKN, TP, TN, BOD and COD, range from a minimum to a maximum value as indicated in the Table 3.12. The rate of pollutant build up is controlled by C2, with values for most land uses falling within a specific range for each pollutant. For example, the range for TSS is from 0 to 3, while TKN stays between 0 and 1.75. Wash-off coefficients C3 and C4 are used to estimate the amount of pollutants washed off a surface during a storm event.

Most of the C3 values for all water quality components are in the range of 0.0-8, while most of the C4 values are in the range of 0.0-5.5. However, exceptions can be seen for certain land uses such as Highway, HDR and Commercial in Istanbul, Turkey. Most of the wash-off parameters concentrate in small numerical regions, suggesting that geographically uniform factors such as land use, temperature, and climate regulate wash-off. Meanwhile, local elements such as topography and slope appear to control wash-off. The values of these parameters are location-specific and are influenced by local factors such as population density and climate, as well as the characteristics of the area such as drainage system configuration and rainfall pattern.

Table 3:12 Build up and wash off coefficients used by different studies around the world in SWMM software

Location	Land use	Normalizer	Pollutants	C_1	C_2	C_3	C_4	Study Area
District 22, Tehran	LDR	Curb	TSS	0.298	0.001003	0.38	1.9	(Zakizadeh et al., 2022)
		Curb	TP	0.745	0.000045	0.6	0.017	
		Curb	TKN	2.086	0.00067	0.15	0.35	
	HDR	Curb	TSS	74.5	2.916	0.455	1.65	
		Curb	TP	1.043	0.00018	1.35	0.045	
		Curb	TKN	1.788	0.0032	0.57	0.04	
	Undeveloped	Curb	TSS	59.6	1.486	0.08	1.275	
		Curb	TP	0.596	0.00002298	0.2	0.04	
		Curb	TKN	2.235	0.00114	0.034	0.15	
	Commercial	Curb	TSS	1.125	1.2	1.05	0.855	
		Curb	TP	0.009	0.000945	7.254	0.341	
		Curb	TKN	0.016	0.004	72.08	3.218	
	Transportation	Curb	TSS	0.937	0.75	2.73	3.588	
		Curb	TP	4.06×10^{-8}	1	4.73	2.92	
		Curb	TKN	1.05×10^{-8}	1	37.01	5.51	
Samawah City, Iraq	Residential	Area	BOD	0.603	0.453	0	0	(Mohammed et al., 2022)
		Area	COD	0.66	0.446	0	0	
		Area	TSS	0.637	0.126	0	0	
		Area	TDS	0.67	0.133	0	0	
	Road	Area	BOD	0.3	0.219	0	0	
		Area	COD	1.2147	0.1883	0	0	
		Area	TSS	0.31	0.0188	0	0	
		Area	TDS	0.324	0.149	0	0	
Bogotá, Colombia	HDR	Curb	TSS	0.16	0.5	160 (EMC)	-	(Huertas et al., 2019)
	LDR	Curb	TSS	0.19	0.5	200 (EMC)	-	
Malaysia	Residential	Curb	TSS	1.5	0.3	0.4	0.9	(Rezaei et al., 2019)
		Curb	TN	0.002	0.05	12	1.7	
	Commercial	Curb	TSS	12	0.3	1.5	0.6	
		Curb	TN	0.1	0.7	0.3	3.5	
Łódź, Poland	Urban (Less polluted surface)	Area	TSS	50	0.15	0.004	1.8	(Zawilski & Dziedziela, 2018)
	Urban (More polluted surface)	Area	TSS	500	0.15	0.004	1.8	

Calgary, Canada	Residential	Area	TSS	56	1	0.087	1.53	(Shrestha & He, 2017)
	Industrial			56	1	0.098	1.79	
Ribeira dos-Covões, Coimbra, Portugal	Low traffic Road	Area	Cu	0.95	0.007	2.3	0.014	(Sha, 2017)
		Area	Zn	4.128	0.038	2.425	0.0104	
	Medium traffic Road	Area	Cu	0.972	0.007	2.3	0.014	
		Area	Zn	1.164	0.038	2.425	0.0104	
	High traffic Road	Area	Cu	1.814	0.007	2.3	0.014	
		Area	Zn	4.605	0.038	2.425	0.0104	
Shenyang, China	Road	Area	TSS	370	0.5	0.003	1.9	(Li et al., 2016)
		Area	TN	4	0.7	0.07	1.7	
		Area	TP	0.2	0.1	0.02	1.8	
		Area	COD	96	0.2	0.002	1.8	
	Roof	Area	TSS	300	0.4	0.005	1.4	
		Area	TN	2	0.5	0.001	1.3	
		Area	TP	0.14	0.2	0.003	1.9	
		Area	COD	54	0.3	0.009	1.5	
	Green	Area	TSS	100	0.3	0.005	1.6	
		Area	TN	9	0.5	0.004	1.2	
		Area	TO	0.4	0.3	0.001	2	
		Area	COD	25	0.1	0.01	1.3	
China	Urban (roof)	Area	TSS	180	7	0.008	1.8	(Wu et al., 2016)
		Area	BOD	10	7	0.002	1.7	
		Area	COD	60	7	0.005	1.7	
		Area	TP	0.3	7	0.015	1.8	
		Area	TN	7.5	7	0.004	1.5	
		Area	NH_4-N	2	7	0.004	1.5	
	Urban (road)	Area	TSS	230	4	0.008	1.8	
		Area	BOD	16	4	0.003	1.7	
		Area	COD	110	4	0.008	1.8	
		Area	TP	0.2	4	0.008	1.6	
		Area	TN	5	4	0.002	1.4	
		Area	NH_4-N	2	4	0.002	1.5	
	Urban (grass)	Area	TSS	100	20	0.03	1.2	
		Area	BOD	20	20	0.008	1.2	
		Area	COD	40	20	0.03	1.2	
		Area	TP	1	20	0.042	1.2	
		Area	TN	10	20	0.007	1.2	
		Area	NH_4-N	1.8	20	0.008	1.2	
Beijing, China	Road	Area	TSS	150	0.5	0.012	1.8	(Gong et al., 2016)
	Roof	Area	TSS	60	0.5	0.007	1.8	
	Green space	Area	TSS	40	0.5	0.004	1.2	
Daejeon, Korea	Urban Mixed	Curb	SS	0.50 (POW)	0.3	0.6	0.05	(Han & Seo, 2014)

		Curb	BOD	0.18 (POW)	0.15	0.3	0.015	
		Curb	COD	0.21 (POW)	0.18	0.3	0.015	
		Curb	TN	0.10 (POW)	0.12	0.3	0.115	
		Curb	TP	0.01 (POW)	0.08	0.3	0.015	
Turkey	Urban	Area (Rainfall I)	TSS	1.65	1.45	187.52 (EMC)	1.74	(Gülbaz & Kazezyilmaz-Alhan, 2014)
		Area (Rainfall II)	TSS	3.64	3.49	489.83 (EMC)	0.45	
Skudai, Johor, Peninsular, Malaysia	Residential	Curb	TSS	0.003	0.8	0.2	1.4	(Chow et al., 2012)
		Curb	TP	0.003	0.05	0.41	1.46	
	Commercial	Curb	TSS	0.015	0.8	1.4	0.9	
		Curb	TP	0.0005	0.1	0.4	1	
	Industrial	Curb	TSS	0.013	0.7	3	0.6	
		Curb	TP	0.0003	0.16	0.8	1	
Australia	Residential	Curb	TSS	-	-	0.03	0.21	(Hossain et al., 2012)
	Impervious	Curb	TN	-	-	0.004-0.005	0.65-0.8	
		Curb	TP	-	-	0.0003-0.0004	0.75-0.9	
	Pervious	Curb	TSS	-	-	0.05-0.055	0.21	
		Curb	TN	-	-	0.0065-0.008	0.65-0.8	
		Curb	TP	-	-	0.0005-0.0007	0.75-0.9	
Istanbul, Turkey	LDR	Area	TSS	1.4516	1.1449	1.9863	567.2804	(Gülbaz & Kazezyilmaz-Alhan, 2012)
		Area	TKN	0.1236	0.1162	0.6902	1.5103	
	HDR	Area	TSS	1.6342	1.5547	2.5825	4890.96	
		Area	TKN	0.3448	0.258	0.4384	0.4979	
	Highway	Area	TSS	1.5632	1.7493	2.1711	2619.174	
		Area	TKN	0.1524	0.1268	0.6031	0.5513	
	Commercial	Area	TSS	1.5912	1.8093	2.2932	3771.2	
		Area	TKN	0.3294	0.39	0.6125	0.9564	

New Zealand	Urban (concrete)	Area	TSS	27.6	0.2	0.24	1	(Wicke, Cochrane, & O'Sullivan, 2012)
	Urban (asphalt))		TSS	13.4	0.23	0.27	1	
Shanghai, China	Urban (roof)	Area	TSS	355	0.4	0.074	1.3	(Li & Yue, 2011)
Australia	Urban (road)	Area	TSS	53	0.222	0.0029–0.0135	0.608-0.986	(Hossain et al., 2010)
		Area	TSS	27.5	0.21	0.0015–0.0059	0.945–1.27	
		Area	TSS	26	0.382	0.0062–0.011	0.753–0.914	
	Urban (roof)	Area	TSS	8.5	0.188	0.051–0.202	0.363–0.603	
		Area	TSS	12	0.122	0.112–0.213	0.333–0.414	
Tallinn, Estonia	Urban	Area	TSS	25	1	4.9 (EMC)	1.57	(Hood et al., 2007)
		Area	TN	0.15	0.0015	250 (EMC)	1	
		Area	TP	0.25	0.0025	500 (EMC)	2.53	
Spain	Residential	Curb	TSS	0.046	0.3	1.811	1	(Temprano et al., 2006)
		Area	TSS	17.5	0.3	1.811	1	
		Curb	COD	0.0027	0.3	3.937	1	
		Area	COD	1.02	0.3	3.937	1	
		Curb	TN	0.0001	0.3	8.661	1	
		Area	TN	0.039	0.3	8.661	1	
Italy	Residential	Area	TSS	18	0.3	0.13	1.2	(Barco et al., 2000)

Note:
LDR: Low Density Residential
HDR: High Density Residential
Unit of C1 is kg/ha in case of normalizer as Area
Unit of C1 is kg/m curb in case of normalizer as Curb
The function for all coefficient is EXP else and otherwise specified (i.e. POW, EMC etc.)

Table 3.13 shows the build-up and wash-off coefficients used as input for the Storm Water Management Model (SWMM) for simulating the runoff quality for different pollutants (TSS, TN, TP, and Zn) in different land uses (Residential, Institutional, Commercial, and Industrial). The coefficients C1, C2, C3, and C4 are used to estimate the pollutant build up and wash-off from different land uses.

These coefficients are used in the Storm Water Management Model (SWMM) to simulate the runoff quality for different pollutants. The values were determined through field measurements and/or literature review and are based on a number of factors that affect pollutant build up and wash-off. The table suggests that the residential land use has the highest build up of TSS, while the institutional land use has the highest wash-off coefficient for TN and TP. The values in the table vary because different land uses have different characteristics that affect the build up and wash-off of pollutants. For example, residential land use generally has a higher build up of pollutants because it has a higher density of impervious surfaces (such as roofs and pavements) that trap pollutants and prevent them from being washed off by rainfall.

Table 3:13 Built-up and wash-off coefficient used as model input in SWMM for runoff quality modeling

Pollutants	**Land use**	**C_1**	**C_2**	**C_3**	**C_4**
TSS	Residential	18.2	0.30	0.130	1.0
	Institutional	137.8	0.35	0.385	1.7
	Commercial	153.6	0.40	0.415	1.9
	Industrial	52.3	0.30	0.186	1.3
TN	Residential	11.0	4.0	0.075	1.2
	Institutional	4.0	17.0	0.008	1.5
	Commercial	2.0	25.0	0.006	1.8
	Industrial	9.0	8.0	0.042	1.3
TP	Residential	15.0	25.0	0.005	1.2
	Institutional	2.4	3.0	0.008	1.8
	Commercial	1.2	1.2	0.015	2.5
	Industrial	6.8	10.0	0.003	1.3
Zn	Residential	9.126	0.045	3.827	0.0316
	Institutional	4.605	0.038	2.422	0.0112
	Commercial	4.128	0.035	2.126	0.0104
	Industrial	5.023	0.041	3.005	0.0284

On the other hand, institutional land use has a higher wash-off coefficient for TN and TP because institutional land use has more open spaces that allow pollutants to be washed off by rainfall. Similarly, the values for industrial land use are usually higher because of the presence of industrial activities like manufacturing, which can generate pollutants and contribute to a higher build up of pollutants. Overall, the values in the table are specific to the pollutant and land use being considered and are used to estimate the pollutant loads that are generated from different land uses and how they contribute to runoff quality.

3.16 Life Cycle Cost Analysis of LIDs

Life Cycle Cost Analysis (LCCA) is a method used to evaluate the costs and benefits of different options over the entire life cycle of a project. In the context of Bangladesh, Life Cycle Cost Analysis (LCCA) of Low Impact Development (LID) components can be a valuable tool for evaluating the long-term economic and environmental benefits of different stormwater management options. LID components such as rain barrels, green roofs, and permeable pavements can help to reduce flooding and improve water quality, while also providing additional benefits such as increased wildlife habitat and aesthetic value. However, due to limited financial resources, LCCA can help decision makers to prioritize the most cost-effective LID options. In addition, LCCA can also help to identify potential funding sources for LID projects and to justify the expenses to stakeholders. Furthermore, since Bangladesh is a developing country, LCCA can play a vital role in identifying the most sustainable options that can be scaled up and replicated in other parts of the country, as well as other developing countries.

The "Assessment of Life Cycle Costs for Low Impact Development Stormwater Management Practices (Final Report 2013)" is a guide prepared by Toronto and Region Conservation and the University of Toronto for conducting Life Cycle Cost Analysis (LCCA) of Low Impact Development (LID) components. This guide was developed as part of the "Sustainable Technologies Evaluation Program (STEP)" project (https://sustainabletechnologies.ca/), which aims to evaluate the long-term economic and environmental benefits of different sustainable technologies, including LID components.

The STEP program was established to provide decision-makers with the information they need to make informed decisions about the selection and implementation of sustainable technologies. The LCCA guidelines provided in this report can be used as a valuable tool for decision-makers in Bangladesh and other countries to evaluate the long-term economic and environmental benefits of different LID options and to prioritize the most cost-effective options for stormwater management. Following are the assumptions considered in this study for LCCA of different LID components:

1. This LCCA's objective is to assess the capital and life cycle costs of six LID practices over 25 and 50 years based on a detailed assessment of regional expenses, maintenance demands, and site-specific design scenarios in the context of Bangladesh.
2. The conceptual LCCA model was designed for each LID practice with the assumption of a 2000 m^2 drainage area.
3. The PWD Schedule of Rates 2022 *(PWD, 2022)* was used as the reference for the majority of the costing. "Approved rates for testing of materials and services" by the Bangladesh University of Engineering and Technology *(BRTC-BUET, 2019)* was also used. Costs were also requested from other local sources (Shop owner, contractors, suppliers, construction managers, developers etc.) in cases where the sources listed above did not include all the necessary data, as required.
4. All products, deliveries, workers, equipment (including rental, functioning, and operator), transporting, and disposal expenses were taken into account during the cost estimation.
5. The cost of mobilization and demobilization was not considered and contingency costs were not included in capital cost.
6. The excavated soil might be discarded elsewhere outside of the project boundary.
7. Each component of the LID is of no salvage value, and the longer lifespan that is anticipated for the LID beyond the specified life span is not given any additional value.
8. Other necessary rates were considered as mentioned in Table 3.14.

Table 3:14 Different rates considered in this study for evaluating LCCA of LIDs.

Name	Rate	References
Cost Inflation rate	7.23% (2022)	(BB, 2022)
Discount rate	5%	(Mecometer, 2022)
VAT	7.5%	(PWD, 2022)
Overhead expense with profit	13.5% (10%+3.5%)	(PWD, 2022)
1 Canadian dollar	75.20 BDT	(BB, 2022)
1 US dollar	100.27 BDT	(BB, 2022)

The lifecycle cost for each LID component was calculated based on evaluation periods of 25 and 50 years, as viability point of view, after all capital, maintenance, and rehabilitation expenditures have been determined.

The following formula (Eq. 3.26) was used to determine the cost of each LID model's Present Value (PV).

PV = design and construction cost + PV of maintenance + PV of rehabilitation   Eq. (3.26)

The following present value formula (Eq. 3.27) was used to obtain the present value of the future cost:

$$PV = \frac{FC}{(1+r)^n} \quad \text{Eq. (3.27)}$$

Where, PV = present value in US $, FC = future cost in US $, r = discount rate, n = year of future cost

Life Cycle Cost Analysis (LCCA), the present value and future costs are important factors to consider when evaluating the long-term economic and environmental benefits of different options. The present value is the current worth of a future sum of money or stream of cash flows given a specified rate of return. In the case of LCCA, the present value is used to determine the net present value (NPV) of future costs and benefits associated with different LID options. This allows decision-makers to compare the costs and benefits of different options on a common basis, which can be useful for identifying the most cost-effective options. Future costs refer to the costs that will be incurred over the life cycle of a project, including the initial costs, operating costs, and replacement costs. These costs are estimated based on historical data and projected costs over time. In LCCA, the future costs are discounted to determine the present value, which is then compared to the present value of the benefits to determine the net present value. By considering the present value and future costs of different LID options, decision-makers can identify the most cost-effective options for stormwater management that also provide long-term environmental benefits.

Chapter 4. RESULTS & DISCUSSION

4.1 General

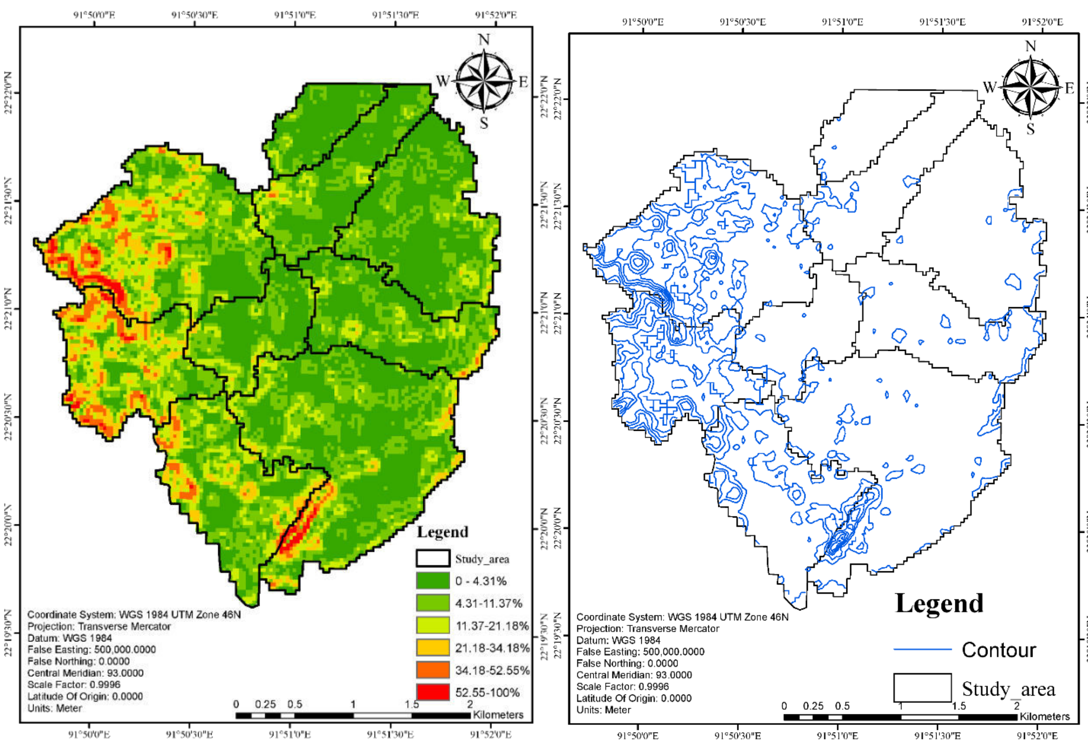
Chapter 4 presents a comprehensive overview of the main findings from the studies included in the thesis. The findings have been enhanced by conducting a new analysis on the entire dataset, which has provided a more in-depth understanding of the results. The chapter begins by presenting the results of catchment simulations that have been performed for different future LID scenarios. These scenarios reflect the potential changes in land use and climatic factors that may occur in the future. The catchment simulations have provided information on the hydrological performance of LIDs in different scenarios and have helped to understand how these systems may respond to changes in the environment.
LCCA is a valuable tool for evaluating the cost-effectiveness of different stormwater management strategies and has helped to provide a comprehensive understanding of the financial aspects of LID implementation. The chapter then presents the findings from the Life Cycle Cost Analysis (LCCA) of different LID components. The findings from the catchment simulations and LCCA are then discussed and compared to the current state of knowledge in the field of sustainable stormwater management.

The chapter also provides a critical analysis of the results and highlights the key findings of the studies. Finally, the chapter discusses the practical implications of the thesis findings for promoting sustainable stormwater management in the context of Bangladesh.

4.2 Physical features of drainage basins

The Figure 4.1 displays the results of various spatial analyses carried out in the Chaktai-Rajakhali watershed, including slope, contour, aspect, stream order, flow direction and flow accumulation. The slope analysis was performed to determine the impact of slope on runoff volume and time of concentration. Steeper slopes were found to cause stormwaters to move at higher velocities. The slope values were expressed as percent rise and were calculated using raster calculation and zonal analysis. The slope analysis showed (Figure 4.1a) that the north and southwestern part of the catchment contains steeper ground slopes (>34%) compared to other parts of the catchment. The average slope value for the entire Chaktai-Rajakhali watershed was found to be 15.45±17.61%, with average slope values for each of the 17 sub-catchments ranging from 10% to 25%.

The contour map (Figure 4.1b) provided a visual representation of the terrain, highlighting the presence of hills in the west portion in accordance with slope and a flat terrain in the east portion. This information could be useful in understanding the topographical features of the catchment and their potential impact on runoff and drainage. The contour map indicated the presence of hills in the west portion and a flat terrain in the east portion of the watershed.



(a) (b)

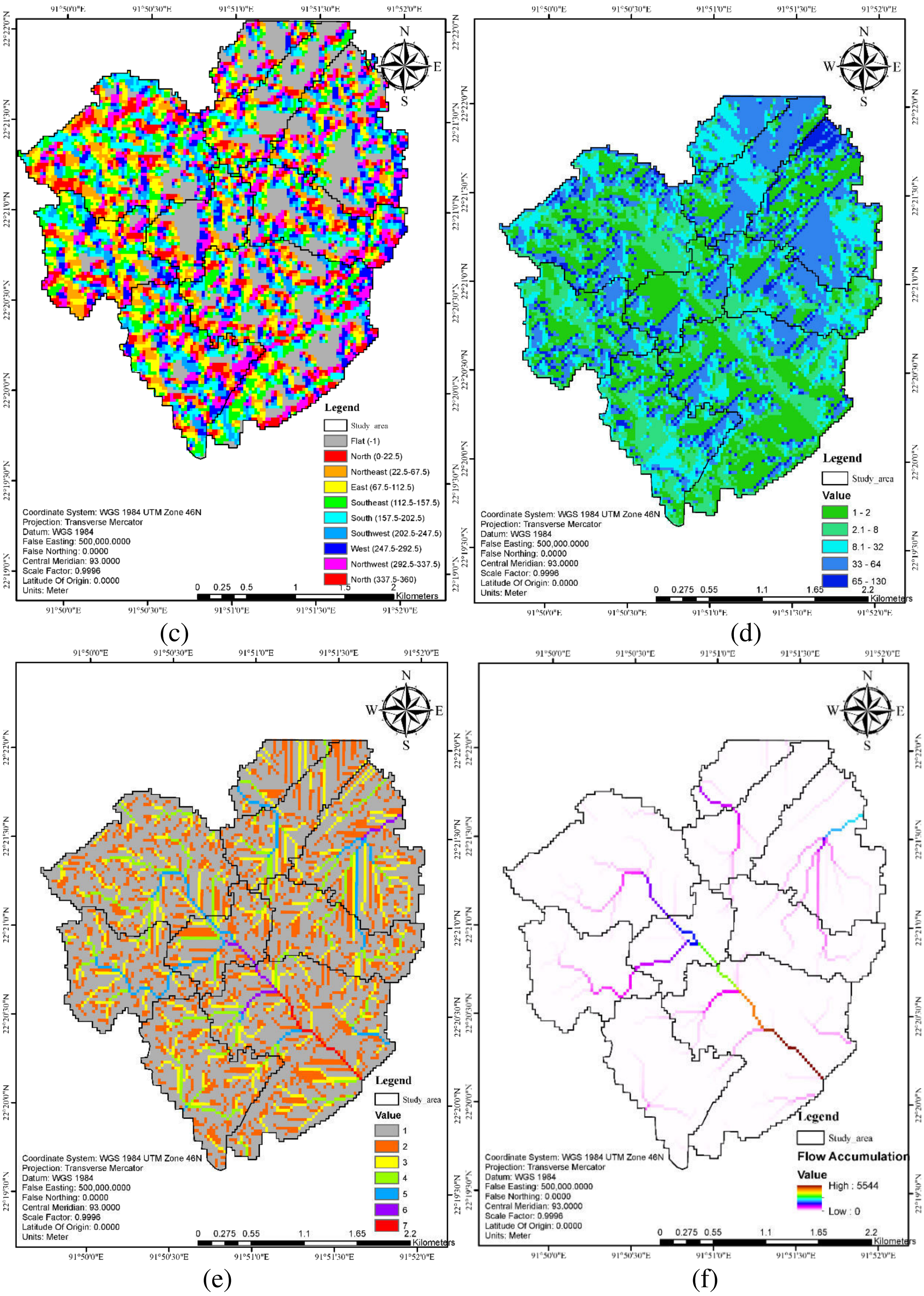


Figure 4.1 Results of spatial analysis, (a) Slope, (b) Contour, (c) Aspect, (d) Flow direction, (e) Stream order, and (f) Flow accumulation.

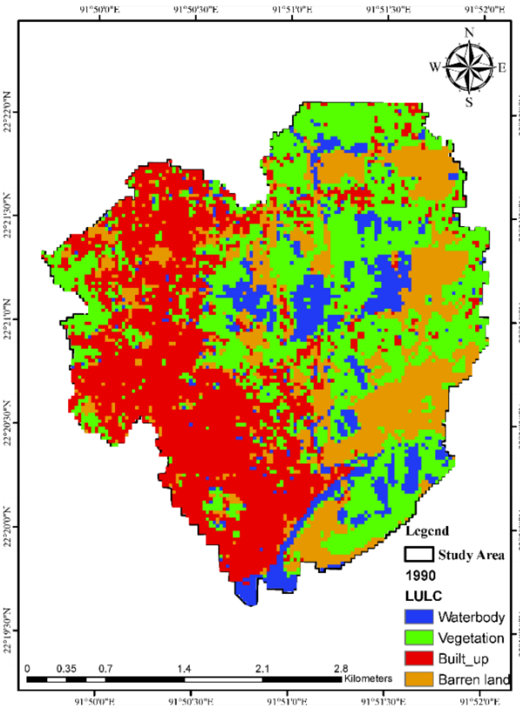
The flow direction and flow accumulation maps (Figures 4.1 d & f) provided information on the direction and magnitude of water flow in the catchment, respectively. The stream order was classified into 7th order (Figure 4.1e) and the canal used for performance evaluation was also in the 7th order. The stream order map and flow accumulation map indicated that the actual drainage network does not follow the stream network and drainage map obtained through spatial analysis.

This information could be useful in understanding the hydrological processes in the catchment and predicting the potential areas of erosion, flooding, and sedimentation. Data was incorporated with each sub-catchment using the add field command in ArcGIS 10.4. This allowed for an integration of various data sets, providing a comprehensive understanding of the catchment and its various hydrological and topographical features.

4.3 Trend of LULC in studied basin

The study analyzed LULC changes in Chaktai-Rajakhali Watershed (see figure 4.2) over a period of 30 years (1990-2020) using Landsat 8, Landsat 7, and Landsat 5 time-series data. Four different land cover classes were considered - vegetation, waterbodies, built-up areas, and barren land. The study found that the vegetation cover in Chaktai-Rajakhali Watershed has increased in the north-eastern part over the years, with a higher increase in the periods of 2000-2005 and 2005-2010 (8.02% and 2.14% respectively). However, there was a decline in vegetation cover in 2010-2015 with a decrease of 28.14%.

The water body had a fluctuating trend, with a decline of 2.32% from 1990 to 1995, followed by increases in the periods of 1995-2000, 2000-2005, and 2010-2015 (7.12%, 3.58%, and 9.83% respectively). The largest decline in the proportion of water bodies was observed in the periods of 2005-2010 and 2015-2020, with a decline of 14.6% and 12.06% respectively. The built-up area showed a significant growth of 47% from 1990 to 2020, with the highest proportion of 63.24% in 2020. This growth indicates an increase in urbanization in the study area.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Waterbody
Vegetation
Built_up
Barren land
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N
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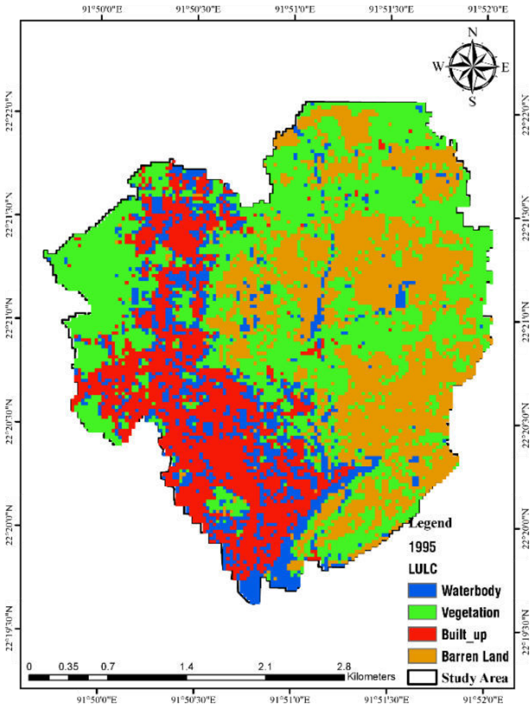
(a)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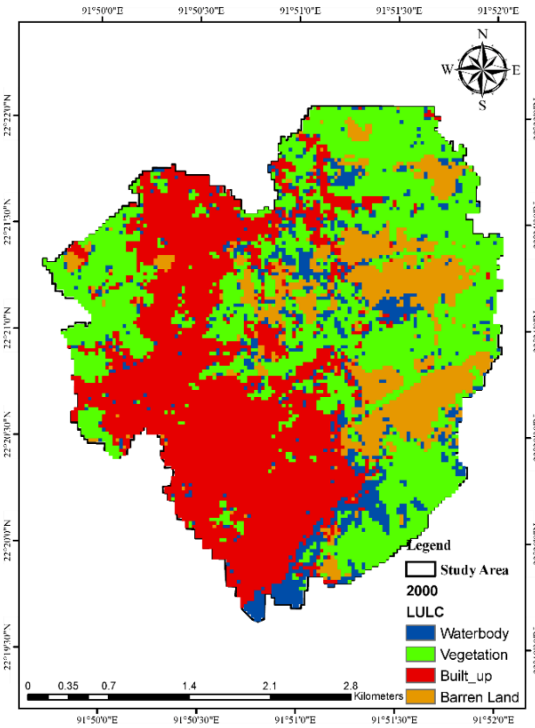
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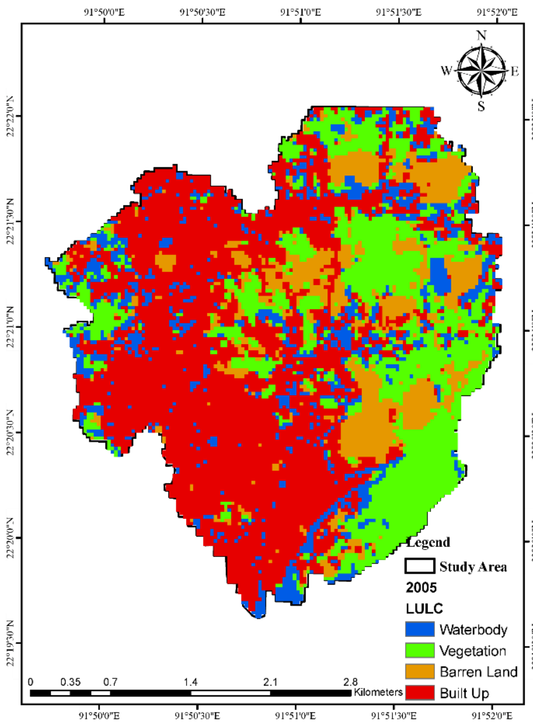
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Waterbody
Vegetation
Barren Land
Built Up
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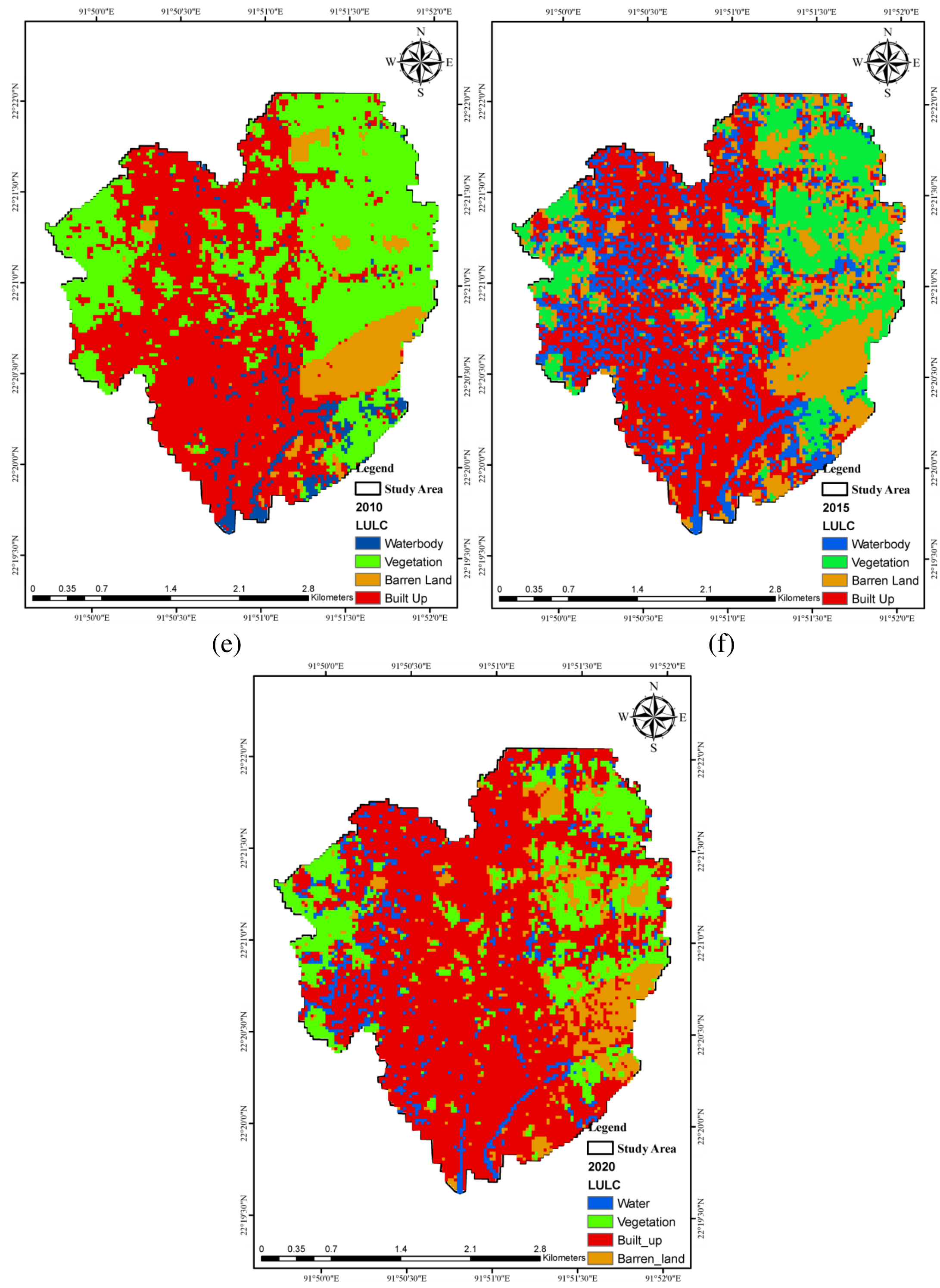
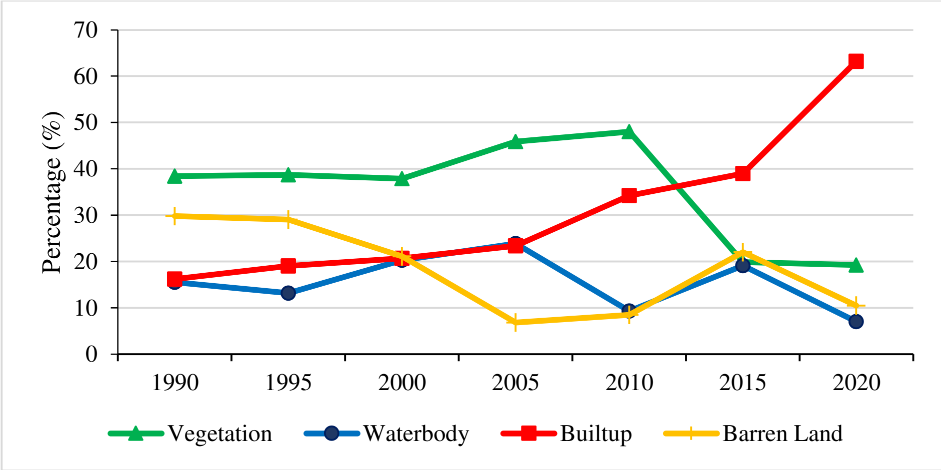


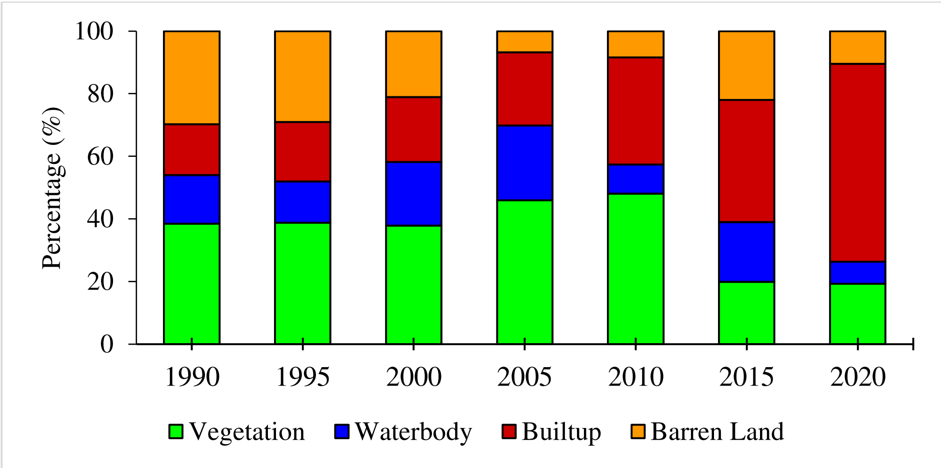
(e) (f)

(g)

Figure 4.2 Classified Land Use-Land Cover (LULC) Map of the study area during 1990-2020.



(a)



(b)

Figure 4.3 Temporal variability LULC changes trend (Figure 4.3a) and their relative share (Figure 4.3b) in Chaktai-Rajakhali watershed from 1990-2020

The proportion of barren land showed a declining trend from 1990 to 2005 but showed a slight increase in the periods of 2005-2010 and 2010-2015, before declining again in 2015-2020. The proportion of barren land declined by 11.57% from 2015 to 2020. The study found that the proportion of built-up areas has significantly grown in Chaktai-Rajakhali Watershed from 1990 to 2020, while the proportions of water bodies and barren land have declined. The vegetation cover increased in the north-eastern part of the study area over the years, with higher increases in the periods of 2000-2005 and 2005-2010 but showed a decline in the period of 2010-2015. The Land Use and Land Cover (LULC) changes in the Chaktai-Rajakhali watershed from 1990 to 2020 were influenced by various factors such as urbanization, industrialization, deforestation, agriculture expansion and climate change.

The increase in built-up areas is primarily due to rapid urbanization and industrialization which led to the conversion of forests and agricultural lands into residential and commercial spaces. The declining trend in the proportion of vegetation, particularly between 2010 to 2015, could be attributed to deforestation activities, conversion of forest lands into urban areas and increasing demand for land to build infrastructure. On the other hand, the fluctuating trend of waterbody can be attributed to changes in rainfall patterns, changes in water management practices, and water withdrawal for various purposes such as irrigation, domestic and industrial use. The decline in barren land could be due to increasing agricultural activities, urbanization and increasing demand for land for various purposes. Climate change could also play a role in LULC changes by affecting rainfall patterns, causing land degradation, and altering ecosystems. These results provide a comprehensive overview of LULC changes in the study area over a 30-year period and could be useful in understanding the patterns of land use and land cover change in the region.

4.4 Land use mapping for Chaktai-Rajakhali watershed

In order to better explain and differentiate land use pattern, it is important to identify the major classes to conceptualize its importance on runoff quantity and quality and LIDs implication scenarios. The land use pattern of the Chaktai-Rajakhali watershed is an important aspect to consider for sustainable land management practices. Figure 4.4 and table 4.1 provide a comprehensive overview of the dominant land use patterns in the study area.

Residential areas are the most prevalent, with availability ranging from 40.33% to 100%. The highest availability of residential areas is seen in sub-catchments SC4 and SC7, while the lowest is seen in SC2. This high demand for residential areas can be attributed to the growing population in the region and the need for housing. Commercial areas also have a significant presence in the Chaktai-Rajakhali watershed, with availability ranging from 10.13% to 48.54%. These areas are distributed throughout the study area, with a higher concentration in the north-western and lower parts of the region. The presence of commercial areas is important as it provides employment opportunities and contributes to the local economy. However, it is also important to consider the impact of commercial activities on the environment, such as land degradation and pollution, and take appropriate measures to mitigate them.

