

Management of Urban Stormwater at Sub-watershed Level

A THESIS
SUBMITTED IN FULFILLMENT OF THE
REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

DOCTOR OF PHILOSOPHY
In
Environmental Science and Engineering

By

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CERTIFICATE

I, hereby certify that the work being presented in the thesis entitled '**Management of Urban Stormwater at Sub-watershed Level**' submitted to the Department of Biotechnology and Environmental Sciences, Thapar University, Patiala for award of the degree of **Doctor of Philosophy**, is an authentic record of my own research work carried out under the guidance and supervision of Dr. Akepati S. Reddy.

The matter embodied in this thesis has not been submitted, in part or full for the award of any other degree/diploma at this or any other university/institute. All the ideas and references have been duly acknowledged.

Date: 23/10/2015

(AMARPREET SINGH ARORA)

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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Dedication

To my Parents

I would like to dedicate this thesis to my beloved parents, Dr. Amarjit Singh and Mrs. Bhupinder Kaur. Their love, moral support and encouragement throughout the completion of this research study are gratefully appreciated.

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This thesis is not a tale of single day but a milestone in more than four years of work done at Thapar University. By that time, I have worked with a number of people whose contribution in assorted ways to the research and the making of the thesis deserved special mention. It is a pleasure to convey my gratitude to all in my humble acknowledgment.

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Amarpreet Singh Arora

Abstract

This thesis presents the outcomes of a comprehensive research study undertaken to investigate the quantity and quality of stormwater generated from the urban areas. The outcome of the information obtained has been utilized in developing a sub-watershed level urban stormwater management system.

Urban stormwater quantity and quality from five different urban sub-watersheds (that differ in land use and development activities) was investigated in the city of Patiala, India. The five sub-watersheds have similar geological, topographical and climatic conditions and were chosen to minimize the effect of these characteristics on stormwater quality and quantity. Assessment on the quantity of stormwater generated was made using Hydrological methods. For characterization, stormwater samples were collected during twelve storm events between April 2010 and March 2013 and analyzed for various water quality parameters. Results of the investigation indicate a strong correlation between land use and development activities and the resulting stormwater quality. TSS, COD, Total Coliform, Fecal Coliform, Oil and Grease, and heavy metals (Fe and Pb) were found to be major pollutants in surface runoff generated from commercial and urbanized catchments (all exceeded the Inland surface water quality standards developed by Central Pollution Control Board, India). The water quality of the smaller residential catchment was better as compared to other catchments.

Principal component analysis was investigated to identify linkages between stormwater quality and urban surface types. Possible inter-parameter relationships among different water quality parameters were identified which was subsequently used in deciding on the scheme of the stormwater treatment system. Multivariate data analysis technique was used to investigate the influence of antecedent dry days and average rainfall intensity on stormwater quality, through regression analysis. Regression models were developed to assess the characteristics

of stormwater runoff produced from any specific storm event with specified antecedent dry days.

Information obtained via quantification and characterization was used in developing a sub-watershed level urban stormwater management system involving collection, treatment and disposal system. An experimental treatment system was developed to test the treatment efficiency of the system in removing pollutants present in the stormwater. Protocol of the ground water recharge facility was also developed.

The primary objective of this research work was to create fundamental knowledge on the quantity and quality of stormwater, to utilize this information in developing an adequate stormwater management system addressing an integrated approach to collection, treatment and disposal. The outcomes of this research can provide practical information for improved urban water management.

Research Publications

Paper published in peer reviewed journals:

1. Arora, A.S. and Reddy, A.S. (2013): Multivariate analysis for assessing the quality of stormwater from different urban surfaces of the Patiala city, Punjab (India), *Urban Water Journal*, 10(6), 422-433. (SCI- Impact factor 1.190)
2. Arora, A.S. and Reddy, A.S. (2014): Development of Multiple Linear Regression Models for predicting the Stormwater quality of Urban Sub-watersheds, *Bulletin of Environmental Contaminant and Toxicology*, 92(1), 36-43. (SCI- Impact factor 1.105)
3. Arora, A.S. and Reddy, A.S. (2015): Conceptualizing a decentralized stormwater treatment system for an urbanized city with improper stormwater drainage facilities. *International Journal of Environmental Science and Technology*, 12(9), 2891-2900. (SCI-Impact Factor 2.190)
4. Bedi M., Arora, A.S. and Reddy, A.S. (2015): Quantification of the hydrological impacts of imperviousness in urban catchments using WIN TR-55, *International Journal of Advanced Technology in Engineering and Science*, 3(1), 551-557. (Non-SCI Impact Factor 1.012).

Papers presented in international and national conferences:

1. Arora, A.S. and Reddy, A.S. (2012): Understanding the role of land use in affecting the quality of the urban stormwater for the Patiala City, Punjab (INDIA), *International Conference on Energy Water Waste Nexus for Environmental Management*, Chaudary Devi Lal University, Sirsa, Haryana.
2. Arora, A.S. and Reddy, A.S. (2013): Regression models for the urban stormwater quality assessment, *National Conference on Environmental Sustainability and Society: The growing paradigm shift*, Jaypee University of Engineering and Technology, Guna, Madhya Pradesh.
3. Arora, A.S., Bedi, M. and Reddy, A.S. (2013): Hydrological Models for quantification of runoff generated in urban and rural catchments/drainage basins/water-sheds, *Green Technology for Sustainable Environmental Management*, Doon University, Dehradun.

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Abbreviations

ADD	Antecedent dry days
Bgl	Below ground level
BOD	Biochemical oxygen demand
Cd	Cadmium
CN	Curve number
COD	Chemical oxygen demand
Cu	Copper
CV	Coefficient of variation
Fe	Iron
GWT	Ground water table
HRT	Hydraulic retention time
LCLU	Land cover land use
MSW	Municipal solid waste
Ni	Nickel
Pb	Lead
PCs	Principal components
PCA	Principal Component Analysis
QA	Quality assurance
QC	Quality control
SS	Suspended solids
SW	Sub-watershed
SWMM	Stormwater management model
Tc	Time of concentration
TDS	Total dissolved solids
TKN	Total kjeldahl nitrogen

TP	Total phosphorous
TSS	Total suspended solids
Zn	Zinc

Chapter-1

Introduction

1.1 Background

Urbanization directly impacts water quantity and quality owing to construction of urban infrastructure and changes in landscape and runoff conveyance networks (Goonetilleke et al., 2005; Marsalek et al., 2006). It transforms natural areas, like forests and grasslands to impervious surfaces such as roads, roofs and parking lots. The increased percentage of impervious surfaces lead to increased runoff volumes, whilst a variety of anthropogenic activities produce a range of pollutants such as nutrients, solids and organic matter, which accumulate on catchment surfaces (US EPA, 1983; Ha and Stenstrom, 2003, Hatt et al. 2006, Birch et al., 2006, Mahbub et al. 2011, Chow. et al., 2013). As a result, both hydrologic and water quality characteristics are significantly affected (ASCE, 1975; Codner et al., 1988; Mein and Goyen, 1988, Sansalone et al. 2005).

Conventionally, centralized urban stormwater management systems have been used to collect and convey the urban stormwater beyond the urban boundary limits for disposal, with or without any treatment (Shuster et al. 2008). Many urban human settlements do not have proper urban stormwater management systems. Where they are present they may not be covering and serving the total urban settlement.

Depleting groundwater resources (rapidly declining groundwater table) and deteriorating groundwater quality have been the serious problems in urban areas. Because of expansion in the impervious areas, recharging of groundwater is minimal. Over exploitation of groundwater for

municipal use is also adversely affecting both quantity and quality of the groundwater resources. With less groundwater recharge, water levels decline more rapidly and accelerate the unwanted consequences of groundwater pumping, such as reduction in groundwater availability, sea water intrusion, land subsidence etc (Stephens et al. 2011).

Augmentation of the available groundwater resources through rain water harvesting and artificial recharge can prove to be an effective strategy. However, the current and more widely used roof top rainwater harvesting, augments the urban groundwater resources (through recharging) but, only to a limited extent. For making the much needed difference, urban stormwater will need to be collected and used for recharging groundwater. This can tackle the urban flood problems and avoid pollution of the environment, specially the receiving water bodies. However, urban stormwater is heavily polluted and cannot be used for groundwater recharge without the necessary prior treatment.

Urban Stormwater Management focused on localized or decentralized collection, treatment and disposal of the stormwater through, reuse and groundwater recharging is needed. But this should be done without causing urban floods and pollution of urban groundwater resources. The stormwater management should in fact become an integral part of sustainable urban water management.

1.2 Study area and the research problem

Patiala (29°49' and 30°47' north latitude, 75°58' and 76°54' east longitude), an erstwhile princely city of the Punjab state of India was chosen as the study area for undertaking the research work and resolving the stormwater management related problems of the city.

Traditionally the city had a multitude of ponds, temporarily storing the urban stormwater and allowing slow groundwater recharging. Expanding urban development has almost engulfed all these ponds. As a consequence, Patiala city is experiencing flooding of many of its low lying locations even with very small rainfall events. The groundwater table of the city is rapidly declining and TDS (Total Dissolved Solids) levels of the groundwater are rapidly increasing. The stormwater drainage of the city is very poor.

Management of the city's stormwater for sustainability needs to tackle these problems. The key areas to address are:

- Avoiding stormwater flooding
- Maximizing local groundwater recharge
- Avoiding the groundwater pollution
- Minimizing and/or eliminating stormwater runoff beyond the urban limits
- Minimizing the dependence on urban groundwater resources

Development of a stormwater management system that addresses the above mentioned problems has been the problem statement under research for this Ph.D. work. Patiala city was divided into a multitude of sub-watersheds, and decentralized urban stormwater management systems were developed for the sub-watersheds. The study involved quantification and characterization of the stormwater and development of a sub-watershed level stormwater collection system, treatment system and a treated stormwater disposal system (through groundwater recharging). Dependence on groundwater resources was minimized by using the treated effluent as reclaimed water.

1.3 Objectives of the Ph.D. work

In order to contribute towards a resolution of the research problem stated above, the main objectives identified were:

- To quantify and characterize the stormwaters of Patiala city.
- To study the stormwater systems of Patiala city and collect the background information.
- To conceptualize, develop and design a sub-watershed level urban stormwater management system.

1.4 Scope of the research work

The research study was confined to Patiala city. It considered only the area falling within the 5 Km radius of the city in order to limit the influence of spatial variations in the topographical and climatic parameters. The area was divided into finite number of sub-watersheds (having no stormwater drainage facilities), and from these 5 selected sub-watersheds, which got flooded with stormwater at the outlet, were studied. Stormwater management system was then developed for only one of those selected sub-watersheds.

Rainfall data of 7 years (ranging from January 2006 to December 2012) was considered in the study. The storm events that occurred between April 2010 and March 2013 period which generated runoff and accumulated flood water at the sub-watershed outlet were only considered in the present study.

Characterization of grey water was done to incorporate the grey water into the overall stormwater management system to be conceptualized and designed.

Seasonal variations, meteorological factors (such as wind) and influence of traffic in pollution build-up was not considered.

Assuming existence of well established procedures, design of the stormwater collection system was not included in the study. Similarly design of cyclone de-gritters, diversion systems during extreme rainfall events and micro-filter/slow sand filter were kept outside the scope of this study.

1.5 Significance of the research work

The study was carried for establishing and developing the protocols, procedures and methods for the development and design of a decentralized stormwater management system for urban sub-watersheds. This model has been applied on one of the sub-watershed studied.

The present study came out with a model system for the decentralized urban stormwater management, which can be replicated in any of the urban sub-watersheds.

The model system can become an integral part of the larger sustainable urban water management system.

1.6 Justification for the research

In India, urban infrastructure development is by and large unplanned. Illegal encroachments alongside the natural drain and low lying areas often result in inefficient and ineffective storm drainage. Groundwater depletion and pollution, urban floods, poor sanitation conditions, and serious environmental pollution, is common in most of the Indian cities. Urban growth most often also neglects the important environmental functions of natural waterways. Permanent

changes to the catchments are increasing the surface runoff, changing the drainage patterns, and enhancing the magnitude and frequency of floods.

To come up with a sustainable stormwater management plan for the Indian cities was the paramount objective of this research. A paradigm shift is required in India for considering stormwater as a potential resource rather than a liability or waste. With the regular annual flooding of cities across India coupled with the other associated problems, a visionary stormwater management approach comprising of the management at the urban sub-watershed level, involving collection and treatment of the stormwater, and disposal of the treated water through groundwater recharge was thought of as an effective answer to the multitude of problems.

1.7 Contribution to the knowledge

Stormwater characteristics and quantification studies for Indian cities are almost not available. The present study provide the information for Patiala city, which is Class-C (3rd level) Indian city. The study further reviewed the protocols, procedures and techniques employed globally for the characterization and quantification of the stormwater and came out with the protocol, procedures and techniques that can be employed for Indian cities.

Many of the Indian cities do not have properly designed and functional stormwater management system. In the cities where present, they are stormwater drainage systems collecting just the stormwater and conveying the same beyond the city boundaries. The systems were not addressing the problems of sustainable urban water management. The present study made an effort to develop sample stormwater systems that drain, treat and dispose off the urban stormwater, while addressing the issues and problems associated with sustainable urban water

management. The study proposed decentralized urban sub-watershed level stormwater management (apparently new) for collection, treatment and disposal of stormwater.

The stormwater management system proposed segregation of grey water from bath water and leave enough scope for the ecological sanitation practices implementation in urban areas.

Management of grey water along with the stormwater has been suggested in this study for the first time mainly to serve the following purposes.

1. Keeping the treatment system viable and functioning.
2. Increased use of the stormwater treatment system and facilitating the reclamation and reuse of the grey water.

Here sewerage system provided will be handling only the black water. The above mentioned approach is considered as very important for the sustainable urban water management.

The study also reviewed the groundwater recharge systems for assessing their suitability in the proposed urban stormwater management system. A scientific protocol for the sizing and design of the groundwater recharge system is not existing and needs further study.

1.8 Outline of the thesis

This thesis includes five chapters. Chapter 1 describes the research background, research problem and objective of the research study. Chapter 2 provides a critical review of past research relevant to the current research study. It includes information on the various aspects related to urban stormwater management (collection, treatment and disposal) and identifies gaps in the previous studies in context to the present study. Chapter 3 presents the research methodology

followed to achieve the objectives of this work. Chapter 4 provides the results and discussion on the extensive work undertaken involving first the selection and identification of the sub-watershed followed by their characterization and then carrying out the work of quantification and characterization of stormwater generated from the selected sub-watersheds. Design details along with the experimental results obtained for the experimental stormwater treatment system are also presented and finally a sub-watershed level urban stormwater management system has been conceptualized. Chapter 5 is about conclusions and future research. Finally all the references cited in the thesis are listed. Important raw data and a design case of stormwater-grey water treatment system and a groundwater recharge well for one of the selected sub-watersheds are given in the appendices of the thesis.

Chapter-2

Review of Literature

The literature review was carried out from sources like research papers published in peer reviewed journals, technical reports, working papers of sponsored projects, proceedings of international conferences and technical manuals published by various national and international agencies, like, USEPA, Global Water Partnership (GWP), Center for Watershed Protection (CWP), CALTRANS, Central Ground Water Board (CGWB) etc.

In-depth study was done on the following aspects:

- Urban stormwater management (including BMPs)
- Quantification of stormwater
- Characterization of storm water and grey water
- Stormwater treatment systems
- Groundwater recharge systems for stormwater disposal

2.1 Urban stormwater management

Stormwater has long been regarded as a major culprit in urban flooding, but only in the past 30 years have policymakers appreciated its significant role in degrading the streams, rivers, lakes, and other water bodies in urban and suburban areas. Large volumes of rapidly moving stormwater can harm species habitat and pollute sensitive drinking water sources, among other impacts (Huong and Pathirana, 2013). Even in the absence of regulatory changes, there are many stormwater management approaches that can be used to prevent, reduce, and treat stormwater flows. Central to the EPA Stormwater Program is the requirement to develop stormwater

pollution prevention plans that include stormwater control measures. When designed, constructed, and maintained correctly, stormwater control measures have demonstrated reduced runoff volume, peak flows and pollutant removal (Pearson et al., 2010; Zhou, 2014).

For taking care of the pollutants the stormwater treatment practices are required (which can be used either alone or in combination) to meet the treatment standards. Stormwater retrofit practices (both off-site storage and on-site retrofit techniques) are required that can capture and treat stormwater runoff, before it is delivered to the stream, in order to remove stormwater pollutants, minimize channel erosion, and help in restoring stream hydrology.

Despite development over the years, it remains a significant challenge to design an effective functioning drainage system. In particular, impacts due to climate change and urbanization have been widely acknowledged, which could entail a substantial increase in the frequency and magnitude of urban flooding in many regions of the world (Zhou et al., 2012, Huong and Pathirana, 2013). At the same time, water quality problems also emerge as a result of urbanization which increases the variety and amount of pollutants and nutrients in receiving water bodies (Wang et al., 2008; Arora and Reddy, 2013).

One of the most important reasons of the problem faced in urban areas is the lack of planning during and prior to the construction phase of the project (Charlesworth, 2010). Technical literature contains many examples of adverse economic and environmental impacts associated with the traditional approach of centralised urban water supply, sanitation, and drainage systems to water service provision (Butler and Maksimovic, 1999; Mouritz, 2000; Marsalek et al., 2001; Vlachos and Braga; 2001, Mitchell et al., 2003). The emergence and eventual widespread acceptance of the paradigm of Integrated Urban Water Management (IUWM) has occurred

globally during the last 25 years or so (Marsalek et al., 2001). So, this “new paradigm” of IUWM places an emphasis on demand-side management as well as supply-side management, utilization of nontraditional water resources, and the concept of fit for-purpose and decentralization, which appears in much of the literature discussing urban water and sustainability (Newman and Mouritz, 1996; Varis and Somlyódy, 1997; Niemczynowicz, 1999; Mitchell, 2002).

Since the Brundtland Report, the Rio declaration and Agenda 21, sustainable drainage systems have been highly promoted as an alternative and/or complement to the traditional approach to address long-term sustainability in the design of the system (United Nations, 1992; Larsen, 1997; Stahre, 2006). There is a growing trend towards managing water in a more sustainable way by activating its natural behaviors and process in the urban environment (Ashley et al., 2007; Fryd et al., 2012). Unlike conventional drainage focusing on the “end-of-pipe” or “at the point of the problem” solutions (Faram et al., 2010), with small and decentralized techniques, sustainable drainage systems can largely alleviate the adverse impacts of non-point source pollution to urban water bodies (D’Arcy and Frost, 2001; Mitchell, 2005; Echols, 2007). Such solutions rely on local treatment, retention, re-use, infiltration and conveyance of water runoff in urban areas and thus are in better agreement with sustainable principles (Ashley et al. 2007; Roy et al. 2008). At the same time, there is rising acknowledgement of the potential of such systems with respect to their positive effects on urban landscape (Stahre, 2006, Zhou, 2013). It is suggested to treat water as a positive source in sustainable drainage design to create new recreational sites in the urban landscape (Ferguson, 1991; France, 2002). By doing so, the urban water is no longer hidden from the public, but used as an asset to increase user satisfaction and perceived values (Semadeni-Davies et al., 2008; Fratini et al., 2012).

In Europe, Sustainable Urban Drainage System (SUDS) is used with its main focus on maintaining good public health, protecting valuable water resources from pollution and preserving biological diversity and natural resources for future needs (Butler and Parkinson, 1997; Hellström et al., 2000; Willems et al., 2012). In Australia, the term Water Sensitive Urban Design (WSUD) was proposed as a catchment-wide approach of which SUDS is a part and mainly refers to a planning and engineering approach to sustainably integrate urban water management into city landscape to minimize environmental degradation and achieve harmony between water and the urban environment (Sharma et al., 2008; Roy et al., 2008). SUDS is known as Low-Impact Development (LID) in the United States and Canada, describes an approach promoting the interaction of natural processes with the urban environment to preserve and recreate ecosystems for water management (Coffman et al., 1998). LID puts the emphasis on conserving and using natural features in combination with small-scale hydrological controls to mitigate adverse impacts of urbanization (County, 1999; Dietz, 2007; Elliot and Trowsdale, 2007). Examples of similar approaches are Best Management Practices (BMP) in the United States and LIUDD (low impact urban design and development) in New Zealand.

Stormwater **Best Management Practices (BMP's)** are implemented as a way of treating or limiting pollutants and other damaging effects of stormwater runoff. There are two major categories of BMPs: non-structural and structural. In North Carolina, the management of stormwater runoff through non-structural BMPs is the preferred method of reducing pollution from developing urban and suburban areas. In cases where the preferred methods are not feasible or are insufficient, or where stormwater controls are being used to retrofit existing development, engineered or structural BMPs are viable solutions to reducing pollution.

Non-structural BMPs normally do not have technical or engineering designs associated with them. Some typical non-structural BMPs are listed below (NCDENR BMP Manual, 2007):

- Public education and participation.
- Land use planning and management (vegetative controls, reduced impervious areas, disconnected impervious areas).
- Material use controls (housekeeping practices, safer alternative products, pesticide and fertilizer use).
- Material exposure controls (material storage control, vehicle-use reduction).
- Illegal dumping controls (household hazardous waste collection, used oil collection).
- Spill prevention and cleanup (vehicle spill control, aboveground tank spill control).
- Connection controls (illicit connection detection, removal, and prevention, leaking sanitary sewer control).
- Street and storm drain maintenance (roadway cleaning, catch basin cleaning, vegetation controls, storm drain flushing, roadway/bridge maintenance, drainage channel and creek maintenance).

Structural BMPs:

Structural BMPs refer to physical structures designed to remove pollutants from stormwater runoff, reduce downstream erosion, provide flood control, and promote groundwater recharge. Structural BMPs typically require engineering design and engineered construction. The several types of structural BMPs vary greatly in their design and have advantages and disadvantages relative to each other. Some structural BMPs provide considerable stormwater quantity handling capability through the use of infiltration and/or detention/retention facilities (e.g. infiltration devices, stormwater wetlands, wet detention basins). Others provide many types of pollutant

removal mechanisms such as sedimentation, filtration, microbial action, and plant uptake (e.g. bioretention, stormwater wetlands). Some BMPs provide high levels of both stormwater quantity handling and pollutant removal ability. In addition, structural BMPs can be divided into those that help reduce the pollutants or quantity of stormwater entering a collection system (e.g. permeable pavement, filter strips, rooftop runoff management), and those that treat the stormwater at the “end of pipe” (e.g. sand filter, stormwater wetlands, wet detention basins).