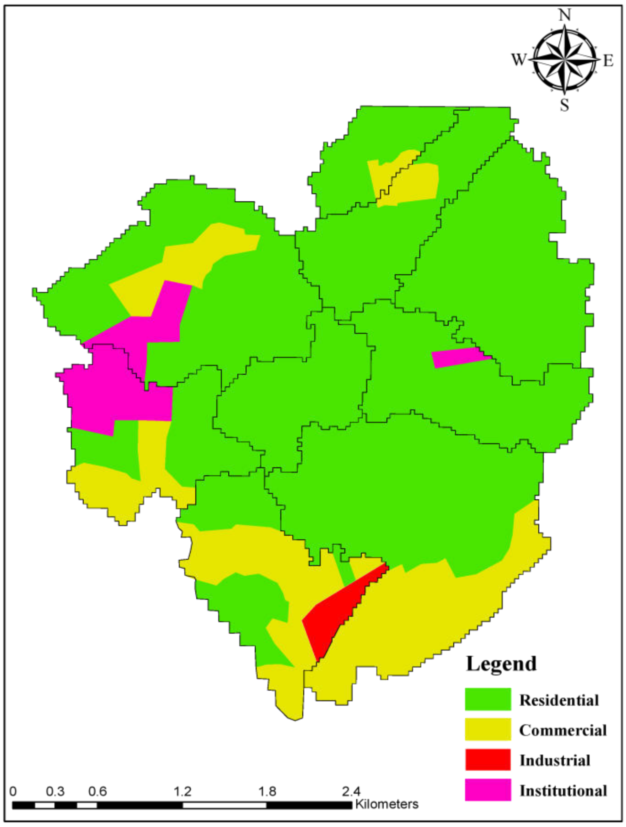


Figure 4.4 Land-use mapping of Chaktai- Rajakhali watershed

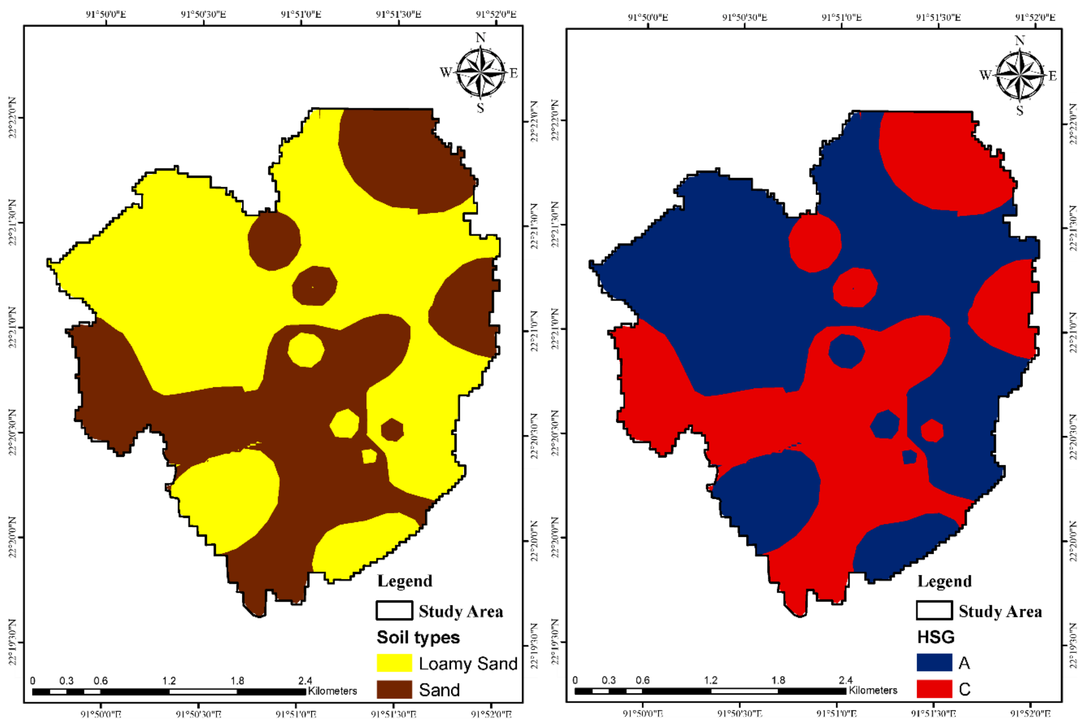
Table 4:1 Proportion of different land use pattern in Chaktai- Rajakhali watershed

SCs	Residential	Commercial	Institutional	Industrial
SC1	40.51%	48.54%	0.00%	10.95%
SC2	40.33%	28.20%	31.47%	0.00%
SC3	76.07%	13.75%	10.18%	0.00%
SC4	100.00%	0.00%	0.00%	0.00%
SC5	88.37%	11.63%	0.00%	0.00%
SC6	89.87%	10.13%	0.00%	0.00%
SC7	100.00%	0.00%	0.00%	0.00%
SC8	95.98%	0.00%	4.02%	0.00%
SC9	65.22%	34.78%	0.00%	0.00%

Institutional areas are limited to specific sub-catchments, with the highest availability seen in SC2. These areas include schools, hospitals, government buildings, and other public institutions. The presence of institutional areas is important for the overall development and welfare of the community. They provide essential services and contribute to the overall quality of life in the region. Finally, the industrial areas are limited to only one sub-catchment, SC1, indicating that the region has limited industrial development. Industrial areas can bring significant economic benefits to the region, but they can also have negative impacts on the environment and human health if proper regulations and management practices are not in place. It is important to consider the balance between economic development and environmental protection when planning for industrial growth in the region.

4.5 Hydrological Soil Group identification

The study area's textural soil classification is depicted in figure 4.5. Soils in the study area are classified by texture and the U.S. Bureau of Soils system is based on the proportion of sand particles. There are two types of soil found in the research region, namely loamy sand, and sandy soil



(a) (b)

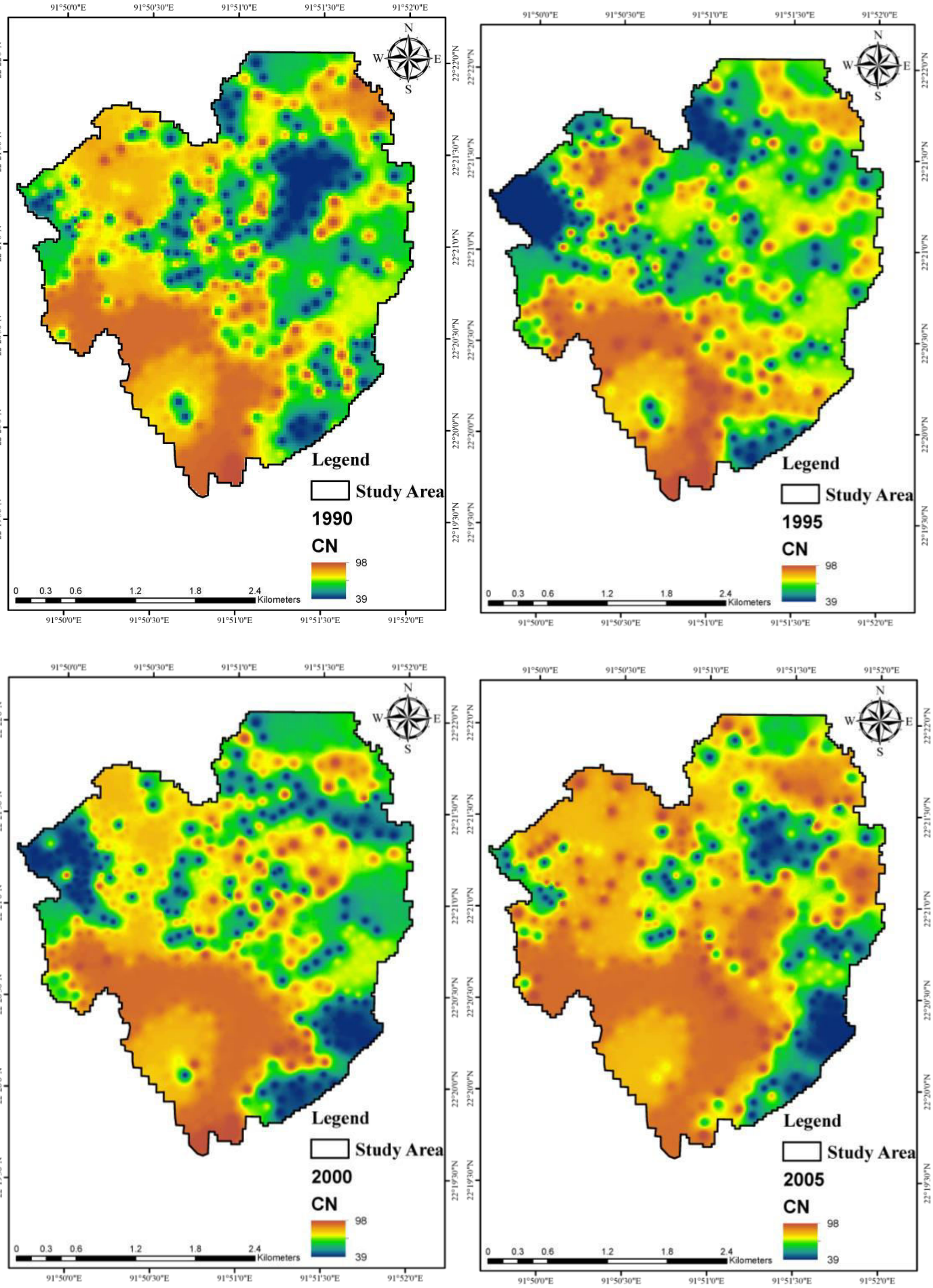
Figure 4.5 Soil Characterization in the Study Region (a) Textural classification and (b) Hydrological Soil Group

Loamy sand is the dominant soil type in the north, northeast, and northwest (mostly East Sholashahar and West Bakalia) of the study area, while sandy soil is mostly found in the central region with some presence in the northeast and south-western (mostly in Baxir Bazar, Dewan Bazar) region of the study area. To calculate the curve number, a reclassification of the soil from textural to Hydrological Soil Group (HSG) characteristics is necessary. Figure 4.5 (b) shows the reclassified soil groups, where HSG-A, which has low runoff potential due to high infiltration rates, is more common north, northeast, and northwest (mostly East Sholashahar and West Bakalia) of the study area. HSG-C, with moderate runoff potential due to slow infiltration rates, is mainly located in the northeast and south-western region of the study area (mostly in Baxir Bazar, Dewan Bazar).

4.6 Generated CN grid and trend of CN values changes

A comprehensive overview of the CN values in the Chaktai-Rajakhali watershed over the past 30 years is shown in Figure 4.6 and Table 4.2. The CN values are an indicator of the rate at which runoff occurs on a given catchment area. Higher CN values indicate more runoff and less infiltration, while lower CN values indicate less runoff and more infiltration. The CN values for all the sub-catchments show an increasing trend over the years, except for sub-catchments SC7 and SC8, which showed a decline in CN values between 2010 and 2015. The average CN values in the watershed have increased, with the highest CN value recorded in 2020 at 78.65%.

The highest increase in CN was recorded in SC9, which had a value of 70.60% in 1990 and increased to 82.37% in 2020. Other sub-catchments such as SC1 and SC5 also experienced significant increases in CN over the years. This increase in CN values may be due to several factors, such as changes in land use, soil degradation, and increased human activities. It is important to monitor and manage these factors to maintain a healthy and sustainable watershed. On the other hand, sub-catchments such as SC7 and SC8 recorded relatively low CN values over the years, with an average increase of 6.6% and 10.32%, respectively.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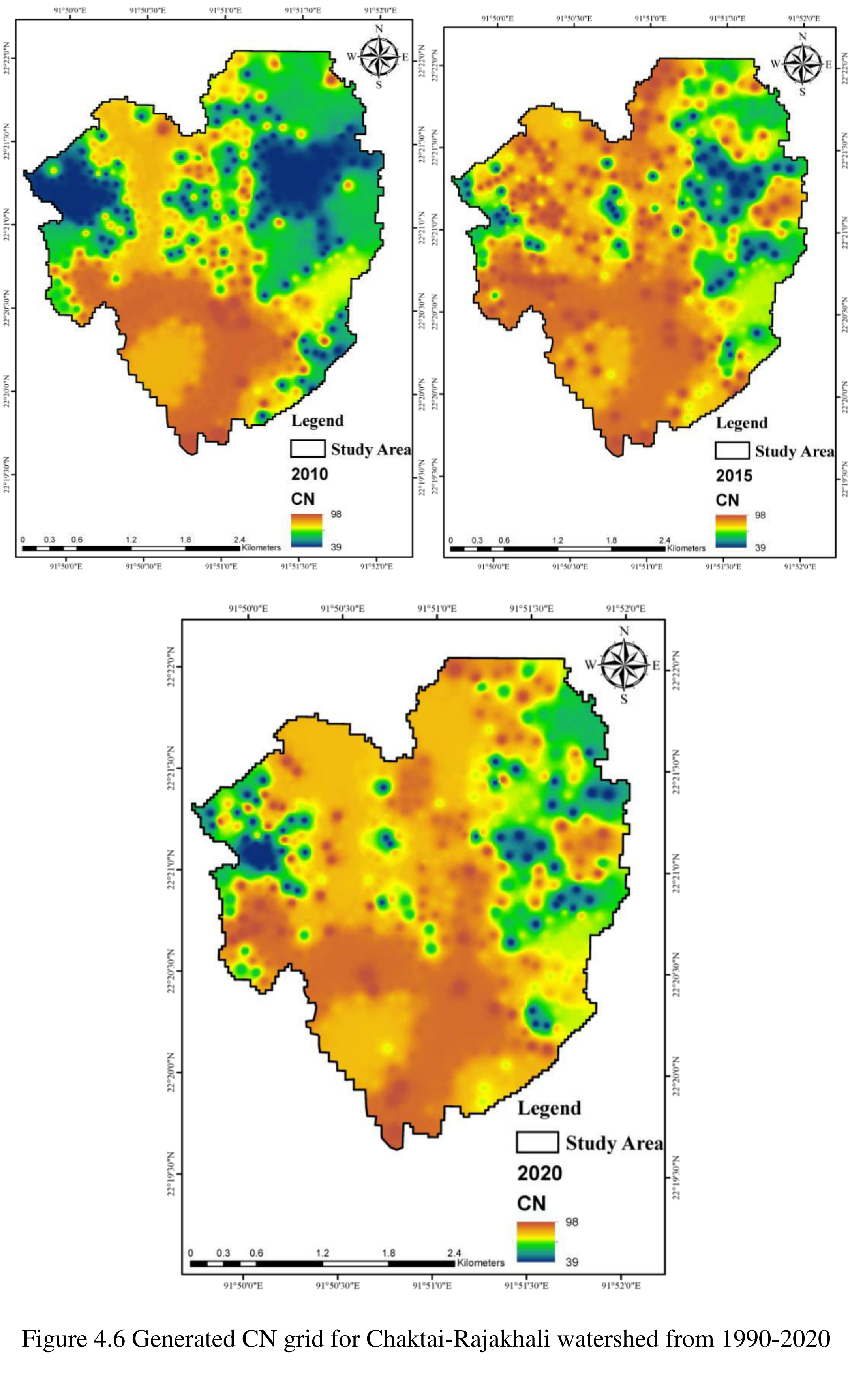


Figure 4.6 Generated CN grid for Chaktai-Rajakhali watershed from 1990-2020

Table 4:2 Curve number (CN) values for nine sub-catchments in the watershed (1990-2020)

SCs	Area (ha)	Slope (%)	1990	1995	2000	2005	2010	2015	2020
SC1	126.31	11.12	84.37	85.88	85.91	86.08	86.70	88.24	87.24
SC2	109.89	18.3	80.60	74.05	77.34	84.81	73.65	84.46	81.17
SC3	191.92	14.85	72.10	65.47	65.79	78.52	64.63	80.88	74.90
SC4	71.75	5.12	64.89	62.82	69.83	76.44	72.76	83.03	81.31
SC5	47.29	2.64	58.18	74.00	59.95	72.67	65.42	84.56	82.88
SC6	92.09	4.42	66.28	62.46	64.22	72.48	61.66	76.55	80.54
SC7	146.58	3.97	63.49	67.70	65.27	71.59	50.20	65.21	67.38
SC8	104.52	5.37	60.79	65.63	65.40	71.88	58.14	68.11	70.11
SC9	252.73	7.2	70.60	74.00	70.70	74.22	77.32	82.51	82.37
Total/avg.	1143.08	8.11	69.03	70.22	69.38	76.52	67.83	79.28	78.65

The slope of the sub-catchments varies, with SC2 having the steepest slope of 18.3% and SC4 having the lowest slope of 5.12%. The sub-catchments with steeper slopes tend to have higher CN values compared to sub-catchments with gentler slopes. This is because steeper slopes lead to faster runoff, resulting in higher CN values. In conclusion, the CN values in the Chaktai-Rajakhali watershed have increased over the years, and this trend is expected to continue in the future. The highest CN values were recorded in sub-catchments with steep slopes, and the lowest CN values were recorded in sub-catchments with gentler slopes.

4.7 Trend analysis of LULC pattern changes and CN values

The trend analysis in Table 4.3 provides a comprehensive picture of the change in land use patterns and curve numbers over time. The Z value and significance level (Sig.) are calculated to determine the statistical significance of the trend. The Q (unit/year) column provides the rate of change for each parameter. Vegetation, Waterbody, and Barren Land have a negative trend, indicating a decline in each of these land use patterns over the 1990-2020 period. This may be due to various factors such as urbanization, land conversion for agriculture or other uses, and changing water management practices.

Table 4:3 Trend analysis of Land use pattern and CN values

Parameters	Z value	Sig.	Q (unit/year)
Vegetation	-0.716		-0.163
Waterbody	-1.073		-0.260
Built up	3.935	***	1.291
Barren Land	-1.610		-0.548
CN_SC1	3.399	***	0.108
CN_SC2	0.716		0.143
CN_SC3	0.716		0.226
CN_SC4	2.326	*	0.658
CN_SC5	1.789	+	0.681
CN_SC6	1.789	+	0.506
CN_SC7	0.179		0.060
CN_SC8	1.610		0.246
CN_SC9	3.041	**	0.464
CN_avrg	1.790	+	0.321

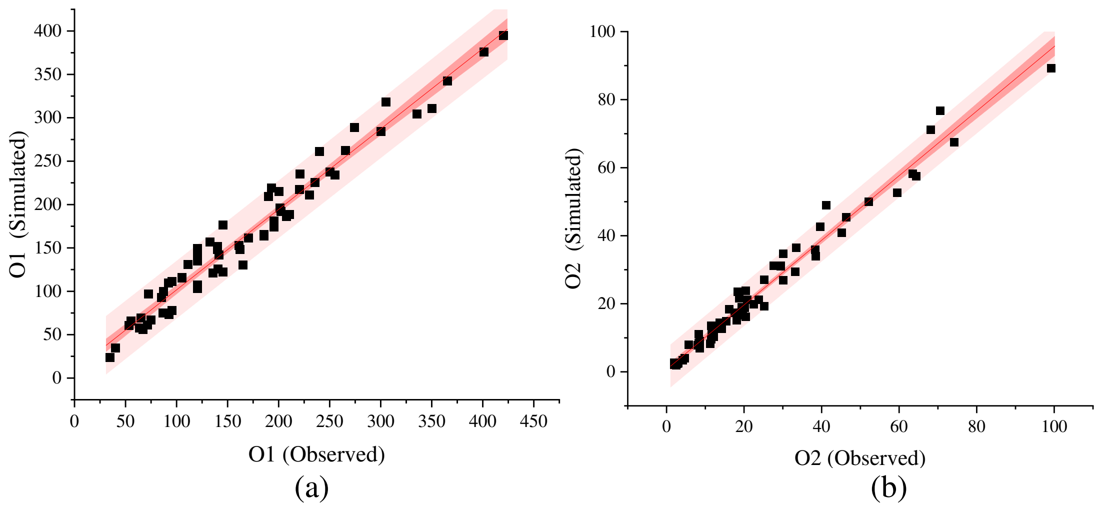
Note: **** 99.99% confidence level ($p < 0.001$); ** 99% confidence level ($p < 0.01$); * 95% confidence level ($p < 0.05$); + 90% confidence level ($p < 0.10$).*

However, the change is not significant at any confidence interval (99.99%, 99%, 95%, or 90%) meaning that the decline in these land use patterns may not change significantly as expected. The Built up pattern, on the other hand, displays a significant increase, with a rate of 1.291% per year and a 99.99% confidence level. The results reflecting that the industrialization and urbanization increased at a steep rate comparing with water bodies and barren land.

In this align, the curve numbers (CN) of SC1, SC4, SC5, SC6, and SC9 show a significant increasing trend at different confidence interval, with rates of 0.108%, 0.658%, 0.681%, and 0.506% per year, respectively, as expected from the change land use and built-up areas. This may be due to factors such as changes in land use patterns, soil properties, and runoff patterns. The increasing trend in these curve numbers may impact runoff and erosion in the region, which could lead to soil degradation, water pollution, and reduced ground water availability. This changes in the hydrological conditions, vegetation, or other factors that affect the curve numbers. Finally, the average curve number value shows a positive trend, with a rate of 0.321% per year and 90% confidence level. In conclusion, the trend analysis in Table 4.3 provides valuable insights into the changes in land use patterns and curve numbers. The reasons for these trends could be due to various factors such as urbanization, land conversion, changes in water management practices that all affects local hydrological conditions.

4.8 Accuracy assessment of quantity and quality model

The Figure 4.7 and Table 4.4 show the accuracy assessment parameters for the simulated and observed water level and runoff quality data in the Chaktai-Rajakhali watershed. The parameters include the correlation coefficient (R), R-squared, adjusted R-squared, standard error of the estimate, mean absolute deviation (MAD), mean square error (MSE), root mean square error (RMSE), and mean absolute percentage error (MAPE). The accuracy assessment parameters in the table provide insights into how well the simulated values match the observed values for various parameters such as water depth, total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and Zn (zinc). The correlation coefficient (R) indicates the strength of the linear relationship between the observed and simulated values, with a value close to 1 indicating a strong positive relationship and a value close to -1 indicating a strong negative relationship. The R values for the different parameters range from 0.988 for water depth (O1) to 0.839 for Zn, indicating a strong positive relationship for water depth (O1) and a relatively weak positive relationship for Zn.



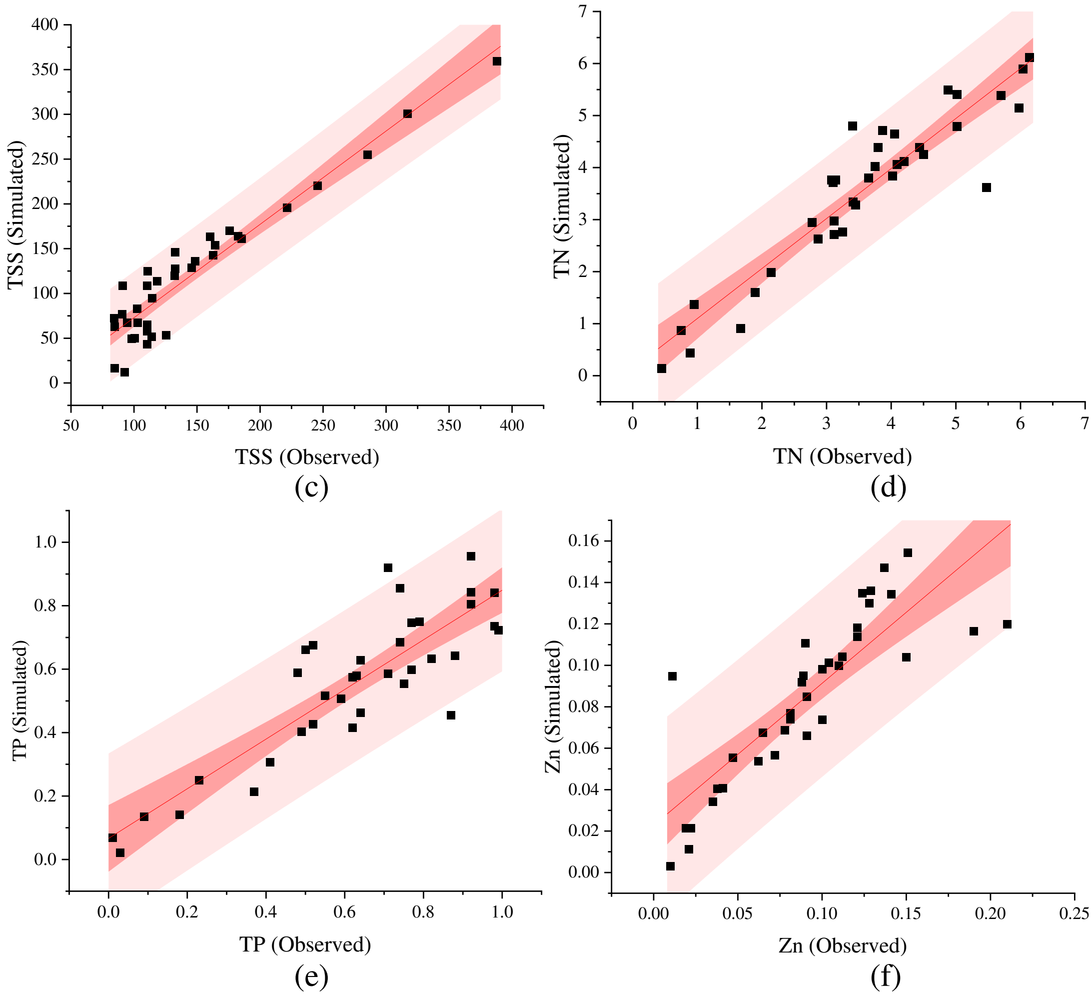


Figure 4.7 Validation curve for quantity (a) Depth at O1, (b) Depth at O2 and runoff quality (c) TSS, (d) TN, (e) TP and (f) Zn

Table 4:4 Basic statistical parameters for observed and simulated water level and runoff quality data.

Parameters	R	R^2	Adjusted R^2	Std. Error of the Estimate	MAD	MSE	RMSE	MAPE (%)
Depth (O1)	0.988	0.977	0.977	3.110	2.428	10.789	3.285	11.654
Depth (O2)	0.981	0.963	0.962	16.460	15.858	315.489	17.762	11.313
TSS	0.947	0.897	0.894	24.870	27.871	1227.330	35.033	23.806
TN	0.930	0.865	0.861	0.575	0.415	0.315	0.562	15.630
TP	0.869	0.754	0.747	0.121	0.119	0.022	0.148	36.198
Zn	0.839	0.704	0.695	0.022	0.015	0.001	0.027	34.744

Note: MAD: Mean Absolute Deviation, MSE: Mean Square Error, RMSE: Root Mean Square Error, MAPE: Mean Absolute Percentage Error

Table 4:5 Initial and calibrated values for rainfall-runoff and runoff quality model

Parameters	Initial Values	Calibrated Values
CN	45.00-98.00	50.20-88.24
N-impervious	0.010-0.150	0.045-0.124
N-pervious	0.200-0.700	0.278-0.645
D-impervious	1.00-5.00	1.77-4.57
D-pervious	0.50-2.50	0.75-2.13
C1	1.0-200.0	1.2-153.6
C2	0.01-30.000	0.041-25.0
C3	0.001-5.000	0.003-3.827
C4	0.01-3.00	0.0104-2.5

The R-squared value measures the proportion of variability in the observed values that can be explained by the simulated values, with a value close to 1 indicating that the simulated values explain a large proportion of the observed values. The R-squared values for the different parameters range from 0.977 for water depth (O1) to 0.704 for Zn, indicating that the simulated values explain a large proportion of the observed values for water depth (O1) but a relatively small proportion for Zn. The adjusted R-squared value is a modified version of the R-squared value that considers the number of variables in the model and the sample size and provides a more accurate measure of the goodness-of-fit of the model. The standard error of the estimate measures the variability of the residuals (the difference between the observed and simulated values), with a lower value indicating that the residuals are less variable, and the model is a better fit.

The standard error of the estimate values for the different parameters ranges from 3.110 for water depth (O1) to 0.575 for TN, indicating that the residuals are less variable for water depth (O1) than for TN. The mean absolute deviation (MAD), mean square error (MSE), and root mean square error (RMSE) provide measures of the average deviation of the simulated values from the observed values, with lower values indicating a better match. The mean absolute percentage error (MAPE) provides a measure of the average deviation of the simulated values from the observed values as a percentage, with lower values indicating a better match. The MAPE values for the different parameters range from 11.654% for water depth (O1) to 36.198% for TP, indicating that the simulated values are a better match for water depth (O1) than for

TP. In various studies, different R^2 values have been reported for the calibration and validation of various parameters. For instance, in Skudai, Johor, Peninsular Malaysia, the R^2 values for quantity calibration range from 0.987-0.998 and for TSS it ranges from 0.768-0.998 (Chow et al., 2012). In Shenyang, China (Li et al., 2016), the R^2 values for quantity calibration range from 0.86-0.95. Similarly, for TP validation, R2 values range from 0.669-0.825 in Daejeon, South Korea, and from 0.285-0.991 in Skudai, Johor, Peninsular Malaysia. The R^2 values for TN in Daejeon, South Korea, were reported as ranging from 0.769-0.807 (Han & Seo, 2014). Other studies have reported R^2 values for TSS in City of Calgary, Alberta, Canada (0.81) (Shrestha & He, 2017), Santander, Spain (0.93) (Temprano et al., 2006), and Chattogram, Bangladesh (0.5937) (Alam, 2018).

Overall, the results of the accuracy assessment indicate that the simulated values match the observed values relatively well for water depth (O1) but less well for TSS, TN, TP, and Zn. The variations in the accuracy assessment parameters for the simulated and observed values of water depth, total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and Zn (zinc) can be due to several factors including model complexity, input data quality, model assumptions, natural variability in the watershed, and measurement error in the observed values. The specific reasons for the variations will depend on the details of the study and the watershed system being modelled.

4.9 Influence of Land-use changes on hydrological variables

Hydrological parameters including surface runoff, infiltration rate, evapotranspiration, and groundwater recharge can be affected by changes in land use. Surface runoff may increase as built-up area expands, but the volume of runoff may decrease if vegetative land expands. Planning and managing land use effectively requires an understanding of these linkages.

A correlation plot, as seen in figure 4.8, was created to determine the relationship between 11 variables related to land use in 9 sub-catchment areas. The time series plot of different hydrologic parameters at two outlets are shown in Appendix D. The variables included CN, maximum runoff rate, total runoff, maximum infiltration, total infiltration, total rainfall, maximum rainfall intensity, vegetation, waterbody, built up, and barren land. The purpose of this plot was to understand if these variables had a positive or negative relationship with each other. The results showed that CN, maximum runoff rate, and total runoff were positively related to each other and to build up, while they had a negative correlation with maximum infiltration, total infiltration, and vegetation.

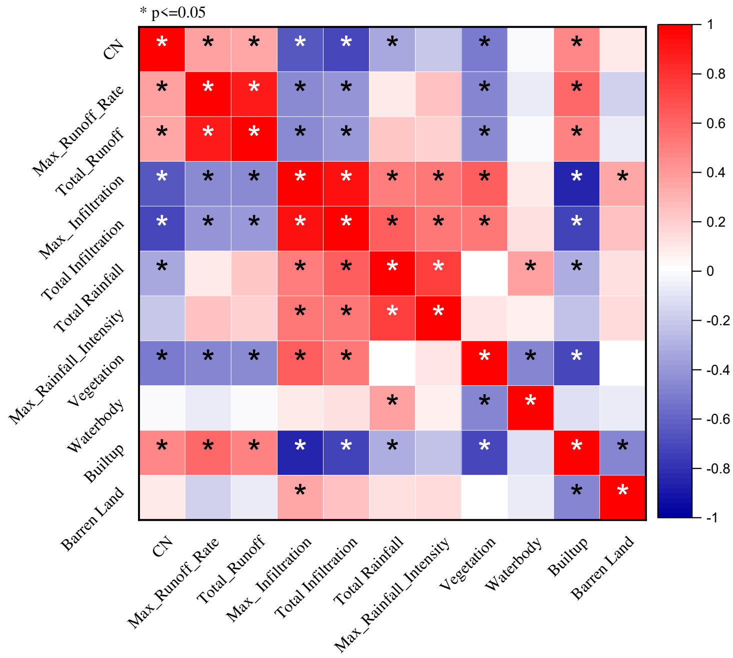
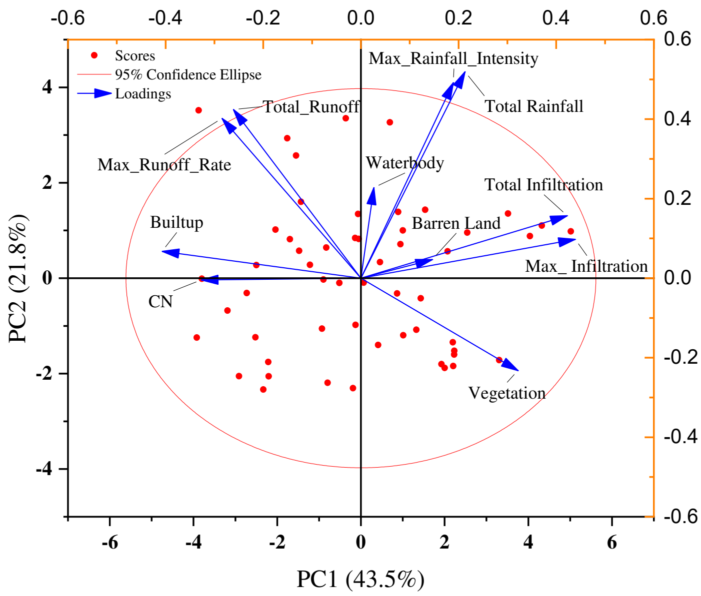
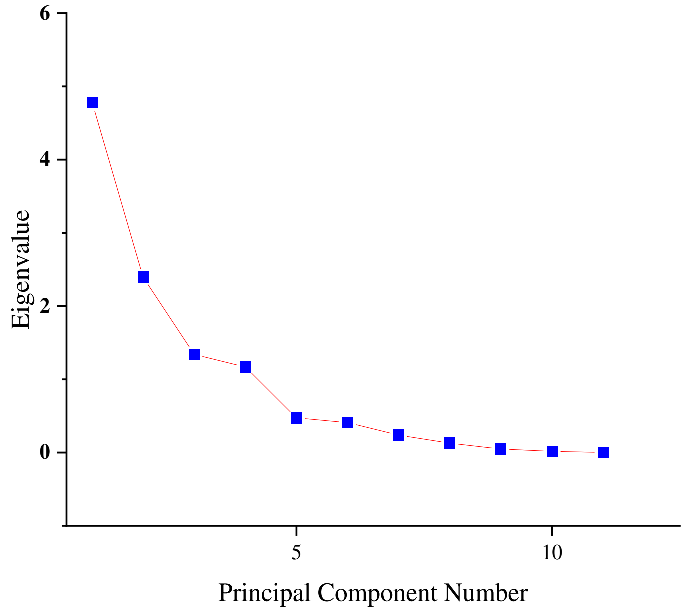


Figure 4.8 Correlation plot among the variables at the outlets of nine (9) sub-catchment.



(a)



(b)

Figure 4.9 (a) Plot of loadings (PC1 versus PC2), (b) Scree plot among the eleven (11) variables at the outlets of nine (9) sub-catchment.

On the other hand, maximum infiltration and total infiltration showed a strong positive relationship with total rainfall, maximum rainfall intensity, and vegetation. Built up had a negative correlation with maximum infiltration, total infiltration, total rainfall, vegetation, and barren land. Total rainfall and maximum rainfall intensity both had a strong positive correlation with each other, and waterbody had a positive correlation with total rainfall and a negative correlation with vegetation. To further simplify the data, a principal component analysis (PCA) was carried out. The PCA was accompanied by varimax rotation to make it easier to assess the data. PC1 accounted for 43.5% of the data variance and PC2 accounted for 21.8%. The PCA plot showed three different groups of variables: cluster1 (Total runoff, Max runoff rate, CN, Built up), cluster 2 (maximum infiltration, total infiltration, total rainfall, maximum rainfall intensity, Waterbody, barren land), and cluster 3 (vegetation).

The PCA plot demonstrated that PC1 was primarily influenced by barren land, built up, maximum infiltration, total infiltration, and CN, while PC2 was strongly influenced by maximum runoff rate, total rainfall, maximum rainfall intensity, total runoff, waterbody, and vegetation. The angle between the variables in the PCA plot revealed a positive correlation between vegetation and Max runoff rate, and CN and maximum infiltration. However, there was no relation between built up and waterbody, and vegetation and total rainfall.

The reasons for the variation in the relationships between these variables can be attributed to various factors such as land use patterns, local climate, and hydrologic conditions. For example, the presence of built-up areas can lead to increased runoff and decreased infiltration, while vegetation can lead to increased infiltration and decreased runoff. Understanding these relationships can be important for developing effective water resource management strategies in the sub-catchment areas.

In conclusion, the correlation plot and PCA analysis were carried out to understand the relationship between 11 variables related to land use in 9 sub-catchment areas. The results showed that the variables were divided into three different groups, with each group having its own characteristics and influences. The angle between the variables in the PCA plot indicated the positive and negative relationships between the variables, helping to understand their impact on each other.

4.10 Hydrologic Performance of LIDs scenarios

Figure 4.10 and figure 4.11 are showing the flow hydrograph and flow reduction rate for different types of Low Impact Development (LID) scenarios (S2-S4) at two different outlets (O1 and O2) of a studied catchment, for different return periods, respectively. The flow reduction rate is the percentage of runoff that is reduced because of implementing LID practices.

The figures (Figure 4.10 and Figure 4.11) show that as the LID scenario increases from S1 to S4, the flow reduction rate also increases, meaning that the more types of LID practices that are implemented, the more effective they are in reducing runoff. As well as, as the return period increases, the flow reduction rate also increases, meaning that the LID practices are more effective in reducing runoff during more severe storms. For example, for a 2-year return period, the flow reduction rate at outlet O1 for LID scenario S2 is 24.82%, and at outlet O2 for LID scenario S2 is 24.06%. And for a 100-year return period, the flow reduction rate at outlet O1 for LID scenario S4 is 50.49% and at outlet O2 for LID scenario S4 is 37.49%.

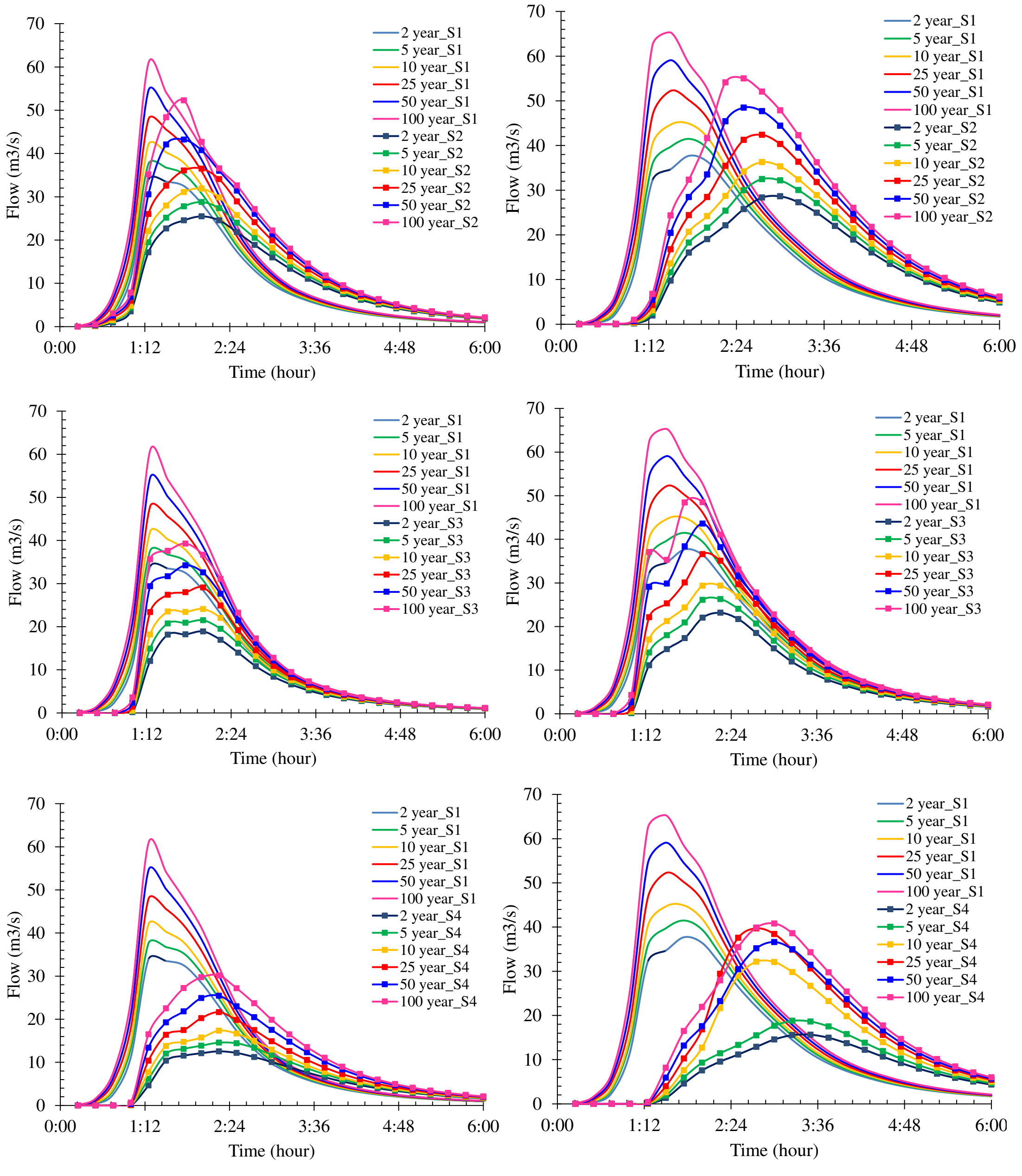


Figure 4.10 Performance evaluation of specific LID scenarios in different return periods at two outlets (O1 is in left and O2 in right)

It is important to note that the specific values and the effect of different LID practices on runoff reduction may vary depending on the specific site conditions, climate, and other factors. Additionally, the difference between the flow reduction rates for different return periods can be observed. For example, for a 2-year return period, the flow reduction rate for LID scenario S4 is 62.96% at outlet O1 and 58.5% at outlet O2, but for a 100-year return period, the flow reduction rate for LID scenario S4 is 50.49% at outlet O1 and 37.49% at outlet O2. It's also worth mentioning that the flow reduction rate for different LID scenarios also differ for different return periods, for example, for a 100-year return period, the flow reduction rate for LID scenario S2 is 14.1% at outlet O1 and 15.73% at outlet O2, while for LID scenario S4 is 50.49% at outlet O1 and 37.49% at outlet O2.

The trend of efficiency of different scenarios can be observed as follows: S1 (No LIDs) has the lowest flow reduction rate among all the LID scenarios, showing that it is less efficient in reducing runoff compared to other LID scenarios. S2 (VS) has a slightly higher flow reduction rate than S1, but still lower than S3 and S4. S3 (BR, GF, PP, IT, and RB) has a higher flow reduction rate than S1 and S2, showing that it is more efficient in reducing runoff. S4 (S2 and S3 combined) has the highest flow reduction rate among all the LID scenarios, showing that it is the most efficient in reducing runoff. This trend is consistent for all the return periods and for both outlets O1 and O2, indicating that combining different types of LID practices (S3) and VS (S2) together is more effective in reducing runoff than using any one of them alone (S1 and S2).

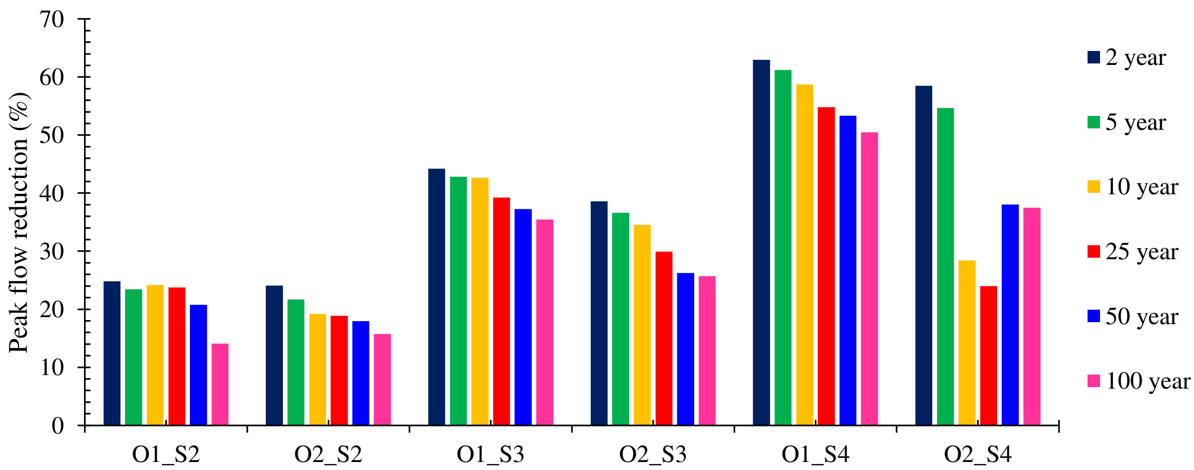


Figure 4.11 Total peak flow reduction rate under different LID scenarios in different return periods at two outlets.