Besides these BMP's, the best way to manage stormwater pollution is by adopting a new framework for targeting pollution source control at the sub-watershed level (Center for Watershed Protection (CWP) Manual, 2005, ‘Pollution Source Control Practices’). Several methods can be used to assess sub-watershed pollution sources in order to develop and target education and enforcement efforts that can prevent or reduce polluting behaviors and operations. Conceptualizing urban areas as being made up of various component surfaces has developed with the emergence of Water Sensitive Urban Design (WSUD). WSUD involves management practices (e.g. rainwater tanks and grass swales) that can be implemented at a small scale within individual lots. The success of WSUD as an urban planning and design paradigm will rest largely on the ability of the urban design industry to provide engaging and informative landscape design solutions within the public realm (Kay et al., 2004).

Numerous case studies are available highlighting the use of urban stormwater for portable use. One such study was conducted by Lim and Lim (1999) in Singapore where urban stormwater collection for portable use was being practiced. Almost half of the city's total land area has been utilized as water catchments. Public Utilities Board (PUB) of the city had embarked on a unique scheme to implement urban stormwater pond collection systems in catchments to exploit the harnessing of storm runoff from new townships and augment its limited water supplies.

According to the authors, the urban stormwater collection systems are feasible, through implementation of a coordinated and integrated approach to development control and land use planning, together with innovative design and effective catchments management. Close monitoring and control of pollution, through the adoption of stringent anti-pollution measures, and enforcement actions have resulted in the collection of good quality raw water from these urbanized catchments with very low levels of heavy metals and low coliform counts. Since then, newer urban stormwater pond collection stations have been implemented or are being planned in the northern and northwestern parts of Singapore to replace the existing stream abstraction stations. In New South Wales (NSW), managing urban stormwater for harvesting and reuse is considered as an invaluable part of the Government's Metropolitan Water Plan which aims at utilizing all the cost-effective means that help meeting the water demands of Sydney as it grows while sustaining the health of the rivers. Review of studies conducted on Australian stormwater treatment and recycling practices with focus primarily on the recycling of general urban runoff (runoff generated from all urban surfaces) for non-potable purposes was carried out by Hatt et al. (2006) in which the author indicated the need for the development of innovative techniques for the collection, treatment and storage of stormwater. Even Hamel et al. (2013) on reviewing the impacts of urbanization on base flow in peri-urban catchments, with the aim to better understand the potential role of stormwater infiltration source-control technologies in restoring pre-development base flows, suggested that the adoption of a clear framework for base flow assessment in pre- and post-development states, along with fundamental research on the translation from site-scale processes to catchment-scale effects, are essential research steps to guide future stormwater management for base flow in peri-urban catchments.

In Denmark, large national research programs include the “Water in urban areas” project working on transformation of the city water infrastructure to climatically robust systems (VANDIBYER, 2014), and the 2BG “Black, Blue & Green” project committed to integrated infrastructure planning for sustainable urban water systems (Fryd et al., 2009). The working papers from 2BG further expound their main goals and include case studies on sustainable urban drainage design implemented in Denmark and the Netherlands (Fryd et al., 2009). In the United Kingdom, the Construction Industry Research and Information Association (CIRIA) promoted sustainable drainage systems and also published a series of documents on design practices and applied projects (Ashley et al., 2007). In Ireland, Dublin’s strategic drainage study involves several local authorities to perform an in-depth drainage assessment of integrated constructed wetlands (Hennelly, 2005). In Sweden, a large six-year research project entitled “Sustainable Urban Water Management” was initiated by the Swedish Foundation for Strategic Research Programme with its focus on protecting valuable water resources in urban areas (Malmqvist, 1999; Hellström, 2000). In Australia, one of the largest research activities on sustainable drainage solutions is the Cooperative Research Centre (CRC) for Water Sensitive Cities, which brings together over 70 inter-disciplinary partners to deliver sustainable water strategies facilitating transformation of the city into a more liveable and resilient environment (Langenbach et al., 2008; Wong and Brown, 2009).

From a management and governing perspective, Brown and Farrelly (2009) explored transition bundles from conventional drainage approaches to sustainable solutions and revealed that the barriers are largely socio-institutional rather than technical. Butler and Parkinson (1997) addressed new elements of sustainable drainage design and strategies to facilitate the transition from current practices to the new paradigm. To facilitate decisions on SUDS, Lai et al. (2008)

reviewed a multi-criteria decision aid for integrated sustainability assessment, where three other popular decision-making support tools were also analyzed and compared. All of these previous reviews provide valuable background on the concepts, features, objectives, techniques and tools for sustainable drainage design, with a specific focus on one of the components.

Strategies for sustainable stormwater management are needed at different decision levels (political, regional or local scale, for instance) but all of them need information and a clear understanding of the possibilities that are at stake as well as the main consequences of each decision. A sound approach to stormwater management should be flexible, based on local characteristics, and should take into consideration temporal, spatial and administrative factors and law, among other issues.

2.2 Quantification of Stormwater

Quantification of stormwater forms an essential component for managing the stormwater, deciding and designing the treatment schemes. Hydrologic analysis provides estimates of flood magnitudes as a result of precipitation. These estimates consider processes in a watershed that transform- precipitation to runoff and water through the system to a project's location (Hydrology Design Manual, Texas Department of Transportation, 2011). In the design of facilities such as storm drain systems, culverts, and bridges, floods are usually considered in terms of peak runoff or discharge in cubic feet per second or cubic meters per second. For systems that are designed to control the volume of runoff, such as detention storage facilities, or where flood routing through culverts is used, the discharge per unit time will be of interest. Thus, the hydrology study may provide:

1. Peak flow rate/ peak runoff rate

2. Volume of runoff expected with a specified storm duration,
3. Hydrograph (flow rate as a function of time)

For quantification of runoff generated during a storm event within a watershed, various methods and hydrological models can be used. Each such model demands data in the form of watershed and rainfall based parameters.

Rational and modified rational methods have been the most commonly used methods due to the ease in formulations and lesser parameter requirements. The New Jersey Stormwater Best Management Practices Manual (2004) discusses the fundamentals of computing stormwater runoff rates and volumes from rainfall through the use of various mathematical methods. It provides guidelines for the use to NRCS, Rational and Modified rational methods.

These two methods require runoff coefficient for the catchments i.e. the ratio of fraction of total rainfall that appears as total runoff volume ($\text{Runoff} = K \cdot \text{Rainfall}$) or the percentage of precipitation that appears as runoff. The runoff coefficient depends upon physical characteristics of the catchments like vegetation, depression, disturbances, etc. Its value increases with increasing rainfall depth (Hydrology Design Manual, TxDOT, 2011). Watersheds with more impervious surfaces tend to have a higher runoff coefficient and vice-versa.

The Rational and Modified rational methods use the assumption that duration of storm equals the Time of Concentration (T_c) which is the time required for a drop of water to travel from the most hydrologically remote point in the sub-catchment to the point of collection (HydroCAD Stormwater Modeling, 1986) or the time required for the entire watershed to contribute to runoff at the outlet point. When runoff is computed using the rational method, T_c is the appropriate

storm duration and in turn determines the appropriate precipitation intensity for use in the rational method equation (Hydraulic Design Manual, TxDOT, 2011).

A summary of the values of runoff coefficients developed by different research works in India for different soil conditions is given in Table 2.1.

Table 2.1: Values of Runoff Coefficient (C) for different soil conditions in India

Type of Vegetation	Slope Range (%)	Runoff Coefficient (C) in		
		Sandy Loam Soil	Loam / Loam Clay Soil	Stiff Clay Soil
Woodland and forests	0-5	0.1	0.3	0.4
	5-10	0.25	0.35	0.5
	10-30	0.3	0.5	0.6
Grassland	0-5	0.1	0.3	0.4
	5-10	0.16	0.36	0.55
	10-30	0.22	0.42	0.6
Agricultural land	0-5	0.3	0.5	0.6
	5-10	0.4	0.6	0.7
	10-30	0.52	0.72	0.82

Source: Central Ground Water Board, Manual on Artificial Recharge of Ground Water, 2007

Runoff coefficients for rural sub-watersheds could be calculated from the Table 2.2.

Table 2.2: Runoff Coefficients for Rural Sub- Watersheds

Watershed Characteristics	Extreme	High	Normal	Low
Relief- C_r	0.28-0.35 Steep, rugged terrain with average slopes above 30%	0.20-0.28 Hilly, with average slopes of 10-30%	0.14-0.20 Rolling, with average slopes of 5-10%	0.08-0.14 Relatively flat land, with average slopes of 0-5%
Soil Infiltration- C_i	0.12-0.16 No effects soil cover, either rock or thin soil mantle of negligible infiltration capacity	0.08-0.12 Slow to take up water, day or shallow loam soils of low infiltration capacity or poorly drained	0.06-0.08 Normal; well drained light or medium textured soils, sandy loams	0.04-0.06 Deep sand or other soil that takes up water readily; very light, well-drained soils
Vegetal cover- C_v	0.12-0.16 No effective plant cover, bare or very sparse cover	0.08-0.12 Poor to fair, clean cultivation, crops or poor natural cover, less than 20% of drainage area has good cover	0.06-0.08 Fair to good; about 50% of area in good grassland or woodland, not more than 50% of area in cultivated crops	0.04-0.06 Good to excellent about 90% of drainage area in good grassland, woodland, or equivalent cover
Surface Storage- C_s	0.10-0.12 Negligible; surface depressions few and shallow, drainageways steep and small, no marshes	0.08-0.10 Well-defined system of small drainageways, no ponds or mashes	0.06-0.08 Normal; considerable surface depression, e.g., storage lakes and ponds and marshes	0.04-0.06 Much surface storage, drainage system not sharply defined; large floodplain storage, large number of ponds or marshes

Source: Hydraulic Design Manual TxDOT, (2011)

The runoff coefficient for rural watersheds is given by:

$$C = C_r + C_i + C_v + C_s$$

Akan (2002) gave a simple method to size infiltration structures like infiltration basins and trenches to control storm water runoff. The runoff hydrograph is assumed to be trapezoidal in shape with a peak runoff rate calculated using the rational formula. Given the watershed time of concentration and the allowable runoff rate, the method determines the required size of the infiltration structure. Rational method was also used by Chena et al. (2007), for estimating the maximum discharge of a landslide-induced debris flow. The results show that the peak debris velocity was between 2.4 and 4.7 m/s and the peak debris discharge was between 6.7 and 35.7m³/s. The peak discharge initially increased at the upper portion of the channel, then decreased at the lower portion, indicating that the upper channel experienced erosion but the lower channel experienced deposition. The location with the maximum debris flow discharge corresponds to the point where the volume of the debris flow started to decrease.

Another very commonly used method is US-SCS method, now known as the NRCS method.

The US-SCS CN method uses Curve Number (CN) of the catchment as a representation of impervious area. The runoff curve number is based on the area's hydrologic soil group (A, B, C and D), land use, treatment and hydrologic condition (based upon level of grazing) and antecedent moisture condition. Its range varies between $100 \geq CN \geq 0$, where, 100 represents condition of zero retention (impervious catchment) and 0 represents full retention (pervious catchment).

The Soil conservation service curve number (SCS-CN) methodology by Water Science & Technology Library is aimed at presenting an up-to-date account of the SCS-CN method and clarify its potential for practical applications, and especially those other than originally intended. It provides introduction of rainfall-runoff modeling and elements of catchment, precipitation, interception, surface detention and depression storage, evaporation, infiltration, runoff, and the

runoff hydrograph, the factors affecting the curve number (CN), the determination of CN, the use of NEH-4 tables, sensitivity analysis, advantages and limitations of the SCS-CN method, and application to distributed watershed modeling, etc.

Mishra and Singh (2004) have also advocated the use of SCS-CN for their study conducted under Indian conditions and presented a critical review of daily flow simulation models based on the Soil Conservation Service curve number (SCS-CN). A more versatile model based on the modified SCS-CN method was introduced which specializes into seven cases. The proposed model was applied to the Hemavati watershed (area = 600 km²) in India and was found to yield satisfactory results in both calibration and validation. The model conserved monthly and annual runoff volumes satisfactorily. Similar work was done by Millhollon et al. (2009), where they used NRCS runoff curve number method to estimate runoff from the watershed in its natural, forested state and in its current state of cultivated crop land and pasture.

Among the various methodologies of the NRCS method the most commonly used is the TR-55. Paul Schiariti (TR-55, 1975) in his study demonstrated a comparison between TR-55 and MRM (Modified Rational Method) stating that, rational/MRM peak flow rates are reasonably close to TR-55 for larger drainage areas; runoff volumes are significantly different for the two methods, (Rational / MRM volumes can be 3 to 4 times less than TR-55 volumes); the Time to Peak is significantly different for both methods; rational/MRM peak flow rates can be significantly different from TR-55 for smaller drainage areas.

Besides the above methods of quantification, dimensionless unit hydrograph using the kinematic wave approach (KWUH) was used Guo, (2006) in his study. For verifying the applicability of the KWUH derived in the study, a set of hypothetical rectangular watersheds ranging from 20 to

200 acres were investigated. The predicted 100-year peak flow rates from these five hypothetical rectangular watersheds are compared with the Soil Conservation Service dimensionless unit graph Method (SCSUH) and the Colorado Unit Hydrograph Procedures (CUHP). In general, the KWUH produced results that were in good agreement with the CUHP when the catchment has an area between 60 and 120 acres. Based on the study of hypothetical rectangular watersheds, it is recommended that the KWUH be applicable to urban catchments with a drainage area of up to 120 acres. He (Guo, 2012) expanded the rational method into the rational hydrograph method in which the time of concentration is considered as the system memory and the contributing rainfall depth to the present runoff rate is defined as the accumulated precipitation over the past up to the time of concentration. In doing so, the complete runoff hydrograph can be generated under a continuous non uniform hyetograph. The event-averaged time of concentration and runoff coefficient can be derived by the least-square method.

Apart from the above methods, the synthetic unit hydrograph method is an upcoming new technology which has emerged because of the unavailability of rainfall and watershed data. Such a method uses synthetic data rather than the natural. Fang et al., (2008) reevaluated dimensionless unit hydrograph by using several examples to develop synthetic unit hydrographs. It was found that it is necessary to change the shape of dimensionless hydrograph if different peak rate factors (PRF) are used. Regional regression equations have been developed for basin-mean time to peak T_p and peak discharge Q_p of Gamma unit hydrographs with respect to watershed parameters: drainage area, main channel slope and length. A procedure has been established for development of synthetic unit hydrographs for Texas watersheds. The study found that mean peak rate factor for Texas watersheds is 370, which is lower than standard NRCS PRF of 484.

Models and computer softwares are also being used for the purpose of modeling. These softwares are based upon the methodology of an existing method. The following softwares are readily available online and can be used further in the calculations:

- HydroCAD storm water modeling system (based upon SCS-NRCS)
- NRCS WinTR-55
- The EPA Storm Water Management Model (SWMM)
- HEC-HMS (based upon NRCS)

Storm Water Management Model (SWMM) user manual provide detailed information on the EPA Storm Water Management Model (SWMM), a comprehensive mathematical model for simulation of urban runoff quantity and quality in storm and combined sewer systems. It attempts to provide adequate information in this manual for most users so that they can conceptualize a stormwater problem and simulate it using SWMM. Mancipe-Munoz, et al. (2014) performed the calibration of the storm water management model version 5 (SWMM5) using high temporal resolution rainfall and flow data to perform a 10-month continuous simulation on a physically distributed urban catchment. Detailed analyses of parameters that physically represent the area in the SWMM5 model were done using remote sensing and geographical information systems techniques. The outcomes of the study showed the possibility to reproduce accurately the urban runoff from a highly detailed, semi-distributed SWMM5 model, even when the calibration process is restricted to physical parameters and not allowed to distort the geometric representation of the project area.

Apart from these models many others have also been used by researchers for quantification.

Lowe et al. (2003) used the EPA's BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) software to create a HSPF watershed model of the Mamaroneck River,

located in lower Westchester County, New York. . The model was successfully calibrated and verified using 20 years of flow data. . Land use, river reach and topographic data supplied with BASINS were compared to local county data and some discrepancies were noted, particularly with the reach data.

Ghnanapala (2006) assessed the probable impact of urbanization upon the magnitude of flood peaks using the Basic Model HEC-I that has been used to estimate Runoff and HEC-RAS model that has been used to establish the Rating Curve. Two urban watersheds were gauged mathematically and modeled using the HEC model to identify the behavior for urban watersheds in Colombo and also to identify parameters applicable to these. Land cover of the watersheds showed that in the urbanized areas the pervious extent was approximately 62% while in less urbanized areas the previous extent was about 76%. Average Curve Numbers for the urbanized areas were 95 and 70 for impervious and pervious areas respectively. The HEC rainfall-runoff model developed for both watersheds produced very good peak discharge matching and hence these models could be used for drainage environment improvement projects in urban areas.

Lemons et al. (2007) developed a calibrated hydrologic model called SWAT (Soil and Water Assessment Tool) for the Blue River watershed (867 km²) in Summit County, Colorado. Comparison of simulated and observed stream flow hydrographs at two U.S. Geological Survey gauging stations resulted in good fits to average monthly values.

Schoener (2010) compared AHYMO (the Arid-Lands Hydrologic Model) and HEC-HMS for Runoff Modeling in New Mexico Urban Watersheds and concluded that, for all sub-basin sizes modeled in this study, HEC-HMS peak flow rates were significantly higher for scenarios with low imperviousness. Scenarios with high imperviousness and small sub-basins resulted in

significantly higher AHYMO peak flows. Differences between the two models can be reduced by adjusting the storage coefficient R in HEC-HMS.

Models using more mathematical terms in the flow-governing equations are more physically based and expected to be more accurate than models using approximations, however, are more complex due to more intensive but approximate numerical schemes. Models using approximate equations with analytical solutions may provide a balance between complexity and accuracy. Other factors such as data intensiveness, user friendliness, and resource requirements are also important considerations (Borah, 2011).

Table 2.3 summarizes the characteristics and application of the methods studied, to assist the designer in the selection of the appropriate method.

Table 2.3: Runoff Models

Method	Drainage Area	Required Information	Variables	Output	Applications
Rational Method	<20 acres (APWA) <500 acres (FHWA)	-Land Cover -Time of Concentration -IDF Curves	Runoff Coefficient (C)	Peak Flows	Minor and Major Storm System Design
Unit Hydrograph		Rainfall		Hydrograph	Flood Flows
SCS Unit Hydrograph	Up to 20 sq. Miles if large water-shed, break down to 20 sq. miles	Time of Concentration	Runoff Curve No. (CN) Runoff (Q) inches >1.5 CN >60	Hydrograph	Minor and Major Storm Flood Flow Systems Storage Volumes
SCS Tabular Method	Up to 20 sq. Miles. if large water-shed, break down to 20 sq. miles.	-Soil Type -24 Hr. Cumulative Rainfall -Time of Concentration	Runoff Curve No. (CN) accounts for Hydrological Abstractions	Hydrograph	Flood Flows Major Storm System Storage Volumes
SCS Graphical Method	<20 sq. Miles.	-Soil Type -Cumulative Rainfall	Runoff Curve No. (CN) Runoff (Q) inches >1.5 CN >60	Peak Flow	Flood Peaks Minor and Major Storm Systems
Rational Mass Inflow	<20 Acres	-Land cover -IDF Curves	Runoff Coefficient (C)	Storage Volume	Detention and Infiltration Facility Design
Simplified Equivalent Triangular Hydrograph	<200 Acres	-Soil Type -Rainfall Hyetograph -Time of Concentration	Runoff Curve No. (CN) (Q) inches > 1.5 CN>60	Hydrograph	Small Storage and Infiltration Facility Design

2.3 Characterization of stormwater

Stormwater quality depends on the environmental media and surfaces that the runoff is in contact with. Stormwater additionally contains substances from long distance atmospheric transport or scavenged from the atmosphere above urban areas. The runoff generated during rain events flows across the urban surfaces, where different substances are released and/or removed by runoff. These substances identified in stormwater, can have different concentrations and their loads may vary significantly depending on the land use, the human activities and the materials used in the catchment area. Stormwater pollution is thus characterized by significant spatial variability across urban catchments. Stormwater presents very distinct quality characteristics from domestic sewage. It is recognized as the most important source of heavy metals whereas wastewater constitutes the main source of organic and nitrogenous pollution (German et al., 2005; Gasperi et al., 2010; Hvitved-Jacobsen et al., 2010). Anthropogenic and transportation activities have been identified to generate considerable amount of solids, organic matters, nutrients, and heavy metals on the catchment surfaces (German et al., 2005; Miguntanna et al., 2010; Huang et al., 2010; Mahbub et al., 2011; Gunawardana et al., 2012; Chow et al., 2013). Stormwater pollutants, both organic and inorganic have been divided into six specific groups by Hvitved-Jacobsen et al. (2010). This information is presented in Table 2.4 along with the information on analytical parameters used to measure the pollutants. Although Eriksson et al., 2007 and Bjorklund, 2011 consider it as a simplified view; and believe that there are huge amount of pollutants that can be identified in stormwater and may cause relevant impacts in aquatic systems.

Table 2.4: Characterization of stormwater pollutants

Pollutant group	Measurement parameter	Sources	Comments
Solids (suspended solids, SS)	TSS	Pavement wear; construction sites or rehabilitation works; atmospheric fallout; anthropogenic wastes, etc.	60-80% of SS in stormwater could be less than 30 mm diameter. Other sewer solids are present in CSO. Solids also accumulate within the sewer system and may be discharged at different times. Heavy metals and PAHs are bond to the smaller particles (e.g.: 100-250 mm)
Heavy metals	Cu, Zn, Cd, Pb, Ni and Cr	Vehicles parts and components; tire wear; fuel and lubricating oils; traffic signs and road metallic structures. Industries may also be an important source of heavy metals.	They are relevant because of toxic effects. Generally the focus is on copper (Cu), zinc (Zn); cadmium (Cd) and lead (Pb). The relevance of Pb is minor in countries using unleaded gasoline.
Biodegradable organic matter	BOD ₅ & COD	Vegetation (leaves and logs) and animals such as dogs, cats and birds (either fecal contributions or dead bodies)	Organic matter (o.m.) from stormwater is less biodegradable (dominated by plant material), therefore is also less problematic for the environment than the o.m. from CSO.
Organic Micro-pollutants	They are numerous. Among them: PAHs, PCBs, MTBE etc	e.g.: PAH: incomplete fossil fuel combustion; abrasion of tire and asphalt pavement, etc. Phthalate esters: urban construction plastic materials.	Presently, a large number of compounds (over 650 identified) are discharged in trace concentrations and sometimes there is no accurate chemical determination method available for them.
Pathogenic microorganisms	e.g.: Total coliforms; Escherichia coli	Contributions from cats, dogs, birds.	Stormwater sources are much different than domestic wastewater contribution in the case of CSOs.
Nutrients	Nitrogen and phosphorous (e.g.: total Kjeldahl N; NO ₂ & NO ₃ ; Total-P; soluble-P)	Fertilizers and atmospheric fallout	Nutrients can cause not only eutrophication problems but also water discoloration, odors, toxic releases and overgrowth of plants.

Source: Hvitved-Jacobsen et al., (2010) and Barbosa et al., (2012)

The temporal behaviour of stormwater pollution is influenced by the stochastic nature of precipitation and by the temporal emission pattern of the various sources. These factors generate a high temporal variability in the concentrations and loads in stormwater, which is very difficult to monitor. Season and land use are frequently referred to as the most relevant factors affecting stormwater runoff characteristics (Goonetilleke et al., 2005; Hathaway and Hunt, 2010; Barbosa et al., 2012). Some researchers have established the relationships between land-use types and storm runoff pollution characteristics for various catchment land use that include residential, commercial, industrial, highway, parking lot, bridge, elevated roadway structure, street, and roof (Sansalone et al., 2005; McLeod et al., 2006; Kim et al., 2007; Kayhanian et al., 2007; Ballo et al., 2009; Davis and Birch, 2010; He et al., 2010; Francey et al., 2010; Lee et al., 2011; Tiefenthaler et al., 2011). Therefore, the characterization (qualitative and quantitative) of stormwater runoff should be performed at national and regional bases, with monitoring studies, for it has been proved that site specific, climatic and other local variables play an important role. It is known that the presence (both concentration and load) of a given pollutant at the same site varies considerably between different rainfall events; the variables usually correlated with these variations are the precipitation event characteristics and the antecedent dry period. Pollutant variability within a single event is also common; the highest concentrations or the largest mass of pollutants are often transported during the initial period/volume of the stormwater event in a phenomena defined as “first flush” or “first foul flush” (Hvitved-Jacobsen et al., 2010 and Bach et al. (2010). For instance, (Chang et al., 2008) refer that the first 6-8 mm of storm volume included more than 60% of the pollutant loads from industrial parks in Taiwan. Existence of a seasonal first flush in California (having Mediterranean climate) was also reported by Lee et al. (2004) in his study analyzing major storm event data sets collected during wet seasons over the

years 1999-2000 to 2002-2003. Trends in seasonal loads were quantified by plotting pollutant concentrations or cumulative pollutant load versus cumulative rainfall or cumulative runoff volume. Pollutant concentrations in the first part of the wet season ranged from 1.2 to 20 times higher than concentrations near the end of the season, and mass emission rates were similarly higher at the beginning of the season. Seasonal first flush existed for most cases and was the strongest for organics, minerals and heavy metals (except lead).

Nevertheless there is a lot to be said concerning the first flush: it is not a universal and constant phenomenon and depends on the characteristics of the catchment and on the climate; it may also only take place for some of the pollutants. Study conducted by Soller et al., 2005 for the City of San Jose, CA between May 1997 and April 2000 characterizing the concentrations of pollutants in local water bodies during eight storm events suggested that first flush phenomena did not occur consistently throughout most of the stations investigated. Further, the existence of specific combinations of site and storm conditions resulting in a first flush effect with respect to dissolved metals was observed.

From the studies carried out on first flushes it can be inferred that for the areas where catchment characteristics have a major role to play therein the application of Treatment Best Management Practices (TBMPs) early in the season could remove several times more pollutant mass than randomly timed or uniformly applied TBMPs.

With regards to the studies conducted for characterization of stormwater across different catchments, Brodie and Porter (2006) were the ones who monitored five stormwater monitoring sites having small catchments (of 50 to 450 m² area) representing both urban impervious areas (galvanized iron roof, concrete car park and bitumen road pavement) and pervious areas (grassed

and exposed bare soil). Flow-weighted samples were taken at each of the sites to determine the event's mean concentration of Non-Coarse Particles, NCP (particles of size less than 500 μm). Overall, runoff from 24 storms with rainfalls from 2.5mm to 48.5mm was sampled, during the period December 2004 to June 2005, and characteristics of the particles including size distribution, inorganic content and mass loading generated were determined. Their finding revealed that Bituminous road had the highest NCP load for small to moderate storms (<20 mm rainfall). No runoff occurred from the pervious surfaces in the storms of < 15 to 20 mm.

Kim et al. (2005) took a different catchment and modeled highway stormwater runoff (on the basis of a 3-year study conducted to quantify stormwater pollutant concentrations, mass emission rates, and the first flush of pollutants) to understand the magnitude and nature of stormwater emissions. Eight highway sites were monitored over 3 years for a large suite of pollutants. Grab and flow-weighted composite samples, rainfall, and runoff data were collected. The monitoring protocol emphasized detecting the first flush and quantifying the event mean concentration. A new runoff model with four parameters was developed to describe the first flush of pollutants for a variety of rainfall and runoff conditions. The model was applied to more than 40 events for 8 pollutants, and the parameters were correlated to storm and site conditions, such as, total runoff, antecedent dry days, and runoff coefficient.

Water quality parameters, such as, pH, turbidity, TSS, COD, TN, Zn, Pb, and Cu were analyzed and TN and COD were found as the major pollutants with mean concentrations of 8.5 and 201.4 mg/l respectively by Huang et al. (2007) in the surface runoff from a 0.14-km² urban catchment with separate storm sewer in Macau during five rainfall events analyzed between August and November, 2005. The concentrations were over 4-fold higher to the Class V surface water quality standards developed by SEPA, China.

In addition to the above essential parameters a study to determine nutrient loads associated with different particle size ranges for dry surface pollutants and stormwater samples collected from an urban road surface was carried out by Jai and Francis (2004). The results indicated that, although more than half of the surface pollutant is coarser than 300 μm , less than 15% of the total phosphorus (TP) and total nitrogen (TN) are attached to particle sizes greater than 300 μm . Practically all the particulate TP and TN in stormwater samples are attached to sediments between 11 and 150 μm . This suggests that, to effectively remove TP and TN, pollutant treatment facilities must be able to remove particulates down to 11 μm . Similar study was conducted by Miguntanna et al. (2013) for characterizing nutrients wash-off for effective urban stormwater treatment design. The outcomes of the study confirmed that the composition of initially available nutrients in terms of their physical association with solids and chemical speciation determines the wash-off characteristics the common approach of replicating nutrients wash-off based on solids wash-off could lead to misleading outcomes particularly in the case of nitrogen. A large number of studies have confirmed the presence of over 650 organic pollutants and 30 metals and inorganic metals as potential stormwater pollutants (Eriksson et al., 2007; Ledin et al., 2001). There is a varying level of knowledge about the occurrence of these pollutants in stormwater. For some parameters such as suspended solids, organic matter, nutrients and heavy metals, a fair amount of data can be found in the literature (Göbel et al., 2007; Ingvertsen et al., 2011). Which pollutants are problematic in stormwater runoff depends on the actual location. However some pollutants are more general stormwater pollutants than others. The heavy metals have for a long time been in focus in stormwater runoff. Hence keeping all the factors in mind the choice of the parameters to be selected for characterization studies was made.

2.4 Characterization of grey water

Grey water is wastewater from baths, showers, hand basins, washing machines and dishwashers, laundries and kitchen sinks (Eriksson et al., 2002; Ledin et al., 2001, Ottoso and Stenstrom, 2003). It contains soaps, food particles, grease, oil, lint, hair, pathogens, and traces of other chemicals (Crites and Tchobanoglous, 1998). It also contains high levels of detergents. These contain surfactants (surface active agents), builders, bleaches, enzymes, preservatives, solvents, fillers etc. (Ledin et al., 2001). A number of studies have been conducted to characterise domestic grey water (e.g. Del Porto and Steinfeld, 2000; Eriksson et al., 2003; Eriksson et al., 2002). Following Table 2.5 shows the characteristics of the grey water in low or middle income countries.

With increasing pressures on water resources, the concept of beneficial use of treated wastewater has rapidly become an imperative for water agencies around the world. Water reclamation, recycling and reuse are now recognized as key components of water and wastewater management. In Bangladesh the reuse of the grey water has been introduced. The study undertaken by Tamanna et al. (2011) showed that the highest amount of fresh water is wasted in toilet flushing which can be saved by reuse of the grey water.

Table 2.5: Domestic grey water characteristics in selected countries

Parameter	Palestine ¹	Israel ²	Nepal ³	Malaysia ⁴	India ⁵
Q (l/p/d)	50	100	72	225	90
pH	6.7–8.35	6.3–7.0			6.4 – 8.1
Suspended Solids (mg/l)	1396	85–285	98	76	40 – 340
Turbidity (NTU)	-	-	-	-	15 – 270
BOD ₅ (mg/l)	590	280–688	200	129	45 – 330
COD	1270	702–984	411	212	-
Nitrite (mg/l)	-	-	-	-	0.1 – 1.0
NH ₄ -N (mg/l)	3.8	0.1–0.5	13.3	13	1.0 – 26
TKN (mg/l)	-	-	-	-	2 – 23
Total P (mg/l)	-	17–27	-	2.4	0.1 – 0.8
Sulphate (mg/l)					0.3 – 12.9
Conductivity (µS/cm)	1585	1000–1300	-	-	325 – 1,140
Hardness (mg/l)	-	-	-	-	15 – 50
Sodium (mg/l)	87–248	199	-	-	60 – 250

1: Burnat and Mahmoud (2005); 2: Gross et al. (2006a) 3: Shrestha et al. (2001); 4: Martin (2005); 5: NEERI (2006)

Note: These figures do not reflect national averages but relate to specific cases with specific settings. Type of water supply and living standards appear to be more decisive than the location.

2.5 Stormwater treatment systems

Stormwater treatment systems practiced elsewhere were extensively studied for developing a treatment system which would be viable for Indian conditions taking into account the less availability of land, high concentration of pollutant load and absence of proper drainage

facilities. Historically, in most developed countries, best management practices (BMPs) had been designed and implemented to reduce soil erosion, and attempts were made to use those BMPs to reduce the sediment load entering waterways at the beginning of the 1970s (Rao et al., 2009; Yu et al., 2013). Various infield and off-site best management practices have currently been proposed and applied to treat diverse levels of pollution worldwide (Otto et al., 2008). Since stormwater runoff from impervious or pervious surfaces contributes significant quantities of pollutants to the surrounding surface water bodies (Smith et al., 2000; Datry et al., 2003; Boving and Neary, 2007), increasing environmental concerns regarding the spread of such pollutants have led to the construction and installation of various kinds of treatment. However, it is considered that better information about the performance of different BMPs can improve their application and development. Structural BMP involves systems constructed to treat stormwater at the origin or near the discharge into the receiving waters, or into the urban rain sewer system (Wanielista and Yousef, 1993; Dickie et al., 2010; Hvitved-Jacobsen et al., 2010). They operate by trapping and detaining stormwater runoff until unwanted pollutants settle out or are filtered. Common examples of these systems are: detention or retention ponds, wet ponds, infiltration trenches, infiltration basins, sand filters, grassed swales and constructed wetlands. For deciding on the treatment scheme of stormwater, a previous assessment of its quantity and quality characteristics is very essential along with a good understanding of the local conditions available for the construction of the system. When the local scenario is well defined it is possible to select the treatment system(s) more suitable to the conditions and the objectives of the treatment. The concept of best management decision imposes the need for a correct balance between a sound project with reasonable construction and maintenance costs, able to reduce the pollution to the required level (Barbosa and Fernandes, 2009). Several publications or sites (FHWA, 1996;

FHWA, 2000; Government of South Australia, 2002; US EPA, 2008; Geosyntec Consultants, 2010; Hvitved-Jacobsen et al., 2010) describe the fundamentals of each type of treatment or system, project and design requirements/guidelines, maintenance and monitoring activities, etc. On the other hand, quite a lot of papers published in international conferences or in journals investigated the performance of specific treatment operations and systems (Barbosa and Hvitved-Jacobsen, 2001; Dimova et al., 2005; Maniquiz et al., 2010).

Scholes et al. (2008) had studied the relative performance of different BMP in the removal of five common stormwater pollutants. Many manuals like Stormwater Management Manual, Vol. V: Runoff Treatment BMPs (Western Washington), (2005) provides information on the treatment of runoff, from developed sites, for the removal of sediment and other pollutants. It provides guidance for the selection, design and maintenance of permanent runoff treatment facilities, summarizes available options for the treatment, and outlines a step-by-step process for selecting treatment facilities for new development and redevelopment projects. Information regarding on-site stormwater management BMPs, intended to infiltrate, disperse, or contain runoff on site, as well as to provide treatment is also given in the manual.

Davis et al. (2001) had proposed a practice of bio-retention to manage stormwater runoff from small developed areas. The proposed bio-retention facilities include porous soil, a topping layer of hardwood mulch, and a variety of plant species. A detailed study of the characteristics and performance of bio-retention systems for the removal of several heavy metals (copper, lead, and zinc) and nutrients (phosphorus, total Kjeldahl nitrogen [TKN], ammonium, and nitrate) from synthetic urban stormwater runoff was completed using batch and column adsorption studies along with pilot-scale laboratory systems. Roles of the soil, mulch, and plants in the removal of heavy metals and nutrients were evaluated to estimate the treatment capacity of laboratory

bioretention systems. Reductions in concentrations of metals were excellent (>90%) with specific metal removals of 15 to 145 mg/m² per event. Moderate reductions (60 to 80%) were observed for TKN, ammonium, and phosphorus levels. Importance of the mulch layer in the metal removal was identified. Overall results support the use of bioretention as a stormwater best management practice and indicate the need for further research and development. Few authors like Ancion et al. (2014) had studied the use of biofilm as a novel approach to assess stormwater treatment efficacy by monitoring biofilm associated metals and biofilm bacterial community composition at multiple locations through the treatment system (which included rain gardens, grassy swales, a stormwater filter and a wetland) and in the receiving stream above and below the stormwater discharge. Changes in bacterial community composition were assessed by Automated Ribosomal Intergenic Spacer Analysis (ARISA) and concentrations of biofilm associated metals monitored by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Bacterial communities gradually changed towards a community more similar to that within the receiving stream and the discharge of treated stormwater had little effect on the composition of bacterial communities in the receiving stream, suggesting the effective conditioning of water quality by the treatment system. Concentrations of some biofilm-associated metals declined following sequential treatment, for example copper (73% reduction), zinc (48% reduction) and lead (46% reduction). In contrast, levels of arsenic, cadmium, chromium and nickel were not reduced by the treatment system.

There are simpler and more advanced systems that integrated different methods or operations, in order to improve the treatment efficiency and retain both particulate, colloidal and dissolved pollutants (e.g.: Vollertsen et al., 2009). For instance, a solution to enhance treatment by infiltration may be the purchase of commercial aggregate materials (Nanbakhsh et al., 2007;

Sommer and Sieker, 2005). Higher surface loads have been obtained by addition of appropriate chemicals and/or equipping the structures with lamella settlers (Rietsch et al., 2003). More complex systems usually are more expensive and require more maintenance and monitoring efforts. In combined sewer systems, storage tanks are frequently designed to ensure a pre-treatment by settling to the overflow discharges. Recent upgrades of stormwater sedimentation tanks are showing that high-rate clarification is a promising cost-effective method for wet weather pollution abatement in combined systems (Capodaglio, 2003; David and Matos, 2005). It is noteworthy that the possibility to integrate strategies for pollutant control within the urban rain drainage system, such as sediment traps or commercial products and manufactured technologies may be placed at specific points of the sewer system e.g.: in gutters (Sommer and Sieker, 2005; FHWA,2000). The risk of failure or not achieving the target efficiencies is also something to be faced and evaluated. Another issue of practical importance is the costs associated with project, construction and maintenance of a BMP; several of them are difficult to estimate and may be increased by unexpected occurrences during operation (FHWA, 2000). Moreover what is striking is the use of land for the construction of such BMPs which under Indian scenarios seems unlikely on account of its high population and low per capita availability of land.

The review study then under taken was to focus on the filter media to be used for designing a rapid filtration system with the minimal land requirement. A manual on Design of Stormwater Filtering Systems by Claytor and Schueler (1996), was studied. The stormwater filter designed included a diverse spectrum of stormwater treatment methods (which utilize an artificial media, such as sand, peat, grass, soil or compost) used to filter out the pollutants entrained in the urban stormwater. These include sand filters (surface, underground, perimeter, organic, and pocket

designs), bioretention and vegetated channels (grass channels, dry swales, wet swales, and filter strips). The underlying concept for this definition given in the manual is that a common and unified approach is needed to design all these types of stormwater filters. The manual promotes use of volume-based sizing criteria for all the filtering systems. Further, it provides detailed guidance on the selection of appropriate filter types for various applications, reviews pollutant performance data and pathways for stormwater filtering systems, and detailed engineering design principles and guidance.

Similar studies involving less land requirement was conducted by Birch et al. (2005) who assessed contaminant removal efficiency of a Stormwater Infiltration Basin (SIB), installed in an urban suburb in eastern Sydney (Australia), over seven rainfall events. The assessment included monitoring and assessment of removal of total suspended solids (TSS), nutrients (TP, TKN, TN), trace metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn), organochlorine pesticides and faecal coliforms (FC) from stormwater. Weighted average concentration (WAC) of TSS in the stormwater was reduced by an average of 50%, and WAC of Cu, Pb and Zn were reduced by an average of 68%, 93% and 52%, respectively. The mean removal efficiencies for total phosphorus (TP) and total Kjeldahl nitrogen (TKN) were 51% and 65%, respectively. The SIB was also found very efficient (96%) in removing FC from stormwater (WAC was reduced from almost 70000 cfu/(100 ml) in the inflow to <2000 cfu/(100 ml) in the outflow).

Another author Johnson (2006) studied innovative methods, using mainly media filters and swales, for the capture of metals from stormwater. Twelve media were initially evaluated and three best performing media (peat-sand mix, compost, and zeolite) were selected for in-depth study. Results of the study emphasize the importance of characterizing the stormwater (type and quantity of metals, pH, and other characteristics) before selecting the media.

With regard to the novelty in different filter media used Boving and Neary (2007) also conducted pilot-scale field tests, to determine the effectiveness of wood filters in removing dissolved PAH from the runoff. Four wood filter tests were conducted, lasting from 1 to 9 weeks, to determine the degree of PAH attenuation from the aqueous phase as a function of wood mass, residence time, and seasonal changes. Prototype wood filters removed 18.5% to 35.6% of dissolved PAH contaminants. Removals up to 66.5% were also observed. Heavier molecular weight PAH compounds (e.g. chrysene) were more effectively removed. Effectiveness of the filters was found not affected by changes in temperature or pH, but increasing with the filter size. Highest removal was observed in continuously submerged parts of the filter system.

Since stormwater contains an appreciable amount of heavy metals so the studies conducted for the removal of the same were referred. Marla and Kim, 2014 conducted a monitoring program for fractionating the heavy metals in runoff and its implications for treatment of the particulate-bound and dissolved heavy metals in runoff. Findings revealed that fractionation of heavy metals played an important role in the performance of the stormwater system and their concentration was influenced by flow rate and total suspended solids load. For the stormwater system to be effective, it is recommended to design the system treating not only the early period of a storm (first flush criteria) rather until the peak part of the hydrograph (high flow rate where partitioning was greatest) from a load basis.

Seven simulation experiments on a laboratory-scale gravel infiltration system were conducted by Hatt et al. (2007) to test the pollutant removal under a range of water level regimes, including both constant and variable water levels. Gravel filters were found to be very effective for removal of sediment and heavy metals under all water level regimes, even as the system clogged over time. Despite the sediment particle size distribution being much smaller than the filter

media pore size, sediment and its associated pollutants were effectively trapped in the top of the gravel filter, even when the water level was allowed to vary. A media depth of 0.5 m was found to achieve adequate pollutant removal.

Fuhrman et al. (2007) investigated the potential of using alumina, activated bauxsol-coated sand (ABCS), bark, bauxsol-coated sand (BCS), fly ash (FA), granulated activated carbon (GAC), granulated ferric hydroxide (GFH), iron oxide-coated sand (IOCS), natural zeolite (NZ), sand, and spinel (MgAl_2O_4) as sorbents for the removal of heavy metals (a mixture of As, Cd, Cr, Cu, Ni and Zn) from synthetic stormwater. Ability of the sorbents was evaluated in batch tests at a starting pH of 6.5, and sorption constants were calculated and used to compare the overall heavy metal removal efficiency of the sorbents. The removal efficiency was found decreasing in the order of alumina, BCS, GFH, FA, GAC, spinel, ABCS, IOCS, NZ, bark, and sand. These findings were reported as significant for future development of secondary filters for the removal of dissolved heavy metals from actual stormwater under realistic competitive conditions of initial heavy metal concentrations, pH and ionic strength.

Siriwardene et al. (2007) studied physical clogging of gravel filters under both constant and variable water levels, and for different sediment inflow concentrations by conducting one-dimensional experiments. Formation of a clogging layer was found at the interface of the filter and the underlying soil in all the cases. The clogging was much slower if the water level was kept constant than varied within the column, may be due to the formation of a sediment plug that ‘shelters’ the filter-soil interface. More importantly, it showed that the physical clogging was mainly caused by migration of sediment particles less than $6\text{ }\mu\text{m}$ in diameter. A simple regression model was proposed and tested for the prediction of clogging due to stormwater sediment. Similar studies were conducted by Kandra et al. (2014) for the assessment of clogging

phenomena in granular filter media used for stormwater treatment. Five replicate experimental columns were constructed using zeolite, scoria, riversand and polymeric glass beads, and different flow-through rates were achieved using restricted outlets. It was found that shape and smoothness of filter media grains had limited effect on clogging and sediment removal rate. All media except scoria clogged after similar volumes of stormwater but scoria-based filters were found to be highly variable in performance, most likely due to breakdown of its particles. Conversely, flow-through rate significantly affected clogging and sediment removal rate. For instance, in the case of zeolite filters, the systems with the lowest flow rate clogged after application of over 30 m of stormwater, while the unrestricted zeolite columns (with 200 times the flow rate) clogged after only 10 m of applied stormwater. At the same time, the zeolite filters with the lowest flow rate had an overall treatment efficiency of 88% compared with the unrestricted design's efficiency of 59%. Many field monitoring studies have been conducted in recent years to characterize the ability of underground stormwater treatment structures to remove pollutants from stormwater (Waschbusch, 1999; Strynchuk et al., 2000; England, 2001; Yu and Stopinski, 2001; Roseen et al., 2005; Fassman, 2006).

Unfortunately, monitoring studies are problematic for several reasons: (1) natural storm events are unpredictable and not reproducible; (2) it is difficult to obtain representative samples of suspended sediment at the influent and effluent of the device; and (3) results of monitoring are typically watershed-specific; that is, it is difficult to apply the results to other watersheds with different land uses, climate, and geology (Wilson, 2007). Hence there has been a shift from the conventional technologies towards more specific decentralized treatment technologies for treating the stormwater of a desired sub-watershed.