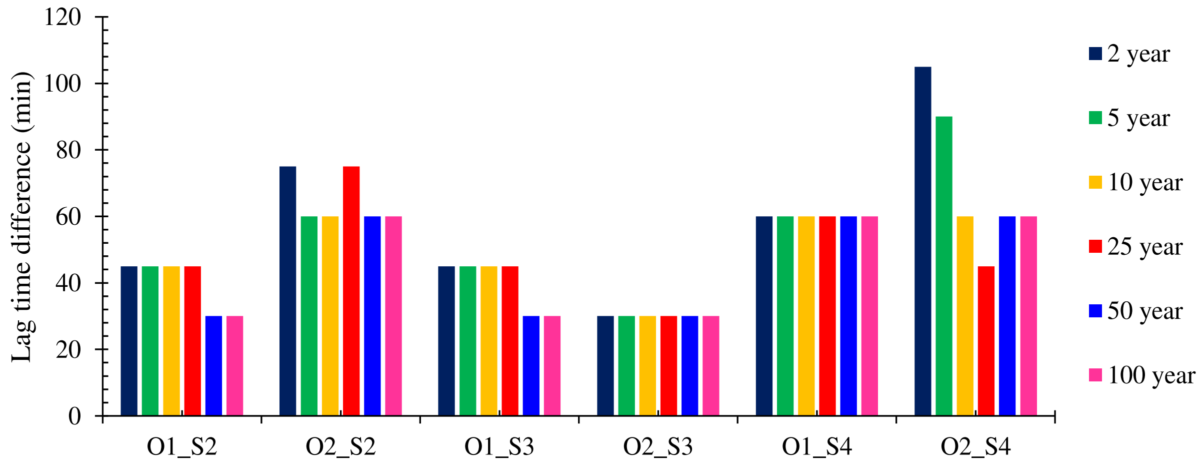


Figure 4.12 Lag time differences between S1 and other LID scenarios (S2, S3, & S4) in different return periods at two outlets.

Figure 4.12 shows that the lag time differences for peak discharge vary depending on the LID scenario, return period, and outlet. In scenario S2 (Vegetative Swales), the lag time difference at outlet O1 is 45 minutes for the 2-year return period, and it remains the same for the 5-year, 10-year, and 25-year return periods. However, at outlet O2, the lag time difference is 75 minutes for the 2-year return period and 75 minutes for the 25-year return period.

In scenario S3 (Bioretention, Green Roofs, Permeable Pavement, Infiltration Trenches, & Rain Barrels), the lag time difference at outlet O1 is 45 minutes for all return periods, and at outlet O2 is 30 minutes for all return periods. In scenario S4 (combination of S2 and S3) at outlet O1, the lag time difference is 60 minutes for the 2-year return period, 60 minutes for the 5-year return period, 60 minutes for the 10-year return period, and 60 minutes for the 25-year return period. At outlet O2, the lag time difference is 105 minutes for the 2-year return period, 90 minutes for the 5-year return period, 60 minutes for the 10-year return period and 45 minutes for the 25-year return period. Overall, it is seen that the lag time difference decreases as the return period increases and the LID scenarios S3 and S4 have a greater impact on reducing the lag time difference in comparison to the S2 scenario.

The reduction rates in peak flow or runoff volume observed in individual LID component conducted in Poland, Turkey, and Korea using rain barrels, bio-retention, and storage-infiltration and tree box filter systems (see table 4.6). Reduction rates varied between 4.5 - 12.0%, 60.24%, 73-84%, and 65-76% for each of the LID components (Nowogoński, 2020, Gülbaz, 2019 and Tobio et al., 2015). Reduction rates varied between 1.7% and 59% and were achieved using combinations of different LID components such as permeable pavements, tree box filters, bio-retention, vegetative swales, rain gardens, rainwater harvesting tanks, and rain barrels (Lee et al., 2022, Seo et al., 2017, Yang et al., 2020 and Gülbaz & Kazezyilmaz-Alhan, 2015). Some studies (Luan et al., 2017 and Seo et al., 2017) reported a reduction in effectiveness (69% to 34%) with increasing return periods, while others reported a removal rate of 23.2% to 35% (Yang et al., 2020 and Tuomela et al., 2019).

Table 4:6 Reductions in peak flow or runoff volume observed in various LID control experiments conducted by different researchers around the world.

Study area	Time span	Consideration	Results	Reference
Chaktai-Rajakhali Watershed, Chattogram, Bangladesh	1990-2020	The study evaluates the storm runoff quantity and quality performance of LID scenarios in stormwater networks under different hydrological attributes.	Inclusion of LIDs in drainage network is seen to be significantly reduce peak discharge by 14–63%, and thus increase lag times (between LID scenarios and no LID scenario) from 30 to 105 minutes.	This study
Seoul & Incheon, South Korea	2022	The study utilized the Storm Water Management Model (SWMM) to investigate the influence of urban features, sewer system type, and precipitation intensity on surface runoff. The objective was to develop an efficient water circulation plan for complex urban areas by optimally allocating LID/GI strategies.	The flow removal efficiency of the GI and LID systems (Permeable pavement and Tree box filter) in Seoul city (urban city) ranges from 1.7% to 15%, while in Incheon city (complex city), it ranges from 3.6% to 8.2%.	(Lee et al., 2022)
Gorzów Wielkopolski City Council, Poland	2020	SWMM was used to compare two techniques: the traditional method and Low Impact Development (LID). LID involves preserving and restoring natural landscape features and reducing impervious surfaces by using rain barrels, permeable walkways, and bio-retention reservoirs.	The maximum outflow rate from the analyzed catchment by employing rain barrels is decreased by a range of 4.5 to 12.0 percent.	(Nowogoński, 2020)

Mirpur, Bangladesh	2020	This study aims to model stormwater using SWMM and assess the impact of LID structures on the drainage system	The SWMM model showed high levels of flooding and surface runoff in the study area, but implementing LID through the use of a rain barrel reduced flooding, flooding time, and runoff, making it a recommended solution for minimizing flood frequency and amount.	(Abdullah-al-masum et al., 2021)
22 Wards of Chattogram City, Bangladesh	2009-2020	The research endeavor aimed to analyze fluctuations in the groundwater level by employing the widely acknowledged MODFLOW-2005 model.	The results of the study revealed that there was a reduction rate of approximately 4.75 meters per year in the central area of the city, with 21% of the wards (five out of a total of 22 wards) experiencing a significant decrease in groundwater levels.	(Akter & Ahmed, 2021)
Chattogram City, Bangladesh	2019-2020	the study assessed the possibilities for Groundwater Recharge (GWR) using geospatial techniques in conjunction with Multi-Criteria Decision Analysis (MCDA),	The findings of the study demonstrated that 5.5% of the overall area possessed a high potential for Groundwater Recharge (GWR), while 11% to 48% of the area was identified as having medium to high potential. Additionally, around 20% of the area was considered to have low potential for GWR.	(Akter, Uddin, et al., 2020)
Istanbul, Turkey	2019	The objective is to assess the pollutant removal efficiency of bioretention by integrating it into a water quality model that includes Zn, Cu, Pb, TN, and TP as pollutants.	The implementation of bioretention led to a reduction of 60.24% in the peak flow rate.	(Gülbaz, 2019)
Risvollan, Norway	2018	A model using PCSWMM was developed to examine how rooftop stormwater management solutions can effectively decrease runoff at a catchment level.	The utilization of 11% of the roof surface in an urban area can lead to a maximum reduction of 32% in the outflow rate.	(Hamouz et al., 2020)
Chattogram, Bangladesh	2018	The primary objective of this study was to investigate the surface runoff's implications on Chattogram city, with particular attention to the	Fifteen locations in Chattogram city were identified as having a substantial risk of flooding, with surface runoff volumes ranging	(Alam, 2018)

		hazards it poses in terms of flood risk and water pollution.	from 1755 m^3 to 8835 m^3,	
Texas, USA	2017	The current research examined how effective LID (Low Impact Development) practices are in three different types of urban areas that vary in their density and design: high-density compact (UHD), medium-density conventional (UMD), and medium-density conservational (UMC). The study focused on the use of rain gardens, permeable pavements, and rainwater harvesting tanks in computer simulations. The researchers also outlined a modeling process for including LID practices in SWAT (Soil and Water Assessment Tool) specifically for this purpose.	The rate of reduction in runoff ranged from 14% to 29%, resulting in a decrease of 53 mm to 136 mm in runoff.	(Seo et al., 2017)
Beijing, China	2012-2016	The study utilized the Storm Water Management Model (SWMM) to simulate past urban storm processes in Beijing's Fragrance Hills region and evaluated the impact of different LID measures such as concave greenbelt, permeable pavement, bio-retention, vegetative swales, and comprehensive measures on reducing urban runoff through numerical simulations.	The most effective LID measures (Concave greenbelt, Vegetable swale, and Comprehensive measures) showed a decrease in their effectiveness as the return periods increased, with their shortening percentage decreasing from 69.4% to 34.0%.	(Luan et al., 2017)
South Agrabad, Chittagong, Bangladesh	2015	This study sought to evaluate the potential of RWH systems in an area with the typical annual precipitation amounts to 3000 mm.	The study's results indicate that RWH systems could potentially decrease stagnant stormwater by a maximum of 26% and provide an annual supplement of up to 20 liters of water per person to the city's water supply.	(Akter & Ahmed, 2015b)
Cheongju, South Korea	2005-2015	In this study, the effectiveness of seven types of LID installations in managing stormwater,	The average runoff reduction rate of 76.6% for seven LID installation types	(J. Kim et al., 2018)

		considering short-term and long-term simulations and analyzing distinct sub-basins and individual facilities within the study site using the Storm Water Management Model (SWMM),	demonstrated their effectiveness, but the reduction rate varied by sub-basin (ranging from 9.0-30.7%) due to the types of LID installations in each area.	
Dresden, Germany	2001-2015	The effectiveness of seven distinct LID (Low Impact Development) practices and six precipitation scenarios were evaluated through simulation using a Storm Water Management Model (SWMM).	the combination of an infiltration trench, permeable pavement, and rain barrel (IT+PP+RB) showed the highest capacity for controlling runoff among the different options tested, with a removal rate between 23.2% to 27.4%	(W. Yang et al., 2020)
Chattogram, Bangladesh	2013-2014	This study investigates the impact of LID on urban flooding by analyzing the flooded area and depth in a specific area in Chittagong and explores the potential of implementing distributed rain barrel RWH systems to mitigate flash flooding in a highly urbanized area.	The study found that implementing LID measures in SWMM can result in a reduction of the flooded area by about 30%. Additionally, the research demonstrated that an impervious surface covering between 10% to 60% of the sub-catchment area can yield a monthly rainwater harvesting potential of 0.04 to 0.45 m3 per square meter of rooftop area.	(Akter, Tanim, et al., 2020b)
Cheonan, Republic of Korea	2010-2013	The study employed the SWMM to simulate and assess the treatment efficacy of storage-infiltration and tree box filter systems on different urban land uses, while optimizing hydraulic and water quality parameters via the Box complex method.	Both the storage-infiltration system and tree box filter were able to reduce the volume by 73-84% and 65-76%, respectively.	(Tobio et al., 2015)
AsanTangjung New Town, Korea	1973-2011	This study evaluated the effectiveness of LID facilities in reducing flooding with a return period of 50 to 100 years in the Jangjae Stream watershed through hydrological analysis.	The study found that the installation of LID facilities resulted in a flood reduction effect of approximately 7-15% compared to before their installation, with the fourth quadrant experiencing a higher reduction (10-15%) effect than the third quadrant during rainfall	(Lee et al., 2012)

			events with a return period of 50 to 100 years.	
Busan, South Korea	2009-2011	The study used LID technologies in four different scenarios: current city conditions, rain barrel use, rain barrel and tree filter box use, and rain barrel, tree filter box, and porous pavement use. The simulations analyzed short-term and long-term effects in different seasons.	The four selected cases showed varying rates of runoff reduction during different seasons. Specifically, the reduction rates during spring, summer, fall, and winter ranged from 0.28% to 53%, 0.97% to 53%, 0.35% to 55%, and 0.16% to 59%, respectively.	(Shon et al., 2013)
Istanbul, Turkey	2009-2010	The study utilized a calibrated hydrodynamic model with SWMM to examine how LID-BMPs, including retention basins, vegetative swales, and permeable pavement, affect surface runoff and TSS, focusing on their impact on peak flow rate and the build up and wash off of TSS pollutants.	The implementation of LID BMPs results in a decrease in the peak of the hydrograph, lowering it from around 7.5 m^3/s to 6.5 m^3/s (13.33 %).	(Gülbaz & Kazezyilmaz-Alhan, 2015)
Espoo, Finland	2003-2006	The evaluation of the effects of ten LID scenarios, which included permeable pavement and bio-retention cells, on urban runoff and pollutant load at the catchment scale was conducted using simulations with the Storm Water Management Model (SWMM).	The catchment scale reduction in runoff during the summers of 2003, 2005, and 2006, for the ten LID scenarios, varied between 15% and 35%.	(Tuomela et al., 2019)

A few studies were also conducted in two major cities of Bangladesh, and the results show that reduction rates varied, with rain barrels being found effective in reducing flooding and runoff in Mirpur (Abdullah-al-masum et al., 2021), while 15 locations in Chattogram were identified to have high flood risk with varying runoff volumes from 1755 m^3 to 8835 m^3 (Alam, 2018). Another study found that an impervious surface covering between 10% to 60% can yield a monthly rainwater harvesting (RWH) potential of 0.04 to 0.45 m^3 per square meter of rooftop area (Akter et al., 2020). The efficacy of individual LID controls in mitigating various pollutants is evidenced by studies conducted in San Angelo, Texas, Azerbaijan, Iran, and Istanbul, Turkey. The retention structures demonstrated a high removal rate of up to 94% for TSS/BOD and

82% for TP/TN (Kim, 2021), while the vegetative swales showed a 20-25% decrease in all pollutant loads (Nazari-sharabian et al., 2019), and the bioretention cells resulted in a reduction of pollutants by 98-99% (Gülbaz, 2019).

4.11 Event Mean Concentration (EMC) of pollutants

The Table 4.7 and Figure 4.13 show the Event Mean Concentration (EMC) of various pollutants in different land uses of Chattogram city. The pollutants considered in table and figure are Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), Zinc (Zn), Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The land uses considered in this table are Residential, Industrial, Commercial and Institutional. TSS (Total Suspended Solids) ranges from 275.25 mg/L in residential areas to 1085.50 mg/L in commercial areas.

TN (Total Nitrogen) ranges from 7.33 mg/L in residential areas to 5.10 mg/L in industrial areas. TP (Total Phosphorus) ranges from 1.145 mg/L in residential areas to 0.3325 mg/L in commercial areas. Zn (Zinc) ranges from 0.1850 mg/L in residential areas to 0.0225 mg/L in commercial areas. These values can be used as input in SWMM for runoff quality modeling. The variation in these values between different land uses is likely due to a number of factors. Residential areas generally have less intense land use compared to commercial and industrial areas, resulting in lower levels of pollutants.

Additionally, institutional areas such as schools and hospitals may have different management practices in place that result in lower pollutant levels. Industrial areas, on the other hand, typically have higher levels of pollutants due to the presence of manufacturing and industrial activities. Furthermore, commercial areas may have more impervious surfaces such as parking lots and buildings which can lead to higher levels of pollutants. The Event Mean Concentration (EMC) of BOD_5 and COD in different land uses of Chattogram city shows significant variation. The BOD_5 EMC levels range from 28.50 mg/L in institutional areas to 51.15 mg/L in residential areas. The COD EMC levels range from 77.28 mg/L in commercial areas to 145.86 mg/L in residential areas. The highest EMC of both parameters is observed in the residential areas, followed by industrial, commercial, and institutional areas. One reason for the high BOD_5 and COD EMC in residential areas could be the presence of a large population density, which generates a substantial amount of domestic wastewater.

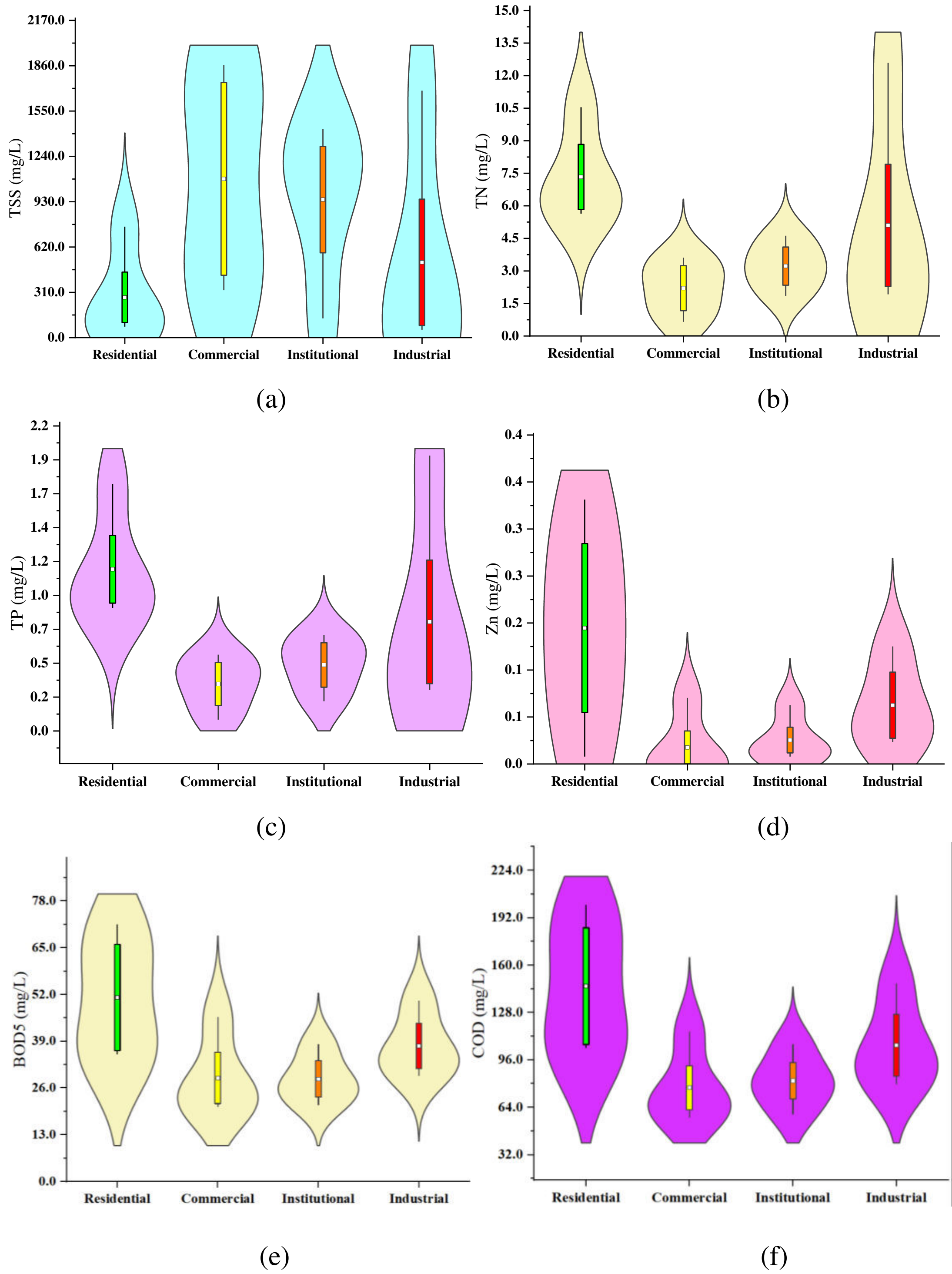


Figure 4.13 Variation of runoff water quality parameters with different LU areas (a) TSS, (b) TN, (c) TP, (d) Zn, (e) BOD_5 and (f) COD

Table 4:7 Event Mean Concentration (EMC) of the pollutants in different land uses of Chattogram city.

Parameters	TSS (mg/L)	TN (mg/L)	TP (mg/L)	Zn (mg/L)	BOD_5 (mg/L)	COD (mg/L)
Residential	275.25	7.33	1.145	0.1850	51.15	145.86
Industrial	515.25	5.10	0.7725	0.0800	37.69	105.94
Commercial	1085.50	2.20	0.3325	0.0225	28.77	77.28
Institutional	944.00	3.22	0.4675	0.0325	28.50	81.89

This domestic wastewater, which contains organic matter and other pollutants, contributes significantly to the BOD_5 and COD levels in the area. Industrial areas also show high EMC levels of BOD_5 and COD, which can be attributed to the discharge of untreated or partially treated industrial wastewater into the environment. Such wastewater contains a high concentration of organic matter, chemicals, and other pollutants that can increase the levels of BOD_5 and COD in the surrounding water bodies. The lower EMC levels in commercial and institutional areas could be due to the lower wastewater generation rate compared to residential and industrial areas. Moreover, these areas usually have better wastewater treatment facilities and management practices, which helps in reducing the pollutant load to the environment. Overall, the land use and management practices in these areas are the major factors that contribute to the variation in pollutant levels.

4.12 LID system in runoff pollution reduction

Figures 4.14 and 4.15 show that the efficiency of different LID systems in reducing runoff pollutant concentrations varies depending on the pollutant (details of the variation of runoff quality parameters are available in Appendix E). The first scenario, S1, with no LIDs (Low Impact Development) in place, showed the highest runoff pollutants concentration at both outlets, i.e., the concentration of TSS is 205 mg/L at outlet 1 (O1) and 160 mg/L at outlet 2 (O2). The greater pollutant concentrations in runoff with S1 is due to the lack of measures to control runoff and prevent sedimentation. Without LIDs, runoff water carries soil particles, pollutants, and other debris, leading to elevated TSS concentrations. The second scenario, S2 (Vegetative Swales (VS)) showed substantial reduction in TSS concentration, while reduction potential continue to grow more with S3 and S4. The introduction of VS reduced the TSS concentration as the vegetation in the swales can filter and retain sediment, organic matter, and other pollutants from runoff water.

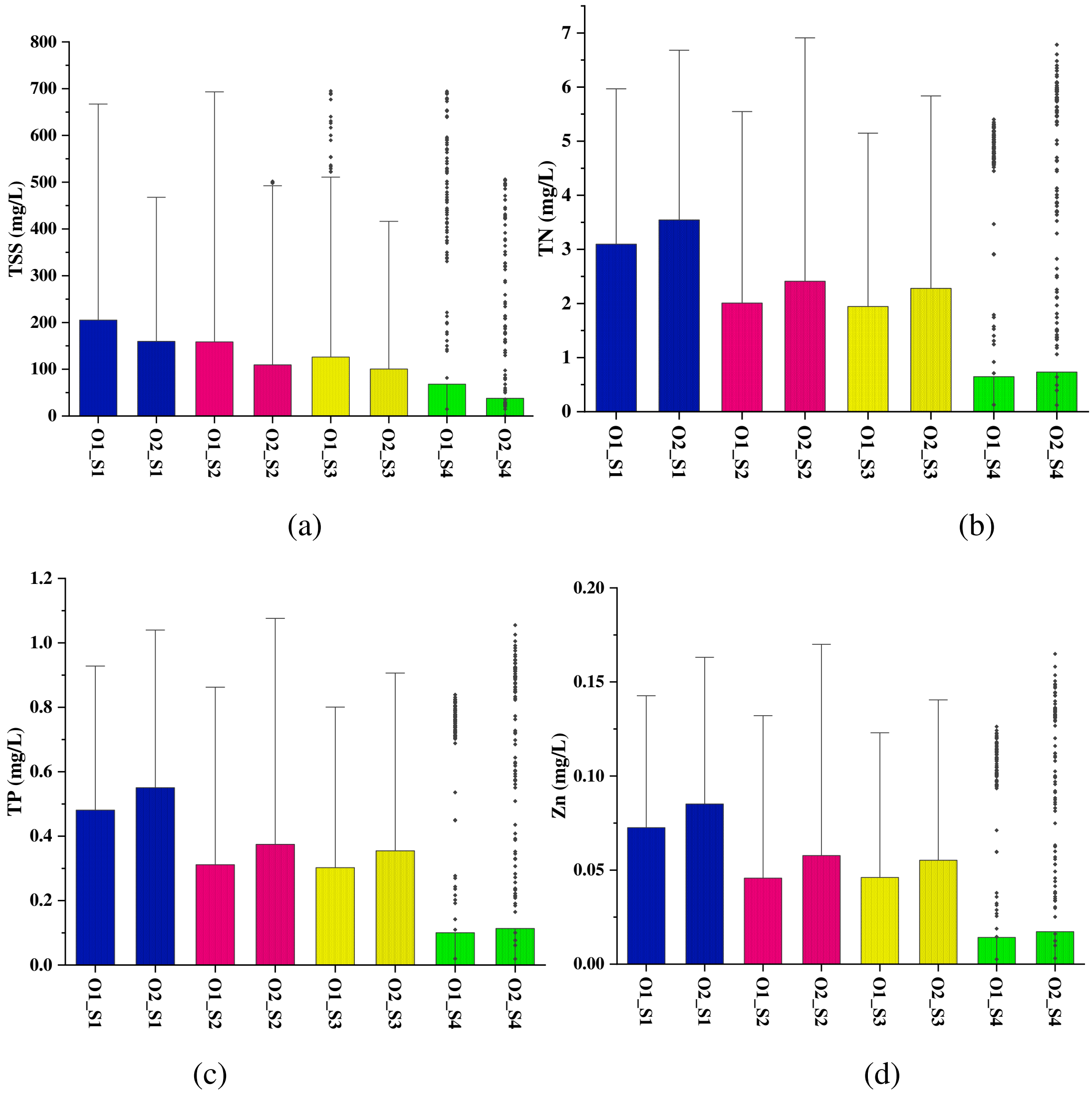


Figure 4.14 Pollutant concentration of different LID scenario at two outlets for various runoff pollutants (a) TSS, (b) TN, (c) TP and, (d) Zn

However, the reduction was not as significant as in S2 due to the limited effectiveness of VS in controlling runoff. The third scenario, S3, included combinations of bio-retention (BR), green roof (GR), permeable pavement (PP), infiltration trench (IT), and rain barrel (RB). Hence, the S3 showed the lowest runoff pollutants concentration i.e., TSS concentration among the four scenarios were ranging from 100 mg/L to 158 mg/L. The implementation of treatment trains compared to an individual process was effective in controlling runoff and reducing sedimentation due to the various mechanisms employed by each BMP.

For example, permeable pavements and infiltration trenches allow water to permeate into the ground, reducing runoff volume and velocity. Bio-retention and green roofs can filter and retain pollutants, while rain barrels can store runoff water for later use, reducing runoff volume. The existing scenario in S4 includes the existing land use and development patterns, as well as the vegetative swales (VS) from Scenario 2. The VS can filter and retain sediment, organic matter, and other pollutants from runoff water, which can reduce TSS concentrations.

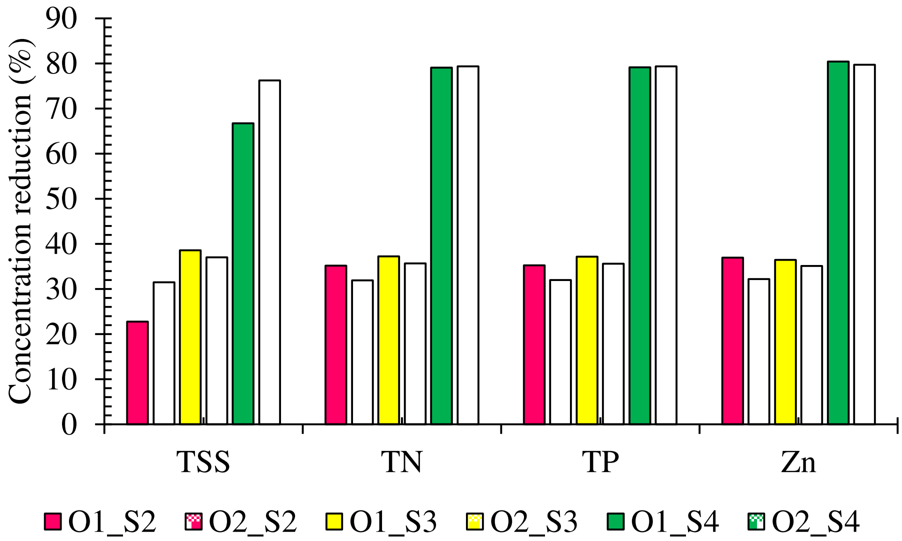


Figure 4.15 Efficiency of different LID scenarios in reducing pollutant concentrations

Figure 4.15 shows quantitatively that in scenario S2, the reduction rate for TSS, TN, TP and Zn were 23%, 35%, 35%, and 37%, respectively. In scenario S3, the reduction rate for TSS, TN, TP and Zn were 39%, 37%, 37%, and 36%, respectively. Similarly in scenario S4, the reduction rate for TSS, TN, TP and Zn were 67%, 79%, 79%, and 80%, respectively, are found. These numbers indicate that the inclusion of additional LIDs, such as bio-retention, green roofs, permeable pavement, infiltration trenches and rain barrels, in addition to existing LIDs, significantly increased the reduction rate of pollutants in stormwater runoff. Among all, the S4 had the highest reduction rate, with an average reduction of 73.94% for all parameters, as S4 (combined S2 and S3). The treatment trains proposed in the S4, including Bio-retention (BR), Green Roof (GR), Permeable Pavement (PP), Infiltration Trench (IT), and Rain Barrel (RB), further reduce runoff and sedimentation by employing various mechanisms to control runoff. Permeable pavements and infiltration trenches allow water to permeate into the ground, reducing runoff volume and quality, and bio-retention and green roofs can filter and retain pollutants, while rain barrels can store runoff water for later use, reducing runoff volume.

Studies carried out in different parts of the world (Tabulated in Table 4.8) have demonstrated the efficacy of employing Low Impact Development (LID) techniques to decrease the level of pollutants in water. For instance, research in South Korea found that BOD and TP removal rates varied between 1.8% to 11.5% and 2.2% to 4.2%, respectively (Lee et al., 2022). Street sweeping and infiltration trenches reduced TSS by 40-51% in Canada (Sofijanic et al., 2023), while in Texas, USA, the application of rain gardens, permeable pavements, and rainwater harvesting tanks reduced NO_3 and TP pollutants by 24-31% and 11-25%, respectively (Seo et al., 2017).

Table 4:8 Reductions in various pollutants' loading observed in various LID control experiments conducted by different researchers around the world.

Study area	Time span	Consideration	Results	Reference
Chaktai-Rajakhali Watershed, Chattogram, Bangladesh	1990-2020	The study evaluates the storm runoff quantity and quality performance of LID scenarios in stormwater networks under different hydrological attributes.	The Event Mean Concentrations (EMC) of TSS, TN, TP, Zn, BOD and COD in various land uses (Residential, Industrial, Commercial, and Institutional) were found as 275 to 1086 mg/L, 2.2 to 7.3 mg/L, 0.33 to 1.14 mg/L, 0.02-0.19 mg/L, 20.79-71.35 mg/L, 57.32-200.62 mg/L, respectively. Different proposed LID scenarios (S2, S3 and S4) reduce the pollutants concentrations of TSS, TN, TP, and Zn in storm water runoff by 23-76%, 32-79%, 32-80%, and 32-79%, respectively.	This study
Seoul & Incheon, South Korea	2022	The study utilized the Storm Water Management Model (SWMM) to	The GI and LID systems in Seoul city have a BOD pollutant load removal	(Lee et al., 2022)

		investigate the influence of urban features, sewer system type, and precipitation intensity on surface runoff. The objective was to develop an efficient water circulation plan for complex urban areas by optimally allocating LID/GI strategies.	efficiency ranging from 1.8% to 11.5%, while in Incheon city, the range is from 2.2% to 4.85%. Similarly, the TP removal efficiency for these systems varies from 2.5% to 11.4% in Seoul city and 2.2% to 4.2% in Incheon city.	
San Angelo, Texas, USA	2020	The focus of the study is to utilize a series of small retention structures in order to mitigate stormwater peak flow and improve the quality of water pollutants.	Small dams significantly reduce peak flow and improve water pollutant removal, with removal percentages as high as 94% for TSS/BOD and 82% for TP/TN, due to their size being based on a 5-year design storm peak inflow and volume. Removal percentages are lower for a 5-year design storm event, with 76% for TSS/BOD and 53% for TN/TP.	(Kim, 2021)
Azerbaijan, Iran	2019	The aim of the study was to assess how urbanization, climate change, and the use of vegetative swales as Low-Impact Development (LID) measures, affect the runoff and pollutant levels.	The implementation of LID measures resulted in significant reductions in pollutant loads. The most noteworthy reductions were observed in scenarios with 20% urbanization, which resulted in a 20-25% decrease in all pollutant loads, and in the case of 50% urbanization with climate change, which led to a 17% reduction in TSS and TP loads and an 8% reduction in TN load.	(Nazari-sharabian et al., 2019)
Istanbul, Turkey	2019	The objective is to assess the pollutant removal efficiency of bioretention by integrating it into a water quality model that includes Zn, Cu, Pb, TN, and TP as pollutants.	The bioretention system resulted in significant reduction percentages of peak values for Zn, Cu, TN, and TP pollutants, with reductions of 98.49%, 98.70%, 98.47%, and 98.91% respectively. Additionally, there was complete elimination of Pb.	(Gülbaz, 2019)
Alberta, Canada	2018	The study provides a distinctive case study in which a Stormwater Management Model (SWMM) was formulated	Implementing all proposed trenches reduces TSS loads by 22-30%. Implementing priority trenches results in up to	(Sofijanic et al., 2023)

		to evaluate how street sweeping and infiltration trenches could help to reduce total suspended solids (TSS) loads in the Town of Jasper in Jasper National Park, Alberta, Canada.	18% TSS reduction, while implementing all control measures together can reduce TSS by up to 40-51%.	
Texas, USA	2017	The current research examined how effective LID (Low Impact Development) practices are in three different types of urban areas that vary in their density and design: high-density compact (UHD), medium-density conventional (UMD), and medium-density conservational (UMC). The study focused on the use of rain gardens, permeable pavements, and rainwater harvesting tanks in computer simulations. The researchers also outlined a modeling process for including LID practices in SWAT (Soil and Water Assessment Tool) specifically for this purpose.	LID practices (Rain Gardens, Permeable Pavements, and Rainwater Harvesting Tanks) can reduce NO_3 pollutants by 24-31% and TP pollutants by 11-25% annually under different land use types.	(Seo et al., 2017)
Melbourne & Brisbane, Australia, Sweden and Auckland, New Zealand	2011	The study examines the reliability of MUSIC in predicting the performance of stormwater treatment options in different regions around the world. Field measurements from existing stormwater treatment systems in Australia, Sweden, New Zealand, and Scotland are collected and analyzed for this purpose.	The application of simulated LID controls, such as Bio-retention Swale and Permeable pavement, can lead to considerable decreases in the percentage of pollutants present. The reduction percentages vary between 18% to 99% for TSS, 17% to 99.5% for TN, and 24% to 100% for TP.	(Imteaz et al., 2013)
Cheonan, Republic of Korea	2010-2013	The study employed the SWMM to simulate and assess the treatment efficacy of storage-infiltration and tree box filter systems on different urban land uses, while optimizing hydraulic and water quality parameters via the Box complex method.	The TSS removal efficiency of the storage-infiltration system and tree box filter LID systems ranges from 80-84% and 63-83%, respectively, while the removal efficiency of heavy metals for the storage-infiltration system and tree box filter is in the range of 56-68% and 38-63%, respectively.	(Tobio et al., 2015)

Busan, South Korea	2009-2011	The study used LID technologies in four different scenarios: current city conditions, rain barrel use, rain barrel and tree filter box use, and rain barrel, tree filter box, and porous pavement use. The simulations analyzed short-term and long-term effects in different seasons.	The study found that all four scenarios resulted in a reduction of BOD, COD, TSS, TN, and TP during each of the four seasons. The reduction rates varied between 11% and 75%, with BOD, COD, TN, and TP showing reductions of 14% to 69%, while TSS reductions ranged from 13% to 75%.	(Shon et al., 2013)
Istanbul, Turkey	2009-2010	The study utilized a calibrated hydrodynamic model with SWMM to examine how LID-BMPs, including retention basins, vegetative swales, and permeable pavement, affect surface runoff and TSS, focusing on their impact on peak flow rate and the buildup and washoff of TSS pollutants.	The study found that the total surface water generated in the watershed showed a reduction of 17.3% (from 120.04 mg/L to 99.24 mg/L) in TSS due to the implementation of LID BMPs.	(Gülbaz & Kazezyilmaz-Alhan, 2015)
Espoo, Finland	2003-2006	The evaluation of the effects of ten LID scenarios, which included permeable pavement and bio-retention cells, on urban runoff and pollutant load at the catchment scale was conducted using simulations with the Storm Water Management Model (SWMM).	The range of pollutant reduction percentages for TSS, TP, TN, Pb, Cu, and Zn, achieved through reduced runoff and removal within the LID unit, varies between 40% - 75%, 24% - 80%, 27% - 63%, 25% - 64%, 16% - 69%, and 33% - 59%, respectively.	(Tuomela et al., 2019)

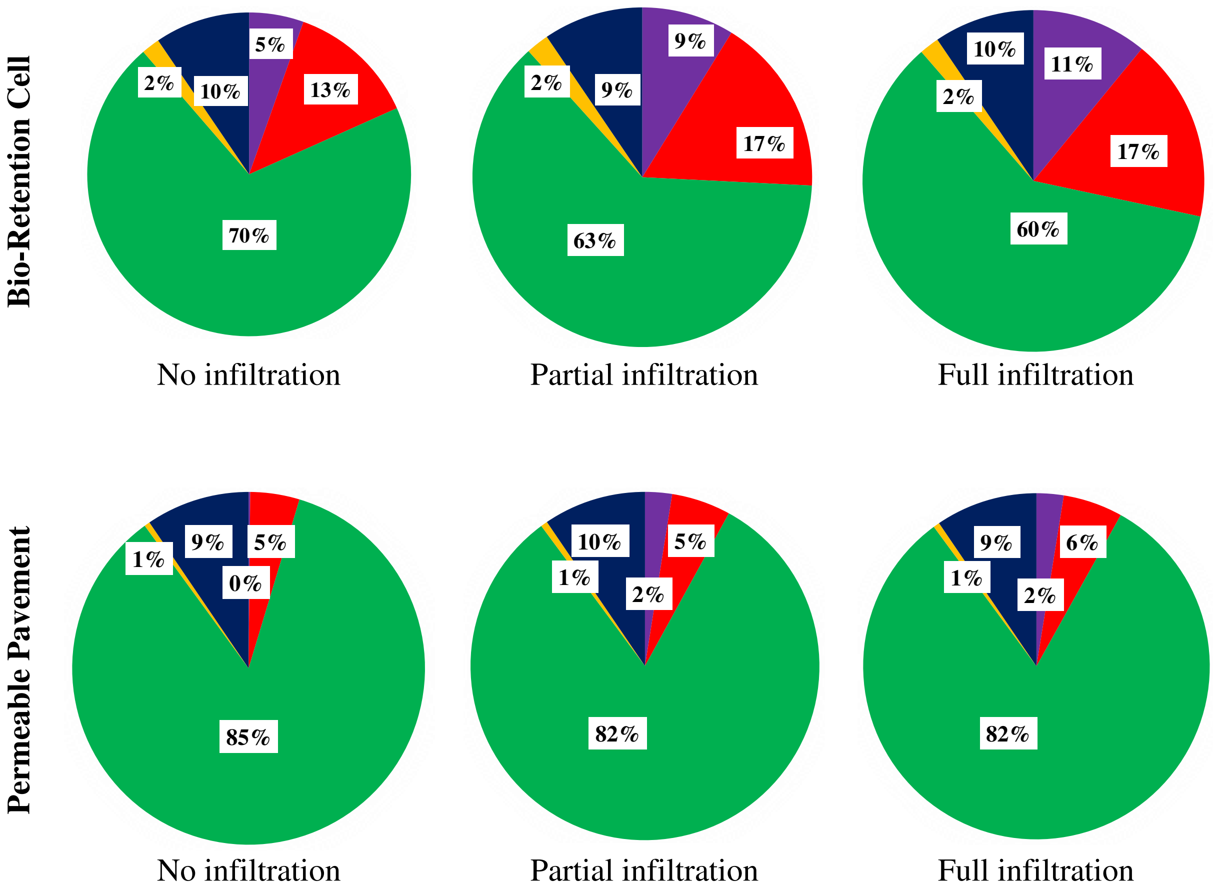
Similarly, in Australia, New Zealand, and Sweden, the use of bio-retention swale and permeable pavements led to reductions ranging from 18-99% for TSS, 17-99.5% for TN, and 24-100% for TP (Imteaz et al., 2013). In Turkey, LID BMPs resulted in a 17.3% reduction of TSS (Gülbaz & Kazezyilmaz-Alhan, 2015), while in Finland, permeable pavement and bio-retention cells demonstrated reductions ranging from 40-75% for TSS and 24-80% for TP, among other pollutants (Tuomela et al., 2019).

4.13 Life Cycle Cost Assessment (LCCA)

Life cycle cost analysis (LCCA) is a systematic approach that assesses the total cost of owning and operating a system or product throughout its life cycle. LCCA is a useful tool for evaluating the economic viability of Low Impact Development (LID) projects, which aim to manage stormwater runoff and protect water quality by mimicking natural hydrological processes. LCCA incorporates several components, including the initial capital expenses associated with implementing LID practices, operation and maintenance costs, and replacement or repair costs over the expected lifespan of the LID practices. By considering all of these factors, LCCA can inform decision-making regarding the selection of LID practices that are cost-effective over their lifespan and can help justify the investment in sustainable infrastructure.

4.13.1 Construction cost

Figure 4.16 shows the distribution of construction costs for various low impact development (LID) components, that includes pre-construction, excavation, materials and installation, inspections, project management, overhead, and other costs. The pie charts shown in Figure 4.16 demonstrate that the materials and installation cost is the most significant factor in each LID component, accounting for 44-90% of the total cost.