2.6 Groundwater recharge systems for stormwater disposal

Flooding and the associated public health hazards are among the major issues in developing countries, where four-fifths of the world population lives, in many cases in overcrowded cities and in regions suffering from water scarcity (Chocat et al., 2007). The construction of combined or separate sewer systems has been the major decision on flood control in urban areas for centuries. In the last decades, some developed countries have used detention inside the sewer system to reduce floods and combined sewer overflows discharges. This requires the construction of underground storage structures and, in some cases, the use of the potential storage capacity through real time control systems. The sustainability of this traditional approach has long been considered unfeasible and, consequently, a wide range of other source control measures have been increasingly used aiming to reduce runoff and pollutant loads entering into the sewers (Begum et al. 2008). Artificial Recharging of stormwater after suitable treatment have come up as a viable option in the last decade. Artificial recharge is the planned, human activity of augmenting the amount of groundwater available through works designed to increase the natural replenishment or percolation of surface waters into the groundwater aquifers, resulting in a corresponding increase in the amount of groundwater available for abstraction. Although artificial recharging is primarily used to preserve or enhance groundwater resources, it has been used for many other beneficial purposes such as conservation of surface runoff and disposal of flood waters, control of salt water intrusion, storage of water to reduce pumping and piping costs, temporary regulation of groundwater abstraction, and water quality improvement by removal of suspended solids by filtration through the ground or by dilution by mixing with naturally occurring groundwater (Asano, 1985). Artificial recharge of groundwater although seems to be a promising solution but it could be associated with environmental risks. A study was conducted

Etteieb et al. (2014) to assess the environmental risk of the groundwater quality as well as the reuse of treated waste water for Korba, Tunisia local aquifer recharge. Results showed high levels of chloride, ammonia, and sodium adsorption ratio (SAR) in the treated waste water and high electrical conductivity, nitrate, chloride concentrations, and SAR in groundwater. Heavy metal concentrations were commonly under the detection limit. On the other hand, groundwater was contaminated with pesticides. Valhondo et al. (2014) studied the behavior of nine selected emerging trace organic contaminants (EOCs) in an artificial recharge system supplemented with a reactive barrier. This barrier contained aquifer sand, vegetable compost, and clay and was covered with iron oxide dust. The results showed that the behavior of most EOCs changed after installing the reactive barrier. The reactive barrier enhanced the removal of some EOCs, either markedly (sulfamethoxazole, caffeine, benzoylecgonine) or slightly (trimethoprim) and decreased the removal rates of compounds that are easily degradable under aerobic conditions (ibuprofen, paracetamol). These studies could act as a caution ascertaining us that the environmental risk monitoring of treated waste water is fundamental to assess its safety reuse on the aquifer recharge and in presenting a coastal barrier against seawater intrusion.

Considering artificially recharge groundwater as one of the key option to manage stormwater different methods have been developed and applied in various parts of the world. Details of these methods, as well as related topics, can be found in literature (Todd, 1980; Huisman and Olsthoorn, 1983; Asano, 1985). Artificial recharging may be carried out by direct and indirect methods and/or combining these methods (CGWB, 2007).

1. Direct methods convey water from surface sources or store in-situ at places above the aquifer areas, where it is made to percolate and recharge the groundwater.

2. Indirect methods transfer surface water which is induced as a consequence of human activity and is injected by locating the groundwater abstraction wells near influent streams. Another type of indirect recharge is from seepage of stream or canal or lakebeds and return flow from irrigation.
3. Combination of the above two methods is the one which is widely used to meet the topography and terrain condition.

CGWB's Manual on Artificial Recharge of Groundwater (2007) covers various aspects of artificial recharge of groundwater including planning of artificial recharge schemes, recharge techniques and design of structures, monitoring of augmented water levels and water quality, economic evaluation of recharge projects and issues related to operation and maintenance of artificial recharge structures.

Artificial recharge practices of Hawaii include stream-water recharge through wells and shafts, storm drainage disposal through wells and pits, induced leakage from ditches and reservoirs and deliberate spreading of excess irrigation water, incidental ditch & reservoir leakage and cesspool seepage (Hargis and Peterson, 1970). The most significant source of artificial recharge to groundwater in Hawaii was probably the recharge incidental to irrigation. Deliberate artificial recharge to groundwater consisted of wells which recharge stream water at Hanapepe, Kanuai and Puukapu. Besides these, recharge through pits which dispose of storm drainage at Wailuku and Kahului, Maui and Hilo, Hawaii, and through excess irrigation water induced by leakage from ditches and reservoirs were the other means of artificial recharge being practiced. In addition to these, Department of land and natural resources of the state of Hawaii was supposed to begin disposal of treated sewage through three deep wells at Waimanalo, Oahu as soon as the sewerage system was completed.

Majumdar et al. (2009) studied interflow characteristics in the multi-aquifer setup of a mountainous watershed in the Maharashtra state of India. Three-dimensional groundwater flow algorithm 'MODFLOW' was used to develop a base case model, incorporating observed subsurface flow conditions. Objective of the study was to know the behavior of an aquifer with different artificial recharge techniques, such as percolation tanks and recharge wells. Results indicate that the interflow followed an integrated and continuous hydraulic gradient across multi-aquifers. Finite aquifer extents supplement the recharge and discharge processes. These findings could be useful in planning artificial recharge schemes.

Among the various techniques, Water spreading is practiced on an increasing scale all over the world. Recharge through pits and shafts have limited application as they have only a small unit capacity. Abandoned stone quarries or open (dug) wells where water table has gone down below the excavated depths may be used as recharge pits and shafts. Recharge through wells can be applied to all hydro geological situations. When direct recharge is practiced by spreading water, the amount of water entering the aquifer depends on factors like a) the infiltration rate, b) deep percolation rate, c) the extent to which the recharge cone develops in the recharge influence zone and d) the transmissivity of the aquifer (Takshi and Chopra, 2004). Infiltration of storm water through soils is a transient flow process. When an infiltration basin is loaded with storm water, the soil medium between the basin and the groundwater table will undergo a storage process in which the soil water moisture varies from an unsaturated to a saturated condition. When the infiltrating water reaches the groundwater table, a water mound will begin to build up. The shape and growth of a mound depend on the infiltration rate, size of the basin, and hydraulic properties of soil medium (Ferguson, 1990). Fluid is drawn above the saturated horizon by capillary forces. This zone is called the capillary fringe, and the fluid is in a state of tension (suction, negative

pressure) (Dendrou, 1999). Capillary fringe may rise as high as 30 cm in medium sands (Bouwer, 2002), above the groundwater mound increasing the effective height of the mound. Water balance calculations and groundwater modeling were utilized by Hashemi et al. (2014) to investigate the performance and hydrological function of an improved water harvesting technique called floodwater spreading system in arid Iran. The research study revealed that with a balanced pumping, the floodwater spreading system could be an efficient way to increase groundwater resources in arid and semiarid areas and suggested the need of further research to optimize the floodwater harvesting system for improving the management in view of uncertain frequency and magnitude of inflow. For deciding on the appropriate groundwater recharge facility all these factors need to be taken into account. Patel et al., (2011) have derived analytical correlations between diameter of recharge well d , depth of pervious strata H , and permeability k with recharging capacity of well Q_r which are predominant geometrical design governing parameter for any recharging technique. These analytical relationships have been used while developing groundwater recharge facility for the selected sub-watershed. Combination of several direct surface and subsurface techniques can be used in conjunction with one another to meet specific terrain and topography condition and recharge needs (Gupta and Deshpande, 2004).

2.6.1 Techniques of artificial recharging in India

In recent years, in many parts of India especially in the arid- and semi-arid regions, due to the vagaries of monsoon and scarcity of surface water, dependence on groundwater has increased tremendously. India is water stressed today and is likely to be water scarce by 2050 (Gupta and Deshpande 2004). Sustainable management of groundwater resources is thus needed to overcome this situation.

Various artificial recharge schemes have been worked out for augmenting the groundwater aquifer. Based on a survey conducted between 1980 and 1985, the Central Ground Water Board (CGWB) identified a number of techniques commonly used for artificial recharge. Among these, surface spreading methods were actively used. To ensure the effective and efficient operation of an artificial recharge system the following basic factors should be considered: the locations of geologic and hydraulic boundaries; the transmissivity, depth to the aquifer and lithology, storage capacity, porosity, hydraulic conductivity, and natural inflow and outflow of water to the aquifer; the availability of land; surrounding land use and topography; the quantity and quality of water to be recharged; the economic and legal aspects governing recharge; and the level of public acceptance (CGWB).

Typically, unconfined aquifers are recharged by surface spreading methods whereas confined aquifers are generally recharged through injection wells. Surface spreading methods require relatively flat or gently sloping lands, while topography has little effect on subsurface recharge methods. Aquifers best suited for artificial recharge are those, which can absorb and retain large quantities of water (GWREC, 1997).

When the quantity and availability of recharge water is highly variable, such as in intermittent stream, any of the surface application methods can be used. Basin and pit techniques have the greatest advantages because they can be designed to accommodate expected flood flows. In contrast, shafts and wells have little storage capacity and, therefore, require a more uniform supply of water. Indirect methods, such as induced recharge, are virtually not affected by changes in surface water flows because the rate of recharge is controlled by extraction rates.

The physical, chemical and biological quality of recharge water also affects the selection of recharge methods. Suspended solids in recharge water causes clogging. It is also important that the recharge water be chemically compatible with the aquifer material through which it flows and the naturally occurring groundwater to avoid chemical reactions that would reduce the aquifer porosity and recharge capacity (Kumar et al., 2006). Similarly, biological agents such as algae and bacteria can cause clogging of infiltration surfaces and wells, limiting the recharge capacity.

The design of recharge structure requires careful consideration to ensure the correct sizing of the pond both to provide sufficient recharge to meet abstraction demands and to adequately contain storm water runoff (Muralidharan and Athavale, 1998). Where there is insufficient storm water runoff to fill the pond, water from the surrounding area should be diverted to the pond through supply channels.

In India, subsurface dike is the most suitable structure for promoting groundwater recharge, as it is safe from floods, needs no elaborate overflow devices, and is least susceptible to silting. In addition, subsurface dikes do not require extensive areas of land for their implementation and, hence, have minimal ecological repercussions following their construction. Since the entire structure is underground, evaporative losses are also insignificant (Muralitharan and Athavale, 1998). Check dams are the least desirable form of this technology, and should generally be used only where the recharge requirement is very high or there is a need to control soil erosion. Check dams require a 30 to 60 cm wide concrete or brick masonry extending down to an impermeable basement stratum or compacted foundation. Sites selected for check dams and underground dikes are typically those that have undergone intense weathering, and as a result, have high fracture porosity, or are in alluvial areas, which are best suited for infiltration.

In areas where rainfall is scanty and drought frequency is high, infiltration of rain water is best accomplished by employing an integrated series of techniques, which, for example, can include damming the gullies of minor streams, constructing subsurface dikes and/or percolation tanks along their tributaries, contour bunding and trenching on slopes, placing farm ponds in the foot hills, and wherever possible, installing check dams-cum- minor irrigation dams on the main stream courses (Kumar et al. 2007). Terracing and afforestation of hillsides, which help to retain runoff and increase infiltration, may also form part of an integrated basin-scale water resources development plan. An important factor to be considered while designing an artificial recharge structure is the consideration of their stability during high flows and minimization of accumulation of silt and organic matter within the structure. Based on the survey and study the following suitability of artificial recharge structures for common water resources development purposes could be considered (Table 2.6).

Table 2.6: Suitability of Artificial Recharge Structure for Common Water Resources Development Purposes

Lithology	Topography	Type of structure
Alluvial or hard rock	Plain area or gently undulating area	Spreading pond, subsurface dike, minor irrigation tank, check dam, percolation tank or unlined canal system
Hard rock down to 40 m depth	Valley slopes	Contour bunding or trenching
Hard Rock	Plateau regions	Recharge ponds
Alluvial or hard rock with confined aquifer to 40 m depth.	Plain or gently sloping of flood plains	Injection well or connector well
Hard rock	Foot hill zones	Farm ponds or recharge trenches
Hard rock or alluvium	Forested areas	Subsurface dikes

2.7 Gaps in previous studies

In Indian cities, especially in northern part of India, stormwater management systems are either absent or when present they included just collection and conveyance of the stormwater beyond the urban limits and disposal into nearby natural drains or water bodies. In some cases, the stormwater is collected along with municipal sewage and managed in combined sewerage systems. In the areas where stormwater management systems are absent, the stormwater is allowed to pond low lying areas leading to percolation of heavily polluted stormwater into the groundwater.

Very little is known about the quantities and characteristics of the urban stormwaters and almost no attempts have been made for characterizing the stormwater in general and the first flushes in specific. Most of the studies are limited to understanding and management of the rooftop rainwater. In the absence of this, planning of stormwater management systems and use of stormwater for groundwater recharging is difficult.

Difficulties associated with the stormwater treatment and recharging into groundwater are sufficiently appreciated, and very few attempts have actually been made to treat and use the urban stormwater in groundwater recharging. Existence of first flush, highly variable quantities and pollution loads of the stormwater (influenced by the frequency and intensity of rains, and by the land uses and surface activities of the urban watersheds), and constraints to store and handle the stormwater make the urban stormwater treatment and use in groundwater recharging a real challenge.

Decentralized systems for stormwater management at sub-watershed level have not been apparently tried in India. This is despite the recent mushrooming of colonies and townships by

private developers. Disposal of stormwater through groundwater recharging is still to be practiced. This may become possible only if reliable and consistent treatment of the stormwater becomes a reality that too at the urban sub-watershed level.

Fragmented or piecemeal approach has been followed for tackling the urban stormwater problems. Storm water management is dealt with separate from the water supply and sanitation, quite often by altogether different agencies. Traditional approaches to stormwater management have been left behind and not worked on for improving and making them more relevant to the changing conditions of the urban settlements.

In the light of the above, development of Stormwater management systems at the urban sub-watershed level with emphasis on the treatment and disposal of storm water for recharging the groundwater was taken up as one of the major objective of the Ph.D. work.

Chapter-3

Methodology

Objectives of the study have been achieved through working on the following work elements. Approach followed for carrying out the work on each of the work elements is described in detail in this chapter

3.1 Work elements

Following work elements were framed for achieving the proposed objectives:

1. Survey of the Patiala city for understanding stormwater drainage patterns
2. Selection and characterization of the urban sub-watersheds
3. Quantification of stormwater
4. Characterization of stormwater
5. Development of experimental storm water treatment system
6. Conceptualization of the sub-watershed level storm water management system
7. Development of design protocol for groundwater recharging

3.2 Survey of the Patiala city for understanding stormwater drainage patterns

Objectives behind the survey were to understand the storm water drainage patterns, to identify all the sub-watersheds, and to know the storm water management systems existing in the Patiala city.

Entire Patiala city was surveyed for understanding the existing stormwater management system and the stormwater drainage patterns. Physical survey of the city, ward by ward, was undertaken. During the survey local people of the city were interviewed for understanding the stormwater

flooding and drainage patterns. The survey was carried with the help of an information sheet (shown in Appendix-A).

Total city was divided into 1.1 km^2 grids and elevation details were obtained for each of the grids through using Google Earth software. On the basis of this information flood water routing for the city was worked. Further, on the basis of the survey and on the basis of the drainage patterns the city was divided into finite number of sub-watersheds. The sub-watersheds wherein storm water flooding usually occurred were identified.

During the survey, Municipal authorities and the Punjab water supply and sewerage board people were also interviewed for knowing about the stormwater management in various parts of the city and for getting necessary land use maps and other secondary data.

3.3 Selection and characterization of the urban sub-watersheds

Working on all the sub-watersheds identified was not practically feasible. Hence, five of the sub-watersheds identified were chosen for further studies. Basis for the selection was to cover the heterogeneity and diversity of the sub-watersheds. However, for the convenience of working with, only the sub-watersheds wherein storm water flooding occurred were chosen. For ensuring uniform rainfall all the sub-watersheds selected have been from within 5 km radius.

Stormwater assessments for the selected sub-watersheds were made using the US-SCS CN method (SCS 1985). Characterization of the selected sub-watersheds has been done for facilitating the use of the US SCS CN method. Area, land use-land cover, impervious surfaces (directly connected and not directly connected), slope, drainage (natural and manmade) facilities, hydraulic path length etc., information was collected for each of the sub-watersheds, mostly

through physical survey. Aerial photographs given in the Google earth package had also been used. Further, each of the selected sub-watersheds was mapped to serve the purpose.

3.4 Quantification of stormwater

Quantification of storm water was required for the design and sizing of storm water collection, treatment and disposal facilities. Quantity of storm water generated depends on both the characteristics of the storm events and characteristics of the sub-watershed in question.

3.4.1 Storm water quantification for the design storm water treatment and disposal facilities

Each of the sub-watersheds was divided into sub-areas on the basis of land cover and land use (LCLU) and impervious areas (directly connected and directly not connected). US SCS Curve number method was selected because of its applicability to small watersheds and the availability of the relevant data required. SCS CN method was selected after the review of different hydrological models vis-a-vis the sub-watershed characteristics and availability of the required data. The sub-watersheds in question are smaller and the SCS CN method is reported as quite appropriate for the small watersheds. With regard to the relevance of the SCS CN method to Indian conditions, the information base on which the method is built indicates that the method is quite appropriate even for Indian conditions. Input data from our sub-watersheds is falling within the data range being used by the SCS CN method. Also Mishra and Singh (2004) had presented a critical review of daily flow simulation models based on the Soil Conservation Service curve number (SCS-CN) and had introduced a more versatile model based on the SCS-CN method. The proposed model was applied to the Hemavati watershed (area = 600 km²) in India and was found to yield satisfactory results in both calibration and validation. The authors have advocated

its use and applicability to the Indian conditions in their book “Soil conservation service curve number (SCS-CN) methodology” on the basis of the similarity in the soil types observed for the Indian sub-continent. This method is categorized for 4 soil groups each having specific characteristics. The most identical soil group among the four types was used for the current study. Curve numbers for each of the sub-areas were obtained using Table 2-2a to Table 2-2d given in TR-55 manual (TR-55, Second Ed., June 1986). NRCS WIN TR.55 SMALL WATERSHED HYDROLOGY software was in fact used for obtaining the curve numbers. Weighted Curve Number (CN) for each of the selected sub-watersheds was then estimated by using following equation (Subramanya, 2012).

$$Weighted\ CN = \sum_{i=1}^n \frac{A_i \times CN_i}{Total\ Area} \quad (3.1)$$

Where,

n is number of sub-areas

A_i is area of the i^{th} sub-area of the sub-watershed

CN_i is curve number of the i^{th} sub-area of the sub-watershed

The weighted curve number was then used for estimating the direct runoff generated from a specific rainfall event for a sub-watershed.

Daily rainfall data for the Patiala city over a period of seven years (from January 2006 to December 2012) was obtained from the Indian Meteorological Department (IMD) and from the website www.wunderground.com. This data was analyzed for finding the size of different percentile rainfall events. Here, the rainfall events that yielded no runoff were identified and eliminated from the data analysis. Minimum rainfall depth required for generating runoff was estimated by the following equation (Subramanya, 2012):

$$P = \frac{200}{CN} - 2 \quad (3.2)$$

Where,

P is precipitation in mm

CN is weighted curve number for the sub-watershed in question

Effective rainfall or runoff depth was estimated for different size rainfall events by using the following equation (Subramanya, 2012):

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad (3.3)$$

Where,

Q is runoff depth in mm

P is rainfall depth in mm

I_a is initial abstraction and it is taken as $I_a = 0.2 \times S$

S is maximum retention in soil and it is given by the following equation as

$$S = \frac{25400}{CN} - 254 \quad (3.4)$$

Volume of the runoff water generated from any specified rainfall event was found by the following equation:

$$V = Q \times A \quad (3.5)$$

Where,

V is Total Runoff Volume in m^3

Q is Daily Runoff in m

A is Area of the sub-watershed in m^2

Runoff volumes generated were plotted against the size of the rainfall events and used. Runoff volume corresponding to 90% rainfall event size was used in the development of the storm water treatment and disposal facilities.

3.4.2 Peak storm flows estimations for the design of the sub-watershed level combined sewerage system

Combined sewer system was envisioned for the collection of both stormwater and grey water of the sub-watershed and conveyance to the sub-watershed outlet for treatment and disposal. Design of the sewers requires the following information for the sub-watershed:

- Peak runoff and time of concentration for each of the sub-areas
- Present peak flow and design peak flow of grey water for each of the sub-areas

Peak runoff for a sub-area can be estimated through two widely used methods, Rational Method and SCS (NRCS) Peak Flow Method.

3.4.2.1 Rational method

This method requires area, intensity of rainfall and runoff coefficient as input information.

Peak runoff by Rational Method could be estimated by the following equation:

$$Q = \frac{CIA}{360} \quad (3.6)$$

Where,

Q is the peak storm water runoff rate (in m³/s)

C is the runoff coefficient for the sub-area

A is the area of the subarea of interest (in hectares)

I is the design rainfall intensity (in mm/hr)

Rainfall Intensity is assumed to be same for the entire drainage area and uniform over time of duration equal to time of concentration, T_c . Rainfall intensity, duration and frequency curves are necessary to use the rational method. Regional IDF curves are available in most state highway agency manuals and if not available, they need to be developed.

Runoff coefficient, C , is a function of the ground cover and a host of other hydrologic abstractions. Typical values for C are given in Table 3.1. Since a sub-area can be consisted of a multitude of land use and land covers, composite runoff coefficient can be computed for each of the sub-areas.

Time of concentration (T_c) which is the time required for a drop of water to travel from the most hydrologically remote point in the sub-catchment to the point of collection or in other words the time required for the entire watershed to contribute to runoff at the outlet point can be estimated using number of methods, some of which are intended to calculate the flow velocity within individual segments of the flow path (e.g. sheet flow, shallow concentrated flow, open channel flow, etc.). The time of concentration can be calculated using as the sum of the travel times within the various consecutive flow segments. Following equation is used for calculating Time of Concentration (T_c).

$$T_c = T_{sh} + T_{sc} + T_{oc} \quad (3.7)$$

Where:

T_{sh} is Travel time for sheet flow

T_{sc} is Travel time for shallow concentrated flow

T_{oc} is Travel time for open channel flow

The details of calculating the individual travel times can be obtained from urban drainage manual (FHWA-NHI-10-009).

Table 3.1: Runoff Coefficients for Urban Areas (ASCE, 1960)

Type of drainage area	Runoff coefficient
Business:	
Downtown areas	0.70–0.95
Neighbourhood areas	0.50–0.70
Residential:	
Single-family areas	0.30–0.50
Multi-units, detached	0.40–0.60
Multi-units, attached	0.60–0.75
Suburban	0.25–0.40
Apartment dwelling areas	0.50–0.70
Industrial:	
Light areas	0.50–0.80
Heavy areas	0.60–0.90
Parks, cemeteries	0.10–0.25
Playgrounds	0.20–0.40
Railroad yard areas	0.20–0.40
Unimproved areas	0.10–0.30
Lawns:	
Sandy soil, flat, 2%	0.05–0.10
Sandy soil, average, 2–7%	0.10–0.15
Sandy soil, steep, 7%	0.15–0.20
Heavy soil, flat, 2%	0.13–0.17
Heavy soil, average, 2–7%	0.18–0.25
Heavy soil, steep, 7%	0.25–0.35
Streets:	
Asphaltic	0.70–0.95
Concrete	0.80–0.95
Brick	0.70–0.85
Drives and walks	0.75–0.85
Roofs:	0.75–0.95

3.4.2.2 SCS (NRCS) peak flow method

The SCS (now known as NRCS) peak flow method calculates peak flow as a function of drainage basin area, potential watershed storage, and the time of concentration. The graphical approach to this method can be found in TR-55. This rainfall-runoff relationship separates total

rainfall into direct runoff, retention, and initial abstraction to yield the equation 3.3 mentioned earlier for rainfall runoff. Peak flow is then estimated with the following equation:

$$q_p = q_u \times A \times Q \quad (3.8)$$

Where:

q_p is Peak flow, m^3/s

q_u is Unit peak flow, $m^3/s/km^2mm$

A is Area of sub-watershed, km^2

Q is Runoff depth, mm (calculated using equation 3.3)

The unit peak flow is calculated with the following equation (graphical depictions are presented in TR- 55):

$$q_u = K_u \times 10^{C_0 + C_1 \log T_c + C_2 [\log(T_c)]^2} \quad (3.9)$$

Where:

C_0, C_1, C_2 are Coefficients, these are a function of the 24 hour rainfall distribution type

T_c is Time of concentration

K_u is 0.000431

3.4.3 Quantification of grey water

Present peak grey water flow and design peak grey water flow were needed in the design of the combined sewerage system that collects both storm water and grey water and conveys to the sub-watershed outlet (point of treatment and disposal).

Water supply demand given in the manual on water supply and treatment by Central Public Health and Environmental Engineering Organisation (CPHEEO) (Table 3.2) was used as the basis for estimating per capita grey water generation rates.

Table 3.2: Recommended per capita water supply levels for designing schemes

S. No.	Classification of towns/cities	Recommended maximum water supply levels (lpcd)
1.	Towns provided with piped water supply but without sewerage system	70
2.	Cities provided with piped water supply where sewerage system is existing/contemplated	135
3.	Metropolitan and mega cities provided piped water supply where sewerage system is existing/contemplated	150

Breakup of the water supplied among different uses and wastewater generated (Table 3.3) for the cities having piped water supply and sewerage system is existing/contemplated, given in manual, was used for estimating the grey water generation rates.

Table 3.3: Breakup of water requirement: domestic purposes and grey water production

Description	Quantity Of Water (l/cap/d)	Estimated Grey Water Production (l/cap/d)
Bathing	55	55
Washing of clothes	20	20
Flushing of WC	30	-
Washing of House	10	5
Washing of utensils	10	10
Cooking	5	-
Drinking	5	-
Total	135	90

Daily grey water generation rates for the sub-areas of the sub-watershed can be calculated by the following equation:

$$Q_D = \frac{N \times Q_s}{1000} \quad (3.10)$$

Where:

Q_D is daily grey water production (m^3/d)

N is number of people contributing to grey water generation

Q_s is per capita grey water generation rate (l/p/d)

For finding the Peaking factor needed for estimating the peak grey water generation rate

Harmon's formula (Imam and Elnakar, 2013) can be used.

$$PF = 1 + \frac{14}{4 + \sqrt{P}} \quad (3.11)$$

Where,

P is the population in thousands

For single-family homes, the peaking factor can be five (or higher). Peak grey water generation rate (Q_P) is then calculated using the formula:

$$Q_P = Q_D \times PF \quad (3.12)$$

3.5 Characterization of Stormwater

For characterizing the stormwater, multiple grab samples were collected for each of the five catchments, immediately after rainfall events from a ditch where runoff from each catchment gets collected. Composite sampling though a preferred option was not possible considering the short duration of the rains. Further multiple grab samples collected served to be the representative samples giving the characteristics of the stormwater collected. From the results of this characterization it was intended to design and implement a stormwater treatment system which will have the provision of first collecting the entire volume of rain and then treating it for disposal or recharge as per the level of treatment achieved. Hence, grab sampling was preferred.

A total of twelve storm events were sampled during the period ranging from April 2010 to March 2013. Information on the rainfall event, such as depth of rainfall and number of antecedent dry days (ADD) were recorded for each of the events sampled. Water samples were analyzed for numerous water quality parameters, including: pH, Conductivity, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Bio-chemical Oxygen Demand (BOD₅) 5 days at 20°C, Chemical Oxygen Demand (COD), Total Kjeldhal Nitrogen (TKN), Total Phosphorous (Total P), Oil and Grease, Total Coliform count, Fecal Coliform count and Heavy Metals: Zn, Cd, Ni, Pb, Fe, and Cu. Selection of the parameters was based entirely on the review of literature and also on studying the characteristics of the catchment and listing the possible pollutants which can be present. During parameter selection TKN was tested but, it was felt at a later stage that Total Nitrogen could have been a better option than TKN as reported in some of the literature. Physical survey revealed possibility of the oil and grease in stormwater samples due to the nature of work being carried out in one of the sub-watershed which had an automobile servicing workshop within the catchment area. This prompted us to include it for analysis. Heavily travelled road also justified this inclusion due to the possibility of leaks or spillage from the automobiles. The selection of the six heavy metals being tested was made on the basis of the earlier research studies carried on the characterization of stormwater.

Samples were collected in polyethylene bottles cleaned in advance by soaking overnight in 10% HNO₃, rinsing twice with tap water and then with ultrapure water, drying to complete dryness in a clean oven at 60°C, and capping in the laboratory. Glass containers were used to collect samples for the determination of Oil and Grease and wide mouthed sterilized bottles were used for microbial examination. Field and laboratory blanks (ultrapure water) were also maintained throughout the sampling, preparation and analytical steps.

Standard field and laboratory quality assurance/quality control (QA/QC) procedures were followed, using the procedures specified in Caltrans Stormwater Monitoring Protocol Guidance Manual (Caltrans, 2000). Principal QA/QC performed on samples include field duplicate (all constituents); lab duplicate (all constituents) and blank runs (all constituents).

3.5.1 Laboratory Analysis

The collected stormwater samples were brought to the Environmental Laboratory of Thapar University and analyzed according to APHA testing procedures for the analysis of water and wastewater (APHA, 2005). Until the analysis was complete, samples were stored in a deep freeze. Table 3.4 shows the analytical techniques adopted.

Table 3.4: Analytical techniques for testing of stormwater parameters

Parameter	Method	References
Biochemical Oxygen Demand (BOD)	5 day BOD test at 20°C, Winkler azide modification	APHA (2005) “manual standard method” 21 st edition (5210: B)
Chemical Oxygen Demand (COD)	Closed reflux method	APHA (2005): (5220: B)
Oil and Grease	Partition-Gravimetric method	APHA (2005): (5520: B)
TSS	Total suspended solids dried at 103-105°C.	APHA (2005): (2540: D)
TDS	Total dissolved dried at 180°C.	APHA (2005): (2540: C)
Ammonical nitrogen	Preliminary distillation step, titrimetric method	APHA (2005): (4500-NH ₃ : B, E)
Organic nitrogen	Macro kjeldahl method	APHA (2005): (4550- org: B)
Total phosphorous	Stannous chloride method	APHA (2005): (4500-P: B, D)
MPN	Serial dilution method	APHA (2005): (9221:B,C)
Heavy Metals (Zn, Cd, Ni, Pb, Fe & Cu)	Acid digestion followed by absorption spectro-photometry	APHA (2005): (3111: B)

3.5.2 Data processing and statistical methods

Statistical analysis was performed on the results obtained by characterizing the stormwater for studying the inter-parameter relationships in order to decrease the number of parameters tested and for developing a model that will be able to predict the concentration at any desired rain event. To begin with correlations between runoff quality parameters were performed using Spearman's non-parametric rank correlation procedure. This Spearman correlation analysis was principally used to identify chemical constituents that potentially serve as surrogates for other constituents. However, for practical purposes and for identifying potential monitoring surrogates, correlations with a Spearman R value larger than 0.8, were considered.

3.5.2.1 Principal component analysis (PCA)

PCA, a multivariate statistical data analysis technique provides information on the most meaningful parameters, and renders data reduction with minimum loss of original information. PCA attempts to extract a lower dimensional linear structure from the data sets.

PCA transforms a data set containing p variables, interrelated or correlated to various degrees, to a new data set containing p new orthogonal, uncorrelated variables called Principal Components (PCs). The PCs are linear functions of the original variables such that the sum of their variances is equal to that of the original variables. The PCs are ordered from largest variance (PC1), to next largest variance (PC2), and so on for all p PCs. The goal is that the first few or k PCs ($k \ll p$) will retain most of the information in all of the p original variables, thus reducing the practical dimensionality of the data set. In other words, if the correlations are high among many of the original variables, the first few PCs will tend to contain (or explain) a large percentage of the total variance and may be used to describe multivariate patterns or variation in water quality

across the watershed, almost as well as does the complete set of p original variables (Olsen et al. 2012).

An attempt was made to relate the different type of land uses with various constituents by using Principal Component Analysis was used for pattern recognition and for identifying possible patterns or clusters between objects and variables..

In the PCA undertaken, the water quality concentration data as mg/L was arranged into a matrix using the software, for each study area. PCA was undertaken on the normalized data for pattern recognition and for the identification of correlations between selected variables. Using the principal components PC1 which described the largest data variance and PC2, the next largest amount of data variance, it was possible to develop Bi-plots for the individual study areas. In the urbanized catchments the data were found to form into a series of clusters. These clusters can be related to rainfall intensity. The angle between loading vectors is significant as the degree of correlation between individual parameters is inversely related to it. Hence as the angle reduces, the degree of correlation increases. Vectors situated closely together represent variables that are highly correlated while orthogonal vectors represent variables that are uncorrelated (Goonetilleke et al. 2005). PCA thus undertaken helped to establish and study such relationships between pollution parameters and identified inter-parameter relationships.

3.5.2.2 Regression modeling

For assessing and formulating relationships between stormwater quality characteristics with average rainfall depth and antecedent dry period regression modeling was performed. Multiple regression analysis was undertaken keeping pollutant concentration as dependent variable, and ADD and Rainfall i.e. average rainfall depth as two independent variables. It was observed that a large variation in the pollutant concentrations existed between different sites that can be

attributed to a complex interaction among many factors. ADD, in general, positively influenced the concentrations of the pollutants in the sense of the more dry days, the higher the pollutant concentration. It is thus considered as one of the most important parameter for pollutant build-up (Egodawatta and Goonetilleke 2006). Pollutant wash off on the other hand depends on the rainfall, more importantly the rainfall intensity and the amount of rainfall i.e. average rainfall depth.

Most of the models commonly use concentrations or loads of pollutants as variables that are dependent upon runoff volume, rainfall intensity, traffic intensity, antecedent dry days, surrounding land use, etc. Our work was focused on the storm water accumulated from a rainfall event, and we have long term rainfall data as daily average rainfall depth. This led us to select average rainfall depth as the variable.

Regression models were formulated using software MiniTab Ver16 and regression equations were formulated for all the identified significant parameters for each of the sub-watershed separately.

The general multiple linear regression (MLR) equation used to develop estimation equations for pollutant concentrations is shown as:

$$\text{Pollutant Conc. or Load} = f(\text{ADD, Average Rainfall Depth denoted as Rainfall})$$

$$\text{Pollutant Conc. or Load} = \alpha \pm \beta \times \text{ADD} \pm \gamma \times \text{Rainfall} \quad (3.13)$$

Where, α is the arbitrary constant; β and γ are the dependent parameter constants; and ADD (day), Rainfall (mm) are the input variables.

Using the above equation individual regression equations were formulated for each of parameters for all the selected sub-watersheds.

To confirm the accuracy of the regression equations obtained and assess its statistical power in predicting the concentration of pollutants, Chi-square tests were employed to evaluate the goodness of fit at the 95% level of significance i.e. at $\alpha=0.05$. This test establishes whether or not an observed frequency distribution differs from a theoretical distribution. The value of Chi-square test-statistic (χ^2) was evaluated using the following equation:

$$\chi^2 = \sum_{i=1}^n \frac{(O_i \times E_i)^2}{E_i} \quad (3.14)$$

Where,

χ^2 is Chi-square test-statistic

O_i is an observed frequency or concentration of pollutant obtained via analysis

E_i is an expected (theoretical) frequency, predicted through regression equations and asserted by the null hypothesis;

n is the number of storm events sampled

The value of Chi-square obtained by above equation for a particular parameter i.e. BOD, COD, TSS; etc was compared with the tabulated value of Chi-squared distribution for the 95% significant level at $n-1$ degrees of freedom i.e. 11 in present study.

3.5.3 Characterization of Grey water

Grey water generally includes three major types of water i.e. bathroom water, laundry or cloth wash water and kitchen basin water. Kitchen grey water contains food residues, high amounts of oil and fat, including dishwashing detergents. It is high in nutrients and suspended solids and hence its use along with the stormwater was considered uneconomical for the functioning of the treatment unit. Bathroom grey water is regarded as the least contaminated grey water source within a household and thus could be considered to be the best possible wastewater for incorporating into the system. It contains soaps, shampoos, toothpaste, body fats, lint, shaving waste etc. The third category i.e. laundry grey water contains chemicals from soap powders, detergents, bleaches, suspended solids and non-biodegradable fibers from clothing.

For incorporating the use of grey water into the scheme of things prior knowledge of the characteristics of grey water was felt essential. For Indian conditions the Grey water characterization data available was only for boarding schools in western Madhya Pradesh (NEERI, 2006). Hence, this study along with international studies undertaken on the grey water characterization was referred for finding the important parameters to be tested for characterization. Sampling and analysis of grey waters obtained from two residential houses was then performed. The characterization results obtained for both the houses have been indicated in the Table 3.5 and Table 3.6.

On analyzing the characterization results obtained, it can be inferred that bathroom grey water as expected was least contaminated and resembled closely with stormwater characteristics obtained. The presence of pathogens in bathroom grey water can be attributed to the traces of urine and faeces which could be present.

Table 3.5: Domestic greywater characteristics of residential house 1 (RH 1): Samples collected on 26th and 29th October, 2014

Parameter	1st Greywater Sample			2nd Greywater Sample		
	Kitchen	Bathroom	Laundry	Kitchen	Bathroom	Laundry
pH	8.20	7.04	6.70	8.10	6.98	6.86
BOD ₅ (mg/L)	186	47	90	150	56	106
COD (mg/L)	318	164	836	318	198	884
TSS (mg/L)	198	52	95	222	64	135
EC (µs/cm)	604	393	1252	626	367	1198
Turbidity (NTU)	114	60	156	134	70	180
Fecal Coliform (MPN/100 mL)	2.4×10^3	2.7×10^3	4.1×10^4	5.6×10^3	1.3×10^4	4.7×10^4

Among the houses studied it was observed that grey water sample (Bathroom and Laundry) obtained from residential house 2 (RH2) had more fecal coliforms than RH1. This can be attributed to the fact the family members of RH2 have a one year old kid and the washing of nappies could have contributed to high level of pathogens in the laundry grey water. High COD was observed in the laundry grey water for both the houses which could be due to the presence of detergents, bleaches and non biodegradable fibers.

Table 3.6: Domestic greywater characteristics of residential house 2 (RH2): Samples collected on 26th and 29th October, 2014

Parameter	1st Greywater Sample			2nd Greywater Sample		
	Kitchen	Bathroom	Laundry	Kitchen	Bathroom	Laundry
pH	7.85	7.18	6.28	8.05	7.32	6.42
BOD ₅ (mg/L)	180	62	103	210	76	124
COD (mg/L)	394	178	894	386	196	1016
TSS (mg/L)	255	72	148	285	78	168
EC (µs/cm)	744	356	1102	796	410	1544
Turbidity (NTU)	156	92	172	174	86	184
Fecal Coliform (MPN/100 mL)	3.7×10^3	1.5×10^5	3.3×10^6	4.1×10^3	1.1×10^5	2.7×10^6

3.6 Development of experimental stormwater treatment system

The experimental stormwater treatment plant was designed and fabricated. Line diagram of the experimental treatment plant is shown in Figure 3.1. The treatment plant was first run with tap water so that the dissolved and suspended impurities of the filter media were washed out. The treatment unit was run on-site on stormwater sample immediately after the rainfall event. The plant was run during three rainfall events. Each time after running at constant flow rate for the duration, much longer than the HRT of the treatment plant, water samples were collected from both the inlet and the outlet. The collected samples were then analysed for BOD, COD, TSS,

TDS, Turbidity and Coliform count for evaluating the performance (removal efficiency) of the treatment plant.

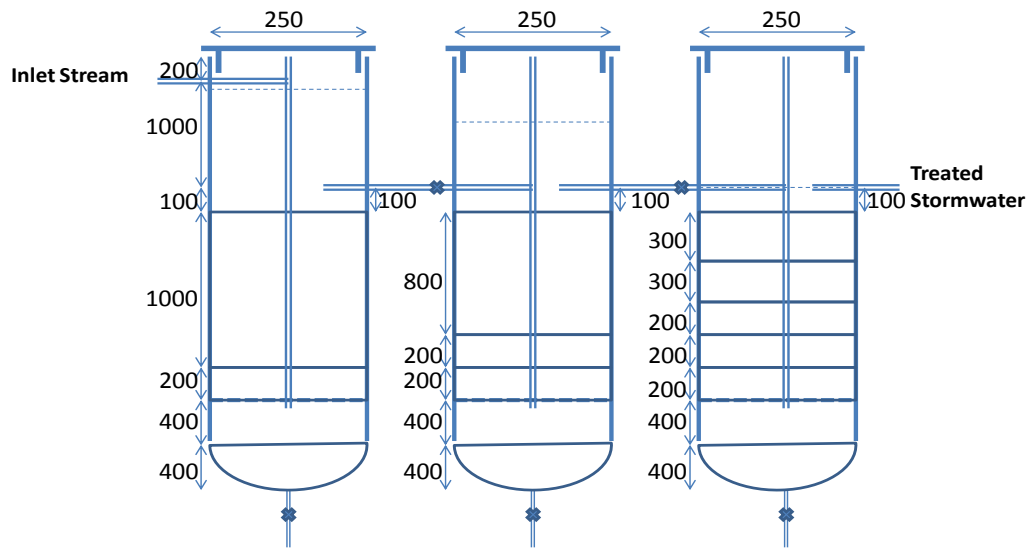


Figure 3.1: Experimental Multi-stage Multi-grade roughing Filter

3.7 Conceptualization of the sub-watershed level stormwater management system

Storm water flows and strengths are highly variable. Quite long and highly varying antecedent dry days (ADD) is also an important issue. The stormwater management system conceptualized was supposed to work under these conditions and should consistently satisfy the treated effluent quality requirements for disposal through the groundwater recharging. Operation and control of the conceptualized system should not require any human intervention especially during the rainfall events. Human intervention should preferably be limited to the annual prescheduled maintenance (may be prior to the monsoon).

Storm water characterization studies have indicated removal of suspended solids and treatment for the BOD/COD strength reduction as the essential features of the conceptualized storm water

treatment system. Viability of the treatment through the highly varying and random intervening dry period (ADD) was identified as the essential feature of the conceptualized system. For ensuring this, collection, conveyance and treatment of even the grey water along with the storm water of the sub-watershed was envisioned. Such a strategy was believed to make available of the treated grey water as reclaimed water for reuse within the sub-watershed. Due importance was also given to the local climate, social and economic conditions, while conceptualizing the system. The system was conceptualized while keeping in mind the local monsoon climate during which most of the rainfall occurs. Maintaining the system viable through the long dry spells of no rains was given due importance. Design of the system to handle 90 percentile rainfall events, requiring no human intervention for the operation of the system during the rainfall events, limiting repair and maintenance activities and cleaning activities to the pre-monsoon period, making the system passive and requiring no pumps and drives and no electrical power, excluding black water and considering only grey water for the management along with the stormwater, and keeping the total system underground that too at the road junction points have been the consequences of giving due importance to the local climate and socio-economic conditions.

The sub-watershed level urban stormwater management system was envisioned to include the following:

3.7.1 Collection system

Collection system comprising a combined system for stormwater and grey water was envisioned. This will convey the storm water as well as grey water to treatment system designed in form of a circular system adjacent to an infiltration well for the ultimate disposal via recharging. Collection system would be having self cleansing velocity with grey water and would be capable of carrying stormwater expected at 90% level.

3.7.2 Treatment system

Treatment system comprised the following sub-units:

- Screening facility for the removal of the litter, leaves and bigger size particles that will come along with stormwater.
- Cyclone de-gritter for grit removal and removal of heavier particles or suspended solids to avoid clogging of the filters
- Plain sedimentation of the received storm water and grey water and upflow anaerobic packed bed for the removal of suspended solids and reduction of BOD/COD strength
- Multistage multi-grade roughing filter for the final clarification and obtaining the treated effluent as reclaimed water.
- Micro-filtration of the effluent and feeding the groundwater recharge well

The treatment plant was sized to rapidly treat the storm water of a design storm event without causing unacceptable storm water flooding. The sizing has been done based on the amount of stormwater as well as the grey water to be handled. Hydraulic design of the conceptualized treatment was done in such a way that the treatment will occur without the need of any pumping and without running any drives that demand electrical energy.

3.7.3 Disposal system

The treated water will be used for recharging the groundwater via an infiltration well adjacent to the treatment unit.

The sizing and the depth of the infiltration facility was decided based on the background information collected from the local drillers as well as water supply department of Punjab. The

design protocol was developed and followed for calculating the mound height, maximum allowable depth and diameter of the recharge bore.