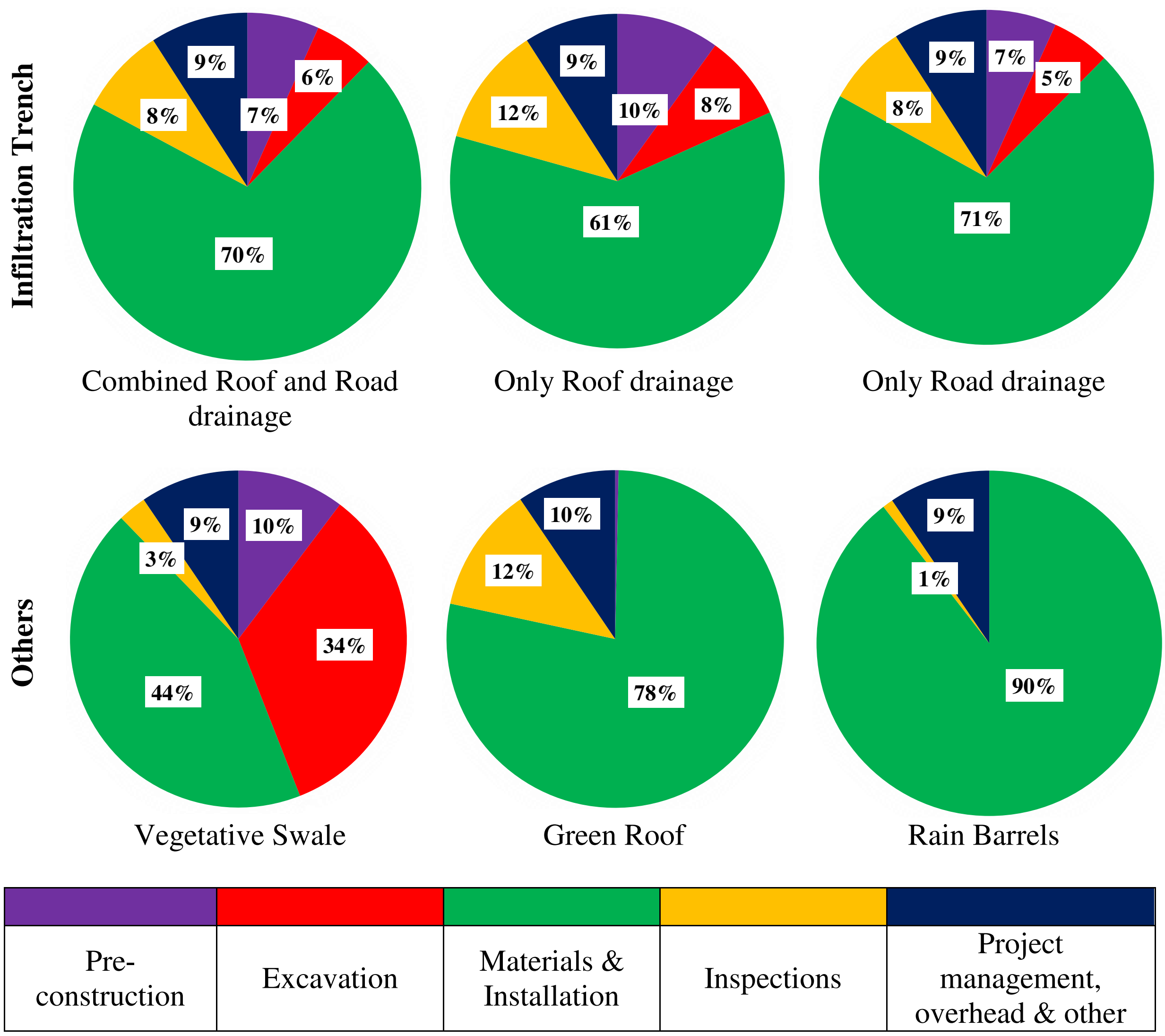


Figure 4.16 Construction cost contribution for different LID components (a) Bio-Retention Cell (No infiltration), (b) Bio-Retention Cell (Partial infiltration), (c) Bio-Retention Cell (Full infiltration), (d) Vegetative Swale, (e) Green Roof, (f) Rain Barrels, (g) Permeable Pavement Cell (No infiltration), (h) Permeable Pavement (Partial infiltration), (i) Permeable Pavement (Full infiltration), (j) Infiltration Trench (Roof and Road), (k) Infiltration Trench (Roof), (l) Infiltration Trench (Road)

The highest cost of materials is attributed to factors, such as the type of materials used, the complexity in installation, site-specific conditions, and the size of the project. Some LID components require specialized materials that can be more expensive, while others may require complex installation processes that increase labour costs. In this sequence, excavation costs come next, that also play a major role in Bio-Retention Cell and Vegetative Swale requires 13-34% of the total cost. Thereafter, the construction site noted specific conditions that require additional materials or labour costing as seen in Figure 4.16. The contribution of pre-construction, inspection, and project management, overhead and other costs ranges from 0-11%, 1-12%, and 9-10%, respectively, marked their contribution and standing in the cost estimation.

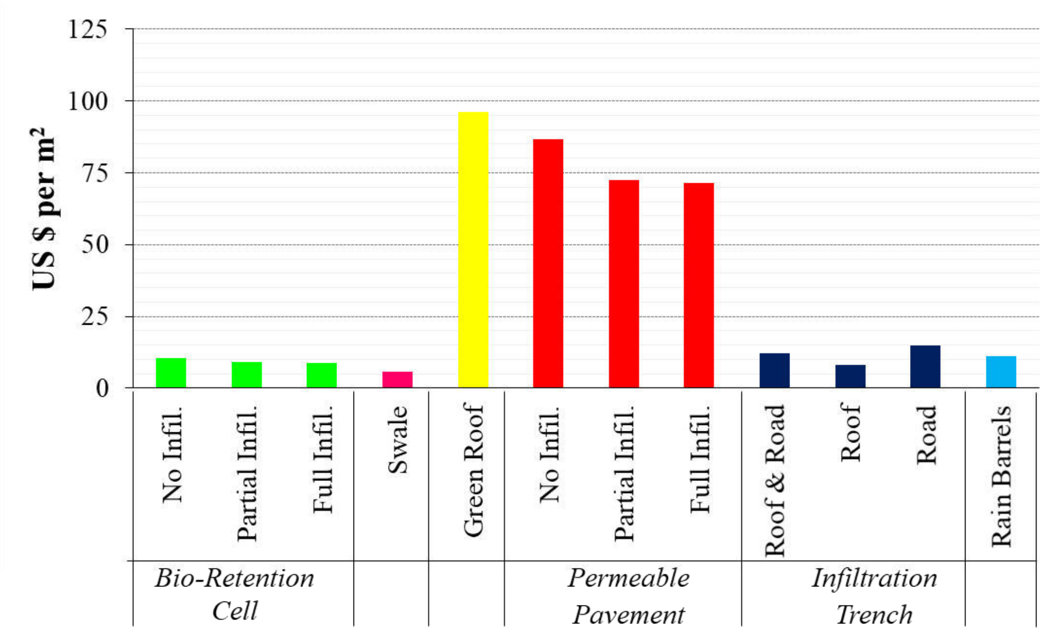
In Bio-Retention Cell, materials, and installation costs for the no infiltration system (70%) are higher than partial (63%) and full infiltration systems (60%). Additionally, the cost of materials and labour can vary regionally, and larger projects may require more materials and labour, leading to an increase in overall cost. These factors all contribute to the distribution of construction costs for different LID components. The excavation and pre-construction costs for the no infiltration system are lower than for the other systems, but the inspection and project management, overhead and other costs are almost the same for all systems.

In Permeable Pavement, materials, and installation costs for no infiltration (85%) are higher than partial (82%) and full infiltration (82%) systems, while excavation costs for all systems are 5-6%. Pre-construction costs for partial and full infiltration systems are 2%, but not required for no infiltration systems. Inspection costs for all systems are 1%, and project management, overhead, and other costs for all systems are 9%. In Infiltration Trench, road drainage system requires the highest materials and installation cost (71%) compared to combined roof and road drainage (70%) and only roof drainage (61%) systems. However, excavation (5%), pre-construction (7%), and inspection costs (8%) are lower for the road drainage system than for the other systems.

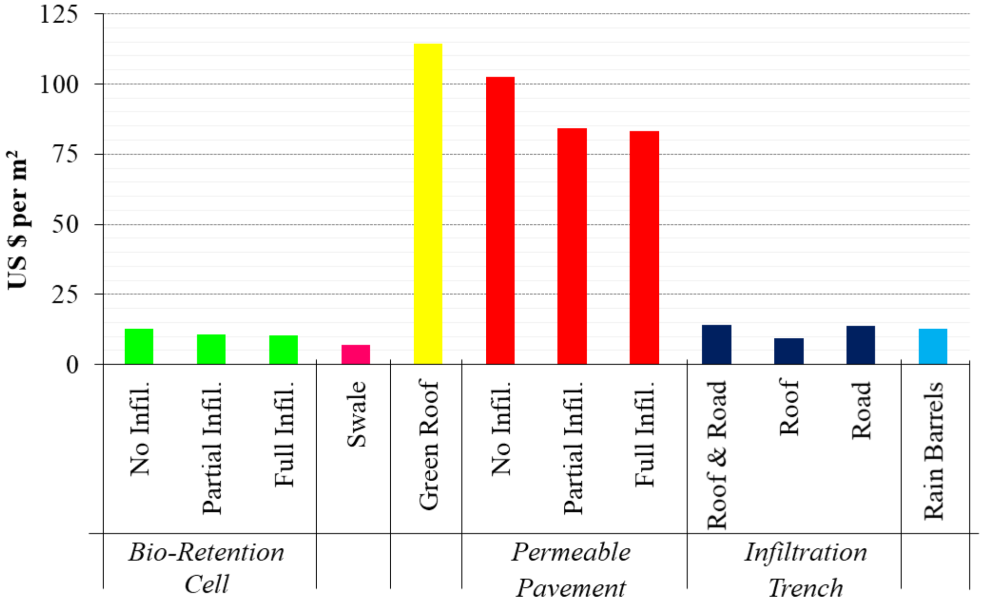
The project management, overhead, and other costs for all systems are 9%. Vegetative Swale has the highest excavation cost (34%) and lowest materials and installation cost (44%), as well as 10% pre-construction cost, 3% inspection cost, and 9% project management, overhead, and other costs. The Green Roof requires 78% materials and installation cost, 12% inspection cost, and 10% project management, overhead, and other costs. Rain barrels requires 90% materials and installation cost, 1% inspection cost, and 9% project management, overhead, and other costs.

Figure 4.17 (a) represents total construction cost needed per m^2 design area, as well as Figure 4.17 (b) represents construction cost with retrofit. It can be seen from Figure 4.17 that green roof and permeable pavement shows highest construction cost per m^2 design area, where partial and full infiltration system of permeable pavement give almost similar value. A very similar result was reported by Chui et al. (2016) and RTI International (June 2015) from elsewhere. On the other hand, Joksimovic and Alam (2014), Zeng et al. (2020), Liao et al. (2015), Garbanzos (2022) and Xu et al. (2017) reported that permeable pavement, bio-retention cell, infiltration trench, constructed wetland, rain barrel, bio-retention cell are least cost-effective respectively.

The construction cost of vegetative swale are lower than all other LID practices. Liao et al., (2015) and Garbanzos & Maniquiz-Redillas (2022) also stated Vegetative swale is most cost effective. But Chui et al., (2016), Zeng et al. (2020) and Xu et al. (2017) reported that permeable pavement is most cost effective than other LID's. Nevertheless, Garbanzos & Maniquiz-Redillas (2022) and RTI International & Geosyntec Consultants, (2015) claimed different result i.e. rain barrels is the most cost effective LID practice.



(a)



(b)

Figure 4.17 (a) Construction Cost, (b) Construction cost with retrofit for different LID components.

In case of bio-retention cell, the graph shows construction cost of no infiltration, partial infiltration and full infiltration system are almost similar. In infiltration trench, only road drainage system required high construction cost than only roof drainage system and combined roof & road drainage system. Rain barrels requires almost similar construction cost as no infiltration system of bio-retention cell and combined roof and road drainage system of infiltration trench. Compiling Figure 4.17 (a) and F4.17 (b), retrofitting cost is found around 16% of construction cost for all type of LID practices in general.

4.13.2 Annual Operation and Maintenance Cost

Figure 4.18 represents average annual maintenance cost of LID practices for 25- & 50-year period. It can be seen from Figure 4.18 that green roof (greater than 19) need highest average annual maintenance cost among all LID practices in this investigation which is completely opposite of what was being reported by Chui et al. (2016) in their study. However, Nordman et al. (2018) reported that green roof require more operation & maintenance cost than other LID's for 2 year and 50 year period similar to the present investigation. The others showing that (found from Garbanzos & Maniquiz-Redillas (2022), RTI International & Geosyntec Consultants, (2015)) bio-retention cell need highest O&M cost.

Furthermore, Liao et al., (2015) reported that infiltration trench is least cost effective according to maintenance cost. In case of permeable pavement, average annual maintenance cost varies from 0.921~0.969 US $ per m^2 among no infiltration, partial infiltration, and full infiltration system.

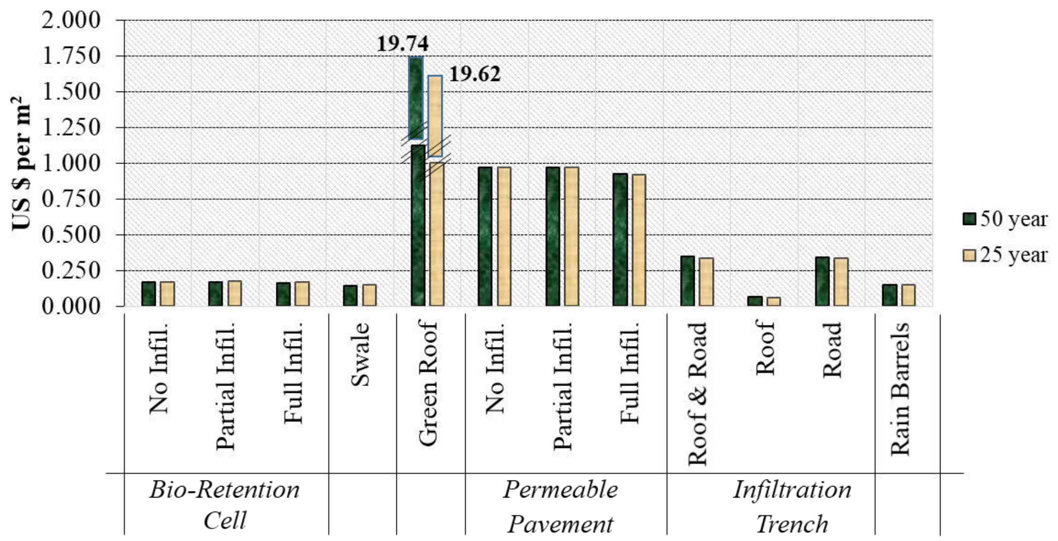


Figure 4.18 Average Annual Maintenance Cost for different LID components

Figure 4.18 also shows that three (3) types of infiltration design system of bio-retention cell, vegetative swale and rain barrels required almost same average annual maintenance cost for 25 year and 50-year period. In case of infiltration trench, the graph reflects that average annual maintenance cost of combined roof & road drainage system and road drainage system are almost same, where roof drainage system is the most cost-effective LID practice among all. On the other hand, for the most effective LID practices, Liao et al., (2015) and Garbanzos & Maniquiz-Redillas (2022) noted permeable pavement, contrariwise, Nordman et al. (2018) and RTI International & Geosyntec Consultants, (2015) mention about the rain barrel.

4.13.3 Integrated Cost Assessment

Table 4.9 shows Life cycle costs of all LID Components for 25- and 50-year evaluation periods. Three different discount rates (0%, 5%, and 10%) were used to compute life cycle costs. Table 4.9 also compares the costs of LID practice for 25 year and 50-year evaluation period maintenance, rehabilitation, and total net present values for discount rates varying from 0 to 10%. Table 4.9 presents that the NPV of maintenance, rehabilitation, and total costs associated with green roofs is higher than that of all other LID components, irrespective of the discount rate applied (0%, 5%, or 10%). The maximum NPV of all costs for green roofs was found to be $4929.34 over a 50-year evaluation period with a discount rate of 10%. On the other hand, vegetative swale has the lowest net present value of all costs, which is $8.31 for 0% discount rate over 25-year evaluation period.

In case of bio-retention cell, net present value of maintenance and rehabilitation for no infiltration, partial infiltration and full infiltration system are almost similar over both the 25 year and 50-year evaluation period for all discount rates. Contrariwise, net present value of all cost for all infiltration system of bio-retention cell shows some variation for both the year and 50 year evaluation period for all discount rate.

Like bio-retention cell, in case of permeable pavement, net present value of maintenance and rehabilitation for no infiltration and partial infiltration system are similar over both the 25 year and 50-year evaluation period for all discount rate, but full infiltration system has different value than other two infiltration system. On the other hand, net present value of all cost for all infiltration system of permeable pavement shows some variation for both the 25 year and 50-year evaluation period for all discount rate.

In case of infiltration trench, table shows that in comparison to the combined roof & road runoff and only road runoff scenario, maintaining the only roof runoff scenario was significantly less expensive, where the net present value of maintenance and rehabilitation for combined roof & road runoff and only road runoff are almost same. Net present value of maintenance and rehabilitation for vegetative swale and rain barrels hold nearly similar value for 50 year evaluation period for 0% and 5% discount rate, while net present value of maintenance and rehabilitation for vegetative swale is doubled of rain barrels over 25 year evaluation period for all discount rate.

Table 4:9 Life cycle costs (US$ per square meter) of all LID Components for 25 and 50 year evaluation periods.

LID Components		Bio-Retention Cell			Swale	Green Roof	Permeable Pavement			Infiltration Trench			Rain Barrels
		No Infil.	Partial Infil.	Full Infil.			No Infil.	Partial Infil.	Full Infil.	Roof & Road	Roof	Road	
50 Year Evaluation Period		**NPV of maintenance and rehabilitation**											
	i= 0%	3.26	3.31	3.22	2.97	370.51	18.26	18.26	17.37	6.39	1.14	6.30	2.87
	i= 5%	8.90	9.04	8.80	8.43	1098.51	55.50	55.50	53.18	17.39	3.55	17.15	8.46
	i= 10%	36.10	36.63	35.72	37.14	4821.07	248.69	248.69	239.69	69.29	16.24	68.37	30.20
		NPV Value of all costs											
	i= 0%	13.84	12.39	11.91	8.88	466.64	104.93	90.57	88.84	18.45	9.16	21.18	13.91
	i= 5%	20.34	18.50	17.90	14.89	1200.29	146.18	128.55	125.29	29.61	11.74	32.19	19.55
	i= 10%	48.52	46.54	45.29	44.24	4929.34	344.00	322.61	312.53	81.71	24.63	83.59	41.35
25 Year Evaluation Period		**NPV of maintenance and rehabilitation**											
	i= 0%	2.54	2.58	2.51	2.41	284.64	14.05	14.05	13.37	4.84	0.85	4.77	1.68
	i= 5%	4.56	4.62	4.51	4.53	546.23	27.70	27.70	26.54	8.47	1.69	8.35	2.63
	i= 10%	8.95	9.08	8.87	9.46	1143.47	59.46	59.46	57.32	16.04	3.61	15.82	4.15
		NPV of all costs											
	i= 0%	13.12	11.65	11.20	8.31	380.77	100.73	86.36	84.84	16.90	8.88	19.65	12.72
	i= 5%	15.99	14.09	13.61	10.99	648.01	118.39	100.76	98.65	20.70	9.88	23.39	13.72
	i= 10%	21.37	19.00	18.44	16.57	1251.74	154.78	133.39	130.16	28.46	12.00	31.03	15.30

Note: i= discount rate

4.13.4 LCCA of different LID scenarios

The table 4.10 presents the comparative cost assessment of different Low Impact Development (LID) scenarios for the Chaktai-Rajakhali watershed reveals different results based on the evaluation period and the discount rate used. The four scenarios evaluated are: S1 (No LIDs), S2 (VS), S3 (BR, GF, PP, IT & RB), and S4 (S2 & S3). S1 has a total cost of $0.00, indicating the absence of LID structures. S2, which involves the existing scenario and the addition of vegetative swales, has a total cost of $5.90. S3, which involves the implementation of a variety of LID practices such as bioretention, green roof, permeable pavement, infiltration trench, and rain barrel, has a total cost of $39.75. S4, which combines S2 and S3, has a total cost of $36.51, making it the most cost-effective option when considering the combined benefits of both S2 and S3.

The higher cost of S3 and S4 can be justified by the improved water quality and reduced runoff that these LID practices can provide. The differences in operation and maintenance (O & M) cost among the four low impact development (LID) scenarios in the Chaktai-Rajakhali watershed can be attributed to various factors. Scenario S1, which has no LIDs, has a cost of $0.00 over both a 50-year and 25-year evaluation period, as there are no LID elements to maintain. Scenario S2, which involves the existing scenario and vegetative strips (VS), has a relatively low O & M cost compared to the other scenarios, as the VS are relatively simple elements to maintain.

In contrast, scenario S3, which includes complex stormwater management techniques such as Bioretention (BR), Green Roof (GF), Permeable Pavement (PP), Infiltration Trench (IT), and Rain Barrel (RB), requires a higher level of maintenance and thus has the highest O & M cost. The high cost is due to the need for regular monitoring and maintenance of the LID elements to ensure their proper functioning and longevity. Scenario S4, which combines the existing scenario and vegetative strips with the Bioretention, Green Roof, Permeable Pavement, Infiltration Trench, and Rain Barrel techniques, has a slightly lower O & M cost compared to S3. This is because the combined strategy reduces the complexity of the individual LID elements, making maintenance easier and less expensive. The differences in O & M cost among the four scenarios are driven by the complexity of the LID strategies and the level of maintenance required to ensure their proper functioning and longevity.

Table 4:10 Comparative Cost assessment of different LID scenarios for chaktai-rajakhali watershed.

Options/parameters			S1	S2	S3	S4
Total area treated (ha)			0	24.03	226.91	250.94
Total construction cost			$0.00	$5.90	$39.75	$36.51
O & M	50 Year Evaluation Period		$0.00	$0.14	$4.35	$3.95
	25 Year Evaluation Period		$0.00	$0.15	$4.33	$3.93
NPV of M & R	50 Year Evaluation Period	i=0%	$0.00	$2.97	$81.75	$74.20
		i=5%	$0.00	$8.43	$242.15	$219.77
		i=10%	$0.00	$37.14	$1,060.22	$962.23
NPV of all costs		i=0%	$0.00	$8.88	$122.43	$111.55
		i=5%	$0.00	$14.89	$284.24	$258.45
		i=10%	$0.00	$44.24	$1,103.93	$1,002.44
NPV of M & R	25 Year Evaluation Period	i=0%	$0.00	$2.41	$62.68	$56.91
		i=5%	$0.00	$4.53	$120.07	$109.00
		i=10%	$0.00	$9.46	$250.87	$227.75
NPV of all costs		i=0%	$0.00	$8.31	$103.36	$94.26
		i=5%	$0.00	$10.99	$162.16	$147.68
		i=10%	$0.00	$16.57	$294.58	$267.95

Note: S1 (No LIDs), S2 (vegetative swale), S3 (Bio-retention cells, Rain barrels, Infiltration trenches, Permeable pavements) and S4 (S2 and S3)

The NPV results provide valuable information for decision-makers to determine the most cost-effective LID scenario. Scenario S1, which represents no LIDs, shows a zero net present value (NPV) for both maintenance and repair (M & R) and all costs, regardless of the evaluation period (25 or 50 years) and discount rate (0%, 5%, or 10%). On the other hand, Scenario S2, which is the existing scenario with vegetation strips (VS), results in a positive NPV for both M & R and all costs, but lower than the NPV of Scenario S3 and S4. Scenario S3, which includes BR (bioretention), GF (green roof), PP (permeable pavement), IT (infiltration trench), and RB (rain barrel), shows the highest NPV for both M & R and all costs, especially when the discount rate is 10%. Finally, Scenario S4, which is the combination of Scenario S2 and S3, results in a higher NPV compared to Scenario S2, but slightly lower than Scenario S3.

The cost-effectiveness of LID practices also varied depending on the location and precipitation scenarios (see Table 4.11). Various studies were conducted on the cost-effectiveness and efficiency of Low Impact Development (LID) practices in various locations around the world w, including Germany, Canada, China, USA, Philippines and Hong Kong. The results of the studies showed that some LID practices such as rain barrels, green roofs, bioretention, infiltration pits, constructed wetlands, and permeable pavement were cost-effective and efficient in reducing runoff volumes (Garbanzos & Maniquiz-Redillas, 2022, Zhang & Ariaratnam, 2021, Xu et al., 2017) Liao et al., 2015, and Joksimovic & Alam, 2014), while others such as green roofs and infiltrating bioretention basins had negative net present values (Nordman et al., 2018).

Table 4:11 Cost effectiveness of different LIDs observed in various LID control experiments conducted by different researchers around the world

Study area	Time span	Consideration	Results	Reference
Chaktai-Rajakhali Watershed, Chattogram, Bangladesh	2020	The study quantified the life cycle cost of different LID scenarios in order to identify the most cost-effective option in drainage system and to compare LID options that are cost-effective having satisfactory runoff quality improvement with drainage network amenity aspects.	The materials and installation costs of each LID component, (ranges from 44 to 90%), makes up the largest portion of capital costs and are found to vary with each type. The cost of construction with the retrofitting of different LID components is between 5-115 US $ per square meter, while the yearly maintenance cost is found between 0.125 and 19.74 US $ per square meter. Among the different LIDs studied, bio-retention cells, swales, infiltration trenches, and RWH are found to be cost effective, while green roofs and permeable pavement have substantially higher costs. The three LID scenarios have different Net Present Values (NPVs), with S2 having an NPV of 17 US$, S4 having an NPV of 295 US$, and S3 having an NPV of 268 US$.	This study
Dresden, Germany	2001-2015	The effectiveness of seven distinct LID (Low Impact Development) practices and six precipitation scenarios were evaluated through simulation using a Storm	The rain barrel was found to be the most cost-effective LID option, with a Cost-effectiveness ratio (C/E) ratio ranging from 0.34 to 0.41 while the permeable pavement (PP) showed the	(W. Yang et al., 2020)

		Water Management Model (SWMM).	highest C/E ratio, which varied between 4.79 to 5.99.	
City of London, Ontario, Canada	2002	This study examined the cost-effectiveness of using various LID (Low Impact Development) techniques.	The study assessed the cost efficiency of implementing several LID techniques for reducing runoff volume. The cost per volume of runoff reduction for each method was found as follows: RWH ($14.46/m^3), VS ($15.16/m^3), IT ($15.91/m^3), BR ($28.69/m^3), PP ($157.24/m^3), and GR ($269.66/m^3). On the other hand, the combination of various LID components resulted in cost ranges varying from $28.82/m^3 to $200.74/m^3.	(Joksimovic & Alam, 2014)
Shanghai, China	2012-2013	The study used the Life Cycle Cost method to conduct a detailed cost-effectiveness analysis of LID techniques.	A benefit-cost (B/C) analysis was conducted for each type of LID, and the study obtained PVB/PVC values for different LID measures. RB had the highest B/C ratio of 0.8129, followed by BR, IT+RB, IT, and GS with respective PVB/PVC values of 0.7724, 0.7032, 0.6195, and 0.6008. The three least favorable options were PP+RB, IT+PP, and PP with PVB/PVC values of 0.4619, 0.4215, and 0.3183, respectively. Based on the analysis, RB, IT, and their combination IT+RB were considered the most suitable LID options for the drainage system.	(Liao et al., 2015)
Arizona, USA	2018-2019	This study explored the potential cost savings of utilizing low impact development strategies, such as green roofs (GRs) and permeable interlocking concrete pavements (PICPs), in comparison to traditional drainage systems using the life cycle cost approach	The implementation of permeable interlocking concrete pavements (PICPs) and green roofs (GRs) in certain projects led to an average life cycle cost (LCC) savings of 27.2% and 18.7% for 50 and 25 years of service, respectively, according to the study.	(Zhang & Ariaratnam, 2021)
Bacoor, Cavite, Philippines	1975-2019	This study seeks to determine the cost efficiency of implementing LID strategies for evaluating cost-effectiveness in a	The study found that the IT + PP scenario was the most cost-effective option for the residential catchment, regardless of the surface area. The BR + IT + PP scenario	(Garbanzos & Maniquiz-Redillas, 2022)

		tropical residential catchment that receives 1780.5 mm of rainfall annually, across different surface areas.	had the best flow reduction and infiltration capabilities, but IT and PP were the least expensive options for capital costs in the optimistic and pessimistic scenarios, respectively.	
China	2016-2017	The environmental and economic impacts of a treatment train system that uses low impact development best management practices (LID-BMP) were estimated through a life-cycle assessment that considered both factors.	In terms of LCC results, the order from lowest to highest was: grassed swale, buffer strip, bio-retention cell, infiltration pit, and constructed wetland.	(Xu et al., 2017)
Michigan, USA	2006-2015	The economic costs and benefits of diverse green infrastructure practices were analyzed in the study. The GI practices were standardized to treat a specific amount of stormwater, which included 84.95 m^3 of water for a 25.4 mm event and the first 25.4 mm of stormwater from larger events.	The study findings revealed that conserved natural areas had the greatest net present value (NPV) of $109 for every cubic meter of water quality volume (WQv) reduction. This was followed by street trees at $46/$m^3$ WQv, rain gardens at $37/$m^3$ WQv, and porous asphalt at $21/$m^3$ WQv. On the other hand, infiltrating bioretention basins and green roofs had negative NPVs of $-3.76/$m^3$ WQv and $-47.17/$m^3$ WQv, respectively.	(Nordman et al., 2018)
Hong Kong & Seattle, USA	2015-2016	This study aims to determine the most suitable design for low-impact development (LID) practices at a residential or commercial level by evaluating their hydrological effectiveness and cost-efficiency.	The study compared the cost-effectiveness of low-impact development (LID) practices in Hong Kong and Seattle and found that Hong Kong's LID practices were less cost-effective. For a 2-year storm, the peak runoff reduction in Hong Kong was 0.02 L/103 US$ s, 0.15 L/103 US$ s, and 0.93 L/103 US$ s for green roofs, bioretention, and porous pavement, respectively. In comparison, Seattle had higher values of 0.03 L/103 US$ s, 0.29 L/103 US$ s, and 1.58 L/103 US$ s for the same LID practices.	(Chui et al., 2016)

The results showed that the rain barrel was the most cost-effective LID option in Dresden, Germany (cost-effectiveness ratio (C/E) for rain barrel and permeable pavement ranging from 0.34 to 0.41 and 4.79 to 5.99) (Yang et al., 2020), while the combination of infiltration trench and rain barrel was the most cost-effective in a residential catchment in the Philippines (Garbanzos & Maniquiz-Redillas, 2022). Green roofs and permeable interlocking concrete pavements were found to have cost savings in Arizona, USA with the savings of 27.2% than the traditional drainage system for 50 years of evaluation period (Zhang & Ariaratnam, 2021), while some LID practices in Hong Kong were found to be less cost-effective (peak runoff reduction were 0.02 to 1.58 $L/10^3$ US$) compared to Seattle, USA (Chui et al., 2016).

The results suggest that incorporating LID practices can significantly reduce runoff and improve water quality, leading to a lower NPV for M & R and all costs over a longer evaluation period. The slight difference between Scenario S3 and S4 could indicate the effectiveness of adding vegetation strips to existing LID practices. This information can be used to compare the costs and effectiveness of different LID strategies, and to make informed decisions about which approach to use in the Chaktai-Rajakhali watershed. The implementation of LID practices can help in reducing runoff and improving water quality, thus promoting a more sustainable and resilient environment.

Chapter 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The traditional drainage systems are not able to cope with the increased volume and velocity of runoff with the rapid urbanization and land-use changes, resulting in floods and water pollution. The need for sustainable stormwater management solutions becomes increasingly important as Bangladesh continues to experience rapid urbanization and land-use change. Low Impact Development (LID) techniques can be a viable solution to mitigate the negative impacts of urbanization on water resources and improve the resilience of cities to climate change. The study aimed to comprehensively evaluate the efficacy and sustainability of Low Impact Development (LID) components for managing stormwater, by analyzing and comparing their quantity, quality, and amenity performance in diverse land uses and under varying climatic scenarios.

The study involved collecting diverse data types, including soil samples from selected locations within the watershed, runoff samples from sub-catchment outlets and canals, cross-sectional data of canals, rainfall data for Chattogram city, and digital elevation models. The collected data was then subjected to statistical and spatial analysis techniques to acquire the necessary parameters for the performance analysis. A more accurate and updated IDF curve was generated for Chattogram city, which had not been updated previously. Furthermore, trend analysis of rainfall patterns and various hydrologic parameters of the watershed were also evaluated. Subsequently, a hydrologic model simulation was conducted using PCSWMM to access the hydrologic performance of different hydrologic parameters.

The study found that, inclusion of LID techniques can lower peak flows and slow down surface runoff before it enters into nearby waterbodies, thereby lowering the danger of frequent water logging. A considerable improvement in runoff quality was also seen in this study. Furthermore, the study conducts a life cycle cost analysis of LIDs and finds that although LIDs may have higher initial costs than conventional stormwater management methods, they provide significant long-term cost savings due to their low maintenance requirements and long lifespan. Bangladesh can create more sustainable and attractive urban spaces by implementing LIDs in drainage watershed while promoting community engagement and improving the overall situation of its water resources.

5.2 Summary conclusions

Performance of LIDs components was evaluated in an urban watershed scale under different climatic and land use changes scenarios in context of sustainable stormwater management. The key findings of this study is given as follows:

- The built-up area in the Chaktai-Rajakhali watershed basin, has increased drastically by 47% while the vegetated land has decreased by 19% over the period of 30 years (1990-2020). As a result of the increase in impervious area and decrease in pervious area, the watershed will experience less infiltration and more surface runoff.
- The hydrological parameters (runoff, infiltration, and CN) are correlated with changed land use patterns, particularly with regard to changes to vegetation and built-up areas, as obtained from correlation and principal component analyses.
- Inclusion of LIDs in drainage network is seen to be significantly reduce peak discharge by 14–63%, and thus increase lag times (between LID scenarios and no LID scenario) from 30 to 105 minutes.
- The Event Mean Concentrations (EMC) of TSS, TN, TP, Zn, BOD and COD in various land uses (Residential, Industrial, Commercial, and Institutional) were found as 275.25 to 1085.50 mg/L, 2.20 to 7.33 mg/L, 0.33 to 1.14 mg/L, 0.02-0.19 mg/L, 20.79-71.35 mg/L, 57.32-200.62 mg/L, respectively.
- Different proposed LID scenarios (S2, S3 and S4) are found to reduce the selected pollutants concentrations of TSS, TN, TP, and Zn in storm water runoff by 23-76%, 32-79%, 32-80%, and 32-79%, respectively, in comparison to existing situation.
- The materials and installation costs of each LID component, (ranges from 44 to 90%), makes up the largest portion of capital costs and are found to vary with each type.

- The cost of construction with the retrofitting and operation and maintenance of different LID components is found 5-115 US $ and 0.125-19.74 US $ per square meter
- The relative standing based on NPV among individual LIDs proposed in this study is found as: Green Roof (1252 US $)> Permeable pavement (130-154 US $)> Infiltration trench (12-31 US $)> Bio-Retention Cell (18-21 US $)> Swale (17 US$)> Rain barrels (15 US$).
- Three LID scenarios have different Net Present Values (NPVs), S2 having an NPV of 17 US$, S4 having an NPV of 295 US$, and S3 having an NPV of 268 US$.
- Therefore, the relative cost-effective standing based on NPV of different LID scenarios can be expressed as S2 (vegetative swale) > S4 (S2 and S3) > S3 (Bio-retention cells, Rain barrels, Infiltration trenches, Permeable pavements).

The findings suggest that the cost-effectiveness of LID components and scenarios should be carefully considered to maximize their environmental benefits while minimizing costs.

5.3 Specific Conclusions

The Chaktai-Rajakhali watershed basin has seen a significant increase in built-up area and decrease in vegetated land, leading to less infiltration and more surface runoff. LIDs (Low Impact Developments) integrated into the Chaktai-Rajakhali drainage network can reduce peak discharge by 14–60%, and the lag times between LID scenarios and no LID scenario vary from 30 to 105 minutes, indicating that LIDs are effective in reducing peak discharge and can help prevent rapid flooding in the city.

The results of the investigation reveal that the Event Mean Concentration (EMC) of various pollutants such as TSS, TN, TP, and Zn in different land uses of Chattogram city spans a wide range, with values ranging from 275-1086 mg/L, 2.20-7.33 mg/L, 0.33-1.15 mg/L, and 0.02-0.19 mg/L, respectively. However, the study indicates that the implementation of Low Impact Development (LID) strategies can considerably reduce these pollutant concentrations by approximately 20-80%. Among the various LID scenarios assessed, the findings indicate that Scenario 4 (S4) demonstrates the most substantial reduction in the concentration of pollutants in runoff water. Thus, the study suggests that the adoption of appropriate LID practices could be a promising approach to mitigate the negative environmental impact of urbanization in Chattogram city.

The study reveals that the cost of implementing Low Impact Development (LID) strategies varies significantly by component, with materials and installation costs accounting for the largest portion of capital costs, ranging from 44-90%. Among the LID components examined, Bio-retention cells, swales, infiltration trenches, and rain barrels were found to be cost-effective options, while green roofs and permeable pavement were relatively expensive.

The LID scenarios proposed in the study were assessed based on their Net Present Value (NPV), with S4, which included vegetative swale, Bio-retention cells, Rain barrels, green roof, Infiltration trenches, and Permeable pavements, being the most cost-effective scenario, with an NPV of 295 US$. The findings suggest that the cost-effectiveness of LID components and scenarios should be carefully considered to maximize their environmental benefits while minimizing costs.

5.4 Recommendations

Based on the study, incorporating Low Impact Development (LID) components into the drainage network for sustainable stormwater management in the Chaktai-Rajakhali watershed basin in Chattogram, Bangladesh is a key recommendation. Other recommendations are as follows:

- Incorporating tidal effects and wet weather flow can be done to assess their impact on peak runoff and water quality in canals. Moreover, Methods can be developed to continuously collect stormwater-induced runoff without altering pollutant concentrations, improving data collection.
- Diverse inflows, such as domestic wastewater, industrial discharge, sewerage flow, etc., can be considered to obtain a more comprehensive understanding of urban stormwater pollution.

- More refined land use patterns can be taken into account to understand their impact on runoff volume and quality.
- Additional constituents, such as heavy metals and conventional stormwater pollutants (pH, temperature, nutrients, organic matter contents, etc.), can be included to gain a more complete understanding of urban stormwater pollution.
- New life cycle tools can be developed in the context of Bangladesh to estimate the life cycle cost of LID options more accurately.

5.5 Implication of the study

Urban drainage design is based on stormwater induced runoff generation analyzing urban hydrology associated. While conventional drainage design is based on modeling of rainfall runoff under predicted rainfall intensity, catchment area and changed climate, it appeared less promising to address quality aspects as well as amenity of design. This study revealed that the thinking beyond the conventional structural measures towards soft solution simulating natural drainage system is not only a promising with multiple benefits but also are with green infrastructure that ensure sustainability aspects. The outcome of this study demonstrates that there is a scope to redesign the urban city drainage network that is far better approach to reduce peak flow volume significantly with increased lag time thus in turn allows city drain to run smoothly at per their performance along with a substantial improvement in runoff water quality ensuring less hazard for aquatic lives. In this align, inclusion of Low Impact Development (LID), as soft measures, is seen not only a cost-effective solution compared to structural measures but also provide a green infrastructure towards green and clean city. Future drainage design must have to consider quantity, quality, and amenity with cost-effectiveness for getting optimum benefits.

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Appendix A

Geographic Locations and cross-section of the reaches

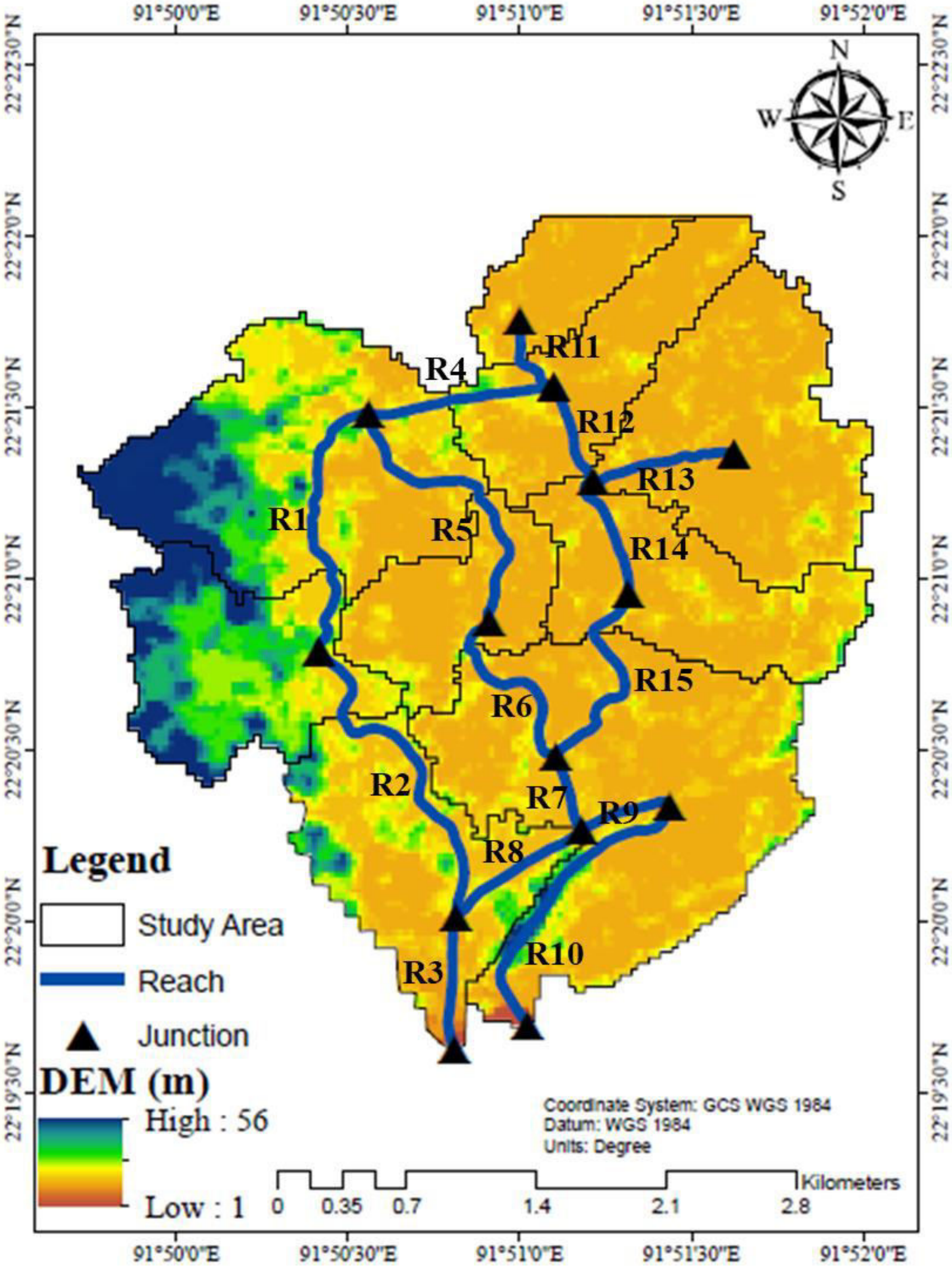
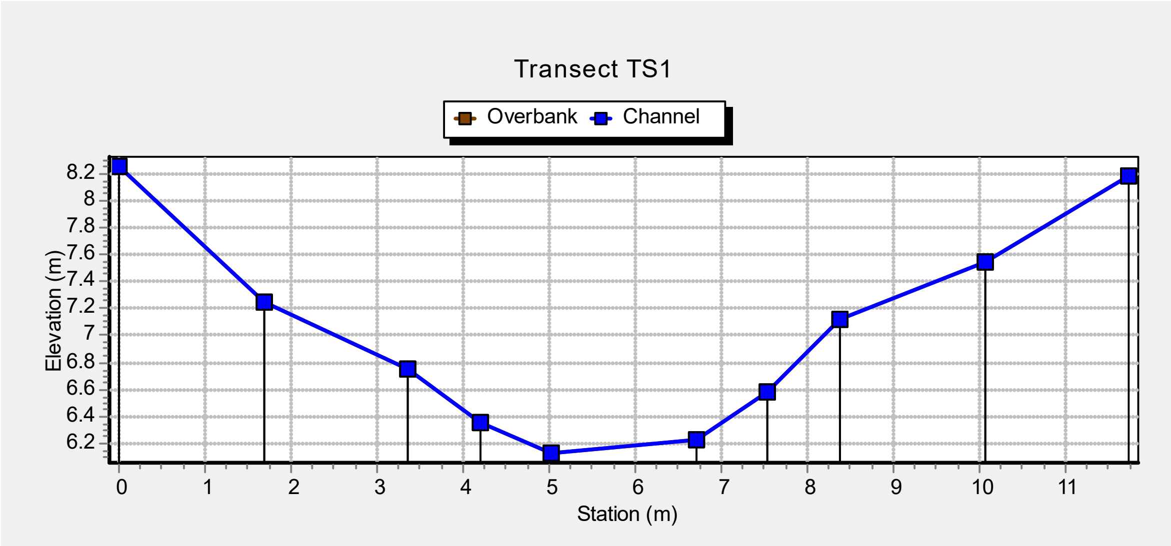
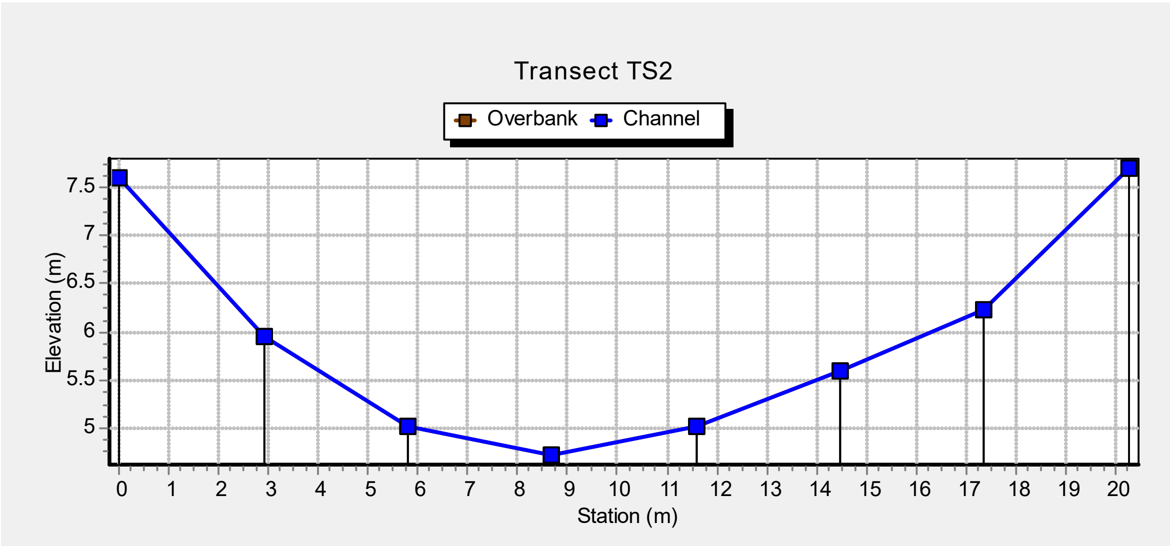


Figure: Geographic locations of reaches in Chaktai-Rajakhali watershed.