Line diagram of the Sub-watershed level urban stormwater management system is shown in Figure 3.2

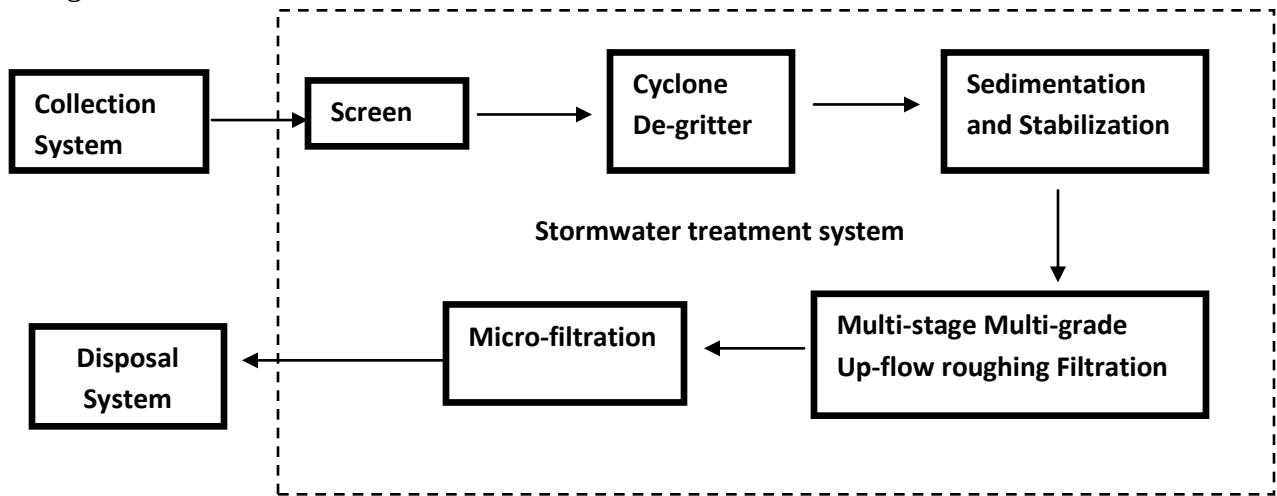


Figure 3.2: Flow Chart of urban stormwater management System

This system will run on grey water throughout the year. Grey water after treatment during non rainy season through stormwater treatment system will be used as reclaimed water; it will not be allowed to enter into the infiltration system for groundwater recharge. Major purpose served by grey water would be to maintain the bio-film developed on the filtration system by preventing the stormwater filter system from getting dried up. During rains, grey water along with stormwater will be allowed to pass through the treatment system and the treated water during this time will be used for groundwater recharging.

3.7.3.1 Protocol for the design of recharge wells

The existing design protocols required testing of a number of parameters on site of recharge and hence cannot be easily adopted, whereas, the need of the hour was a design protocol which can

be easily used with easily acquirable information. Hence for developing the design protocol, information was acquired from local drillers, Patiala Municipal Corporation and Punjab water supply and sewerage board. Based on the review of literature, step-by-step procedure for the design of the recharge facility was developed.

Following steps were performed for the development of the protocol.

Step 1: Collection of background information

Step 2: Determination of Recharge rate

Step 3: Estimation of Mound Height

Step 4: Determination of the maximum allowable depth of the recharge well

Step 5: Determination of the diameter of the recharge well

Chapter-4

Results and Discussion

Objectives of the study have been achieved through working on the work elements mentioned under methodology chapter. The results obtained from the study are presented and discussed in this chapter.

4.1 Patiala city and its stormwater drainage patterns

4.1.1 Patiala City

Patiala, an erstwhile princely city of the Punjab state of India lies between 29°49' and 30°47' north latitudes, 75°58' and 76°54' east longitudes. It is located within a bowl-like drainage basin with planar topography. The elevation of land ranges from 240 to 278 meters above mean sea level. Total geographical area of the district is 3290 sq.km (CGWB, 2007). Population of Patiala has increased from 53,000 in 1951 to 445,196 in 2011 with a median growth rate of 30% to 35% (Census GOI, 2011).

The climate of Patiala can be classified as tropical steppe, semi-arid and hot which is mainly dry with very hot summer and cold winter except during monsoon. The mean minimum and maximum temperature in the area is 7.1°C during January to 40.4°C during June. The city has four seasons in a year: The hot dry summer season from mid March to the last week of June; The monsoon following the summer and lasting upto September; Post monsoon season, the transition period from September to October; and the winter season from late November to the first week of March.

The average annual rainfall is 677 mm, and the average rainy days per year are 29. Out of the total 677 mm, an average of 547 mm rain occurs during the monsoon season. The south west

monsoon which sets in from the last week of June and withdraws in the end of September, contributes about 81% of the annual rainfall. July and August are the wettest months. Rest 19% of the rainfall is received during non-monsoon periods in the wake of the western disturbances and thunderstorms.

Patiala city falls under the Indo-Gangetic alluvial plain of Quaternary age, which extends to Ghaggar river basin. Groundwater occurs in alluvium formations comprising of fine to coarse sand. In the shallow aquifers (up to 50m), the groundwater occurs under unconfined conditions, and in deeper aquifer, the water occurs under semi-confined/confined conditions. The traditional dug-wells tapping the shallow aquifers are abandoned and currently not in use. However, the aquifer is being tapped widely for domestic use by hand pumps and shallow tube wells. The permeable granular zones comprise fine to medium grained sand and occasionally coarse sand and gravel. Borehole data reveals that clay group of formations dominate over the sand group formations in this area. Groundwater occurs in the alluvium under semi confined to confined conditions. Depth to groundwater table ranges from 4.43 to 20.62 m below ground level (bgl) during pre monsoon period and 6.99 to 24.28 m bgl during post monsoon period. Seasonal fluctuations in groundwater table vary from 0.03 to 3.66 m in the area. The long-term water table trends indicate an average fall of 0.50 m/year. Drinking water supply in the city is mainly through groundwater. Short fall in water supply is mostly met by the household level hand pumps. Depth of the shallow tube wells vary from 20 to 70 m and these wells are used mostly to tap water from unconfined aquifers. The tube wells of the municipal corporation and of other agencies have been tapping water from deeper aquifers upto 100 m.

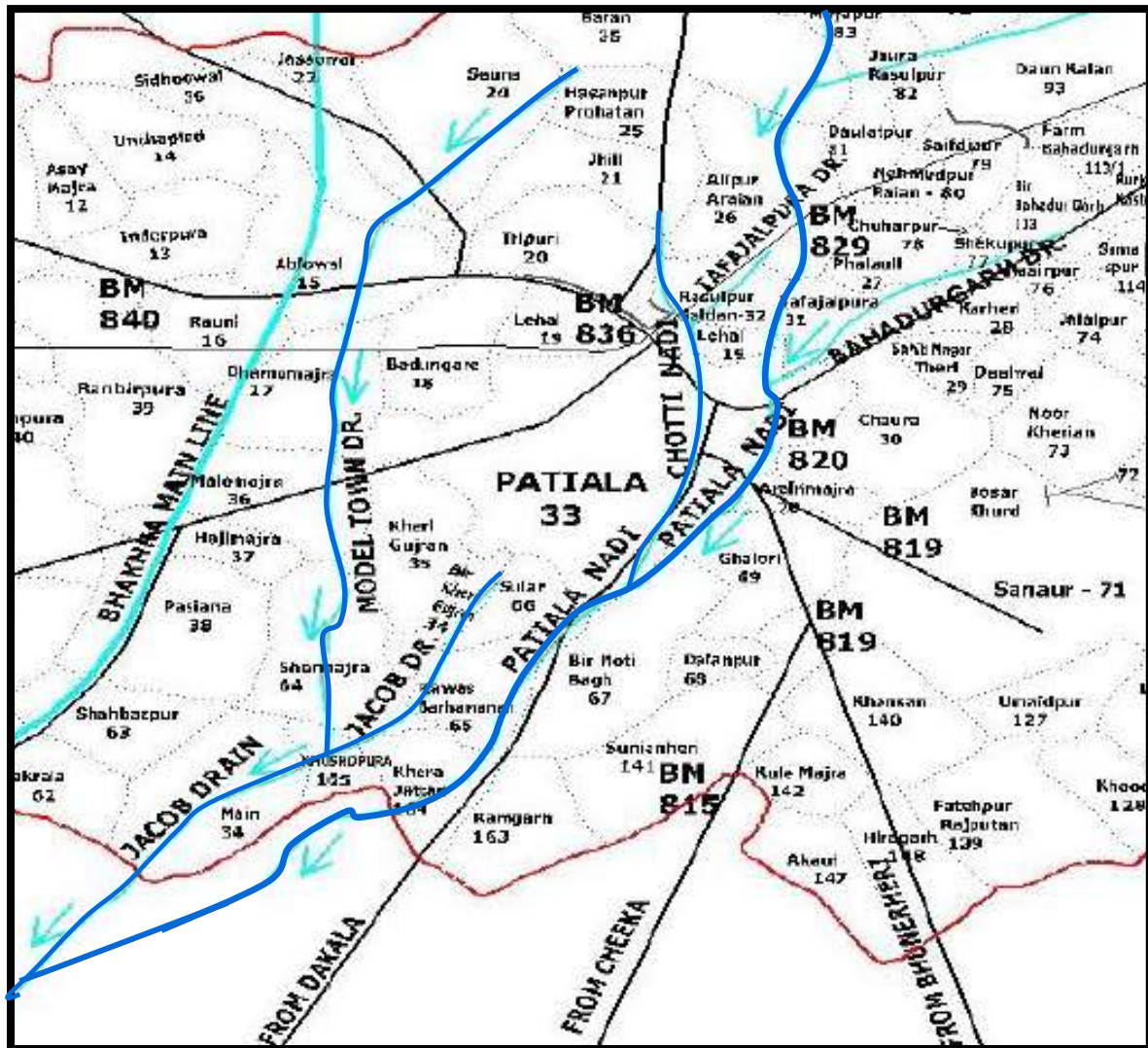
4.1.2 Drainage system of the City

To protect the city from the ravages of annual floods, a drainage network for the walled city was designed in 1870 A.D. The network of drainage is shown in Figure 4.1, the city drains culminate in the Ganda Nallah/Jacob Drain.. Two flood defence bandh's – the first forming the outer edge of the city and the second on the Patiala Nadi - were constructed in 1889 A.D to protect the city from the run on/off of stormwater. Patiala Nadi is a seasonal river. It originates in the Shivalik foot hills, and, after traversing some distance, enters Patiala district. The defence bandh of 15.40 km long was constructed on the left side of Patiala Nadi.

There were a number of ponds, marshes, and other low-lying areas between the Patiala Nadi and the inner defence bandh (the Chotti Nadi). These stored stormwater and allowed slow recharge of the underground aquifer. After independence, Patiala city has grown very rapidly. Currently, these water bodies are encroached upon and developed. As a result large portions of the city get flooded even with modest rainfall events.

Modern stormwater drainage system is in place only in a few selected areas of the city. Newly developed areas of the city, such as, Urban Estate Phase-I, II & III have stormwater drainage systems draining into the Patiala Nadi. Other than this, the city has no defined modern stormwater drainage system. Stormwater of the city currently gets drained into 3 drains, namely Patiala Nadi, Chotti Nadi and Model Town drain. Model Town Drain has a total length of 15.90 km. It originates near the confluence of the boundary of village Seuna, Baran and Hasanpur Prohatan and drains into the Jacob drain near Main factory. Jacob Drain itself is of 14.82 km length. It originates from 'Thandi Khuhi' near Mohindra College and drains into Patiala Nadi near village Darola. The Chotti Nadi, which starts near Patiala-Sirhind road and drains into

Patiala Nadi near Patiala-Dakala road, is encroached upon at several places and subjected to unauthorized developments.

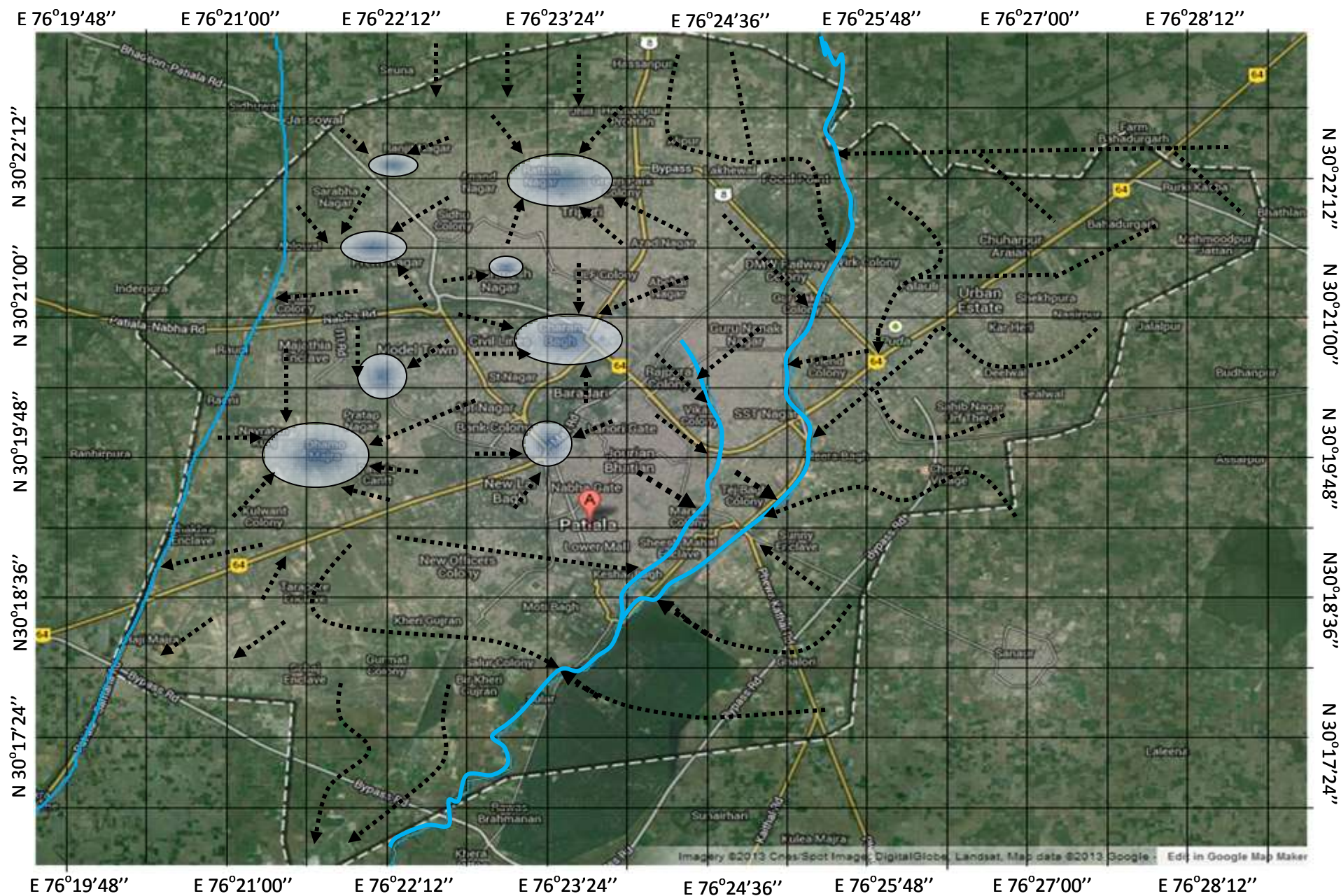


Source: Punjab Water Supply and Sewerage Board, Patiala

Figure 4.1 Drainage map showing the major drains of the Patiala city

4.1.3 Identification and selection of sub-watersheds

The entire city was divided into 1.1 km^2 grids and elevation details were obtained for each of the grids through using Google Earth software. On the basis of this information and the information obtained from the physical survey, flood water routing for the city was worked out. On the basis of the drainage patterns, a few urban sub-watersheds, wherein storm water flooding usually occurred, were identified. Figure 4.2 shows the stormwater drainage pattern and flood routing (dotted lines). The figure also shows the identified sub-watersheds prone to flooding.



○ -- Areas prone to flooding/ Stormwater ponding

Figure 4.2: Map showing the identified sub-watersheds along with the streams flowing through the city

4.2 Characterization of the selected urban sub-watersheds

The following five sub-watersheds were chosen from the identified sub-watersheds for further studies (Figure 4.3):

- Sub-watershed 1: Model Town sub-watershed
- Sub-watershed 2: Civil Lines sub-watershed
- Sub-watershed 3: Manjit Nagar sub-watershed
- Sub-watershed 4: Preet Nagar sub-watershed
- Sub-watershed 5: Bus Stand sub-watershed



Figure 4.3: Map showing the locations of the sub-watersheds studied

Basis for the selection was to cover the heterogeneity and diversity of the sub-watersheds. For ensuring similar rainfall, all the five sub-watersheds were selected from within the 5 km radius. The sub-watersheds differed in the forms of land development activities and housing density. Civil Lines sub-watershed is predominantly a residential catchment. Manjit Nagar sub-watershed is a mix of rural and urban residential acreage. Preet Nagar sub-watershed is of a mixed urban development. Model Town sub-watershed is predominately commercial. Lastly, Bus Stand sub-watershed is a heavily travelled and polluted catchment.

Area, land use-land cover, impervious surfaces (directly connected and not directly connected), slope, drainage (natural and manmade) facilities, hydraulic path length etc., information was collected for each of the sub-watersheds, mostly through physical survey.

Summary of the characteristics of the selected sub-watersheds is given in **Table 4.1**.

Table 4.1: Land use characteristics of selected sub-watersheds

Sub-watershed Name	Catchment Characteristic	Catchment Area (m ²)	Land Use			
			Impervious cover (%)	Grass cover (%)	Bare soil (%)	Tree canopy (%)
Model Town	commercial	8501	75	11	10	4
Civil Lines	residential	31733	55	18	15	12
Manjit Nagar	rural acreage-residential	15673	40	35	20	5
Preet Nagar	mixed urban	6124	75	10	10	5
Bus Stand	heavily travelled urbanized	39950	90	0	7	3

Sub-watershed 1 (Model Town): This sub-watershed is a commercial area having high intensity of urbanization. In addition to the residential buildings, workshops, a theatre and government offices are present in this sub-watershed. Figure 4.4 shows the land use pattern as percentages of the total area.

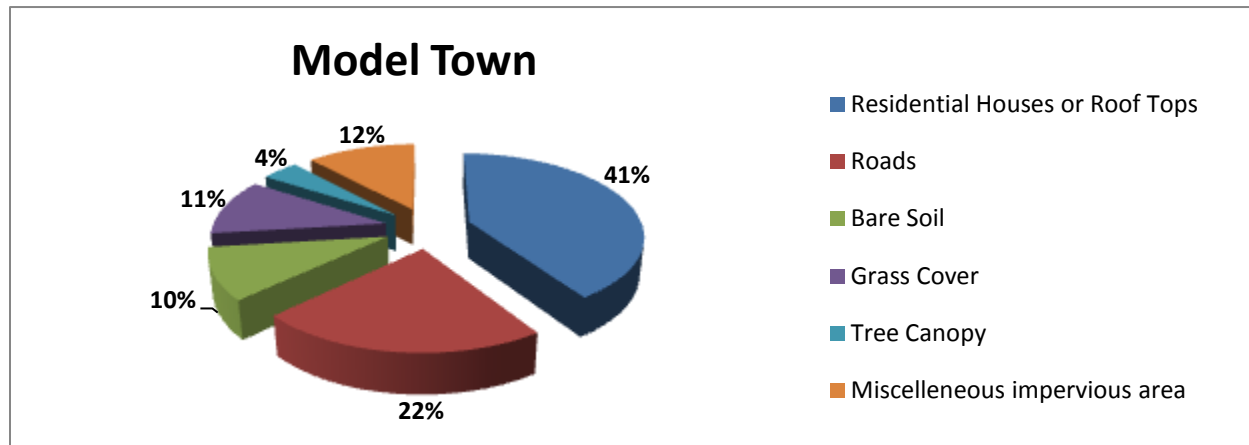


Figure 4.4: Land use in terms of percentages for Model Town Sub-watershed

This sub-watershed is facing the problems of Municipal Solid Waste (MSW) dumping and stormwater flooding. The stormwater gets collected and stagnates the roads. There is no stormwater drainage system for carrying away the stormwater. Stormwater runoff generated from this sub-watershed had high oil and grease concentration as frequent spills were observed from the automobile workshop during the survey visits of the site. Figure 4.5 shows the demarcated Model Town sub-watershed on the Google map of the Patiala city.

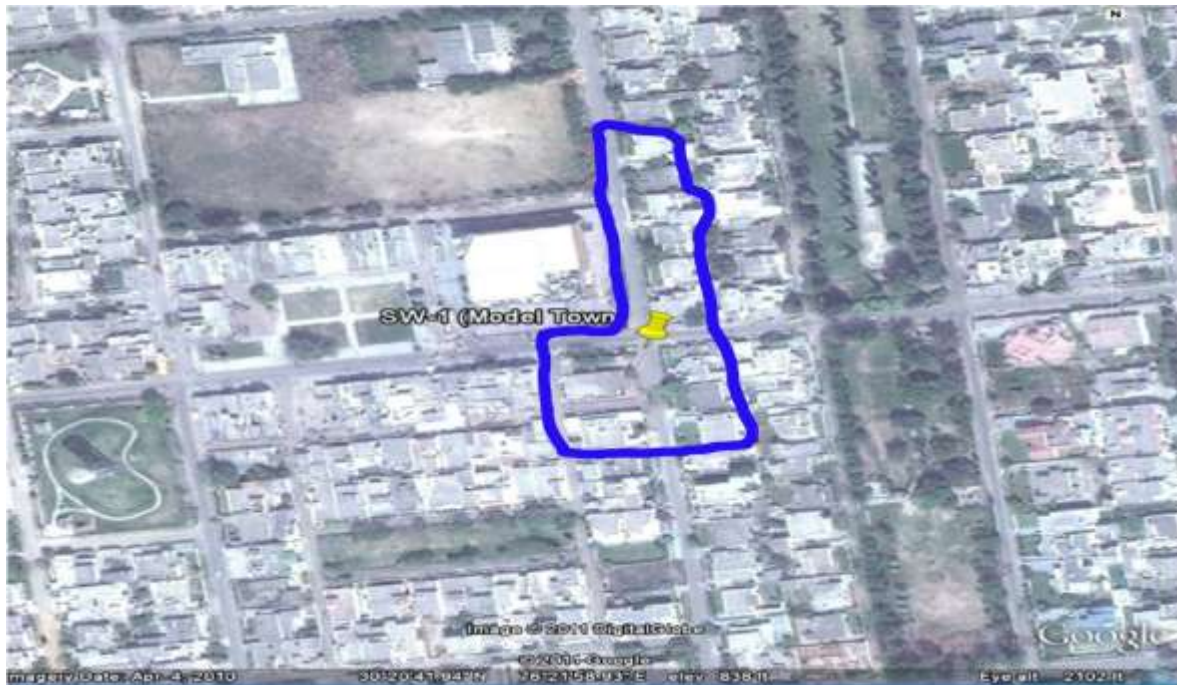


Figure 4.5: Model Town Sub-watershed

Sub-watershed 2 (Civil Lines): This sub-watershed is a residential area with high intensity of urbanization. In addition to the residential buildings, schools and parks are present in this sub-watershed. This area suffers from open defecation (by livestock), urination and stormwater flooding. The stormwater in this sub-watershed collects in an arbitrary outlet formed by contribution of runoff from the adjacent roads having higher elevation than the outlet. Figure 4.6 shows the land use pattern as percentages of the total area. Underground sewers are present for the stormwater drainage, but are not functioning and often remain blocked. This sub-watershed is quite large in size and remains by and large clean. This area is frequently used as a corridor for livestock movement. Figure 4.7 shows the demarcated civil lines sub-watershed on the Google map of the Patiala city.

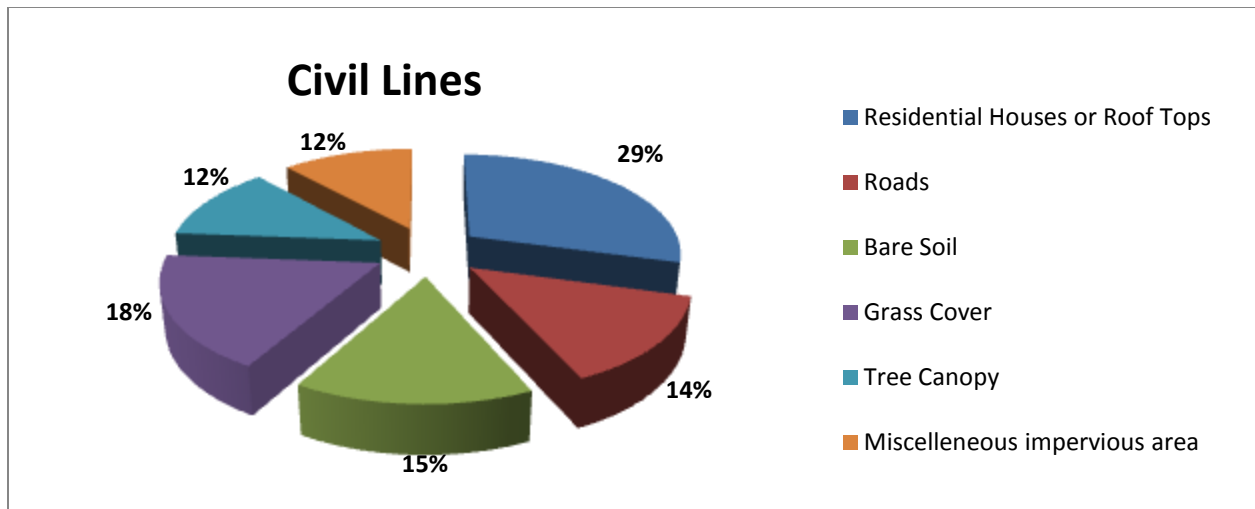


Figure 4.6: Land use in terms of percentages for Civil Lines Sub-watershed



Figure 4.7: Civil Lines Sub-watershed

Sub-watershed 3 (Manjit Nagar): This sub-watershed is predominantly agricultural land with relatively low intensity of urbanization. Consequently it has large portions of grass cover, natural plants and landscaping (Figure 4.8). This sub-watershed also has residential buildings, workshops and slums.

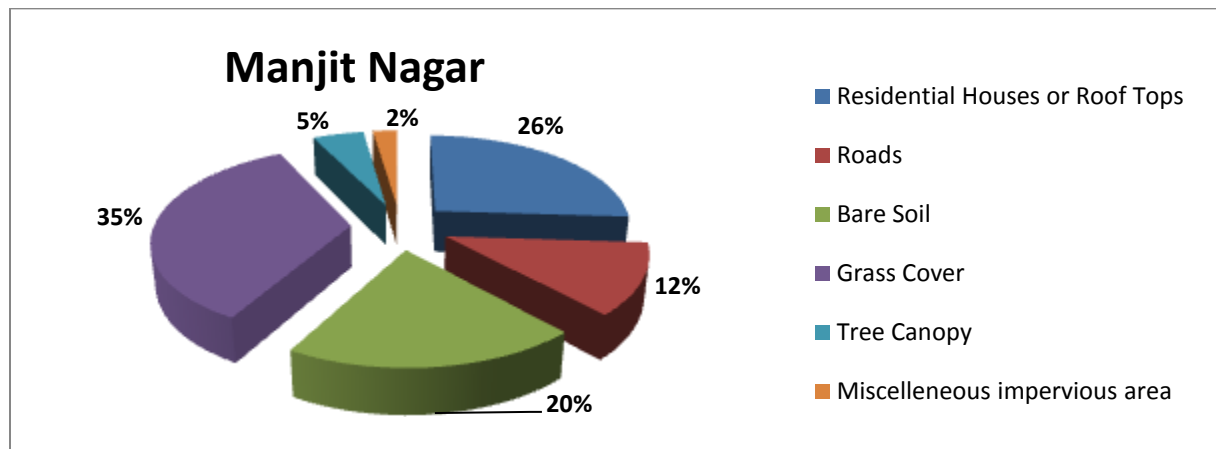


Figure 4.8: Land use in terms of percentages for Manjit Nagar Sub-watershed

Problems faced by this sub-watershed are open defecation and urination, MSW dumping and stormwater flooding. Stormwater of this area flows into a nearby depression or toba. No Sewerage is created in this sub-watershed for the drainage of the stormwater. Figure 4.9 shows the demarcated area contributing to the runoff of the Manjit Nagar Sub-watershed.



Figure 4.9: Manjit Nagar Sub- watershed

Sub-watershed 4 (Preet Nagar): The Preet Nagar sub-watershed is the smallest among all the sub-watersheds selected. This sub-watershed is a developed area. It has high intensity of urbanization. As a consequence, this sub-watershed has the maximum impervious cover as shown in Figure 4.10. Besides residential houses, this sub-watershed has a few shops and one park. Problems faced by this sub-watershed area include a construction waste dump and stormwater flooding. Stormwater of this sub-watershed is collected on the roads and roadside depressions. The stagnated stormwater is lost mainly through percolation and evaporation. At some places in the sub-watershed localized pits or underground tanks are available for the handling of the rain water.

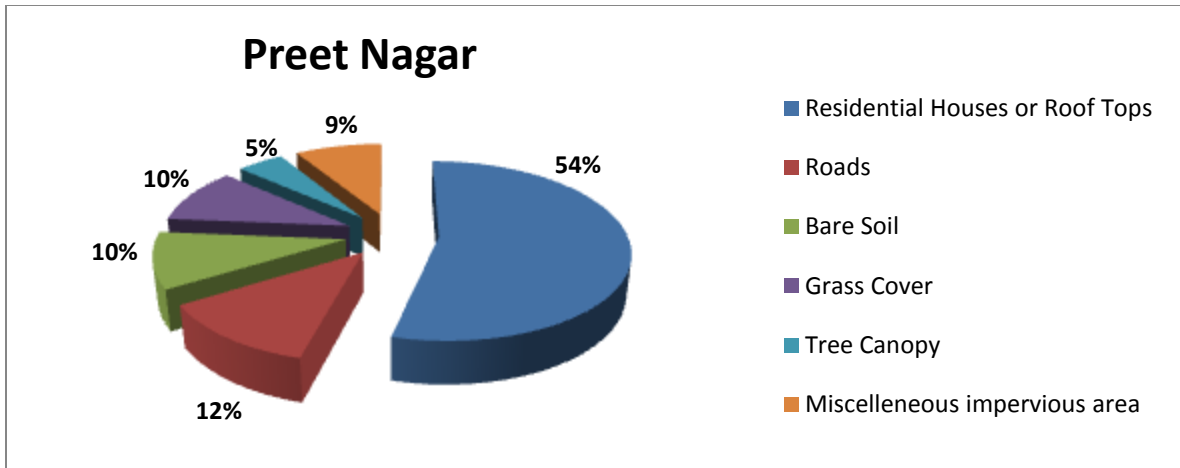


Figure 4.10: Land use in terms of percentages for Preet Nagar Sub-watershed

Preet Nagar Sub-watershed, being close to the highway, also receive some amount of runoff from the area adjoining. Hence, the stormwater is expected to have oil and grease along with metal pollutants. Figure 4.11 shows the demarcated area under the sub-watershed.



Figure 4.11: Preet Nagar Sub-watershed

Sub-watershed 5 (Bus Stand): This sub-watershed is a commercial area having high intensity of urbanization. It has maximum impervious cover and almost negligible tree canopy and bare soil as shown by Figure 4.12.

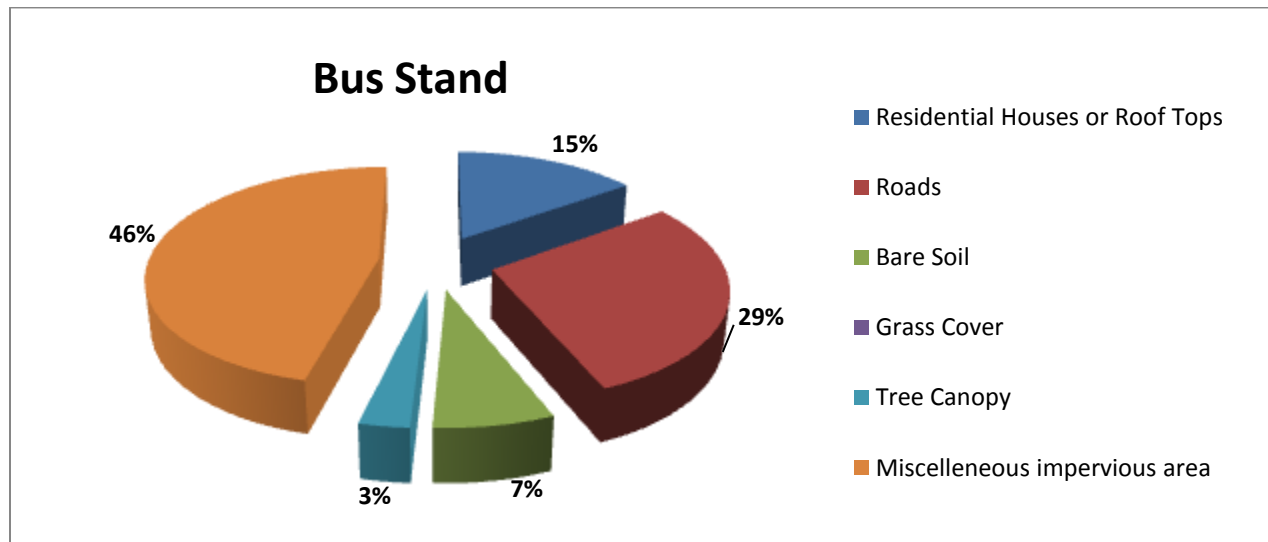


Figure 4.12: Land use in terms of percentages for Bus Stand Sub-watershed

It is the most travelled and most polluted of all the sub-watersheds. Patiala city's bus stand and railway station are located in this sub-watershed. This sub-watershed also has many workshops. Street hawkers selling mainly fruits and vegetables are very significant in this sub-watershed. Problems faced in this sub-watershed include open urination, MSW dumping, municipal sewage flooding, open discharge of sewage and stormwater flooding. Stormwater in this area gets collected on the roads, and adjoining depressions beneath the flyover. The stagnated stormwater is mostly lost through evaporation. Even a small rainfall event causes flooding of roads. This area has very poor stormwater drainage systems. Stormwater from this sub-watershed, besides being heavily polluted with organic matter, is expected to have high concentrations of heavy metals, on account of the nearby mechanical and electrical workshops. Figure 4.13 demarcates the area covered under Bus Stand sub-watershed.



Figure 4.13: Bus Stand Sub-watershed

4.3 Quantification of stormwater at urban sub-watershed level

The sub-watershed characteristics used in the quantification of stormwater for each of the sub-watersheds are given in the Table 4.2.

Table 4.2: Sub-watershed Characteristics

Sub-watershed	Area m ² (acres)	Channel Length m (feet)	Slope
Model Town	8501 (2)	75 (246)	0.02
Civil Lines	31733 (8)	244 (800)	0.0125
Manjit Nagar	15673 (3.84)	141 (462)	0.015
Preet Nagar	6124 (1.5)	104 (342)	0.0051
Bus Stand	39950 (9.8)	177 (580)	0.0147

Rainfall data for the Patiala city was obtained for a period of seven years (January 2006 to December 2012).

The entire rainfall information was arranged in increasing order of its precipitation for evaluating the percentile values. Table 4.3 gives the 90, 80, 70, 60, and 50 percentile values for average precipitation depths for each of the sub-watersheds. These percentile values have been estimated excluding the rainfall events yielding less rainfall than the minimum rainfall required for generating runoff in that particular sub-watershed.

Table 4.3 Average precipitation depth for different percentile values

Average precipitation depth (mm)					
Percentile	Model	Civil	Manjit	Preet	Bus
value	Town	Lines	Nagar	Nagar	Stand
90	65.4	69.8	83	64.6	64
80	43.4	54.2	58.2	42.6	42
70	33	40	43.6	31.9	31
60	28	31.8	38	27.2	27
50	24	28	31	23.5	21

Curve Numbers (CN) for the Sub-watersheds: The Curve Number for the catchments was assessed with the help of hydrologic model WIN TR-55 Small Watershed Hydrology software. The interface of the software used for calculating the weighted curve numbers for each of the sub-watershed is shown in Appendix B. Both individual and weighted CN were found and presented in Table 4.4 for all the 5 sub-watersheds.

Table 4.4: Weighted CN for the selected Sub-watersheds

Sub-watershed	Sub-areas based on land use												Weighted CN
	Residential Houses or Roof Tops		Roads		Bare Soil		Grass Cover		Tree Canopy		Miscellaneous impervious area		
	Area	CN	Area	CN	Area	CN	Area	CN	Area	CN	Area	CN	
Model Town	3457	98	1903	83	850	87	935	69	340	69	1016	85	86
Civil Lines	9287	98	4431	83	4760	72	5712	61	3807	61	3736	85	79
Manjit Nagar	7921	98	1888	83	3135	72	1566	61	784	61	378	85	76
Preet Nagar	3277	98	757	83	612	72	612	69	307	69	559	85	88
Bus Stand	6059	98	11465	89	2796	82	Nil	*	1199	86	18431	95	90

* Bus stand sub-watershed has negligible grass cover

For calculating the runoff volumes generated from the sub-watersheds, effective rainfall was estimated using equation 3.3 (Chapter 3).

Table 4.5 shows the effective rainfall calculated for the selected urban sub-watersheds for different size precipitation events (12 mm, 25 mm, 28 mm, 34 mm, 48 mm, 70 mm, 122mm, and 157mm).

Table 4.5: Estimated Effective Rainfall for the selected Urban Sub-Watersheds

Precipitation (mm)	Effective Rainfall Q (mm)				
	Model Town	Civil Lines	Manjit Nagar	Preet Nagar	Bus Stand
12	0.31	0.03	0.21	0.65	1.17
25	4.82	1.67	0.90	6.20	7.87
28	6.37	2.56	1.55	7.97	9.88
34	9.87	4.77	3.29	11.88	14.21
48	19.47	11.66	9.11	22.28	25.42
70	36.97	25.74	21.70	40.71	44.74
122	83.41	66.88	60.31	88.45	93.64
157	116.38	97.58	89.84	121.93	127.57

Volume of Runoff: Total volume of runoff generated (calculated using equation 3.5) for the selected urban sub-watersheds corresponding to precipitation events of 12 mm, 25 mm 28 mm, 34 mm, 48 mm, 70 mm, 122mm, and 157mm are given in Table 4.6.

Table 4.6: Volume of Runoff for Urban Sub- Watersheds

Precipitation (mm)	Quantification of Stormwater generated				
	Runoff Volume (m³)				
	Model Town	Civil Lines	Manjit Nagar	Preet Nagar	Bus Stand
12	2.6	1.1	3.4	4.0	46.7
25	41.0	53.1	14.1	37.9	314.6
28	54.2	81.3	24.3	48.8	394.8
34	83.9	151.5	51.5	72.7	567.7
48	165.5	370.2	142.7	136.5	1015.5
70	314.3	816.7	340.1	249.3	1787.2
122	709.0	2122.2	945.2	541.7	3741.0
157	989.3	3096.6	1408.0	746.7	5096.4

The maximum volume of runoff is being generated in the Bus Stand sub-watershed because of the largest drainage area and the highest curve number. For all the rainfall events Preet Nagar recorded lowest runoff volume because of its smallest catchment area.

4.4 Characterization of the stormwater

For characterizing the stormwater, twelve rainfall events were sampled during the period from April 2010 to March 2013 (Table 4.7). Multiple grab samples were collected for each of the five catchments, immediately after the rainfall events from the ditches where runoff from the catchments get collected. A minimum gap of 4 days between any two successive storm events being sampled was maintained as per the guidelines specified in Caltrans Stormwater Monitoring

Protocol Guidance Manual (Caltrans, 2000). Information on the rainfall events, depth of rainfall and number of antecedent dry days (ADD), was recorded for each of the sampled events (Table 4.7).

Table 4.7: Characteristics of storm events monitored

Date of Storm Event	Antecedent Dry Days	Rainfall (mm)
8 th June, 2010	30	56
1 st July, 2010	22	33
6 th July, 2010	4	24
12 th July, 2010	5	4
6 th August, 2010	24	15
8 th September, 2010	32	10
9 th July, 2011	16	29
9 th September, 2011	7	125
10 th April, 2012	85	17
6 th July, 2012	30	30
4 th September, 2012	7	35
17 th January, 2013	34	20

The results of the analysis for each of the storm event for all the studied sub-watersheds are given in Appendix C (Tables C1 to C5).

Table 4.8 provides information on the mean concentrations and standard deviations for the parameters analyzed.

Table 4.8: Stormwater characteristics of the studied sub-watersheds

Parameter	Units	Model Town	Civil Lines	Manjit Nagar	Preet Nagar	Bus Stand
BOD	mg/L	19.2 ± 10.1	12.7 ± 5.7	18.6 ± 5.0	12.9 ± 4.9	31.9 ± 7.0
COD	mg/L	212.5 ± 69.3	69.4 ± 13.9	127.2 ± 44.8	112.5 ± 55.6	319.4 ± 83.7
TSS	mg/L	112.3 ± 47.5	30.4 ± 17.2	101.6 ± 44.7	58.6 ± 19.2	262.3 ± 92.7
TDS	mg/L	32.5 ± 11.8	22.8 ± 8.3	42.7 ± 8.1	25.3 ± 7.8	43.6 ± 19.8
Oil & Grease	mg/L	152.4 ± 72.5	6.2 ± 3.0	32.6 ± 18.8	14.2 ± 6.5	111.4 ± 51.4
TKN	mg/L	9.7 ± 1.8	9.3 ± 1.3	10.5 ± 1.2	7.6 ± 2.5	11.1 ± 1.8
TP	mg/L	0.56 ± 0.09	0.64 ± 0.13	0.72 ± 0.09	0.73 ± 0.17	0.76 ± 0.16
Total Coliform	MPN/100 mL	6.44 ± 6.68	6.78 ± 7.13	5.89 ± 5.96	5.66 ± 5.87	6.73 ± 7.08
Fecal Coliform	MPN/100 mL	5.97 ± 6.24	6.37 ± 6.71	5.4 ± 5.55	5.01 ± 5.19	5.72 ± 5.97
Zn	ppm	0.80 ± 0.50	0.31 ± 0.09	0.83 ± 0.51	0.47 ± 0.20	1.90 ± 0.66
Cd	ppm	BDL	BDL	BDL	BDL	BDL
Ni	ppm	BDL	BDL	BDL	BDL	BDL
Pb	ppm	BDL	BDL	BDL	BDL	0.23 ± 0.14
Fe	ppm	44.4 ± 30.3	10.5 ± 4.6	36.4 ± 6.5	18.3 ± 7.3	89.9 ± 65.9
Cu	ppm	0.23 ± 0.16	0.07 ± 0.04	0.09 ± 0.05	0.10 ± 0.06	0.82 ± 0.36

Total & Fecal Coliform count has been expressed in terms of Natural Log values

BDL- Below Detection Limits (0.01 ppm, 0.3 ppm and 0.05 ppm for Cd, Ni and Pb respectively)

The difference in the pollutant concentrations observed among the sub-watersheds can be attributed to the differences in the land use and land cover characteristics, the spatial distribution and fraction of the impervious areas, and to the management practices of the five sub-watersheds.

On the basis of the results obtained the following can be inferred:

- Model Town, a commercial sub-watershed, with an automobile workshop within the catchment boundary, possessed highest concentration of Oil and Grease in the storm water samples.
- Surprisingly, the highest microbial count was observed in the Civil Lines sub-watershed, which may be due to animal dung. The Civil Lines sub-watershed includes bare soil strips surrounding the road, and these are used for open defecation and urination.
- TDS and nutrients (TP and TKN) were observed to be on the higher side for Manjit Nagar sub-watershed. This may be due to runoff from the agricultural fields.
- Preet Nagar and Model Town sub-watersheds surprisingly had different runoff characteristics; although, they catchments contain similar percentages of impervious areas. A number of reasons could be attributed to this situation. Firstly, the spatial distributions of impervious areas in the two catchments are different. This would have significantly influenced the time and velocity of travel of surface runoff and hence the pollutant load. Secondly, as Bannerman et al. (1993) have pointed out, street surfaces are the single most important source of urban water pollution, the fraction of road surface within the impervious area is higher for Model Town when compared to Preet Nagar (Figure 4.4 and Figure 4.10).

- Bus Stand, highly travelled and fully urbanized sub-watershed, showed the highest concentration of BOD, COD and TSS in runoff, with mean concentrations of 31.9 mg/L, 319.4 mg/L and 262.3 mg/L, respectively.

Of the metals analyzed, only Cu, Fe, Zn and Pb were detected in the samples. Concentrations of the metals, Ni and Cd, were below detection limits (0.30 ppm and 0.01 ppm, respectively).

The results indicate that the surface runoff of Patiala is badly polluted, especially in terms of the parameters TSS, COD and bacteria. Pollutant concentrations in the Model Town and the Bus Stand sub-watersheds, which have higher average annual traffic, were higher than those for the Civil Lines and Manjit Nagar sub-watersheds, which are mostly residential sub-watersheds. Concentrations for various parameters showed considerable variations among the events and also among the sub-watersheds.

Water quality parameters, whose concentrations exceeded the effluent standards for discharge into Inland surface waters (EP Rules, 1986), have been identified as the major pollutants. The frequency by which a particular parameter has exceeded the limits has been monitored. Table 4.9 provides the detailed information in this regard.