Transect TS1
Overbank
Channel
8.2
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
Elevation (m)
0
1
2
3
4
5
6
7
8
9
10
11
Station (m)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Overbank
Channel
7.5
7
6.5
6
5.5
5
Elevation (m)
0
1
2
3
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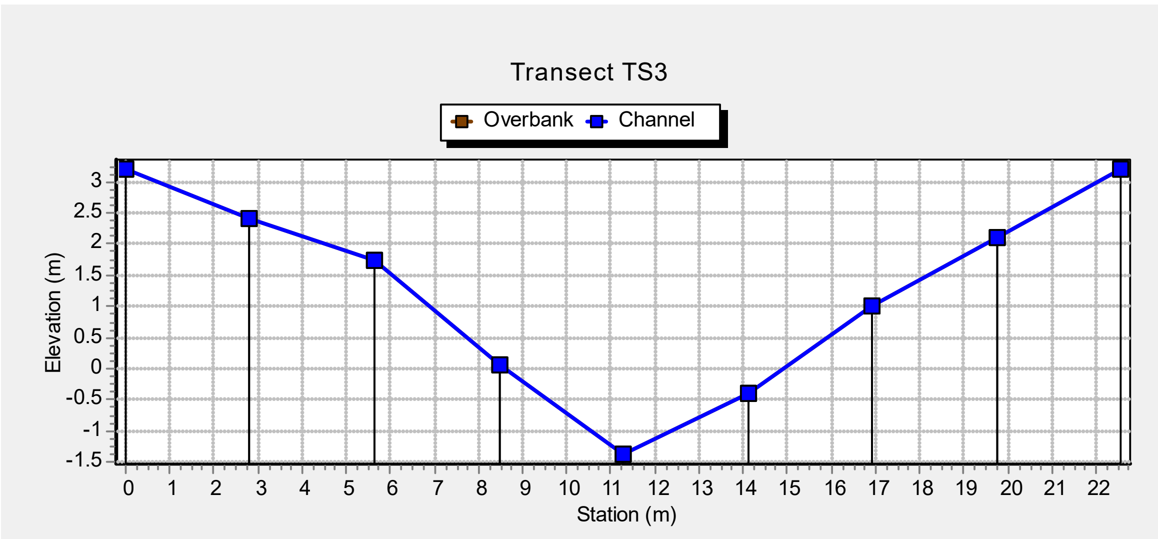
12
13
14
15
16
17
18
19
20
Station (m)


Transect TS3
Overbank
Channel
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
Elevation (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
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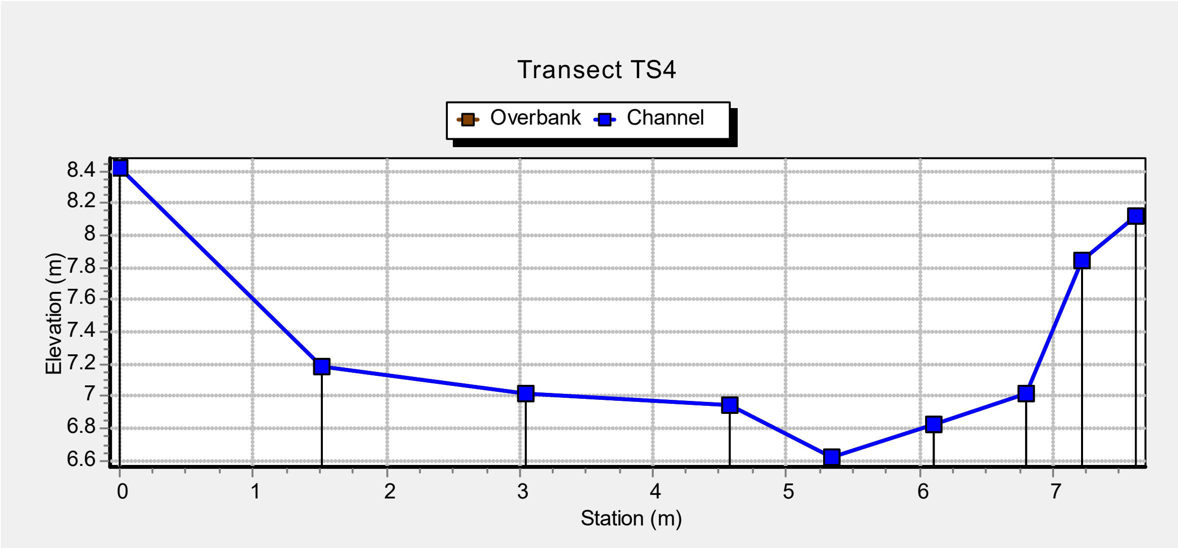
16
17
18
19
20
21
22
Station (m)



Transect TS4
Overbank
Channel
Elevation (m)
8.4
8.2
8
7.8
7.6
7.4
7.2
7
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6.6
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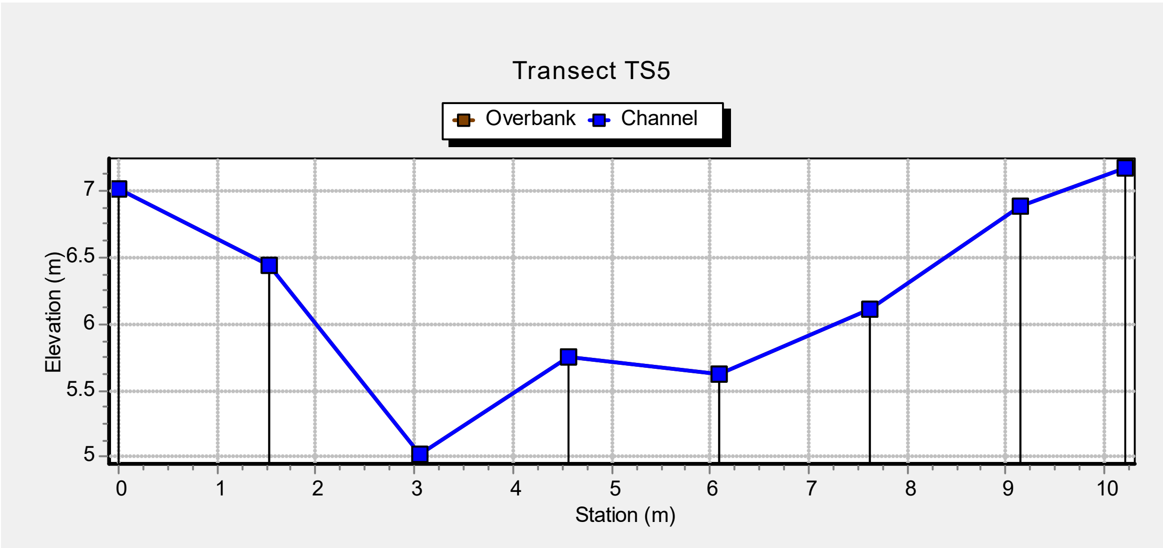
1
2
3
4
5
6
7
Station (m)



Transect TS5
Overbank
Channel
Elevation (m)
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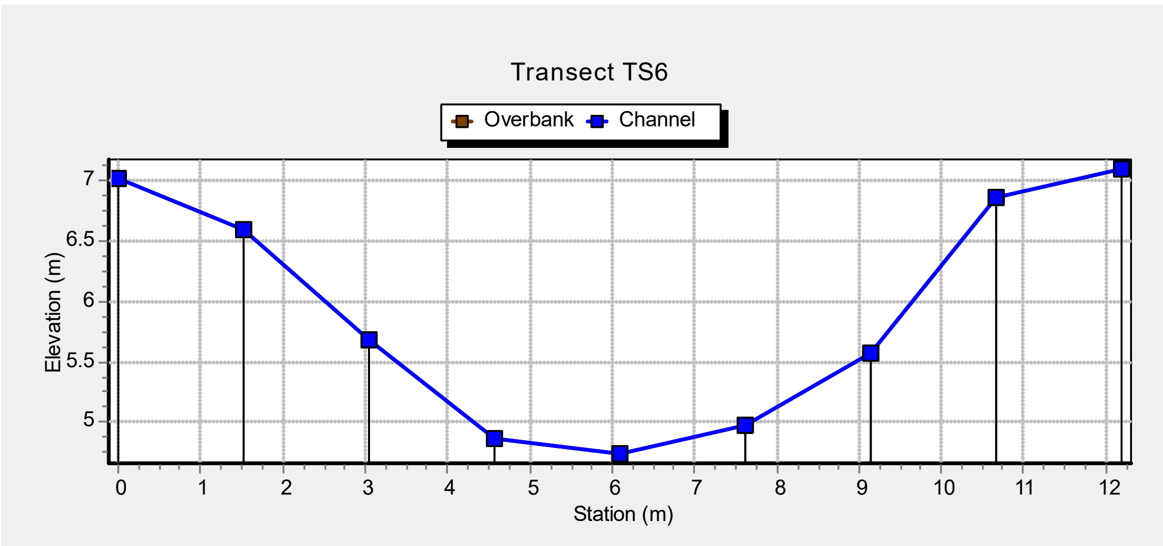
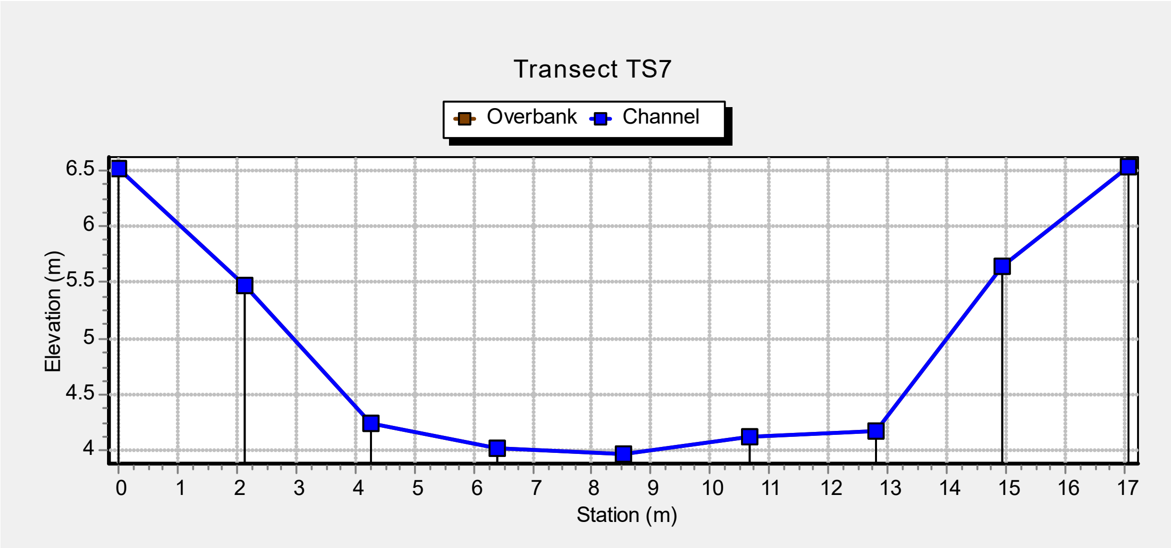
6.5
6
5.5
5
0
1
2
3
4
5
6
7
8
9
10
Station (m)



Transect TS6
Overbank
Channel
Elevation (m)
7
6.5
6
5.5
5
0
1
2
3
4
5
6
7
8
9
10
11
12
Station (m)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Overbank
Channel
Elevation (m)
6.5
6
5.5
5
4.5
4
0
1
2
3
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10
11
12
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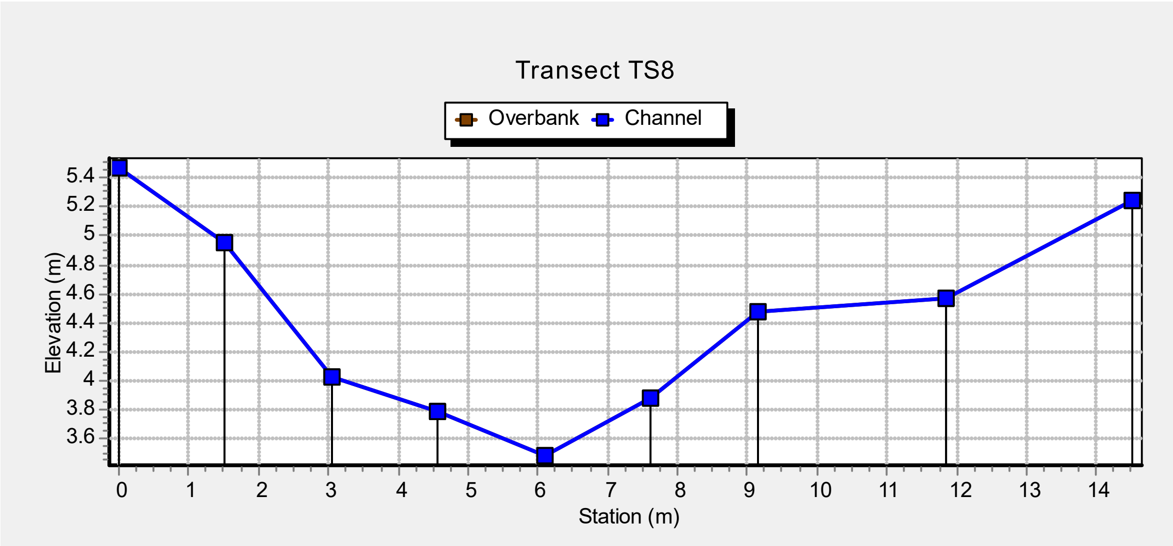
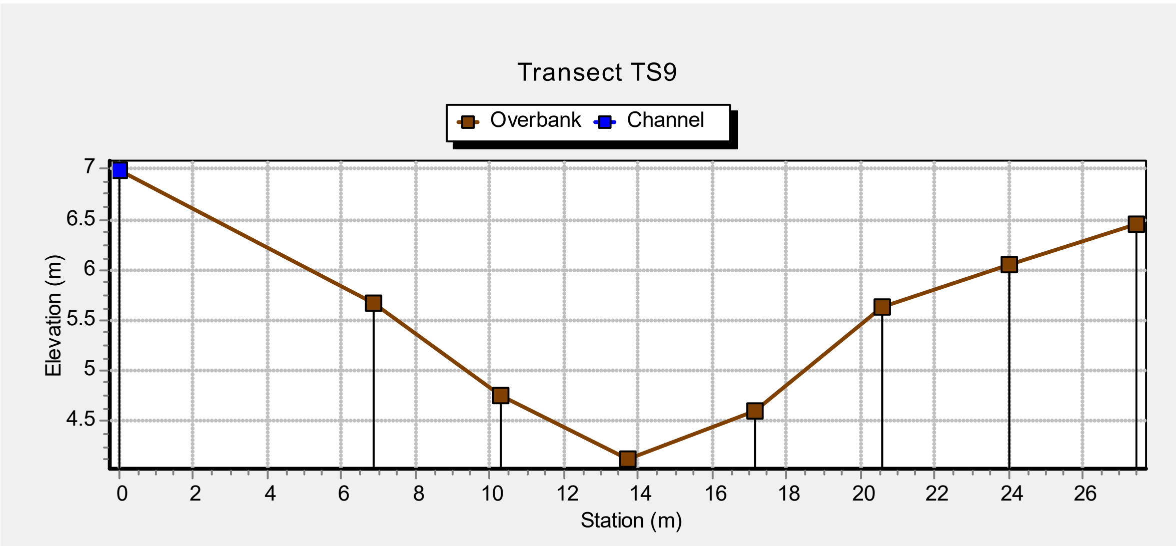
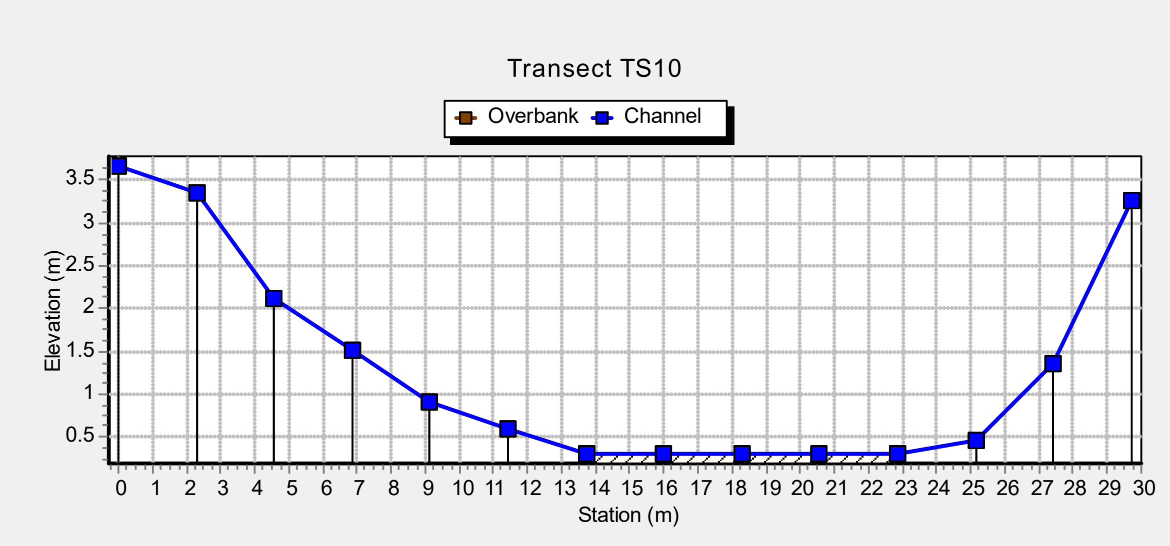
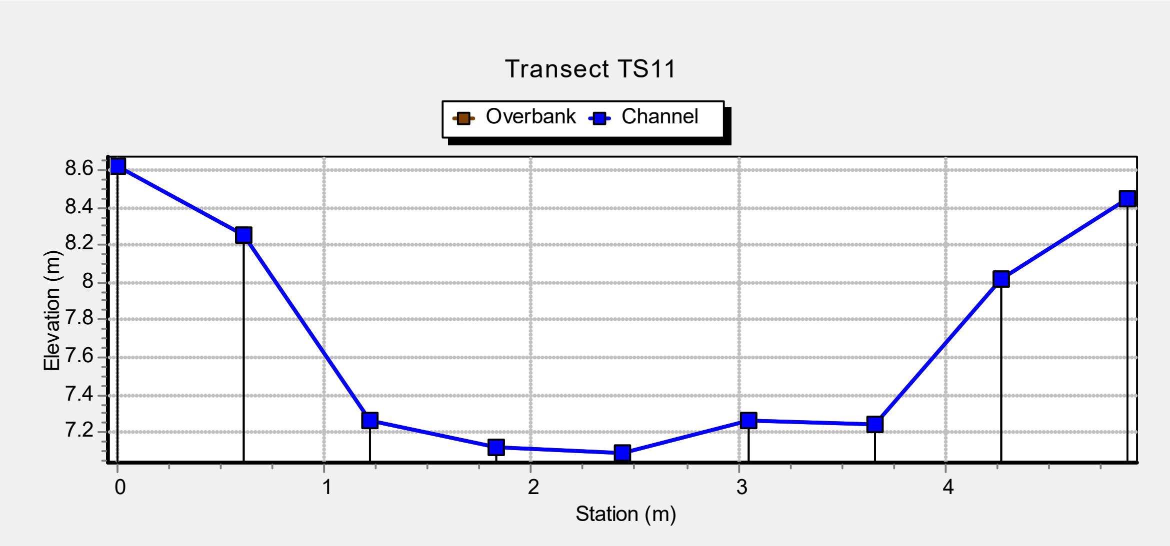
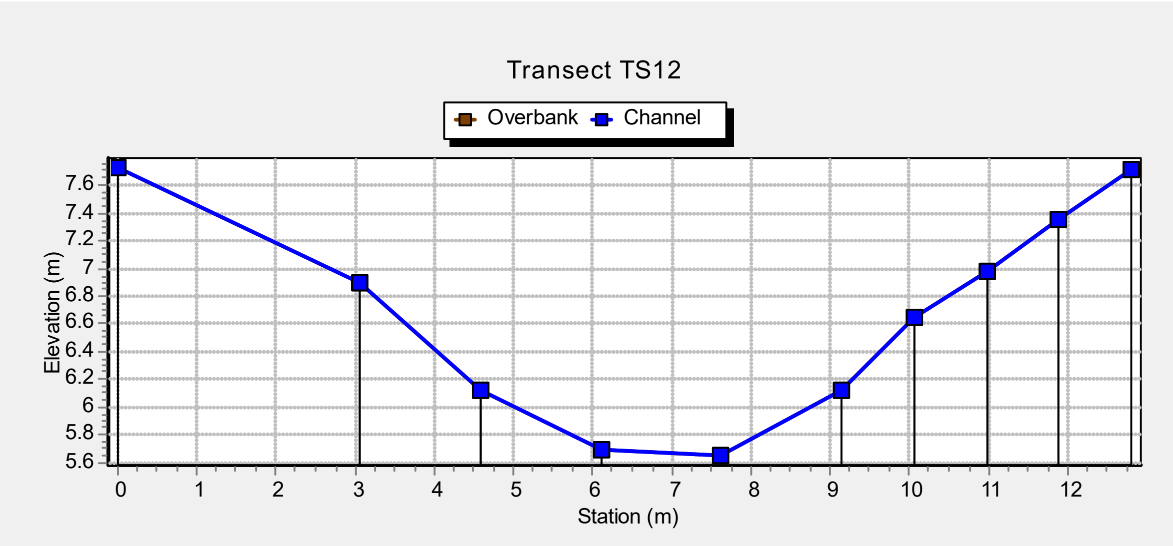
14
15
16
17
Station (m)

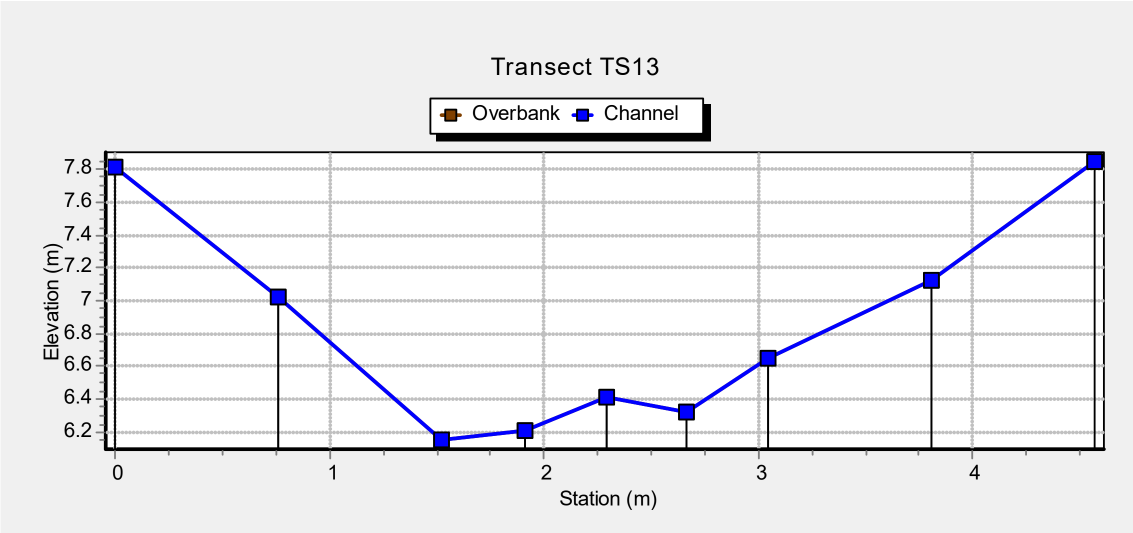

Transect TS8
Overbank
Channel
Elevation (m)
5.4
5.2
5
4.8
4.6
4.4
4.2
4
3.8
3.6
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Station (m)

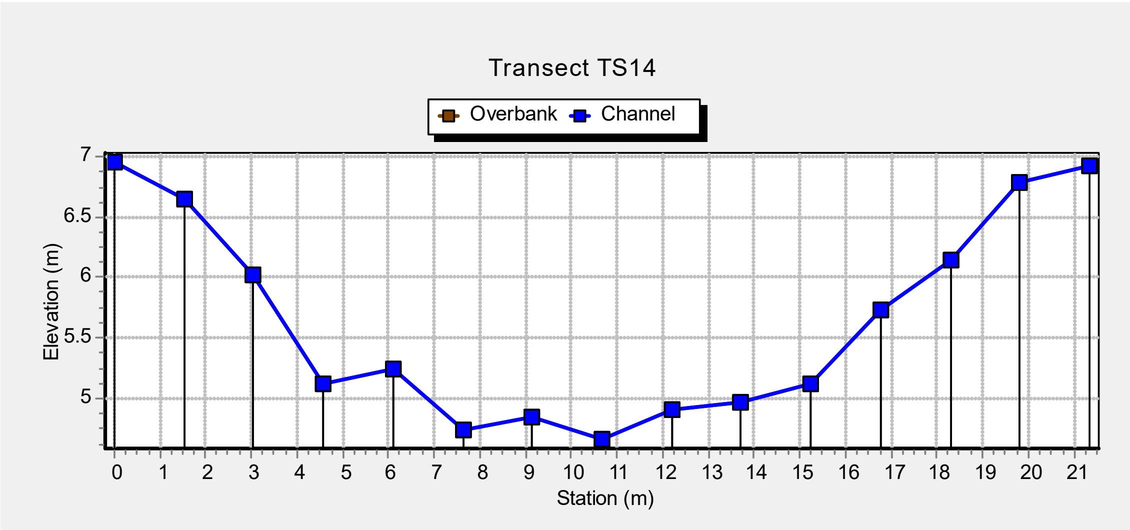

Transect TS9
Overbank
Channel
Elevation (m)
7
6.5
6
5.5
5
4.5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Station (m)


Transect TS10
Overbank
Channel
Elevation (m)
3.5
3
2.5
2
1.5
1
0.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Station (m)


Transect TS11
Overbank
Channel
Elevation (m)
8.6
8.4
8.2
8
7.8
7.6
7.4
7.2
0 1 2 3 4
Station (m)


Transect TS12
Overbank
Channel
Elevation (m)
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
5.8
5.6
0 1 2 3 4 5 6 7 8 9 10 11 12
Station (m)





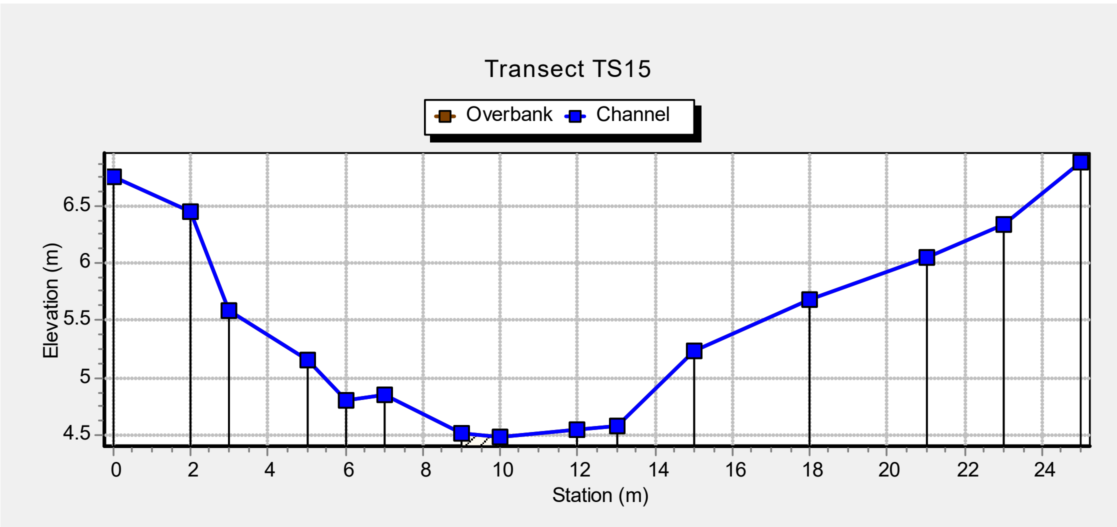
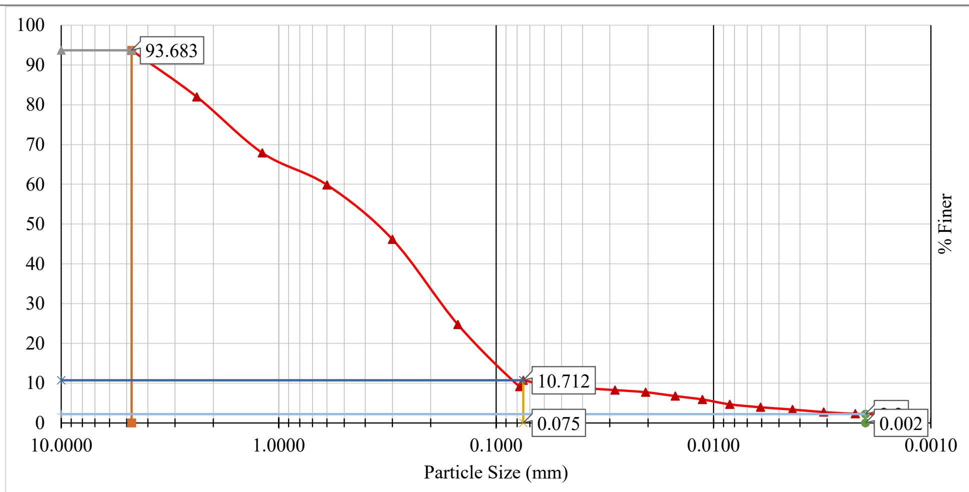


Figure: Cross section of the reaches in Chaktai-Rajakhali watershed (R1-R15)

Appendix B
Soil characterization for the collected soil samples

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**01**	
Name of the location	:	Boxirhat	
Land-use type	:	Water body and Wet land	
LATITUDE (Y)	:	22.333754	
LONGITUDE (X)	:	91.858430	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (℃)	:	27	℃
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	107.12	gm



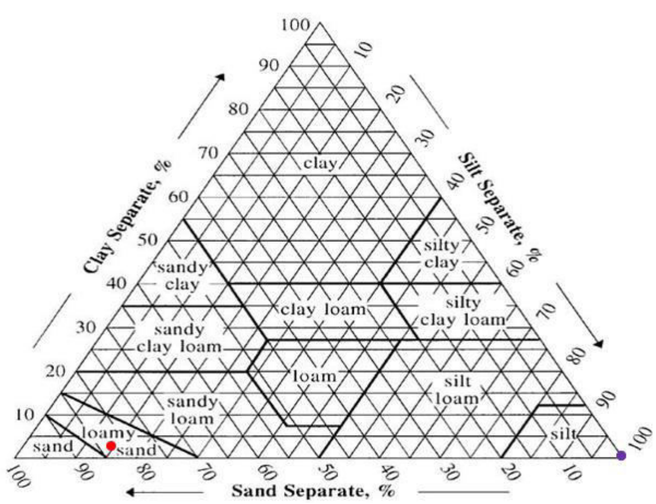
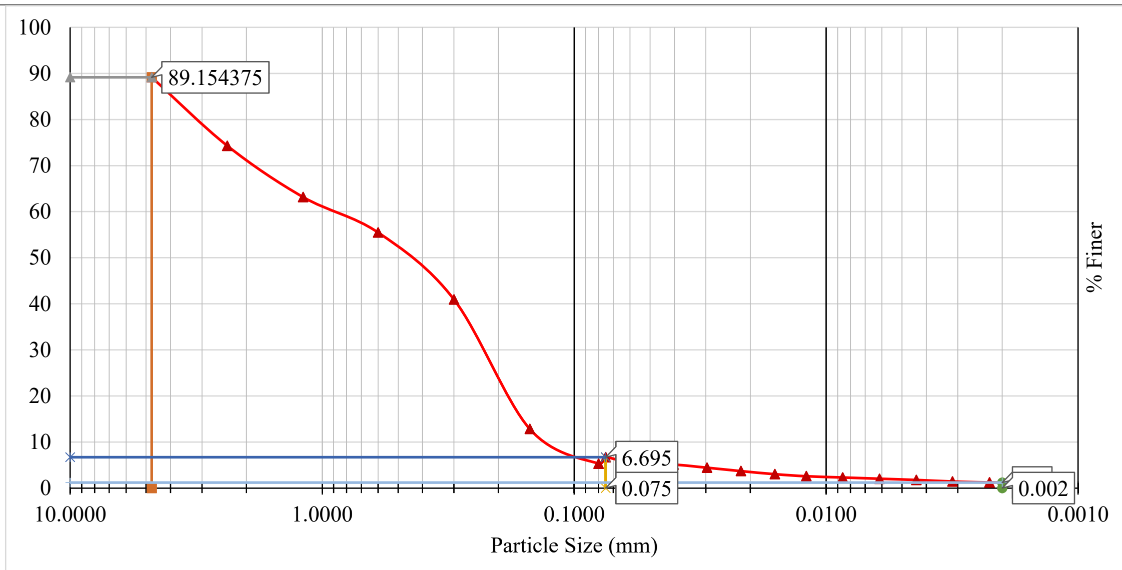


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**02**	
Name of the location	:	Boxirhat	
Land-use type	:	Water body and Wet land	
LATITUDE (Y)	:	22.332097	
LONGITUDE (X)	:	91.854764	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	27	°C
Total wt. of sample	:	1600	gm
Initial wt. of sample passing through #200 sieve	:	107.12	gm



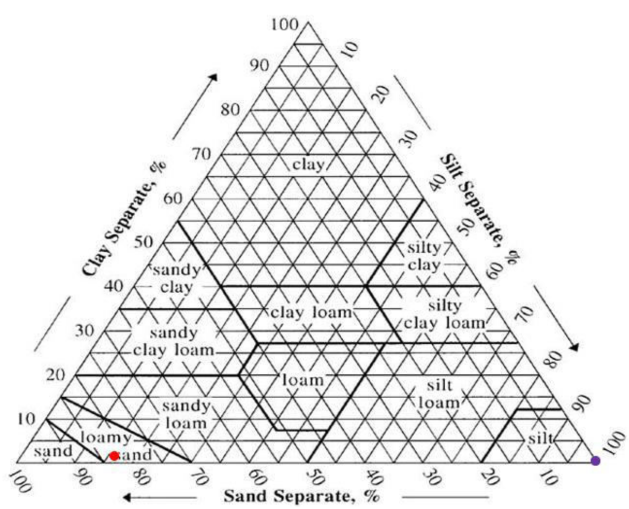
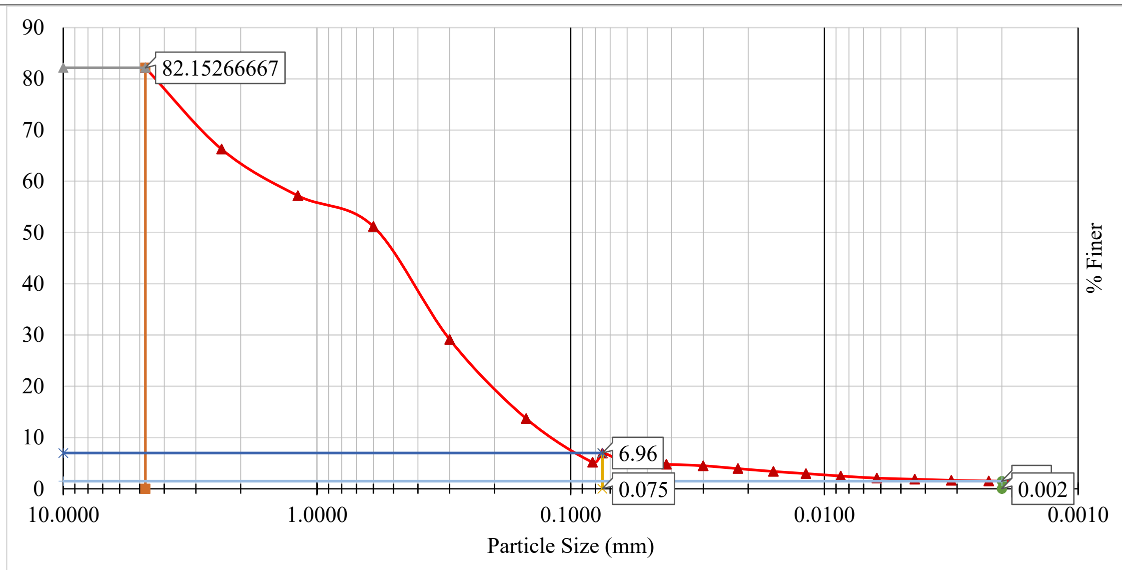


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**03**	
Name of the location	:	Boxirhat	
Land-use type	:	Water body and Wet land	
LATITUDE (Y)	:	22.44434	
LONGITUDE (X)	:	91.861311	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	26	°C
Total wt. of sample	:	1500	gm
Initial wt. of sample passing through #200 sieve	:	104.40	gm



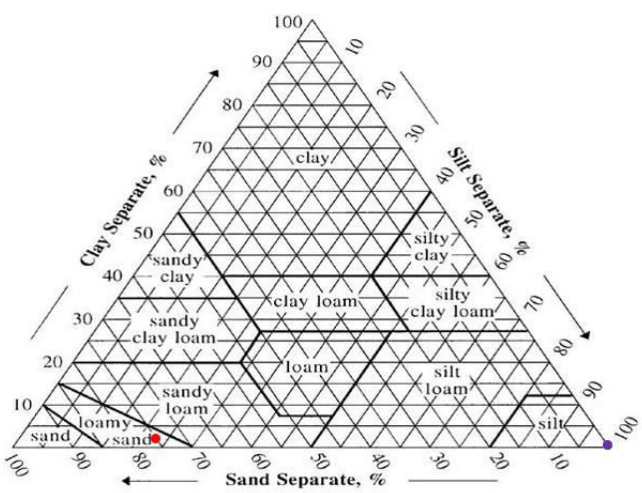
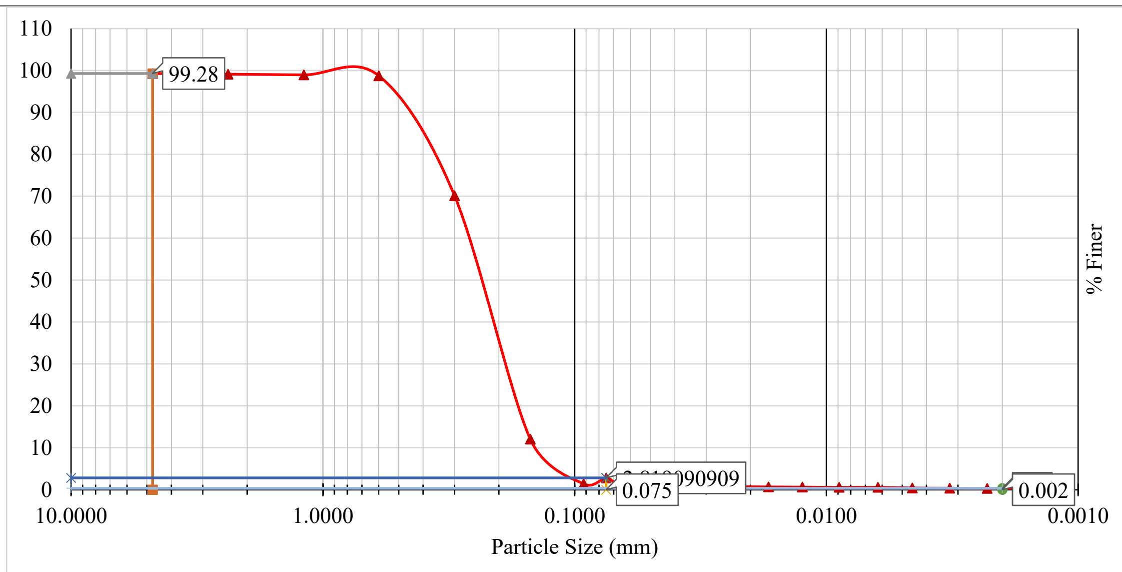


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**04**	
Name of the location	:	Boxirhat	
Land-use type	:	Water body and Wet land	
LATITUDE (Y)	:	22.342499	
LONGITUDE (X)	:	91.854356	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	31.01	gm
Temperature (°C)	:	34	°C
Total wt. of sample	:	1100	gm
Initial wt. of sample passing through #200 sieve	:	31.01	gm



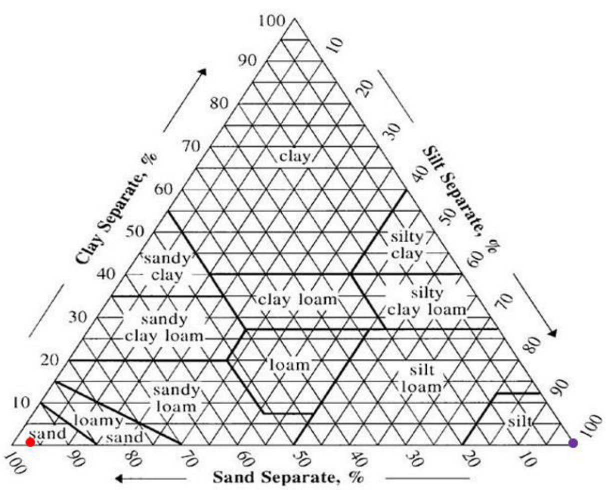
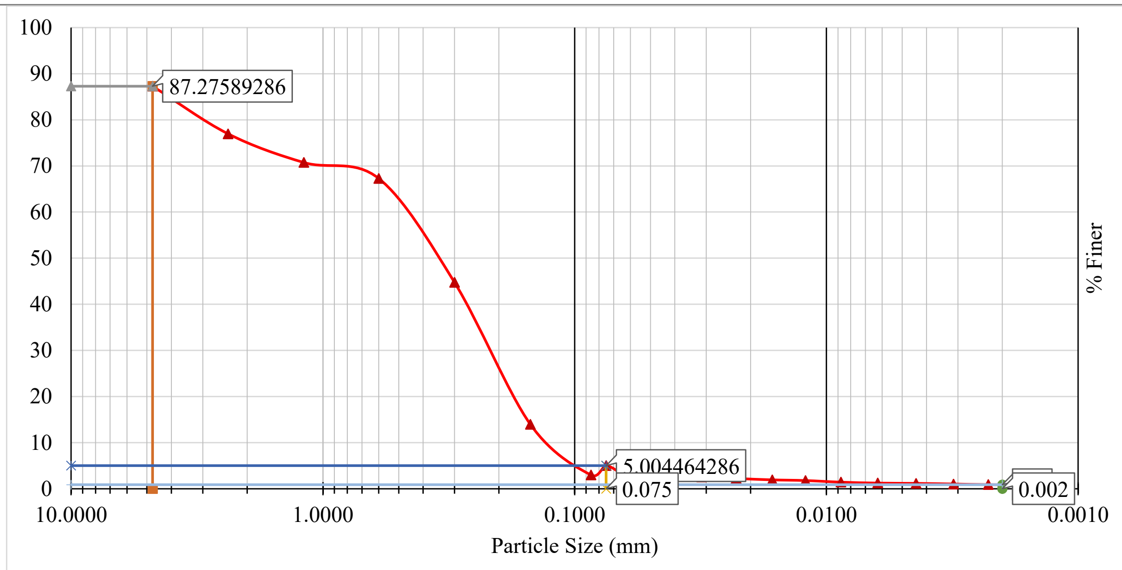


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**05**	
Name of the location	:	Boxirhat	
Land-use type	:	Water body and Wet land	
LATITUDE (Y)	:	22.348584	
LONGITUDE (X)	:	91.850642	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	27	°C
Total wt. of sample	:	1120	gm
Initial wt. of sample passing through #200 sieve	:	56.05	gm



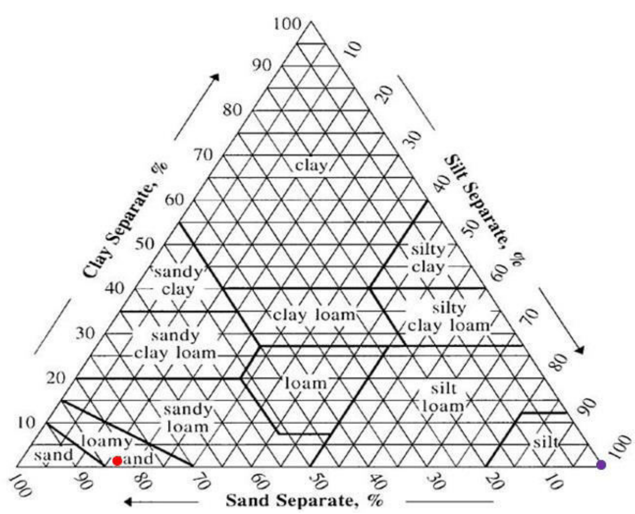
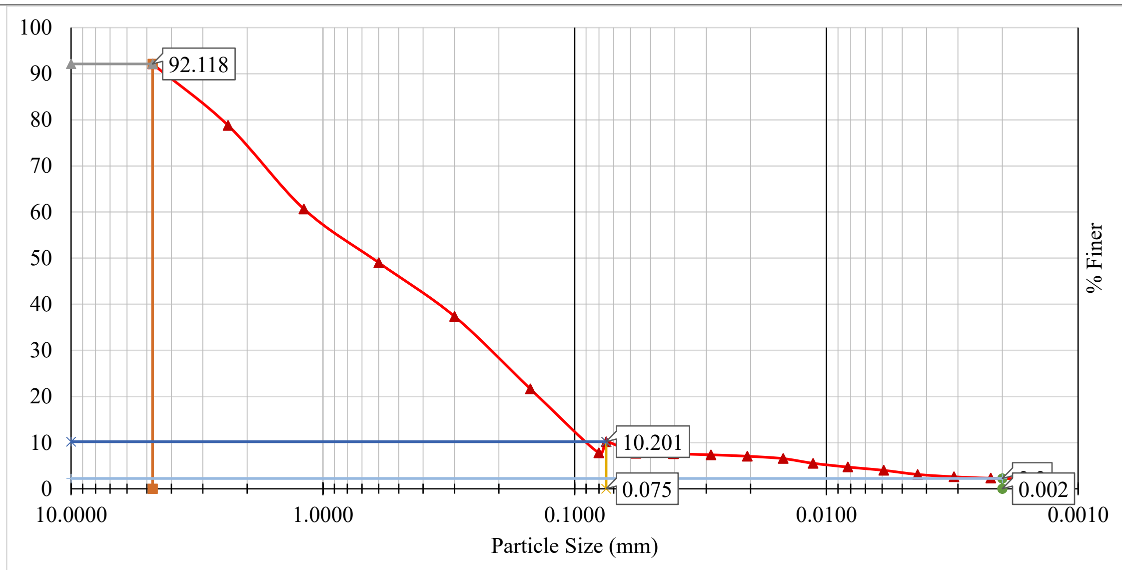


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**06**	
Name of the location	:	Boxirhat	
Land-use type	:	Water body and Wet land	
LATITUDE (Y)	:	22.340097	
LONGITUDE (X)	:	91.856332	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	102.01	gm



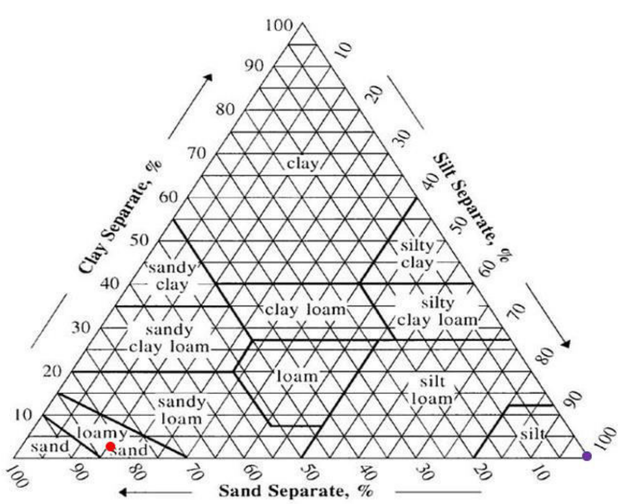
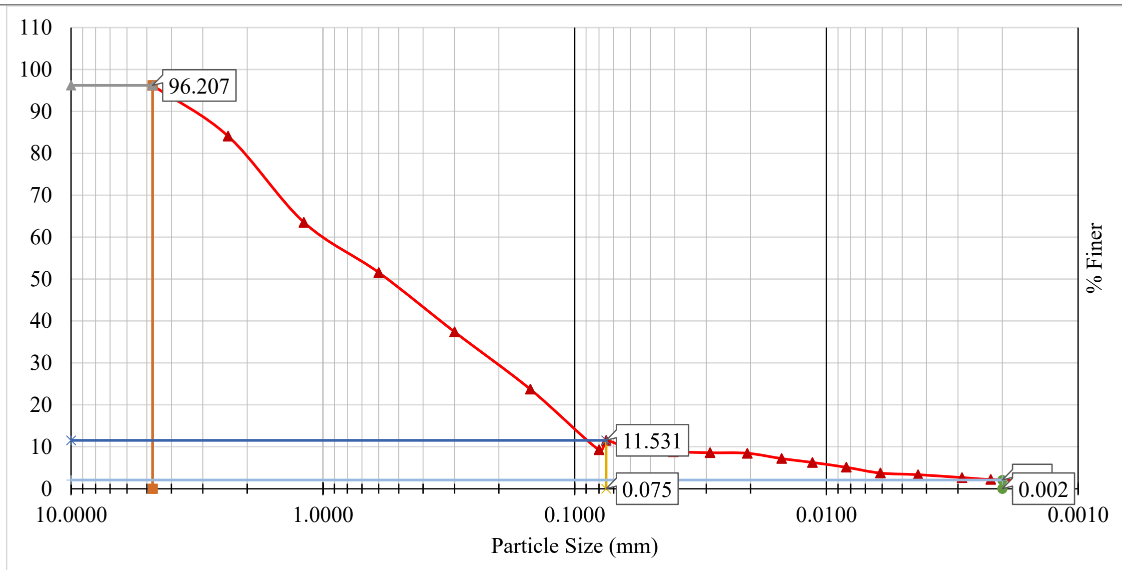


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**07**	
Name of the location	:	Purbo Bakalia	
Land-use type	:	Built Up Area	
LATITUDE (Y)	:	22.340374	
LONGITUDE (X)	:	91..857223	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	26	°C
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	115.31	gm



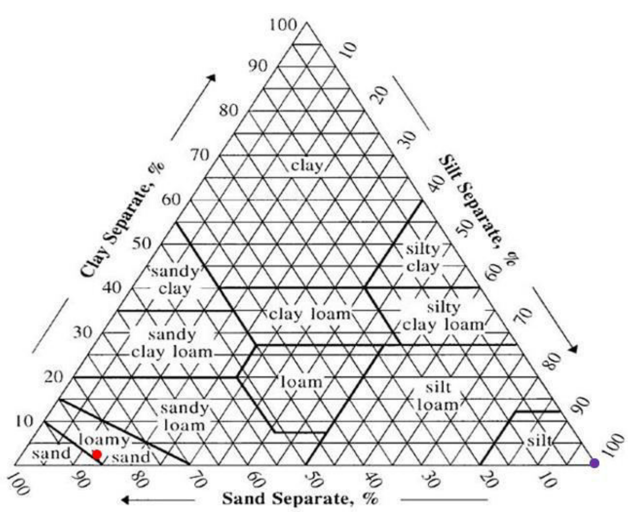
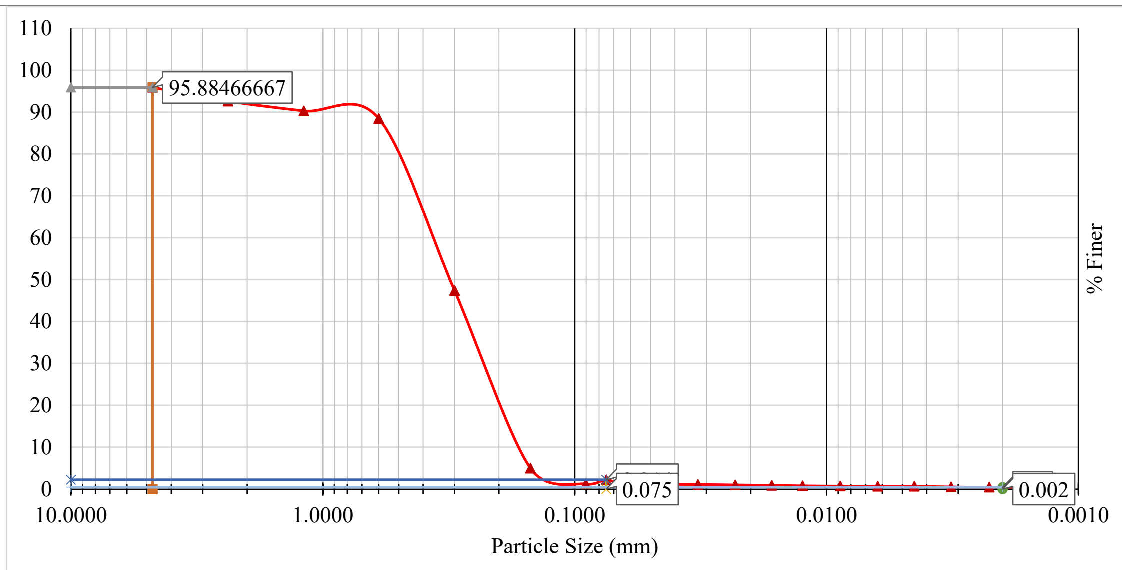


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**08**	
Name of the location	:	Purbo Bakalia	
Land-use type	:	Vegetation	
LATITUDE (Y)	:	22.341117	
LONGITUDE (X)	:	91.860200	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	33.21	gm
Temperature (°C)	:	30	°C
Total wt. of sample	:	1500	gm
Initial wt. of sample passing through #200 sieve	:	33.21	gm



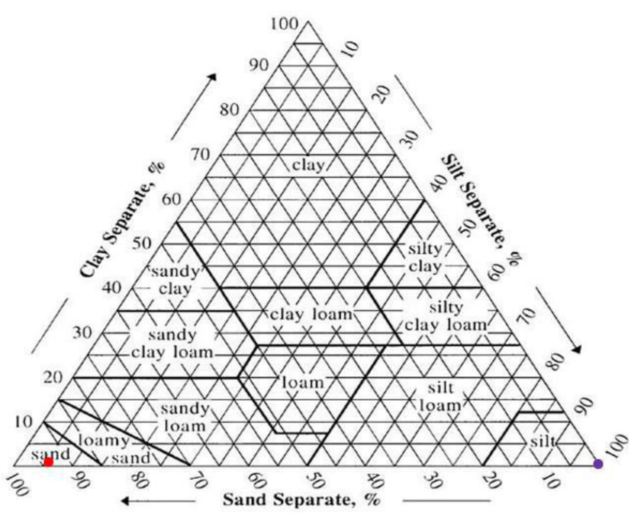
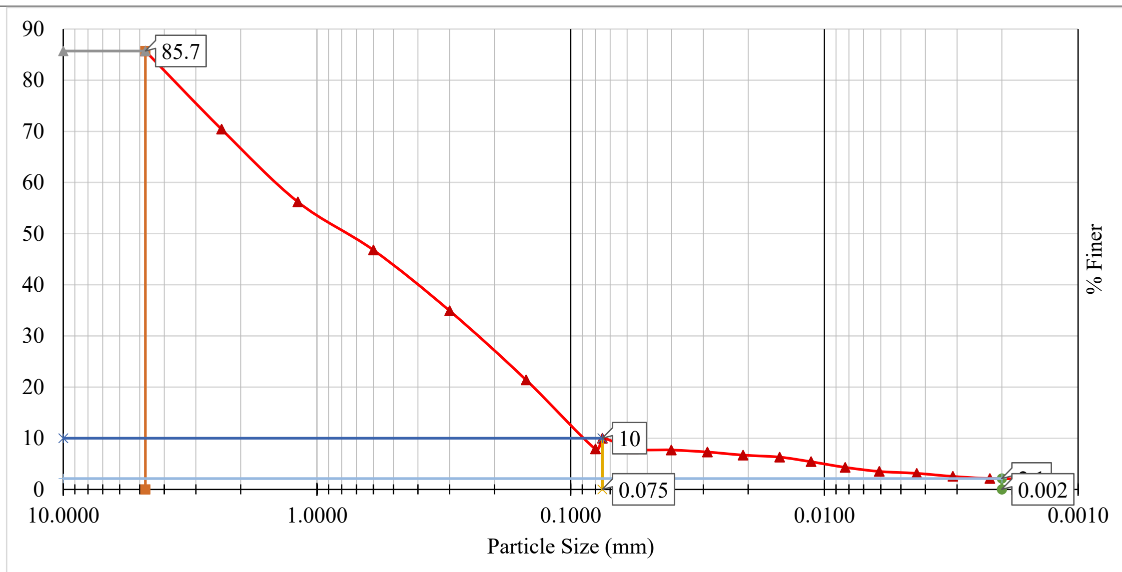


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**09**	
Name of the location	:	Bakalia	
Land-use type	:	Vegetation	
LATITUDE (Y)	:	22.341843	
LONGITUDE (X)	:	91.857864	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (℃)	:	32	℃
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	100	gm



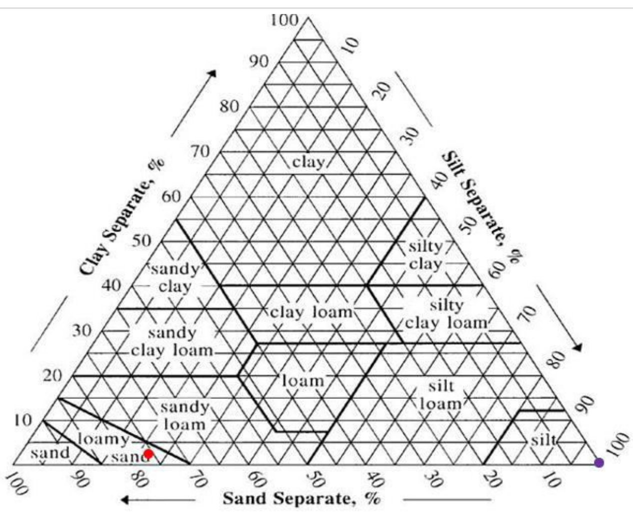
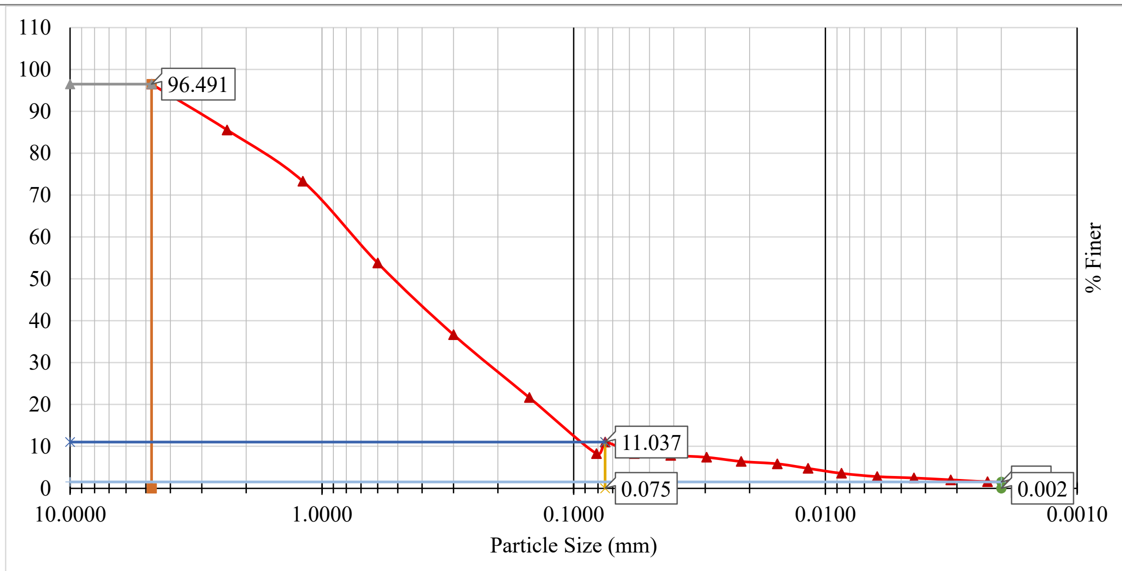


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**10**	
Name of the location	:	East Bakalia	
Land-use type	:	Open Field	
LATITUDE (Y)	:	22.346658	
LONGITUDE (X)	:	91.863691	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	110.37	gm



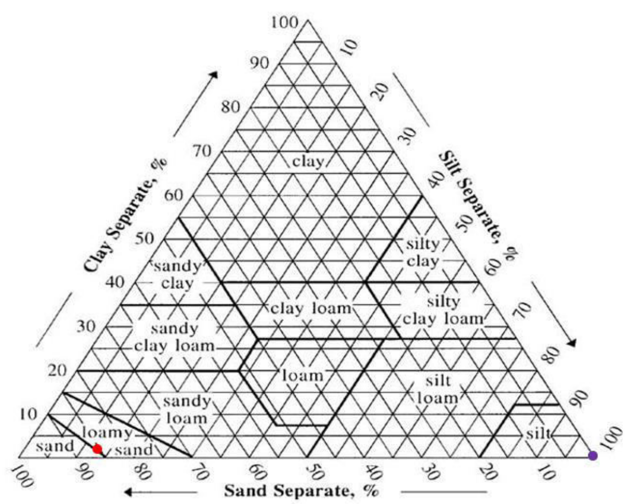
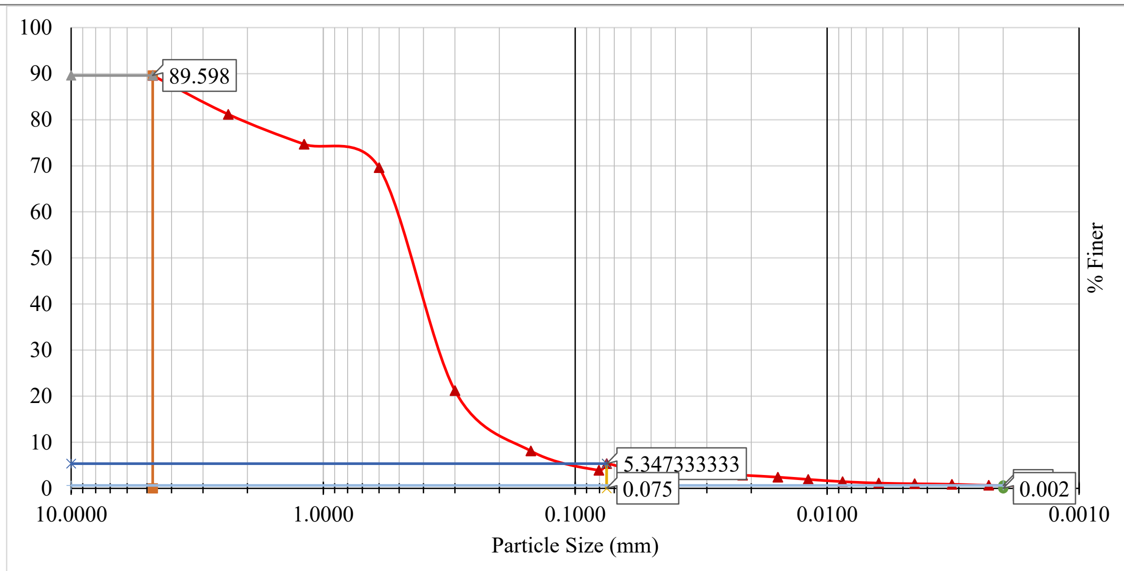


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**11**	
Name of the location	:	East Bakalia	
Land-use type	:	Build up Area	
LATITUDE (Y)	:	22.347539	
LONGITUDE (X)	:	91.866150	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1485.16	gm
Initial wt. of sample passing through #200 sieve	:	80.21	gm



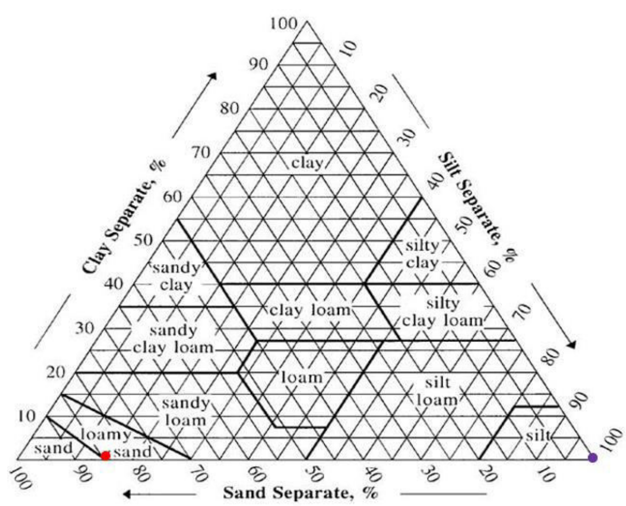
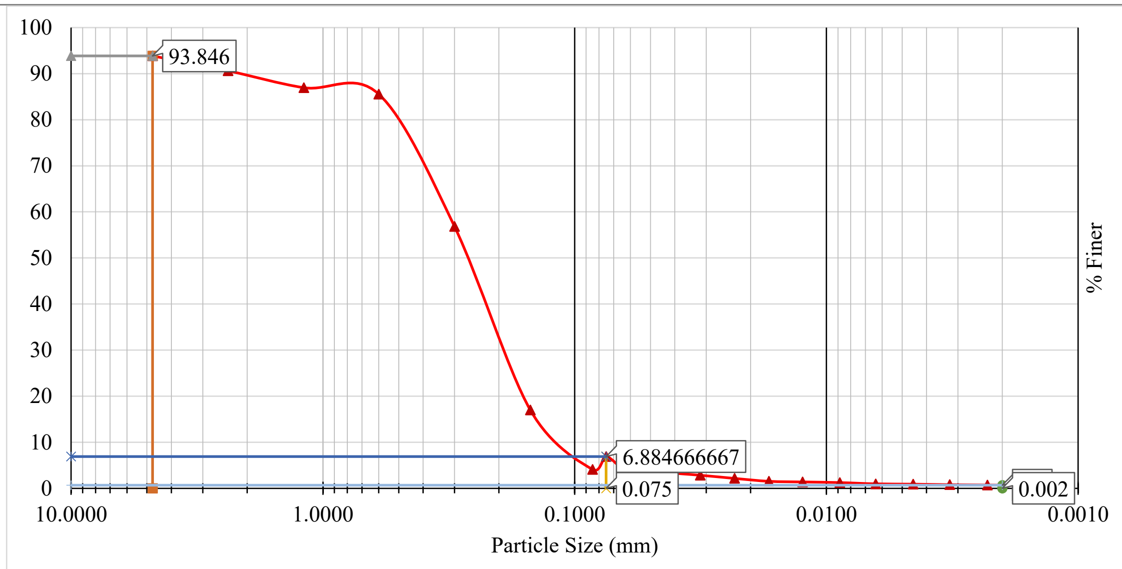


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**12**	
Name of the location	:	Bakalia	
Land-use type	:	Build up Area	
LATITUDE (Y)	:	22.348237	
LONGITUDE (X)	:	91.856156	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1478.34	gm
Initial wt. of sample passing through #200 sieve	:	103.27	gm



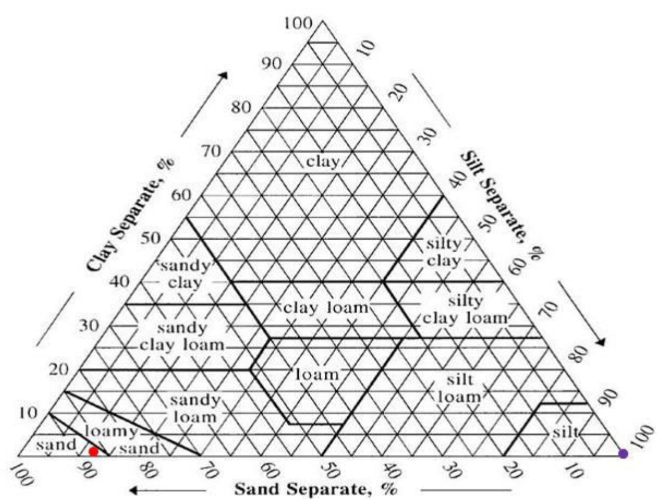
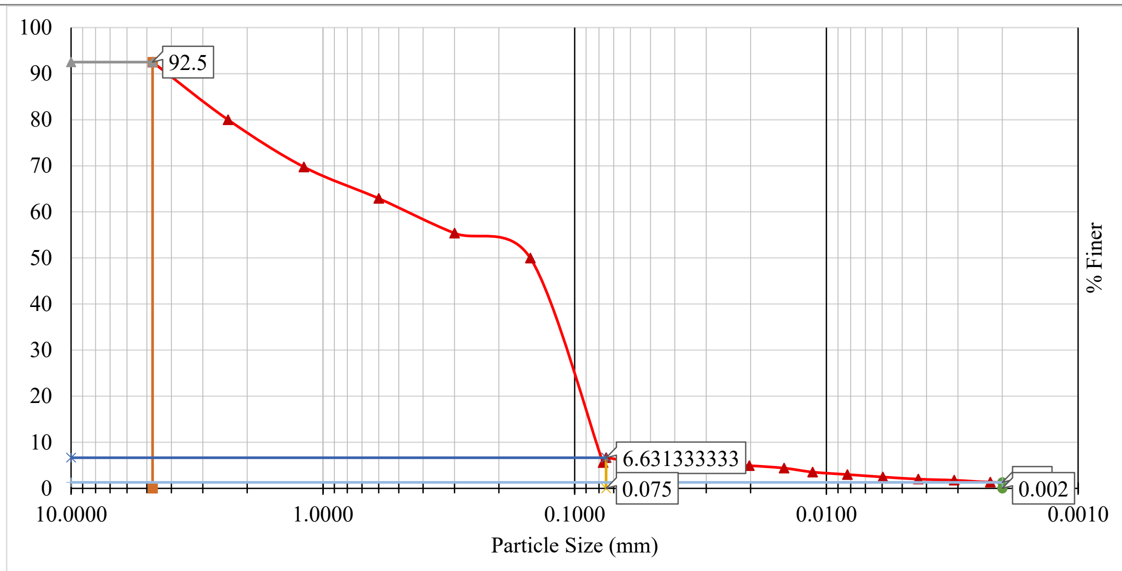


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**13**	
Name of the location	:	East Bakalia	
Land-use type	:	Build up Area	
LATITUDE (Y)	:	22.350048	
LONGITUDE (X)	:	91.865046	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1499.18	gm
Initial wt. of sample passing through #200 sieve	:	99.47	gm



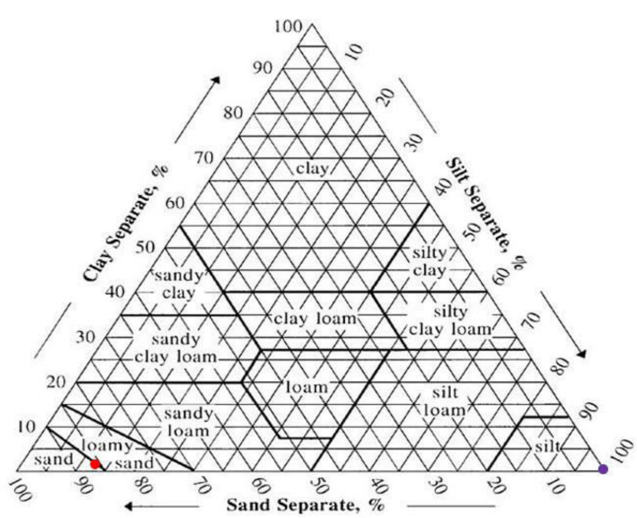
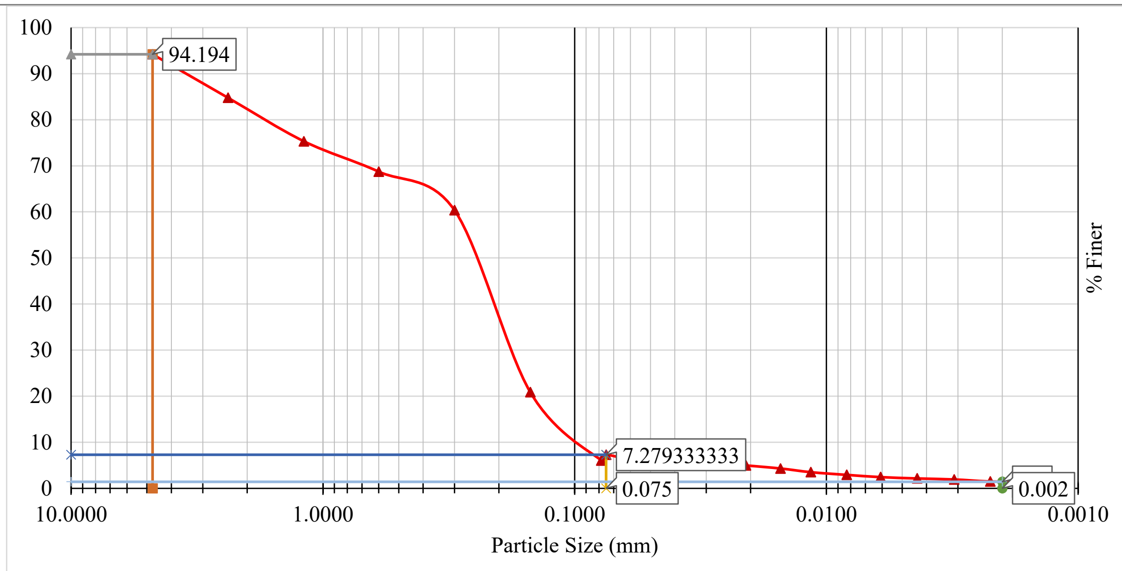


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**14**	
Name of the location	:	Bakalia	
Land-use type	:	Build up Area	
LATITUDE (Y)	:	22.356205	
LONGITUDE (X)	:	91.848346	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1483.43	gm
Initial wt. of sample passing through #200 sieve	:	109.19	gm



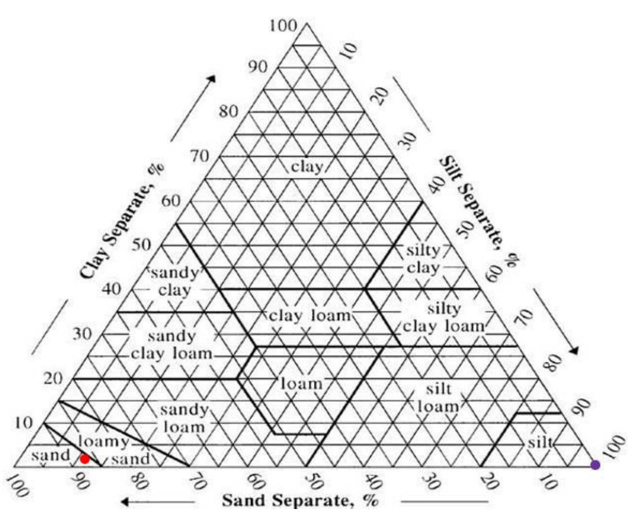
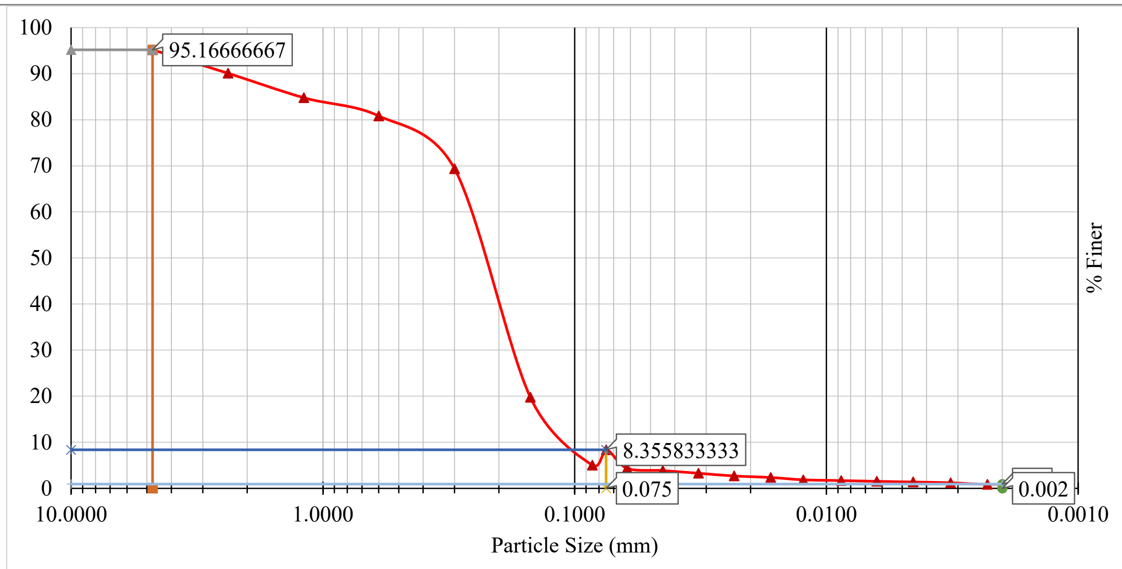


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**15**	
Name of the location	:	Bakalia	
Land-use type	:	Vegetation	
LATITUDE (Y)	:	22.349384	
LONGITUDE (X)	:	91.842437	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (℃)	:	32	℃
Total wt. of sample	:	1156.97	gm
Initial wt. of sample passing through #200 sieve	:	100.27	gm



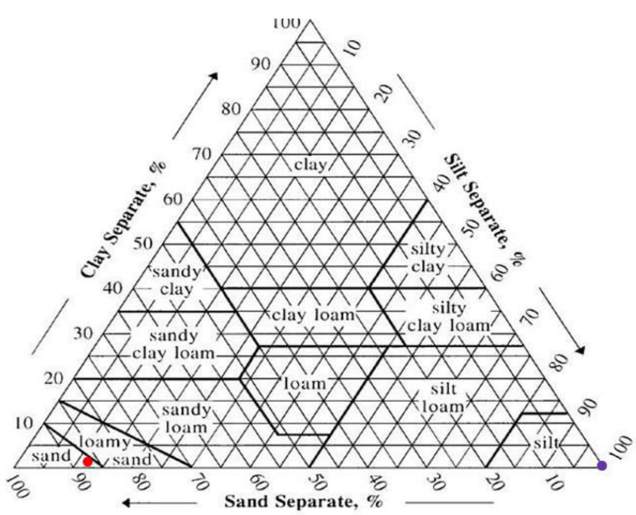
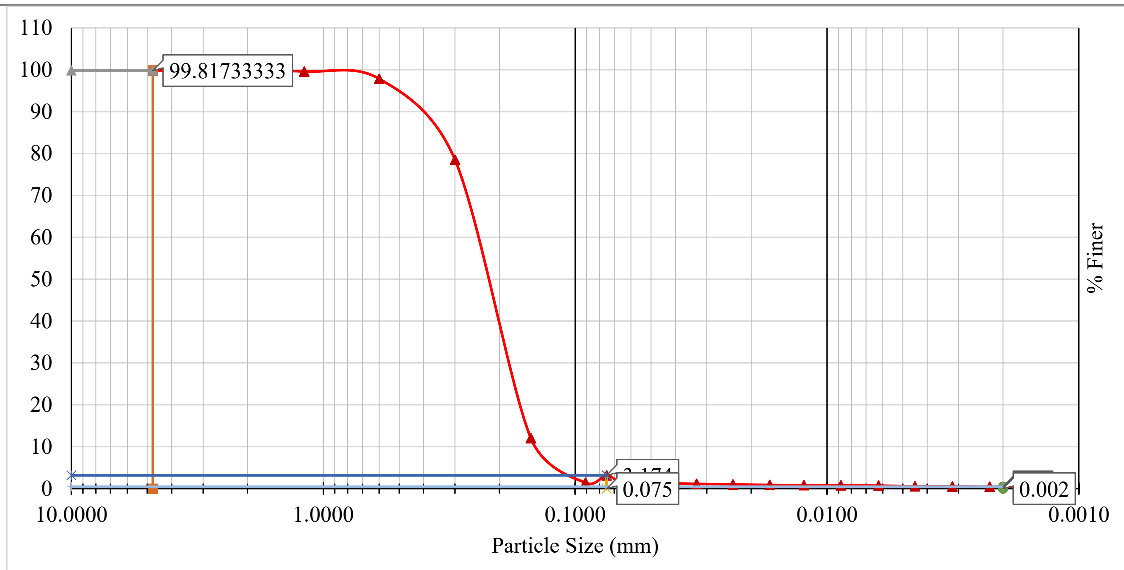


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**16**	
Name of the location	:	Firinghee Bazar	
Land-use type	:	Vegetation	
LATITUDE (Y)	:	22.326709	
LONGITUDE (X)	:	91.837988	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	47.61	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1479.05	gm
Initial wt. of sample passing through #200 sieve	:	47.61	gm



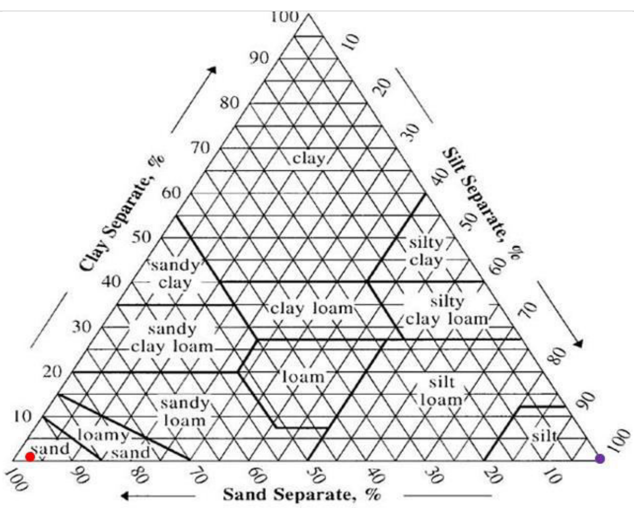
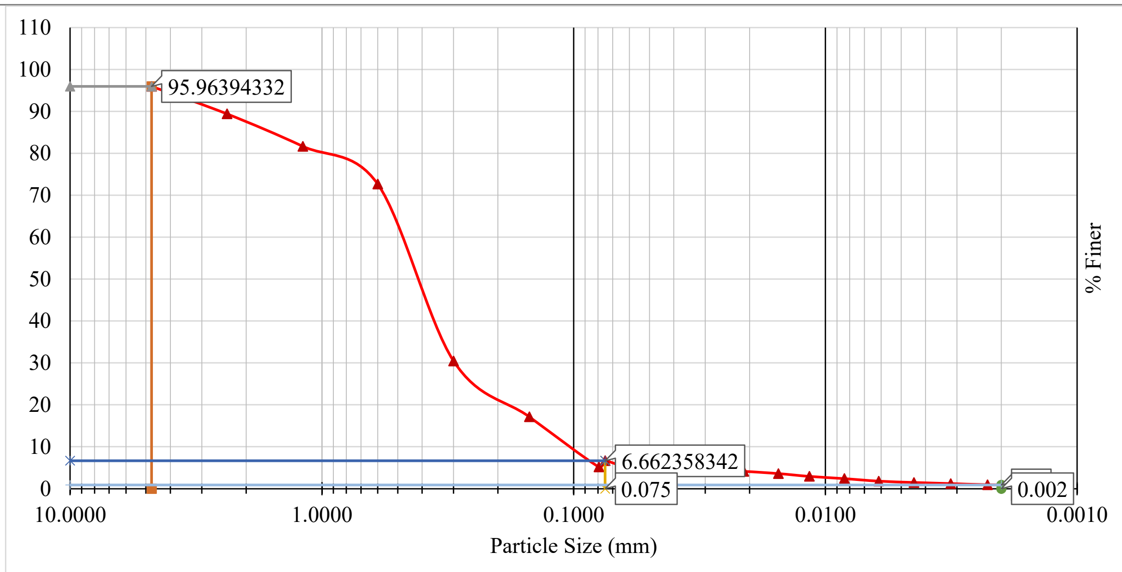


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**17**	
Name of the location	:	Firinghee Bazar	
Land-use type	:	vegetation	
LATITUDE (Y)	:	22.326728	
LONGITUDE (X)	:	91.840025	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1500.97	gm
Initial wt. of sample passing through #200 sieve	:	100	gm



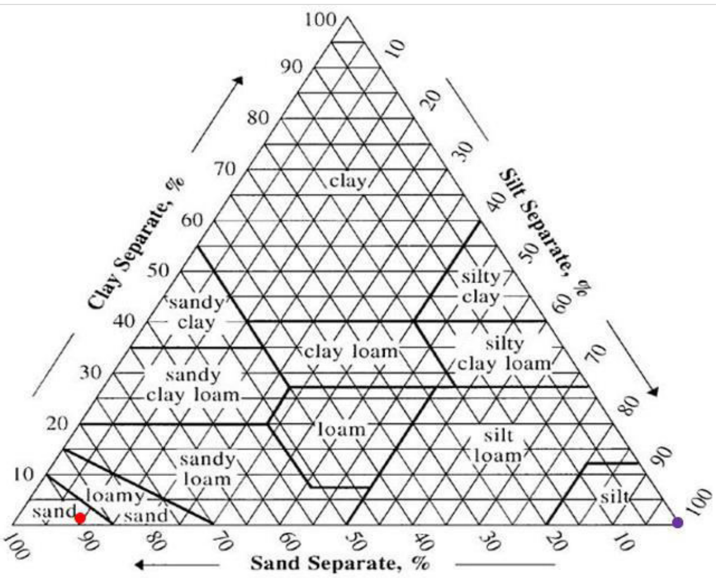
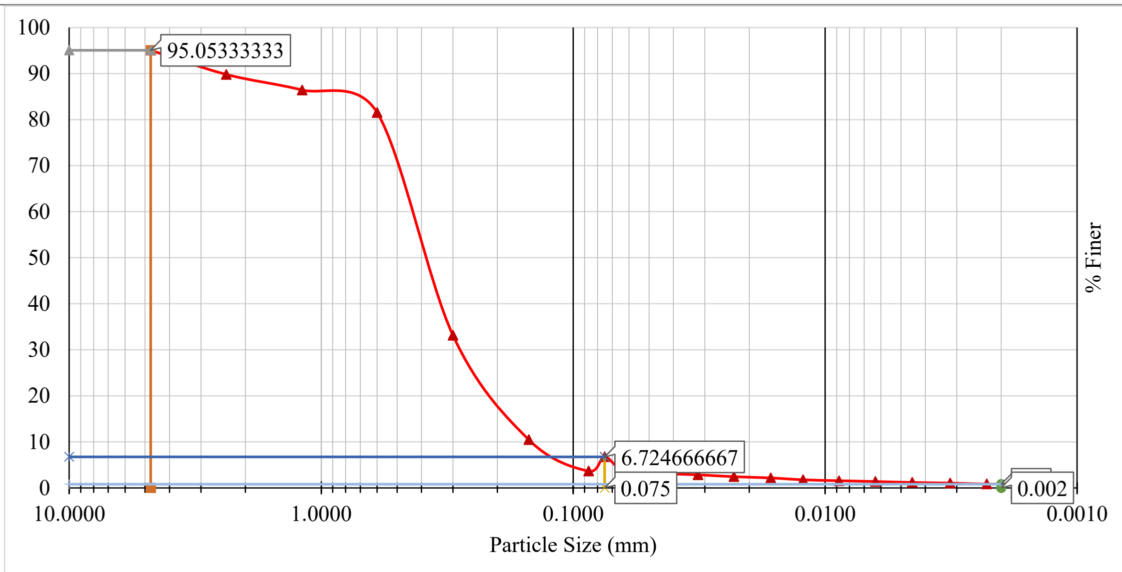


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**18**	
Name of the location	:	Patharghata	
Land-use type	:	Build up Area	
LATITUDE (Y)	:	21.327018	
LONGITUDE (X)	:	91.844097	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1483.76	gm
Initial wt. of sample passing through #200 sieve	:	100.87	gm



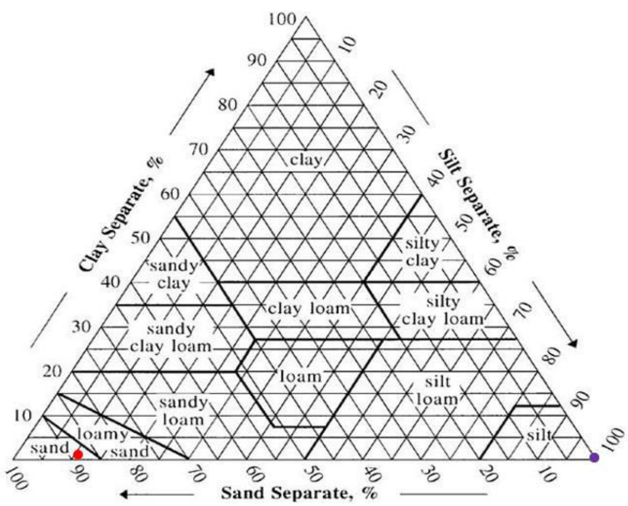
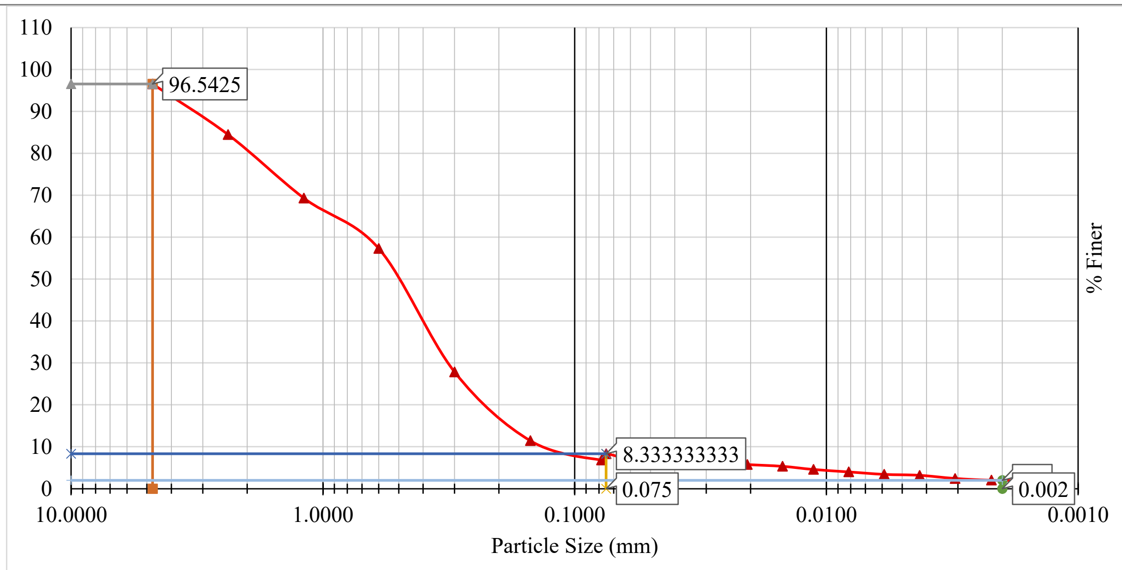


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**19**	
Name of the location	:	Bakalia	
Land-use type	:	Open Field	
LATITUDE (Y)	:	22.363678	
LONGITUDE (X)	:	91.858440	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1200	gm
Initial wt. of sample passing through #200 sieve	:	100	gm



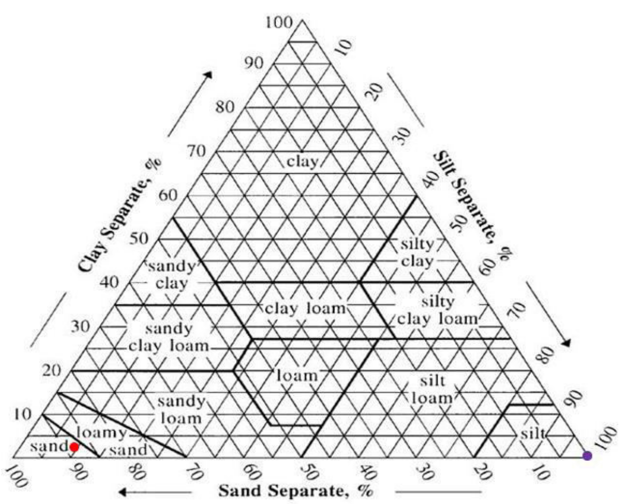
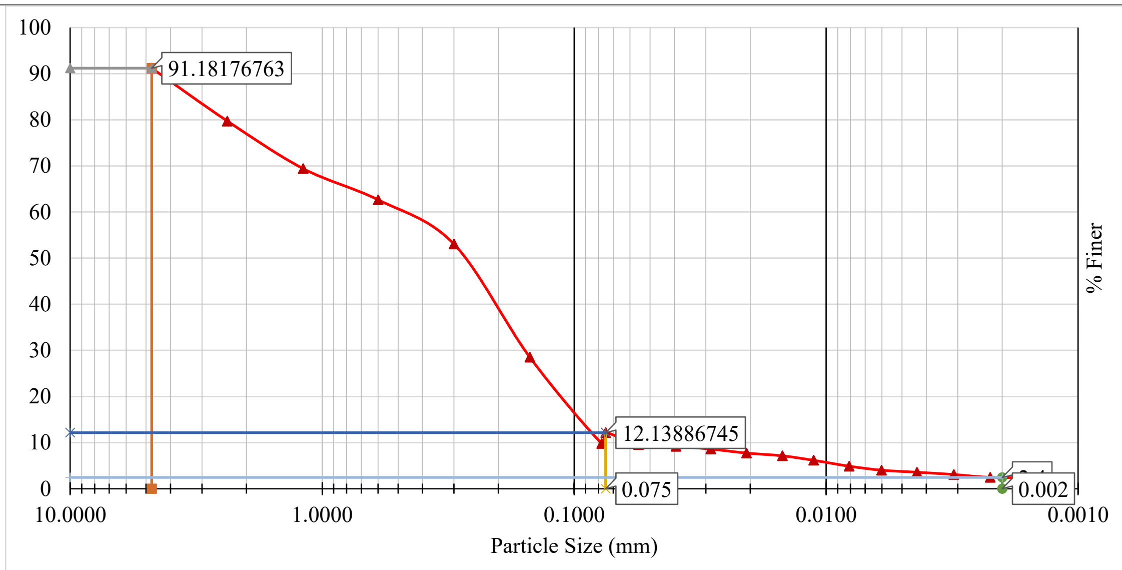


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**20**	
Name of the location	:	Uttar Pathar Ghata	
Land use type	:	Open Field	
LATITUDE (Y)	:	22.332460	
LONGITUDE (X)	:	91.819494	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1204.89	gm
Initial wt. of sample passing through #200 sieve	:	146.26	gm



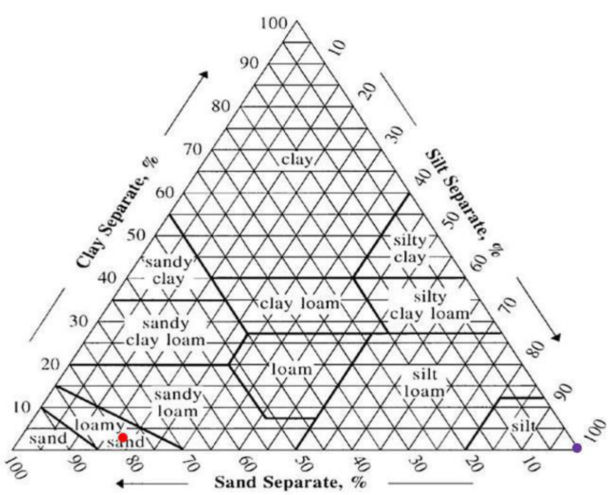
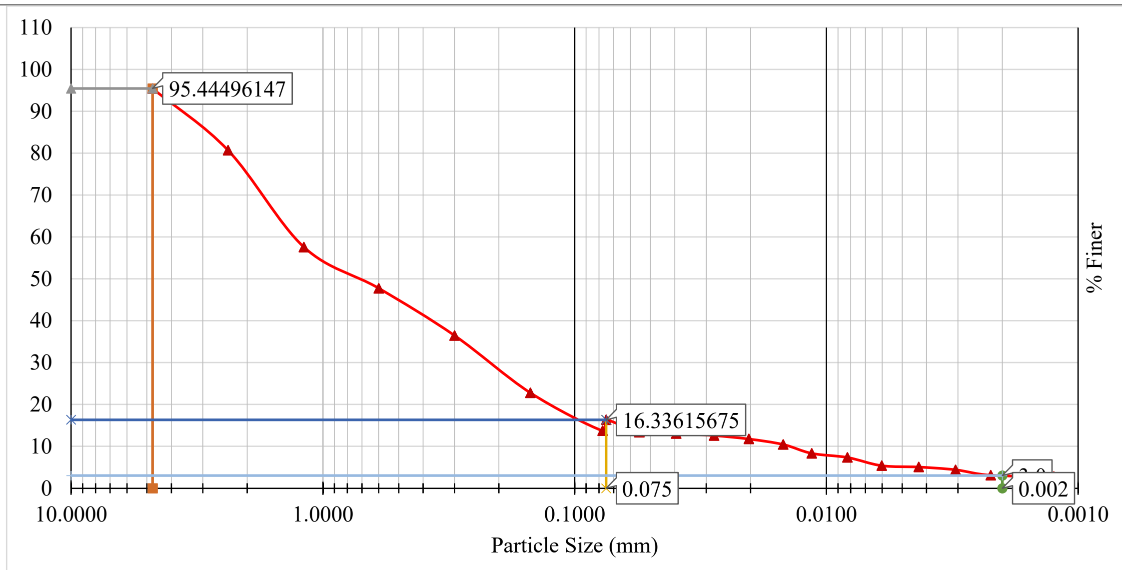


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	:	**21**	
Name of the location	:	Chawk Bazar	
Land-use type	:	Open Field	
LATITUDE (Y)	:	22.355498	
LONGITUDE (X)	:	91.839026	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1100.32	gm
Initial wt. of sample passing through #200 sieve	:	179.75	gm



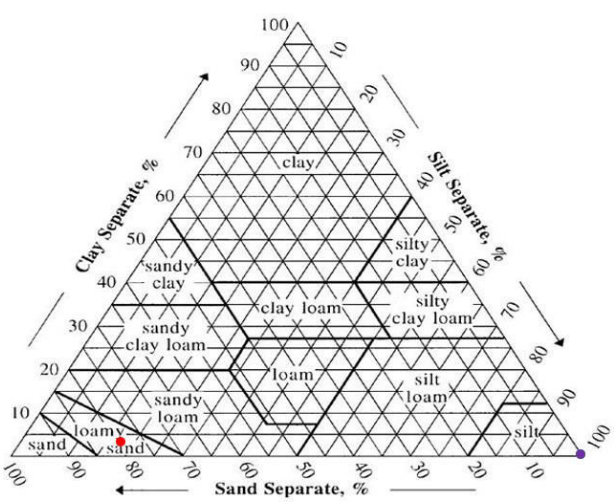
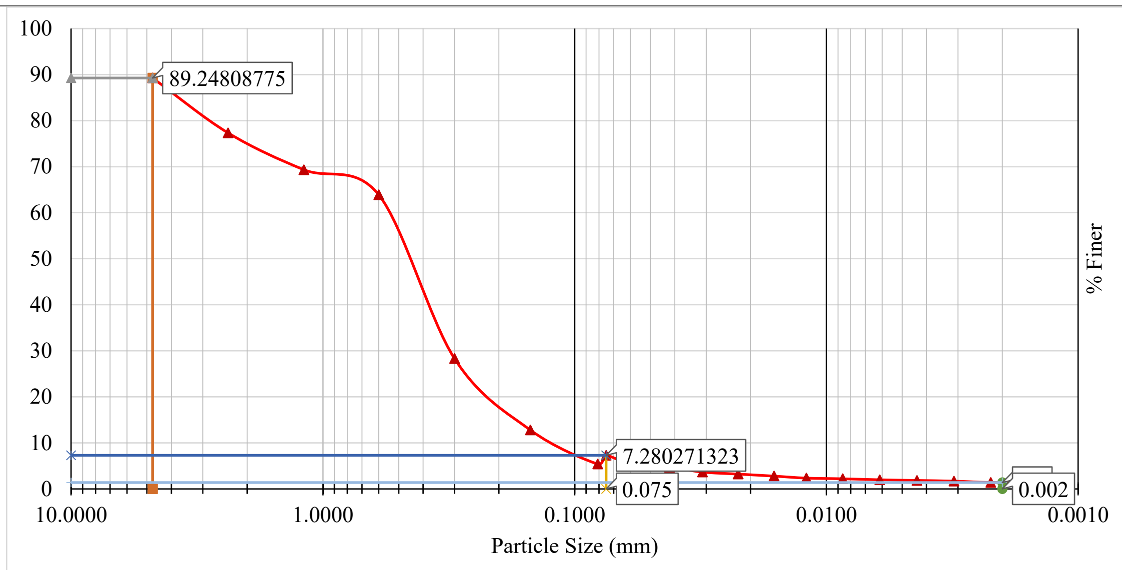


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**22**	
Name of the location	:	Chawk Bazar	
Land-use type	:	Build Up Area	
LATITUDE (Y)	:	22.356397	
LONGITUDE (X)	:	91.828623	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1385.8	gm
Initial wt. of sample passing through #200 sieve	:	100.89	gm



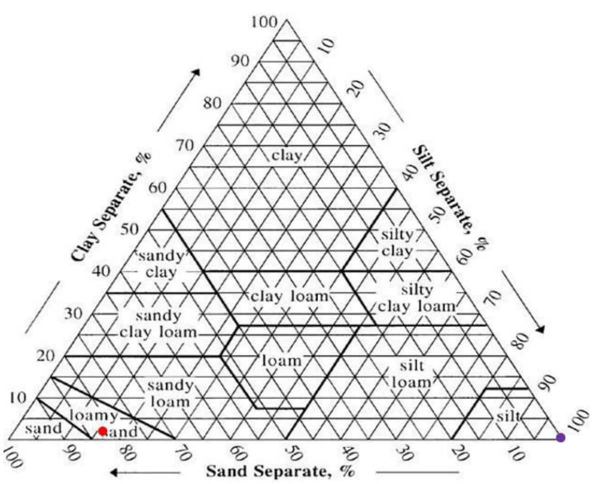
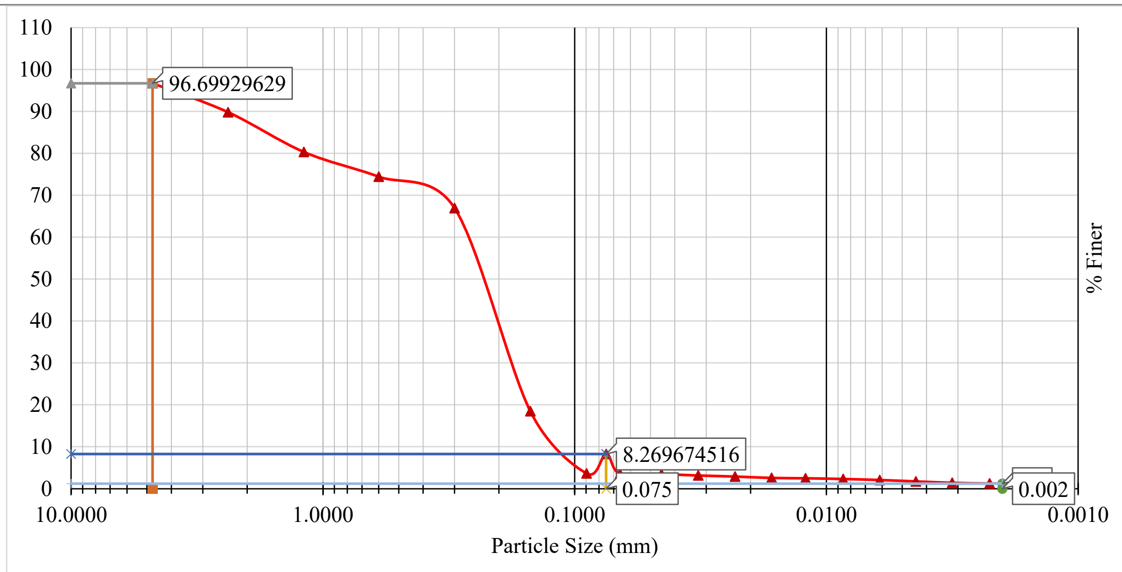


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**23**	
Name of the location	:	Jamal Khan	
Land-use type	:	Build Up Area	
LATITUDE (Y)	:	22.346200	
LONGITUDE (X)	:	91.832203	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1395.46	gm
Initial wt. of sample passing through #200 sieve	:	115.40	gm



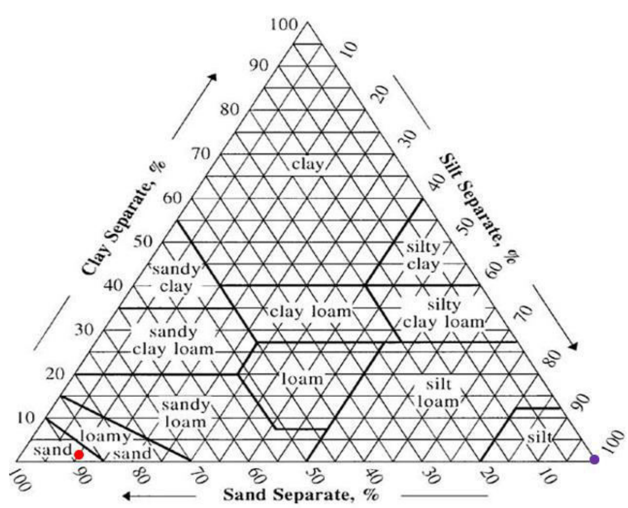
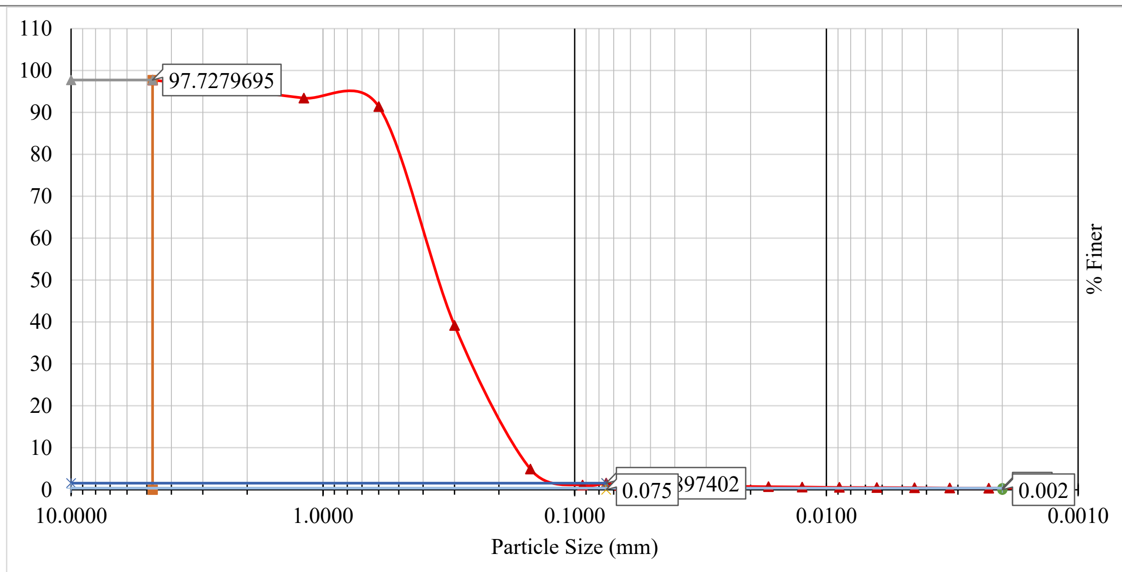


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**24**	
Name of the location	:	Panchlaish	
Land-use type	:	Build Up Area	
LATITUDE (Y)	:	22.360596	
LONGITUDE (X)	:	91.835055	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	23.36	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1500.42	gm
Initial wt. of sample passing through #200 sieve	:	23.36	gm



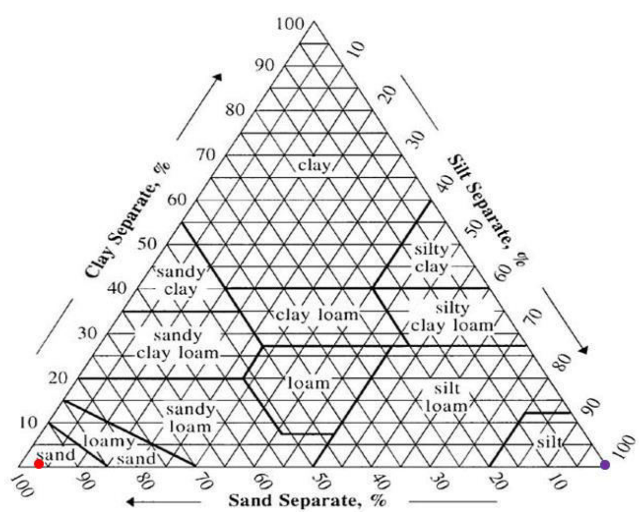
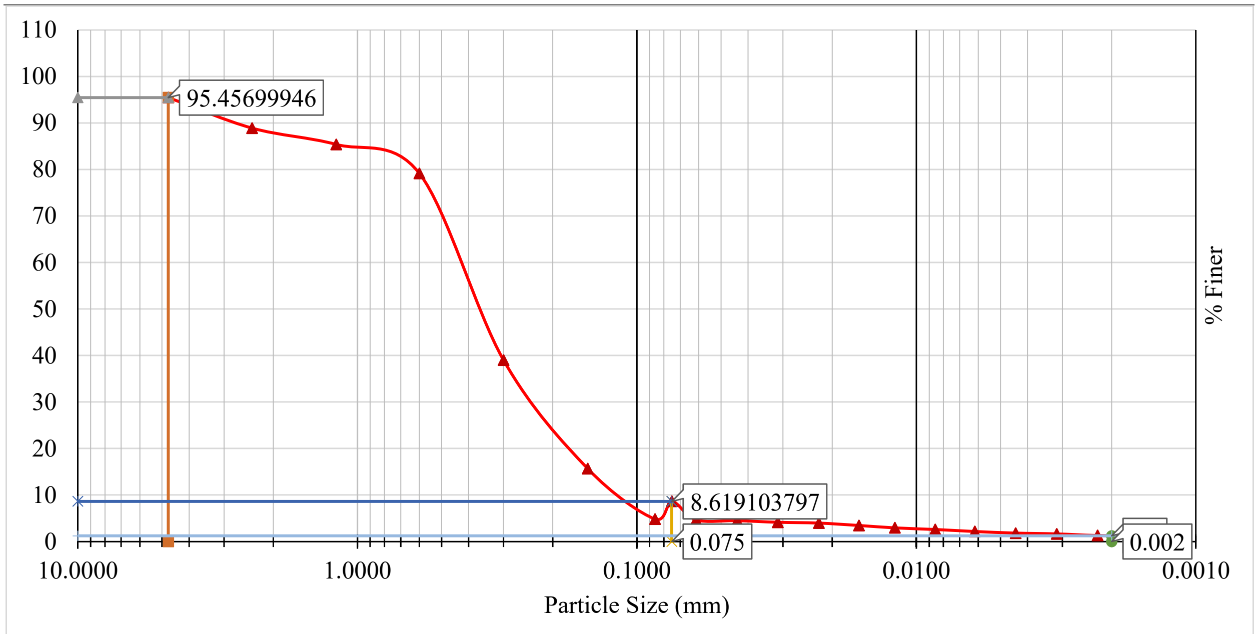


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**25**	
Name of the location	:	Dewan Bazar	
Land-use type	:	Build Up Area	
LATITUDE (Y)	:	22.342524	
LONGITUDE (X)	:	91.842910	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	23.36	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1500.57	gm
Initial wt. of sample passing through #200 sieve	:	23.36	gm



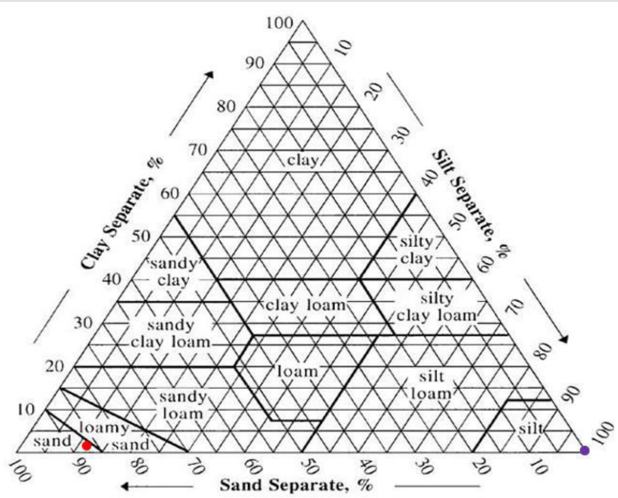
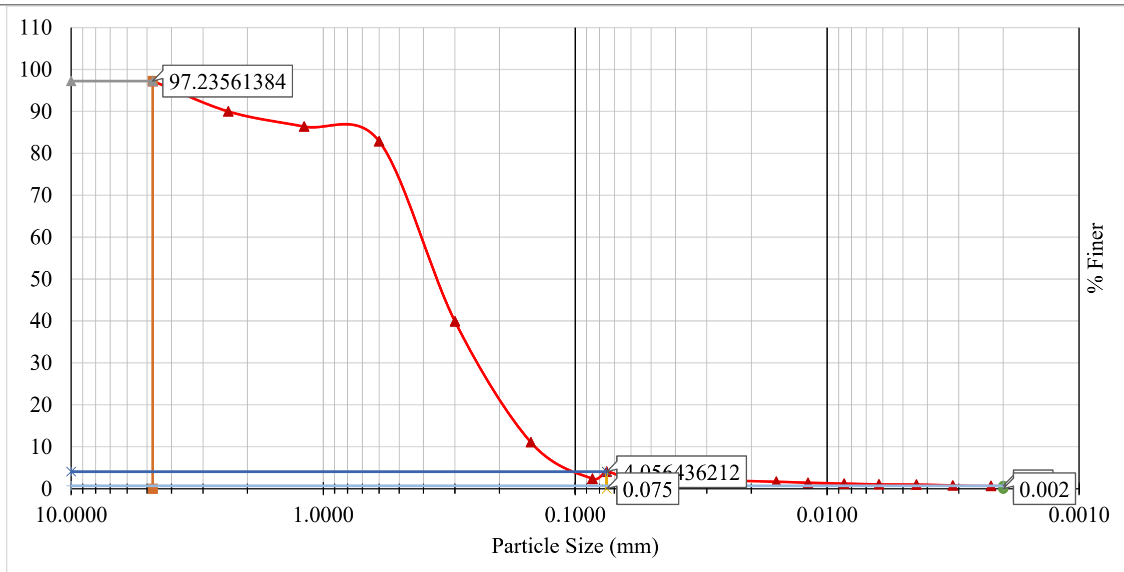


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**26**	
Name of the location	:	Kotowali	
Land-use type	:	Build up area	
LATITUDE (Y)	:	22.341722	
LONGITUDE (X)	:	91.831508	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1500	gm
Initial wt. of sample passing through #200 sieve	:	60.75	gm



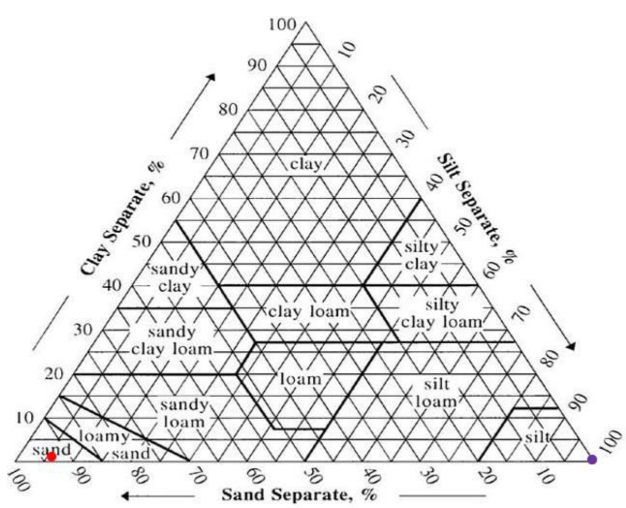
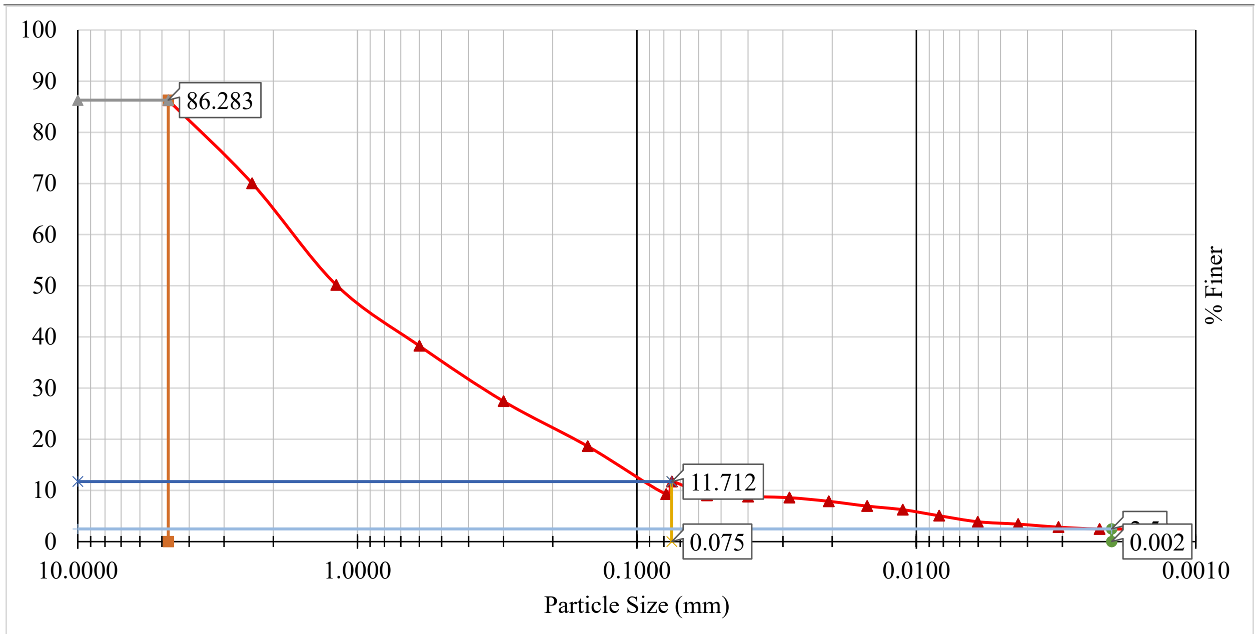


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**27**	
Name of the location	:	Solokbahar	
Land-use type	:	Open space	
LATITUDE (Y)	:	22.365458	
LONGITUDE (X)	:	91.840644	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	117.12	gm



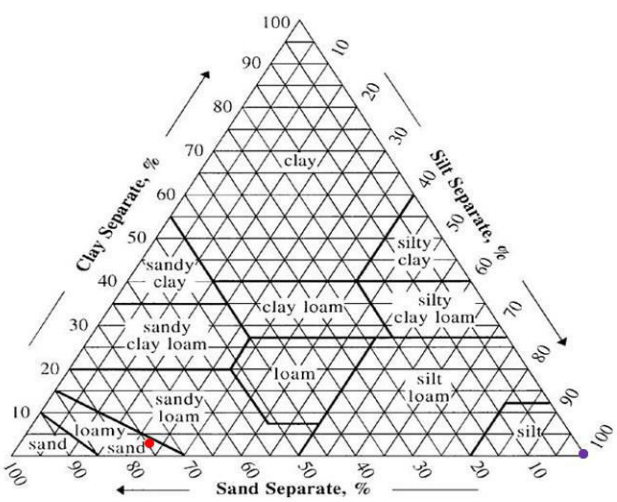
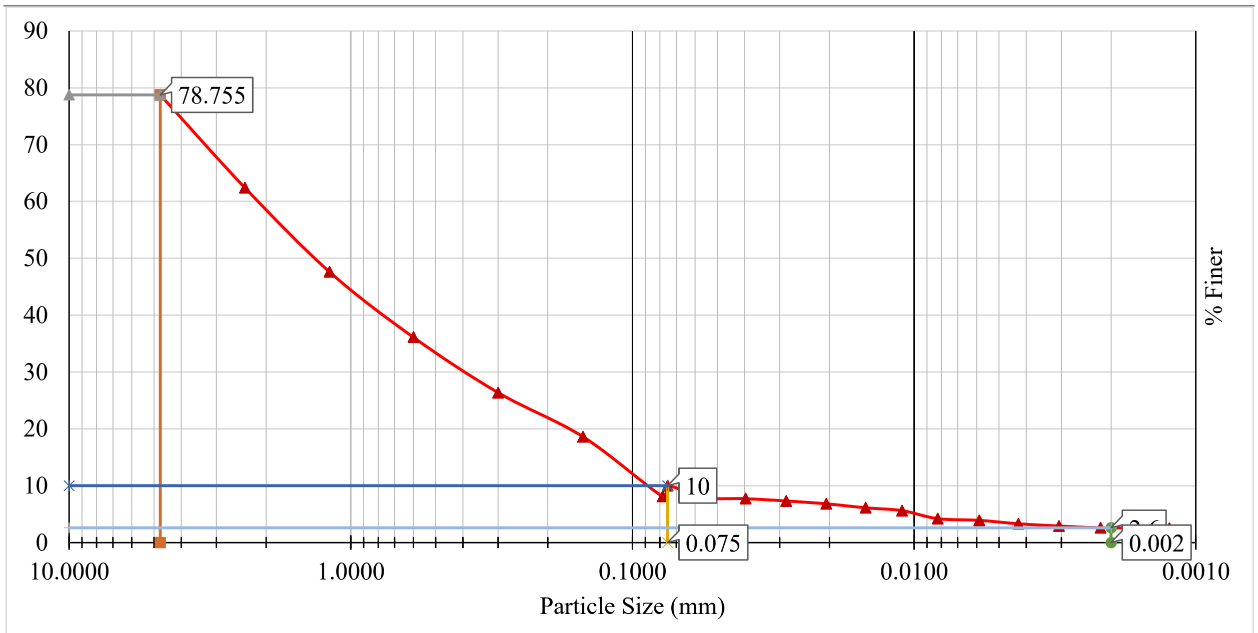


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**28**	
Name of the location	:	Bohaddarhat	
Land-use type	:	Open space	
LATITUDE (Y)	:	22.369825	
LONGITUDE (X)	:	91.843828	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	100	gm



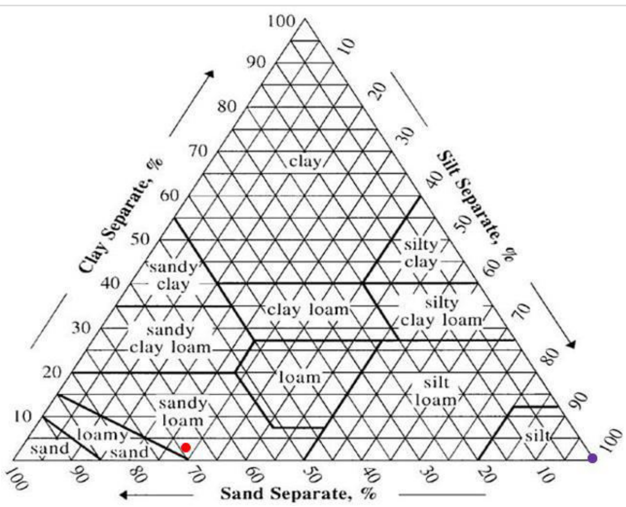
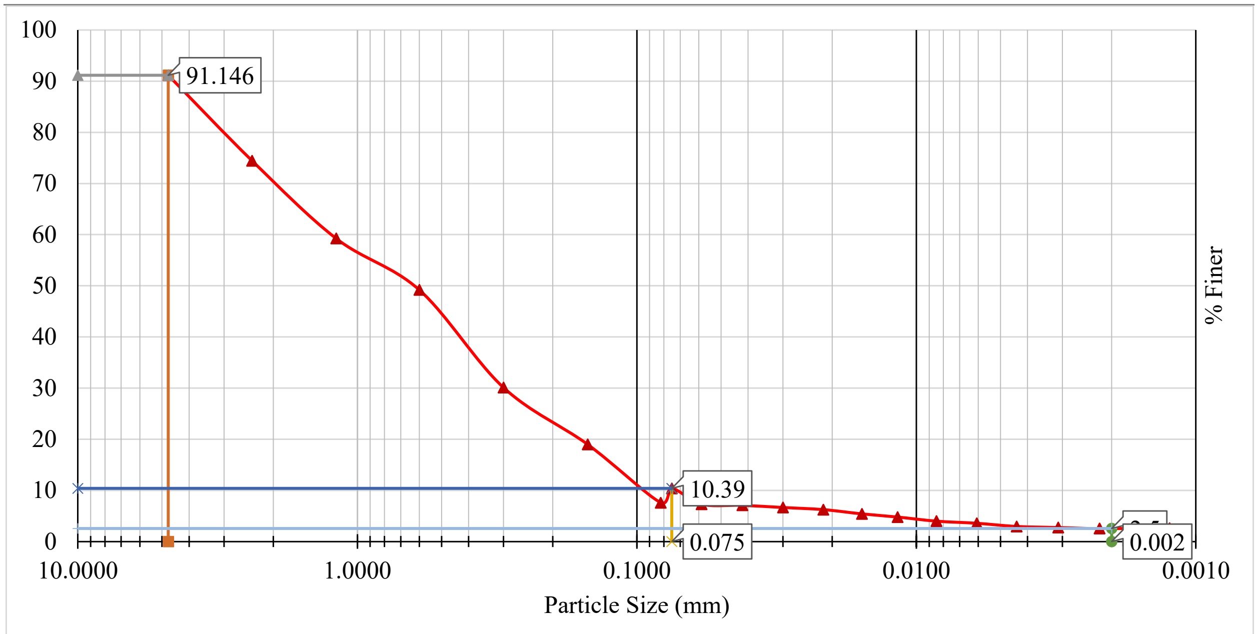


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**29**	
Name of the location	:	Khatunganj	
Land-use type	:	Open space	
LATITUDE (Y)	:	22.337764	
LONGITUDE (X)	:	91.844521`	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	103.9	gm



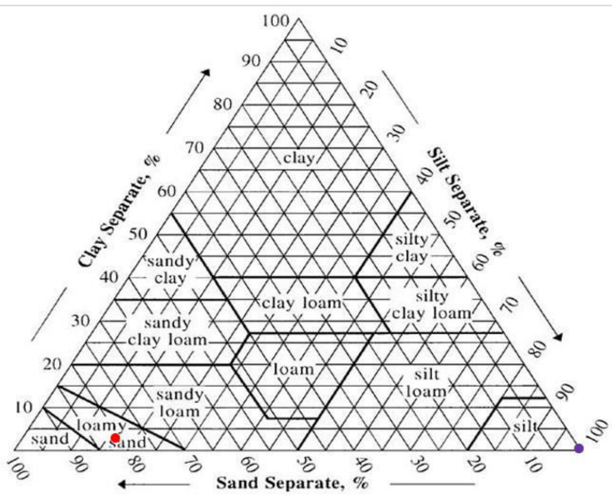
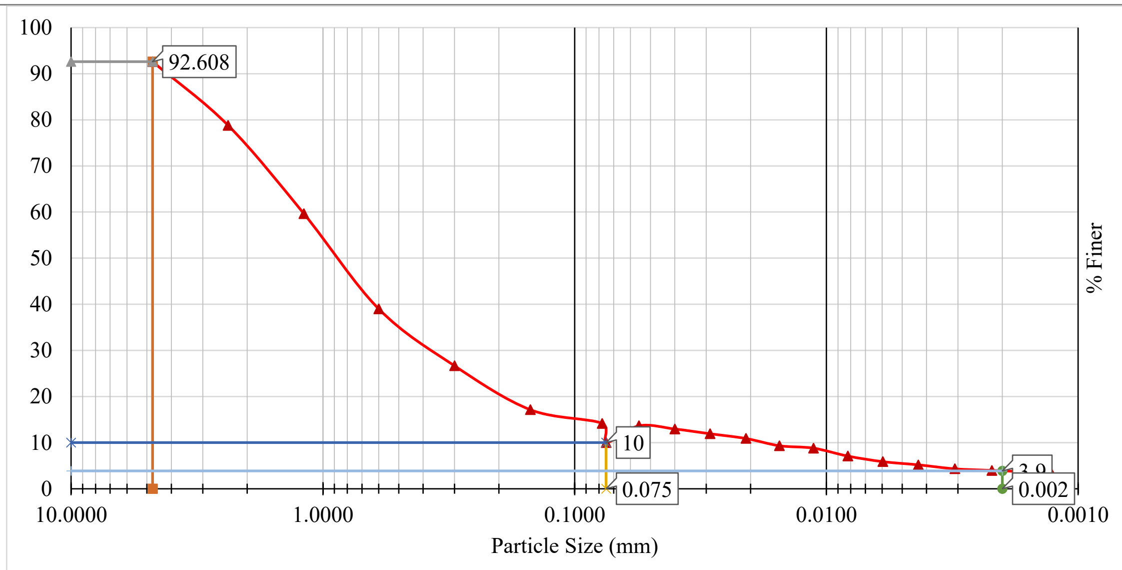


Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Details specification of the collected soil sample from Chaktai-Rajakhali Watershed.

Sample ID	**:**	**30**	
Name of the location	:	South Bakalia	
Land-use type	:	Vegetation	
LATITUDE (Y)	:	22.353380	
LONGITUDE (X)	:	91.851107	
Zero Correction (Cz)	:	1.5	
Meniscus Correction (Cm)	:	1	
Weight of soil sample (Ws)	:	50	gm
Temperature (°C)	:	32	°C
Total wt. of sample	:	1000	gm
Initial wt. of sample passing through #200 sieve	:	100	gm



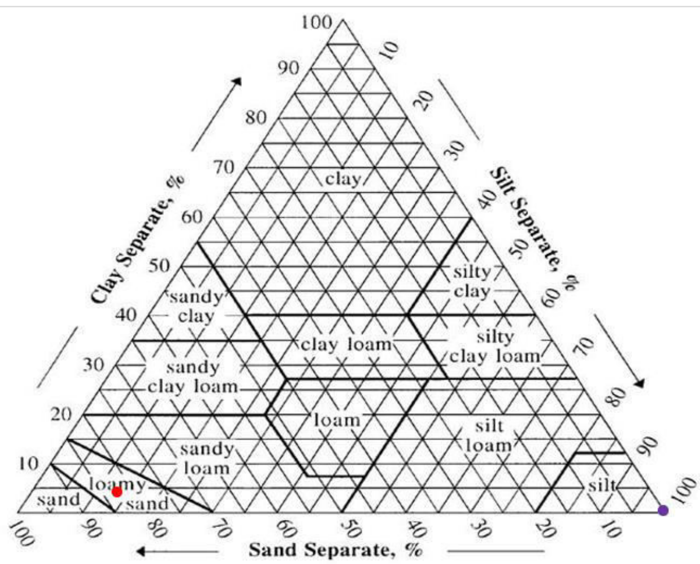


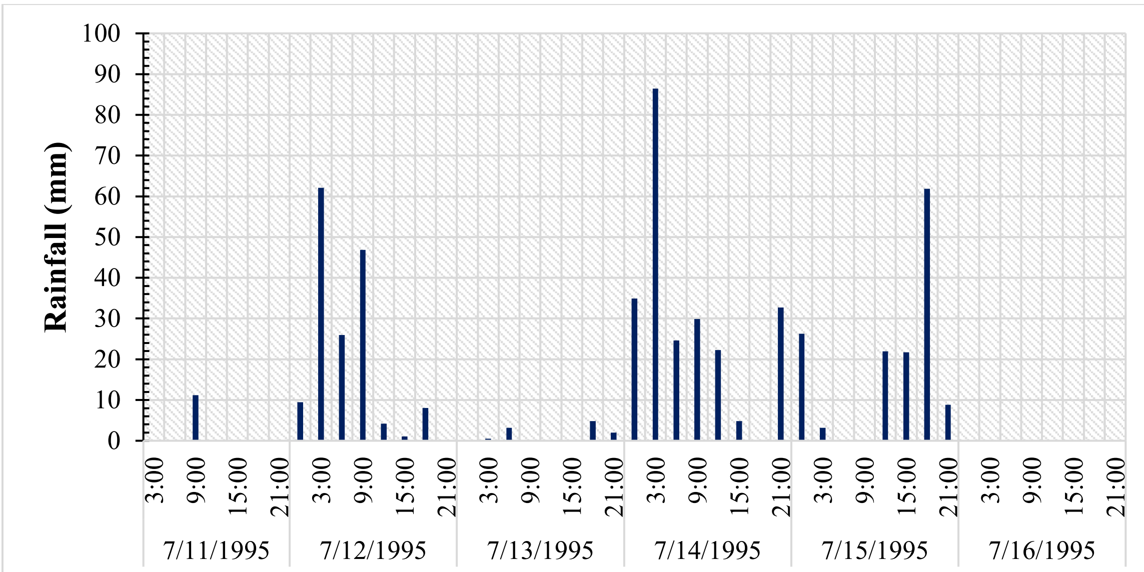
Figure: Textural soil classification of Collected Sample from Chaktai-Rajakhali Watershed.

Table: Compiled information of soil classification for the Collected samples from Chaktai-Rajakhali Watershed.

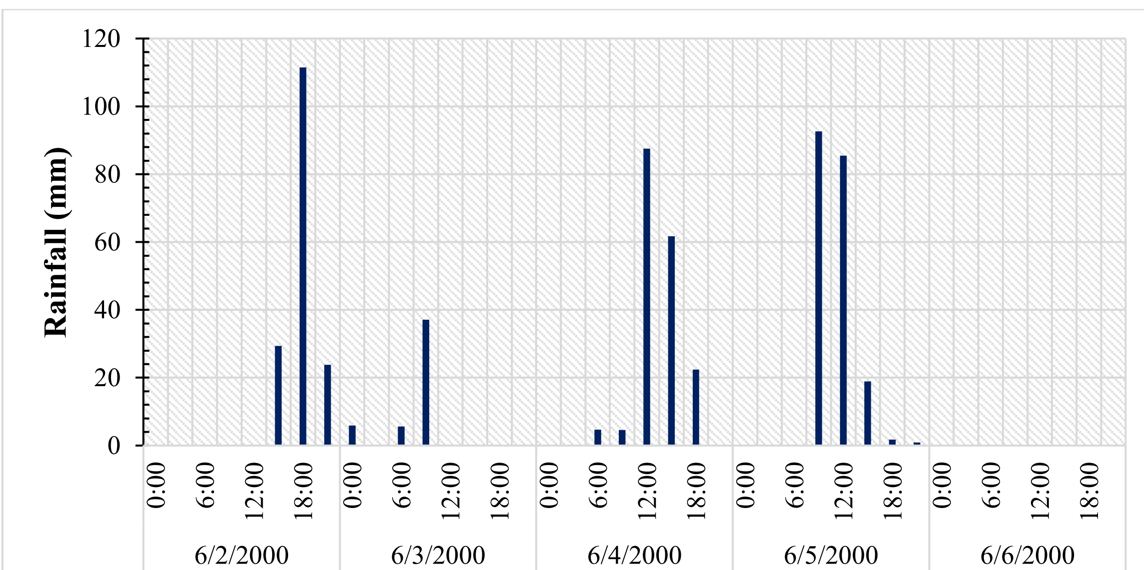
X	Y	Sample ID	Gravel (%)	Sand (%)	Gravel + Sand (%)	Silt(%)	Clay (%)	Soil Classification
91.85843	22.333754	1	6.32	82.97	89.29	8.51	2.2	Loamy Sand
91.854764	22.332097	2	10.85	82.46	93.31	5.51	1.19	Loamy Sand
91.861311	22.44434	3	17.85	75.19	93.04	5.49	1.47	Loamy Sand
91.854356	22.342499	4	0.72	96.46	97.18	2.49	0.33	Sand
91.850642	22.348584	5	12.72	82.27	95	4.14	0.87	Loamy Sand
91.856332	22.340097	6	7.88	81.92	89.8	7.98	2.22	Loamy Sand
91.857223	22.340374	7	3.79	84.68	88.47	9.47	2.07	Loamy Sand
91.8602	22.341117	8	4.12	93.67	97.79	1.77	0.44	Sand
91.857864	22.341843	9	14.3	75.7	90	7.89	2.11	Loamy Sand
91.863691	22.346658	10	3.51	85.45	88.96	9.52	1.52	Loamy Sand
91.86615	22.347539	11	10.4	84.25	94.65	4.73	0.62	Loamy Sand
91.856156	22.348237	12	6.15	86.96	93.12	6.22	0.67	Sand
91.865046	22.350048	13	7.5	85.87	93.37	5.35	1.28	Sand
91.848346	22.356205	14	5.81	86.91	92.72	5.88	1.4	Sand
91.842437	22.349384	15	4.83	86.81	91.64	7.44	0.91	Sand
91.837988	22.326709	16	0.18	96.64	96.83	2.73	0.44	Sand
91.840025	22.326728	17	4.04	89.3	93.34	5.78	0.89	Sand
91.844097	21.327018	18	4.95	88.33	93.28	5.94	0.79	Sand
91.85844	22.363678	19	3.46	88.21	91.67	6.35	1.99	Sand
91.819494	22.33246	20	8.82	79.04	87.86	9.7	2.43	Loamy Sand
91.839026	22.355498	21	4.56	79.11	83.66	13.3	3.03	Loamy Sand
91.828623	22.356397	22	10.75	81.97	92.72	5.91	1.37	Loamy Sand
91.832203	22.3462	23	3.3	88.43	91.73	7.07	1.2	Sand
91.835055	22.360596	24	2.27	96.17	98.44	1.2	0.37	Sand
91.84291	22.342524	25	4.54	86.84	91.38	7.39	1.23	Sand
91.831508	22.341722	26	2.76	93.18	95.94	3.38	0.68	Sand
91.840644	22.365458	27	13.72	74.57	88.29	9.25	2.46	Loamy Sand
91.843828	22.369825	28	21.25	68.76	90	7.42	2.58	Sandy Loam
91.844521	22.337764	29	8.85	80.76	89.61	7.85	2.54	Loamy Sand
91.851107	22.35338	30	7.39	82.61	90	6.15	3.85	Loamy Sand

Appendix C

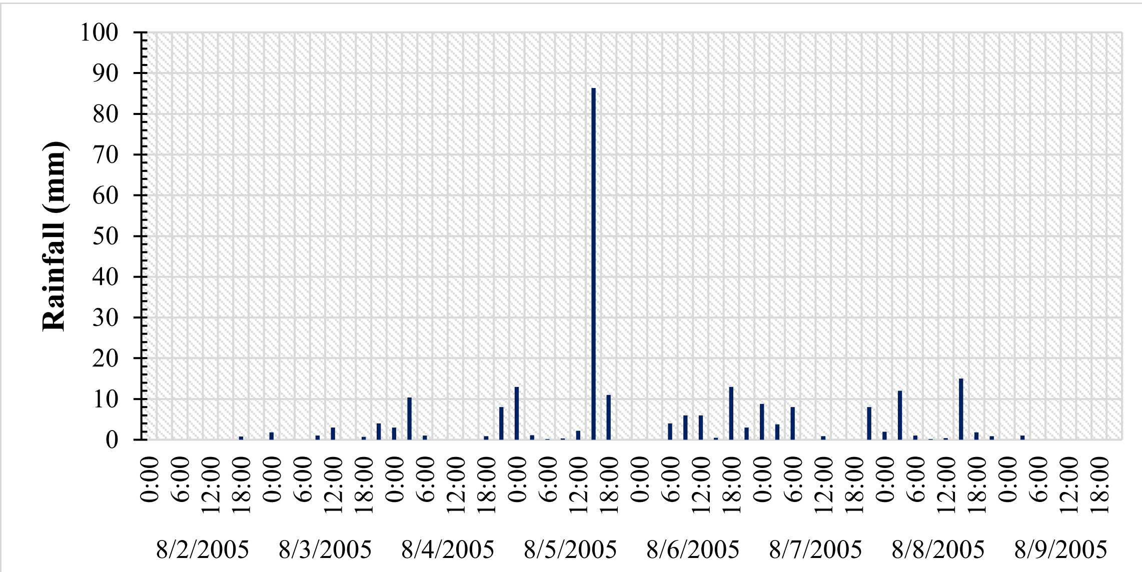
Time series of rainfall for the performance evaluation



(a)

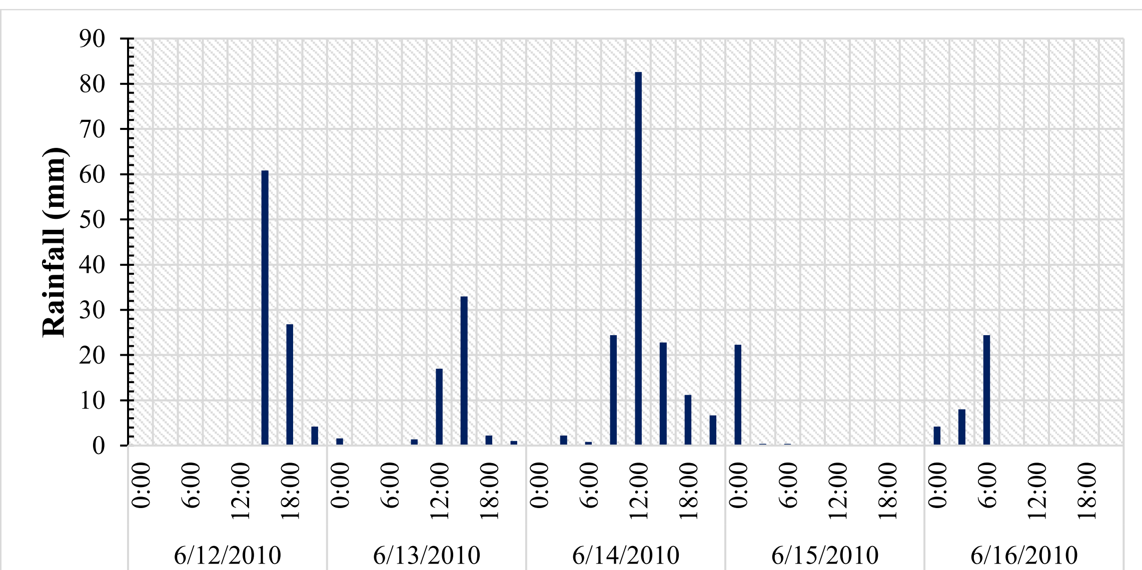


(b)



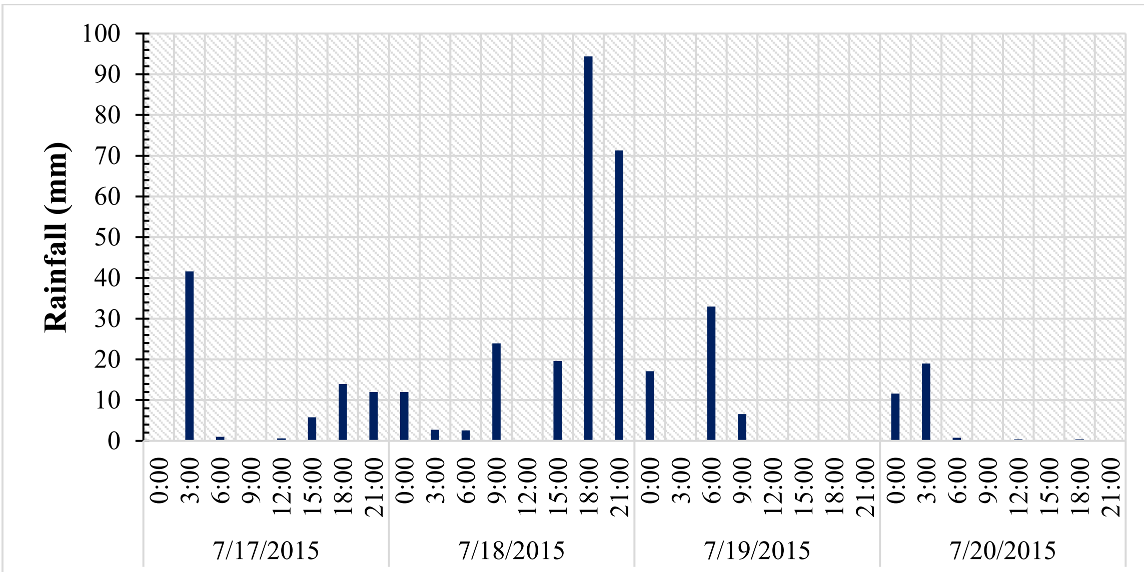
Rainfall (mm)
100
90
80
70
60
50
40
30
20
10
0
0:00
6:00
12:00
18:00
8/2/2005
8/3/2005
8/4/2005
8/5/2005
8/6/2005
8/7/2005
8/8/2005
8/9/2005

(c)

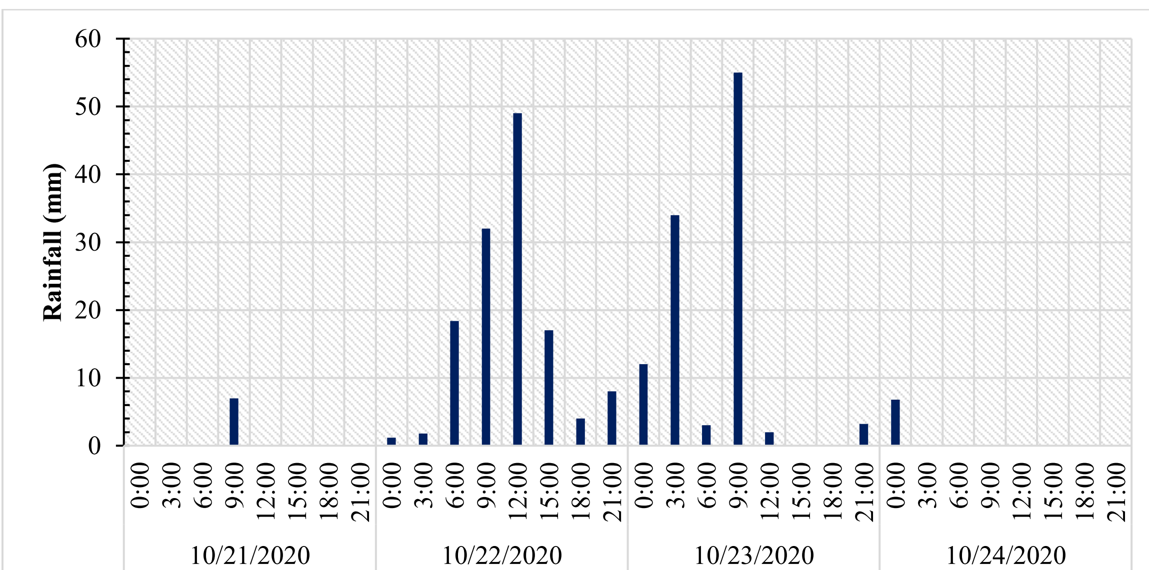


Rainfall (mm)
90
80
70
60
50
40
30
20
10
0
0:00
6:00
12:00
18:00
6/12/2010
6/13/2010
6/14/2010
6/15/2010
6/16/2010

(d)



(e)

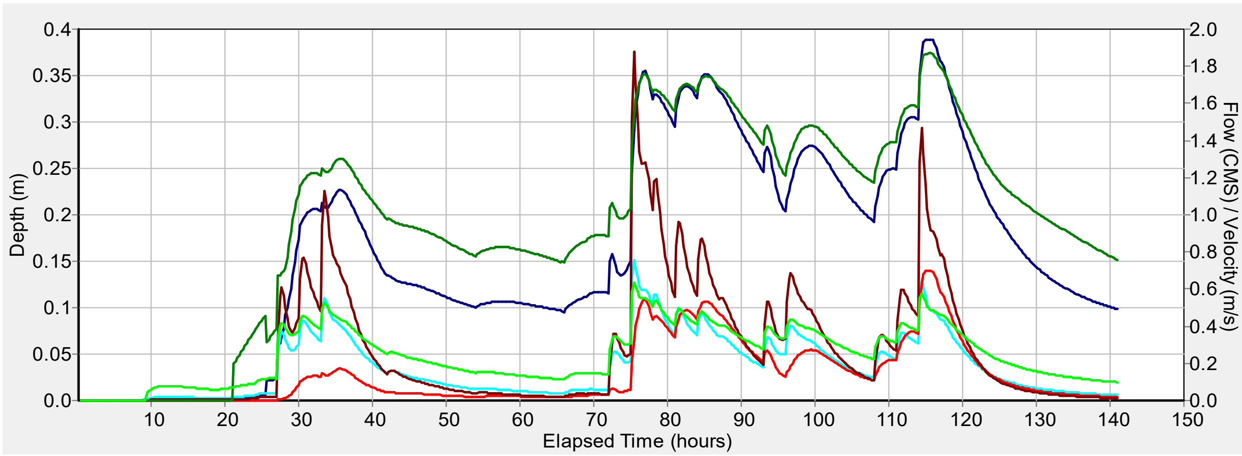


(f)

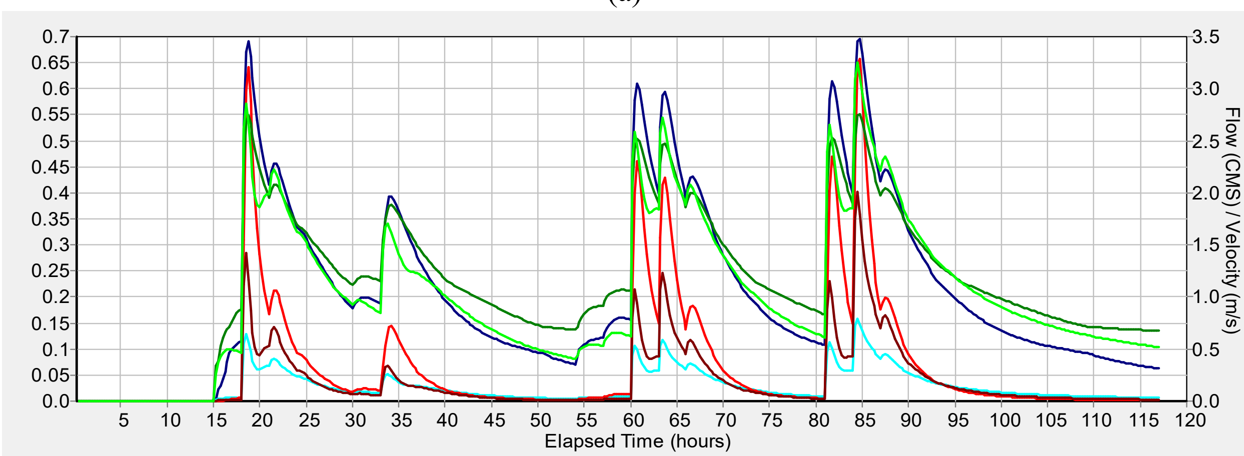
Figure: Selected rainfall events for the performance evaluation of watershed (a) 1995, (b) 2000, (c) 2005, (d) 2010, (e) 2015 and (f) 2020

Appendix D

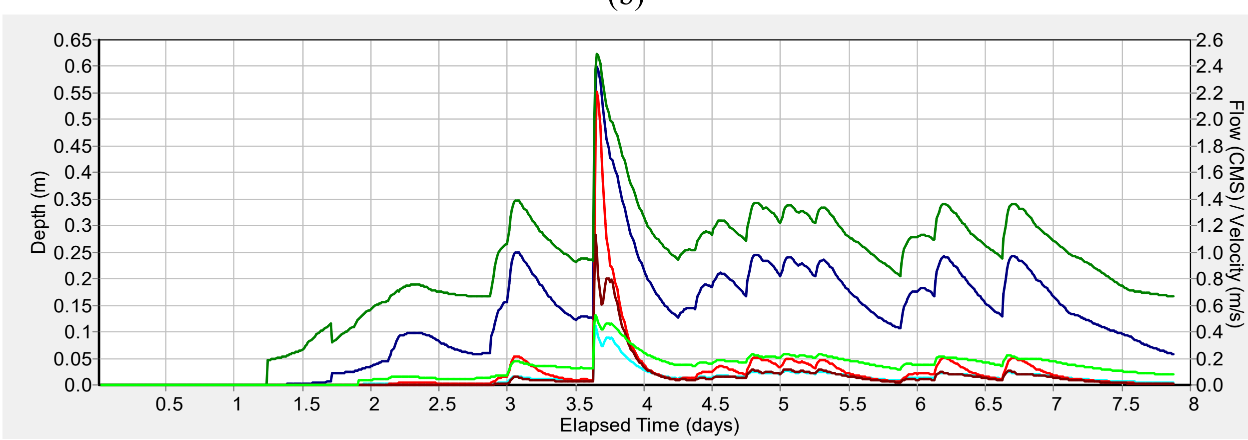
Simulation results of different hydrologic parameters



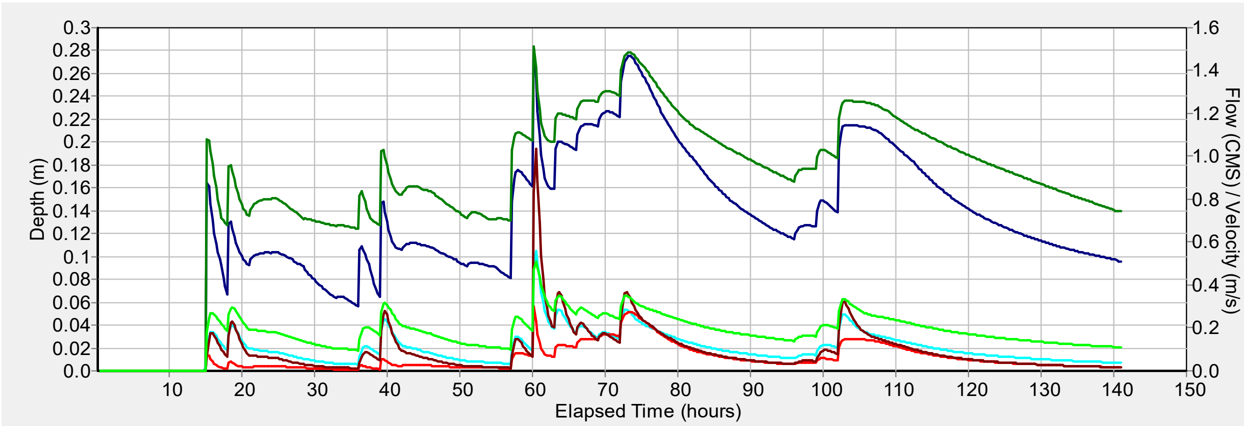
(a)



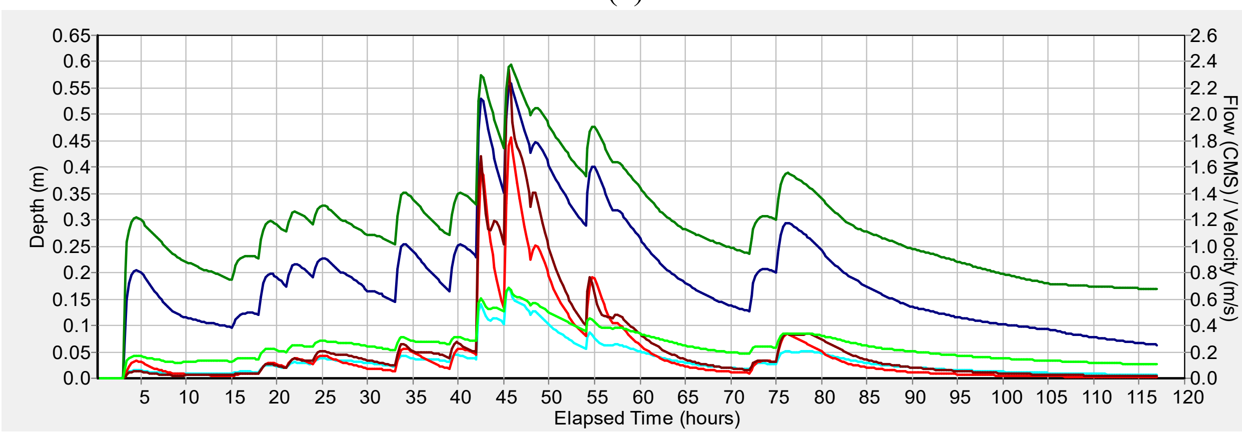
(b)



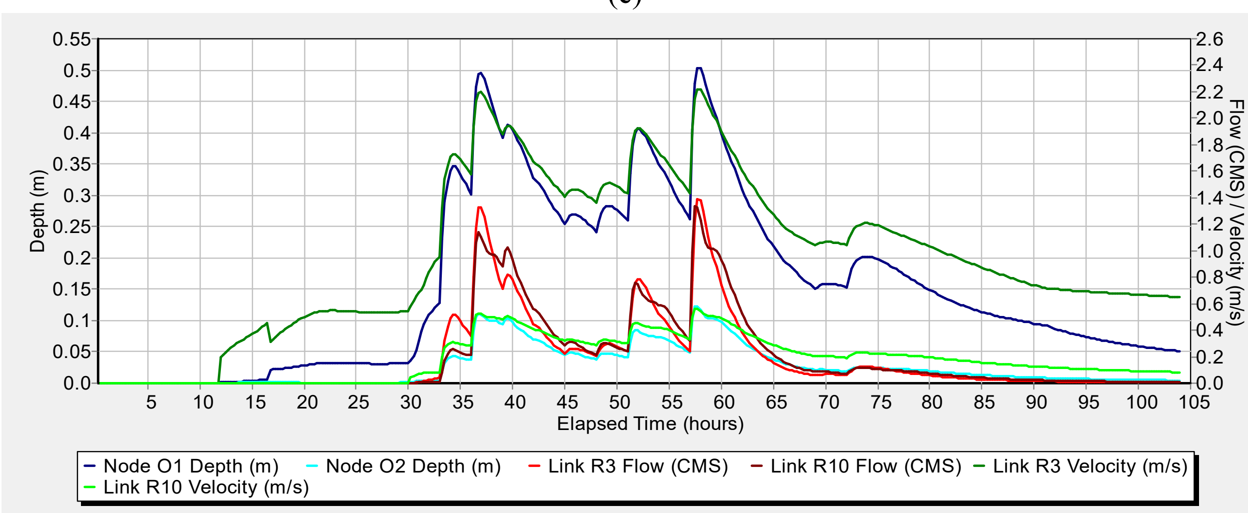
(c)



(d)



(e)



(f)

Figure: Simulation results of different hydrologic parameters (Depth in m, Flow in m^3/s, velocity in m/s) for the selected rainfall events (a) 1995, (b)2000, (c)2005, (d) 2010, (e) 2015, (f) 2020

Appendix E

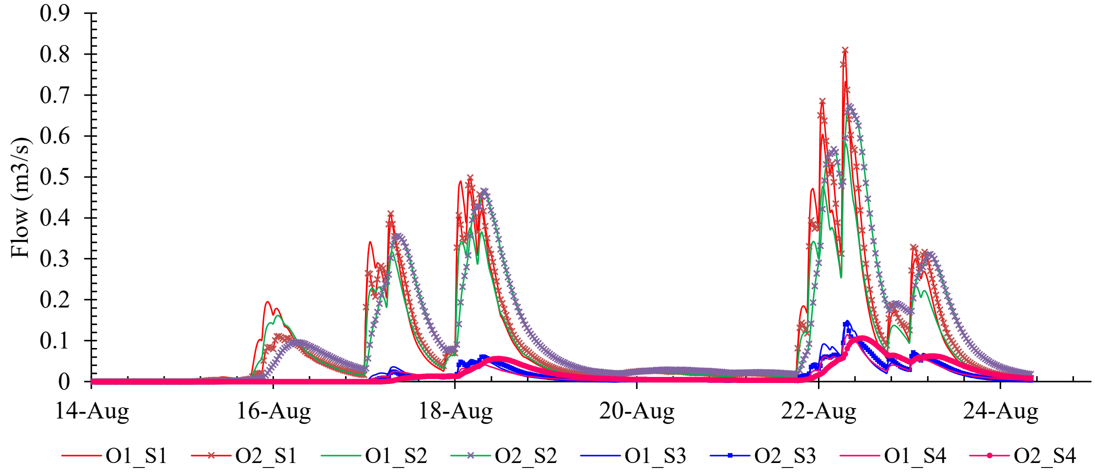
Results of runoff quality parameters

Table: Pollutant Concentrations (training samples) of different land use in Chaktai-Rajakhali canal

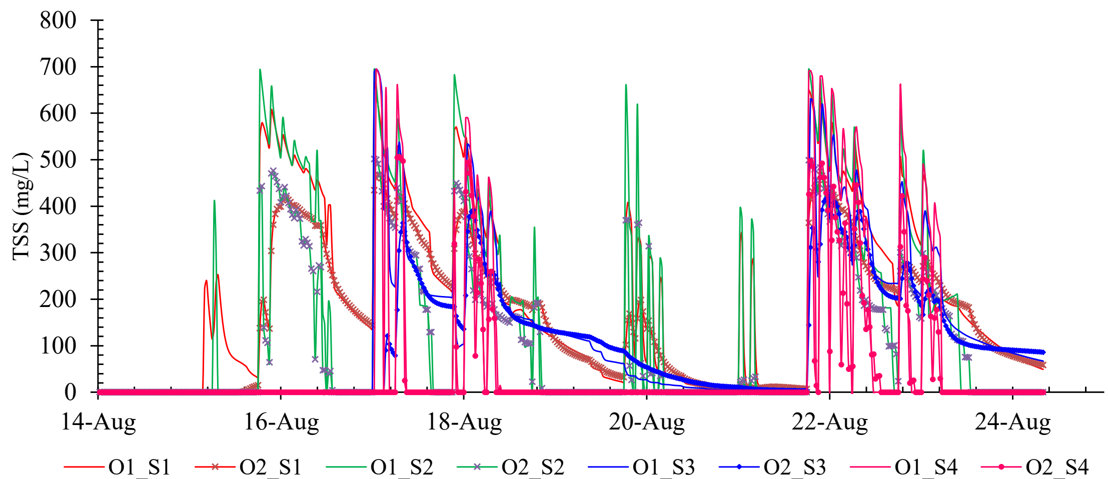
Parameters	Land use	TSS	TN	TP	Zn
TSS (ppm)	Residential	130	137	75	759
	Commercial	324	1625	529	1864
	Institutional	132	1427	1189	1028
	Industrial	54	1689	112	206
TN (mg/L)	Residential	5.64	6.02	7.12	10.54
	Commercial	1.68	3.61	2.87	0.65
	Institutional	2.83	3.58	4.62	1.85
	Industrial	2.65	3.24	12.59	1.92
TP (mg/L)	Residential	0.87	0.94	1.02	1.75
	Commercial	0.28	0.54	0.43	0.08
	Institutional	0.41	0.57	0.68	0.21
	Industrial	0.38	0.47	1.95	0.29
Zinc (Zn) mg/L	Residential	0.13	0.01	0.24	0.36
	Commercial	0.00	0.00	0.09	0.00
	Institutional	0.01	0.02	0.02	0.08
	Industrial	0.04	0.16	0.09	0.03

Table: Observed and simulated pollutant Concentrations (validation samples) of different land use in Chaktai-Rajakhali canal

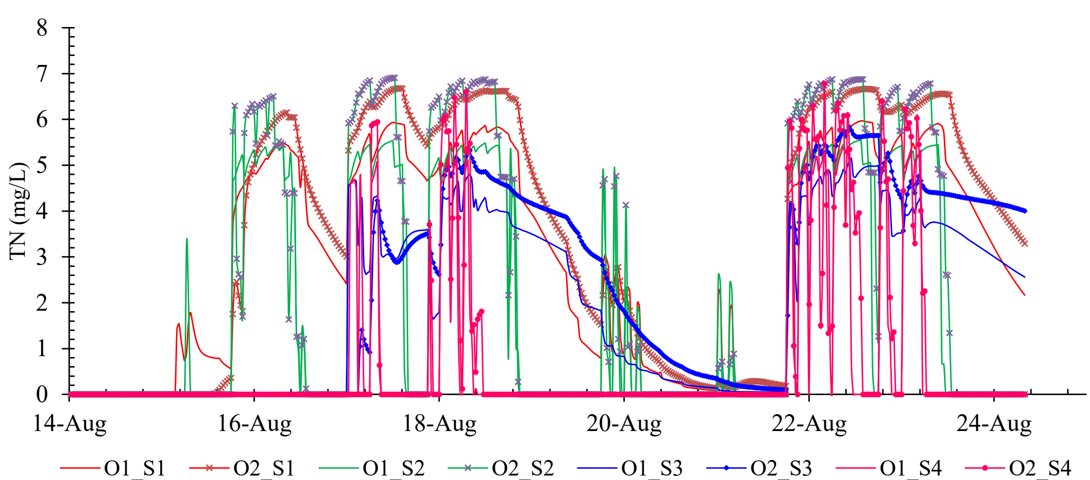
Date & Time	Parameters	TSS (Observed)	TSS (Simulated)	TN (Observed)	TN (Simulated)	TP (Observed)	TP (Simulated)	Zn (Observed)	Zn (Simulated)
08/15/2020, 18.00-08/16/2020,12.00	SC1	317.20	300.60	2.140	1.988	0.410	0.307	0.041	0.041
	SC2	185.30	160.90	3.120	2.711	0.620	0.415	0.047	0.056
	SC3	132.80	145.90	3.100	3.718	0.630	0.580	0.088	0.092
	SC4	84.50	16.64	0.890	0.443	0.010	0.069	0.021	0.011
	SC5	100.50	49.84	1.670	0.908	0.180	0.142	0.019	0.021
	SC6	110.40	43.08	0.750	0.868	0.090	0.135	0.022	0.021
	SC7	98.20	49.38	1.890	1.602	0.230	0.250	0.038	0.040
	SC8	110.30	57.62	0.950	1.366	0.370	0.213	0.035	0.034
	SC9	92.40	11.81	0.450	0.137	0.030	0.021	0.010	0.003
08/16/2020, 21.00-08/17/2020,12.00	SC1	387.90	359.40	3.250	2.760	0.520	0.426	0.072	0.057
	SC2	285.40	255.20	5.470	3.616	0.750	0.554	0.081	0.074
	SC3	90.80	108.80	3.870	4.713	0.980	0.735	0.190	0.116
	SC4	110.20	108.80	4.200	4.115	0.880	0.643	0.150	0.104
	SC5	160.20	163.10	3.120	2.972	0.640	0.464	0.100	0.074
	SC6	175.80	169.90	4.500	4.249	0.500	0.662	0.112	0.104
	SC7	102.40	82.90	3.800	4.382	0.740	0.684	0.090	0.111
	SC8	118.40	113.80	3.400	4.803	0.790	0.749	0.210	0.120
	SC9	245.60	220.30	2.780	2.950	0.870	0.455	0.091	0.066
08/17/2020, 18.00-08/18/2020,21.00	SC1	221.30	195.70	3.410	3.344	0.550	0.516	0.078	0.069
	SC2	145.60	128.70	2.870	2.629	0.490	0.403	0.062	0.054
	SC3	102.70	67.21	4.020	3.840	0.770	0.599	0.011	0.095
	SC4	94.60	67.46	5.980	5.151	0.920	0.805	0.128	0.130
	SC5	164.20	154.10	3.750	4.023	0.640	0.628	0.110	0.100
	SC6	132.40	119.80	4.050	4.645	0.990	0.723	0.121	0.114
	SC7	84.60	62.98	3.080	3.767	0.480	0.589	0.089	0.095
	SC8	90.40	76.65	4.090	4.059	0.820	0.633	0.104	0.101
	SC9	182.40	163.90	3.650	3.800	0.710	0.586	0.091	0.085
08/21/2020, 21.00-08/22/2020,12.00	SC1	110.80	124.90	3.450	3.287	0.590	0.508	0.065	0.067
	SC2	162.60	142.50	3.140	3.758	0.620	0.575	0.081	0.077
	SC3	110.20	65.23	5.020	4.789	0.770	0.747	0.121	0.118
	SC4	114.20	51.67	5.700	5.388	0.980	0.842	0.129	0.136
	SC5	132.80	127.40	5.020	5.405	0.920	0.843	0.141	0.134
	SC6	114.50	94.95	4.880	5.495	0.740	0.856	0.124	0.135
	SC7	125.60	53.45	6.140	6.118	0.920	0.956	0.151	0.154
	SC8	84.20	72.17	6.040	5.894	0.710	0.920	0.137	0.147
	SC9	148.40	135.90	4.440	4.384	0.520	0.676	0.100	0.098


Flow (m3/s)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
14-Aug
16-Aug
18-Aug
20-Aug
22-Aug
24-Aug
O1_S1
O2_S1
O1_S2
O2_S2
O1_S3
O2_S3
O1_S4
O2_S4

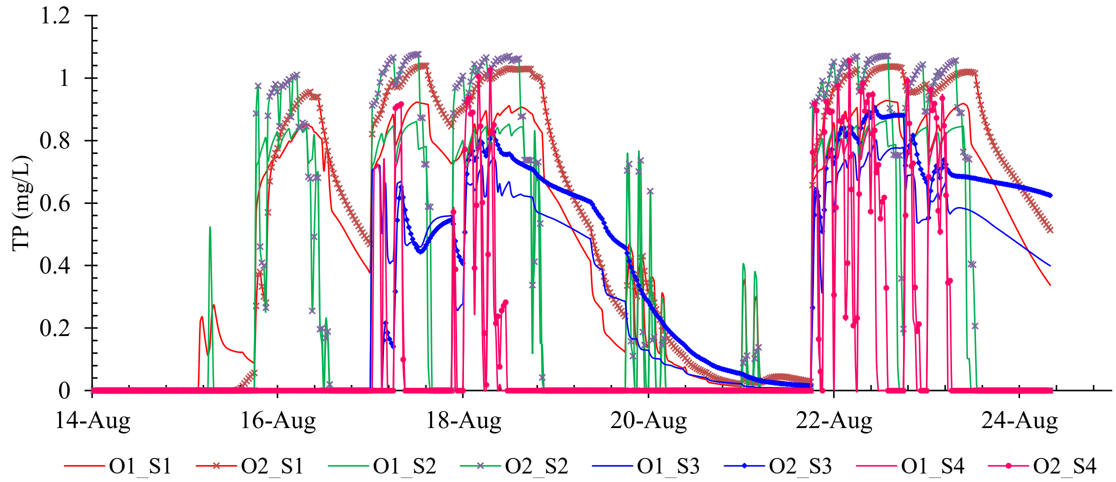
(a)


TSS (mg/L)
800
700
600
500
400
300
200
100
0
14-Aug
16-Aug
18-Aug
20-Aug
22-Aug
24-Aug
O1_S1
O2_S1
O1_S2
O2_S2
O1_S3
O2_S3
O1_S4
O2_S4

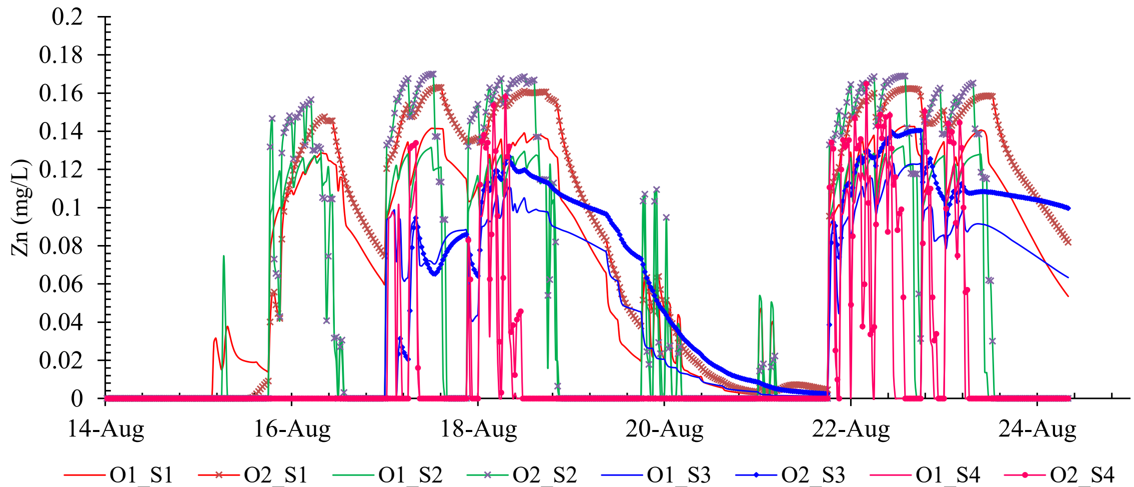
(b)


TN (mg/L)
8
7
6
5
4
3
2
1
0
14-Aug
16-Aug
18-Aug
20-Aug
22-Aug
24-Aug
O1_S1
O2_S1
O1_S2
O2_S2
O1_S3
O2_S3
O1_S4
O2_S4

(c)



(d)



(e)

Figure: Simulation results of runoff quality model from PCSWMM for the selected rainfall event (a) Flow, (b) TSS, (c) TN, (d) TP and (e) Zn.