Table 4.9: Failing frequencies for the pollutant parameters

Parameter	No. of times the parameter exceeded the permissible limits for sub-watershed					Permissible limits (EP Rules, 1986)
	Model	Civil	Manjit	Preet	Bus	
	Town (12)	Lines(12)	Nagar(12)	Nagar(11)#	Stand(12)	
BOD	2	0	0	0	9	30.0
COD	4	0	0	0	11	250.0
TSS	8	0	8	0	11	100.0
TDS	0	0	0	0	0	2100.0
Oil & Grease	12	1	11	7	12	10.0
TKN	0	0	0	0	0	100.0
TP	0	0	0	0	0	5.0
Total Coliform	12	12	12	9	12	*
Fecal Coliform	9	8	9	7	12	*
Zn	0	0	0	0	0	5.0
Cd	0	0	0	0	0	2.0
Ni	0	0	0	0	0	3.0
Pb	0	0	0	0	2	0.1
Fe	12	12	12	11	12	3.0
Cu	0	0	0	0	0	3.0

No. of storm events for preet nagar is eleven and for others is twelve

* At present there is no standard developed or issued by CPCB for the Coliform count WHO standard of 10000 has been considered here

Sub-watershed wise parameters of importance are listed below in decreasing order of importance.

- Model Town Sub-watershed: Oil and Grease, Total Coliform count, Fe, Fecal Coliform count and TSS.
- Civil Lines Sub-watershed: Total Coliform count, Fe and Fecal Coliform count.
- Manjit Nagar Sub-watershed: Total Coliform count, Fe, Oil and Grease, Fecal Coliform count and TSS.
- Preet Nagar Sub-watershed: Fe, Total Coliform count, Fecal Coliform count and Oil and Grease.
- Bus Stand Sub-watershed: Oil and Grease, Total Coliform count, Fecal Coliform count, Fe, COD, TSS and BOD.

Stormwater characteristics reported for few other countries along with those of the Patiala city are outlined in Table 4.10. Most of these studies were in urban areas except for France and some sites in USA, which were actually for urban edge areas. Inspection of the results reported indicate that mean pollutant concentrations for almost all the constituents except for TSS are higher for Patiala city than for USA and China. Relatively low TSS observed for Patiala could be due to the fact that the stormwater samples were collected at the end of the rainfall event from pools of flooded water. Runoff from the catchments in USA is relatively less polluted. In case of Paris and Isfahan of Iran, the catchments were comprehensive urban watersheds, where the stormwater quality was closely related to the layout of land uses, drainage system and environmental background. Pollutant concentrations in terms of all the parameters except Cu (0.262 mg/L in this study against 0.117 mg/L), were higher for Paris than for Patiala. Mean values of COD and TSS (168 mg/L and 113 mg/L respectively) for Patiala are much lower than those for Iran (561 mg/L and 161 mg/L respectively). However, the concentrations of TKN, TP and Zn observed in Patiala are on higher side than those in Iran.

Table 4.10: Comparison of stormwater pollutant concentrations obtained in this study and previous publications

Site		BOD (mg/L)	COD (mg/L)	TSS (mg/L)	TKN (mg/L)	TP (mg/L)	Zn (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Reference
Patiala, India	Range	4.2-42.0	30-476	8.5-448	4.2-15.7	0.35- 1.12	0.19-2.89	BDL	0.03- 1.39	0.08-0.35	This study
	Mean	19.1`	168	113	9.64	0.68	0.86	*	0.262	0.23	
Paris, France	Range	11-241	56-569	36-421	20-36	*	0.17-3.20	0.0005- .013	0.056- 0.175	0.02-0.43	Kafi et al., 2008
	Mean	153	389	264	26.8	*	1.31	0.0023	0.117	0.166	
Guangzhou, China	Range	3.0-28.0	75-518	103-836	0.74-19.2	0.15- 0.68	0.39-4.40	0.0004- 0.005	0.01- 0.25	0.012- 0.43	Gan et al., 2008
	Mean	13	308	416	7.32	0.39	1.76	0.0016	0.14	0.118	
United States	Range	*	*	*	*	*	*	*	*	*	Smullen et al., 1999
	Mean	10.4	66.1	174	1.67	0.337	0.176	*	0.067	0.175	
Isfahan, Iran	Range	*	139-2542	43-467	1.22-22.38	0.064- 0.79	0.015- 2.386	*	*	0.018- 0.558	Taebi and Droste, 2004
	Mean	*	561	161	6.65	0.274	0.342	*	*	0.278	

* Data not available for indicated parameters

Low or negligible concentration of Pb observed in the present study for the Patiala city can be attributed to the ban on the use of leaded petrol. The differences among the studies and wide variations in concentrations observed for Patiala indicate the need for making site specific observations on the stormwater characteristics before planning a stormwater management system for Patiala city.

4.4.1 Assessment of stormwater characteristics

Rainfall events are random and size of rainfall events is highly variable. It is practically impossible to analyze each of the rainfall events and characterize the stormwater. Sampling and analysis of a few rainfall events, using the results in the development of Predictive models, and using such models for characterizing the stormwater for each of the selected sub-watersheds has been attempted. Pollution concentrations in the stormwater were felt to be largely dependent on both build-up (on the surfaces) and wash-off processes of pollutants. The build-up depends on the ADD, land use and development activities of the sub-watershed. Wash-off is considered as a function of rainfall volume and intensity. Keeping these in mind, the predictive modeling was done at individual sub-watershed levels while considering ADD and rainfall as the two independent variables.

4.4.1.1 Predictive models

Regression models were developed at the sub-watershed level for each of the important parameters identified. The models obtained for the parameters and for the sub-watersheds in question along with the respective coefficients are given in Tables 4.11-4.15.

Table 4.11: Regression Models for the Model Town sub-watershed

Parameter	Regression Equation	R ²	χ^2	Null hypothesis
BOD	BOD = 15.61 + 0.31×ADD - 0.12×Rainfall	0.74	17.4	accept
COD	COD = 175.22 + 2.34×ADD - 0.62×Rainfall	0.75	18.2	accept
TSS	TSS = 88.21 + 1.41× ADD - 0.32×Rainfall	0.55	65.4	reject
TDS	TDS = 26.13 + 0.35×ADD - 0.07×Rainfall	0.52	23.7	reject
Oil & Grease	O & G = 92.37 + 2.81×ADD - 0.28×Rainfall	0.80	14.6	accept
TKN	TKN = 9.25 + 0.05×ADD - 0.03×Rainfall	0.82	0.77	accept
Total-P	T-P = 0.56 + 0.002×ADD - 0.001×Rainfall	0.56	0.07	accept
Total Coliform	TC = 5.34 + 0.03×ADD - 0.01×Rainfall	0.69	0.56	accept
Fecal Coliform	FC = 4.77 + 0.03×ADD - 0.01×Rainfall	0.66	0.96	accept
Zn	Zn = 0.39 + 0.02×ADD - 0.002×Rainfall	0.86	0.48	accept
Fe	Fe = 21.01 + 1.15×ADD - 0.15×Rainfall	0.80	16.5	accept
Cu	Cu = 0.09+ 0.01×ADD - 0.001×Rainfall	0.87	0.46	accept

Table 4.12: Regression Models for the Civil Lines sub-watershed

Parameter	Regression Equation	R ²	χ^2	Null hypothesis
BOD	BOD = 8.68 + 0.21×ADD - 0.04×Rainfall	0.80	5.12	accept
COD	COD = 57.35 + 0.53×ADD - 0.03×Rainfall	0.75	8.6	accept
TSS	TSS = 14.40 + 0.67× ADD - 0.01×Rainfall	0.74	28.27	reject
TDS	TDS = 18.91 + 0.20×ADD - 0.05×Rainfall	0.47	15.3	accept
Oil & Grease	O & G = 3.59 + 0.12×ADD - 0.01×Rainfall	0.78	3.9	accept
TKN	TKN = 8.66 + 0.04×ADD - 0.01×Rainfall	0.51	0.98	accept
Total-P	T-P = 0.67 + 0.002×ADD - 0.003×Rainfall	0.66	0.104	accept
Total Coliform	TC = 4.87 + 0.04×ADD - 0.01×Rainfall	0.68	0.92	accept
Fecal Coliform	FC = 4.21 + 0.04×ADD - 0.01×Rainfall	0.64	1.28	accept
Zn	Zn = 0.22 + 0.003×ADD - 0.001×Rainfall	0.95	0.16	accept
Fe	Fe = 6.53 + 0.19×ADD - 0.02×Rainfall	0.92	1.82	accept
Cu	Cu = 0.03+ 0.002×ADD - 0.001×Rainfall	0.90	0.2	accept

Table 4.13: Regression Models for the Manjit Nagar sub-watershed

Parameter	Regression Equation	R ²	χ^2	Null hypothesis
BOD	BOD = 17.49 + 0.16×ADD - 0.08×Rainfall	0.93	0.96	accept
COD	COD = 115.85 + 1.08×ADD - 0.46×Rainfall	0.49	90.83	reject
TSS	TSS = 67.91 + 1.70×ADD - 0.25×Rainfall	0.82	44.47	reject
TDS	TDS = 35.15 + 0.51×ADD - 0.11×Rainfall	0.89	4.81	accept
Oil & Grease	O & G = 14.29 + 0.80×ADD - 0.04×Rainfall	0.91	11.53	accept
TKN	TKN = 9.91 + 0.04×ADD - 0.02×Rainfall	0.96	0.157	accept
Total-P	T-P = 0.65 + 0.003×ADD - 0.002×Rainfall	0.53	0.16	accept
Total Coliform	TC = 5.40 + 0.02×ADD - 0.01×Rainfall	0.65	0.37	accept
Fecal Coliform	FC = 4.45 + 0.02×ADD - 0.01×Rainfall	0.58	0.84	accept
Zn	Zn = 1.35 - 0.03×ADD + 0.008×Rainfall	0.66	4.58	accept
Fe	Fe = 35.85 + 0.18×ADD - 0.11×Rainfall	0.83	2.42	accept
Cu	Cu = 0.05+ 0.002×ADD - 0.001×Rainfall	0.83	0.15	accept

Table 4.14: Regression Models for the Preet Nagar sub-watershed

Parameter	Regression Equation	R ²	χ^2	Null hypothesis
BOD	BOD = 8.05 + 0.19×ADD - 0.02×Rainfall	0.57	12.37	accept
COD	COD = 68.88 + 1.60×ADD - 0.11×Rainfall	0.35	857.31	reject
TSS	TSS = 34.70 + 0.80× ADD +0.01×Rainfall	0.51	49.05	reject
TDS	TDS = 11.89 + 0.39×ADD + 0.07×Rainfall	0.72	10.23	accept
Oil & Grease	O & G = 7.72 + 0.24×ADD - 0.01×Rainfall	0.52	20.82	reject
TKN	TKN = 3.66 + 0.11×ADD +0.02×Rainfall	0.60	4.28	accept
Total-P	T-P = 0.39 + 0.01×ADD - 0.001×Rainfall	0.65	0.48	accept
Total Coliform	TC = 2.94 + 0.05×ADD - 0.01×Rainfall	0.45	4.94	accept
Fecal Coliform	FC = 2.62+ 0.04×ADD - 0.01×Rainfall	0.45	6.07	accept
Zn	Zn = 0.25 + 0.01×ADD - 0.001×Rainfall	0.54	1.12	accept
Fe	Fe = 9.43 + 0.29×ADD + 0.03×Rainfall	0.55	21.11	reject
Cu	Cu = 0.05+ 0.01×ADD - 0.001×Rainfall	0.57	1.19	accept

Table 4.15: Regression Models for the Bus Stand sub-watershed

Parameter	Regression Equation	R²	χ²	Null hypothesis
BOD	BOD = 34.36 + 0.12×ADD - 0.16×Rainfall	0.85	2.68	accept
COD	COD = 301.57 + 2.55×ADD - 1.36×Rainfall	0.90	13.24	accept
TSS	TSS = 228.06 + 3.04× ADD - 1.23×Rainfall	0.86	53.47	reject
TDS	TDS = 29.01 + 0.77×ADD - 0.13×Rainfall	0.87	13.86	accept
Oil & Grease	O & G = 78.95 + 2.01×ADD - 0.51×Rainfall	0.99	3.7	accept
TKN	TKN = 10.06 + 0.07×ADD - 0.02×Rainfall	0.99	0.04	accept
Total-P	T-P = 0.78 + 0.003×ADD - 0.003×Rainfall	0.48	0.21	accept
Total Coliform	TC = 5.18 + 0.03×ADD - 0.01×Rainfall	0.69	0.79	accept
Fecal Coliform	FC = 4.58 + 0.03×ADD - 0.01×Rainfall	0.71	0.46	accept
Zn	Zn = 1.68 + 0.02×ADD - 0.01×Rainfall	0.68	1.06	accept
Fe	Fe = 48.17 + 2.25×ADD - 0.41×Rainfall	0.68	17.8	accept
Cu	Cu = 0.70+ 0.01×ADD - 0.004×Rainfall	0.65	0.66	accept

Out of the total 12 storm events monitored, 8 were used for the predictive model development and the remaining 4 were used for validating the developed predictive models.

For demonstrating the appropriateness of the regression models developed, **sensitivity analysis** was undertaken for BOD and Zn for all the five sub-watersheds. Model sensitivity analysis involved manipulating one of the two model input parameters (i.e. ADD) through a range of values (i.e. mean ± 2 SD) while maintaining the other input parameter (i.e. rainfall) constant and vice a versa, and by comparing the coefficients of variation (CV) for the model output. Model sensitivity to input parameter variance was deemed to be high for changes in CV's > 50%, moderate for changes in CV's between 20-50%, and low for changes in output CV < 20%. Results of the sensitivity analysis performed have been indicated in Table 4.16.

Table 4.16: Results of the sensitivity analysis performed for BOD and Zn

Sub-watershed		Parameter	Range (Mean $\pm$ 2SD)	Coefficient of variation	Sensitivity
Model Town	BOD	ADD (Day)	5-45	66.60 %	High
		Rainfall (mm)	4-60	16.79 %	Low
	Zn	ADD (Day)	5-45	86.12 %	High
		Rainfall (mm)	4-60	5.98 %	Low
Civil Lines	BOD	ADD (Day)	5-45	58.69 %	High
		Rainfall (mm)	4-60	8.05 %	Low
	Zn	ADD (Day)	5-45	40.09 %	Moderate
		Rainfall (mm)	4-60	10.29 %	Low
Manjit Nagar	BOD	ADD (Day)	5-45	24.85 %	Moderate
		Rainfall (mm)	4-60	11.57 %	Low
	Zn	ADD (Day)	5-45	98.63 %	High
		Rainfall (mm)	4-60	24.30 %	Moderate
Preet Nagar	BOD	ADD (Day)	5-45	20.63 %	Moderate
		Rainfall (mm)	4-60	23.14 %	Moderate
	Zn	ADD (Day)	5-45	75.90 %	High
		Rainfall (mm)	4-60	5.29 %	Low
Bus Stand	BOD	ADD (Day)	5-45	21.45 %	Moderate
		Rainfall (mm)	4-60	64.40 %	High
	Zn	ADD (Day)	5-45	43.44 %	Moderate
		Rainfall (mm)	4-60	30.39 %	Moderate

Through this analysis, it was observed that, in most of the cases, ADD generated greater output variability (higher CV) than the rainfall and hence the ADD is the primary model sensitivity parameter. Rainfall showed moderate to low variability except for the case of BOD for the Manjit Nagar sub-watershed and for the Bus Stand sub-watershed. In these two sub-watersheds rainfall was observed as the primary sensitivity parameter.

Regression equations with R^2 (Coefficient of determination) value less than 0.5 was considered not fit for use for making predictions/assessments. The R^2 values for certain parameters are greater than 0.8 suggesting that the equations and data are well matched. To confirm the accuracy of the regression equations obtained and to test the predictive power of the calibrated regression model, Chi-square tests which evaluated the goodness of fit at 95% level of significance i.e. $\alpha=0.05$ were applied. The Chi-square values were compared with the tabulated values at $n-1$ degrees of freedom. For most of the cases, the null hypothesis was valid, as the Chi-square values obtained were less than the tabulated value.

As expected, ADD, in general, positively influenced the concentrations of the pollutants and rainfall has negative influence. The more the antecedent dry days, the higher, the pollutant concentration. It was also observed that in the smaller sub-watersheds (Preet Nagar sub-watershed), the measured endpoints showed lesser correlation with the ADD, while the bigger sub-watersheds (Bus Stand sub-watershed) showed larger positive correlations between the antecedent dry days and the measured end-points. There are no definite similarities among the five sub-watersheds regarding the degree and the extent to which the two variables (ADD and rainfall) impact stormwater pollutant concentrations.

R^2 testing and chi square testing revealed that the regression equations for some of the parameters are not acceptable for prediction purpose. In regard to the predictive models difference among the five selected sub-watershed were observed. Please see Table 4.17 for details.

Table 4.17: Parameters acceptable and unacceptable for prediction through models

Sub-watershed	Parameters with acceptable regression equations	Parameters with unacceptable regression equations
Model Town	BOD, COD, Oil & Grease, TKN, Total-P, Total Coliform, Fecal Coliform, Zn, Fe and Cu	TSS and TDS
Civil Lines	BOD, COD, Oil & Grease, TKN, Total-P, Total Coliform, Fecal Coliform, Zn, Fe and Cu	TSS and TDS
Manjit Nagar	BOD, TDS, Oil & Grease, TKN, Total-P, Total Coliform, Fecal Coliform, Zn, Fe and Cu	COD and TSS
Preet Nagar	BOD, TDS, TKN, Total-P, Zn, Fe and Cu	COD, TSS, Oil & Grease, Total Coliform and Fecal Coliform
Bus Stand	BOD, COD, TSS, TDS Oil & Grease, TKN, Total Coliform, Fecal Coliform, Zn, Fe and Cu	Total-P

4.4.1.2 Assessment of stormwater characteristics through regression models

Stormwater quality assessment was made for the following three sets of conditions.

- Worst case conditions of minimum rainfall (13 mm) and maximum ADD (98 days)
- Moderate case conditions of average rainfall (56 mm) and average ADD (30 days)
- Best case conditions of maximum rainfall (115 mm) and minimum ADD (5 days).

ADD and the rainfall values for the above three sets of conditions were obtained by analyzing the 7 years rainfall data for the Patiala city and finding their percentile values. 90 percentile value for rainfall depth and 10 percentile value for ADD were taken as the best case conditions. Similarly, 10 percentile value for rainfall depth, and 90 percentile value for ADD were taken as the worst case conditions. 50 percentile values for both the rainfall depth and the ADD were taken as the moderate case conditions.

The stormwater quality assessments made are given in Table 4.18. In cases, where the R^2 values are greater than 0.95, the predicted quality was considered more reliable. In cases, where R^2 values were between 0.68 and 0.95, the predicted quality was considered as moderately reliable, and for the cases where R^2 is less than 0.68 the predicted value was taken as less reliable. The cases where the predicted model equations met the criteria of significance stated above, for those the values assessed through the use of model equations are shown in the Table 4.18. The values marked as bold are the values not meeting the above stated criteria of prediction through model equation i.e. in the cases of less reliability, assuming the quality parameters are less dependent on ADD and Rainfall, the maximum, the average and the minimum values obtained through sample analysis have been considered as the assessed quality parameter values.

The stormwater quality assessments were used as inputs in the design of stormwater treatment system and in the assessment of the treated stormwater quality.

Table 4.18: Stormwater quality of the sub-watersheds predicted from regression models

Parameter	Units	Model Town			Civil Lines			Manjit Nagar			Preet Nagar			Bus Stand		
		Best	Worst	Avg.	Best	Worst	Avg.	Best	Worst	Avg.	Best	Worst	Avg.	Best	Worst	Avg.
BOD	mg/L	3.4	44.4	18.19	5.1	28.7	12.7	9.1	32.1	17.8	4.2	24.5	12.9	16.6	44.0	29.0
COD	mg/L	115.6	396.5	210.7	63.4	109.68	74.9	42	198	127	30	210	112.5	157.92	533.79	301.91
TSS	mg/L	35	173.5	112.3	16.6	79.93	33.9	47.6	231.26	104.9	29	96	58.6	101.81	509.99	250.38
Oil & Grease	mg/L	74.2	364.1	161	3.04	15.22	6.63	13.7	92.17	36.05	5.2	26	14.2	30.35	269.3	110.69
Total Coliform#	MPN/100 mL	4.34	8.15	5.68	3.92	8.66	5.51	4.0	6.38	5.89	3.66	6.36	4.87	4.18	7.99	5.52
Fecal Coliform#	MPN/100 mL	3.3	6.66	5.97	3.63	7.17	6.37	3.63	5.97	5.4	3.36	5.66	4.39	3.58	7.39	4.92
Zn	ppm	0.26	2.32	0.88	0.12	0.50	0.25	0.26	1.69	0.83	0.18	1.22	0.49	0.63	3.51	1.72
Fe	ppm	9.5	131.8	47.1	5.18	24.89	11.1	24.1	52.06	35.09	14.3	38.24	19.81	12.27	263.34	92.71
Cu	ppm	0.03	1.06	0.33	0.03	0.21	0.07	0.05	0.23	0.15	0.02	1.02	0.29	0.31	1.39	0.82

Total & Fecal Coliform count has been expressed in terms of Natural Log values

Bold values indicate the assessed quality through sample analysis

4.4.2 Inter-parameter relationships

Land use is considered as the most important factor affecting the stormwater quality. Numerous research studies have attempted to relate land use with the pollutant loadings (Sartor and Boyd, 1972; Hall and Anderson, 1986; Lopes et al., 1995; Parker et al., 2000) and observed variations in physical, chemical and microbial characteristics of stormwater among different land uses.

In the present study an attempt has been made to relate different types of land uses with various constituents of the stormwater, through Principal Component Analysis (PCA). All the parameters tested were analyzed through PCA. Ammonical-N and Organic-N were taken together as TKN, among heavy metals the analysis of Cd, Ni and Pb yielded their concentration values to be below detection limits of the instrument and hence were left out of the PCA analysis.

The PCA was undertaken on the normalized data for the pattern recognition and for the identification of correlations among the selected variables. A minimum of 70 percent of data variance was used as the bench mark in selecting/determining the number of PCs to be used. This selection criterion has been adopted in most of the research studies undertaken in the past (Goonetilleke et al. 2005, Miguntanna et al. 2010). This came out as two PCs. Using the principal components PC1, (that described the largest data variance), and PC2, (that described the next largest data variance), Biplots were developed for the individual study areas.

In all the sub-watersheds, the data was found forming a series of clusters that can be related to the rainfall. Angle between the loading vectors is significant as the degree of correlation between individual parameters is inversely related. Similarly, as the angle reduces the degree of correlation increases. Vectors clustered together indicate that the variables are highly correlated. Orthogonal vectors on the other hand represent the uncorrelated parameters. The Biplots

developed are shown in Figures 4.14-4.18. The conclusions drawn from the PCA are briefly given below:

Subwatershed-1: Model town (commercial), Figure 4.14

- COD and Oil and Grease are strongly correlated with each other and with TSS. Hence, most of the COD and the Oil and grease constituents are particle bound. Removal of TSS will result in the coincidental removal of these two pollutants as well.
- The metals, Cu, Fe and Zn, are correlated with TSS suggesting that most Suspended Solids (SS) would be inorganic particles.

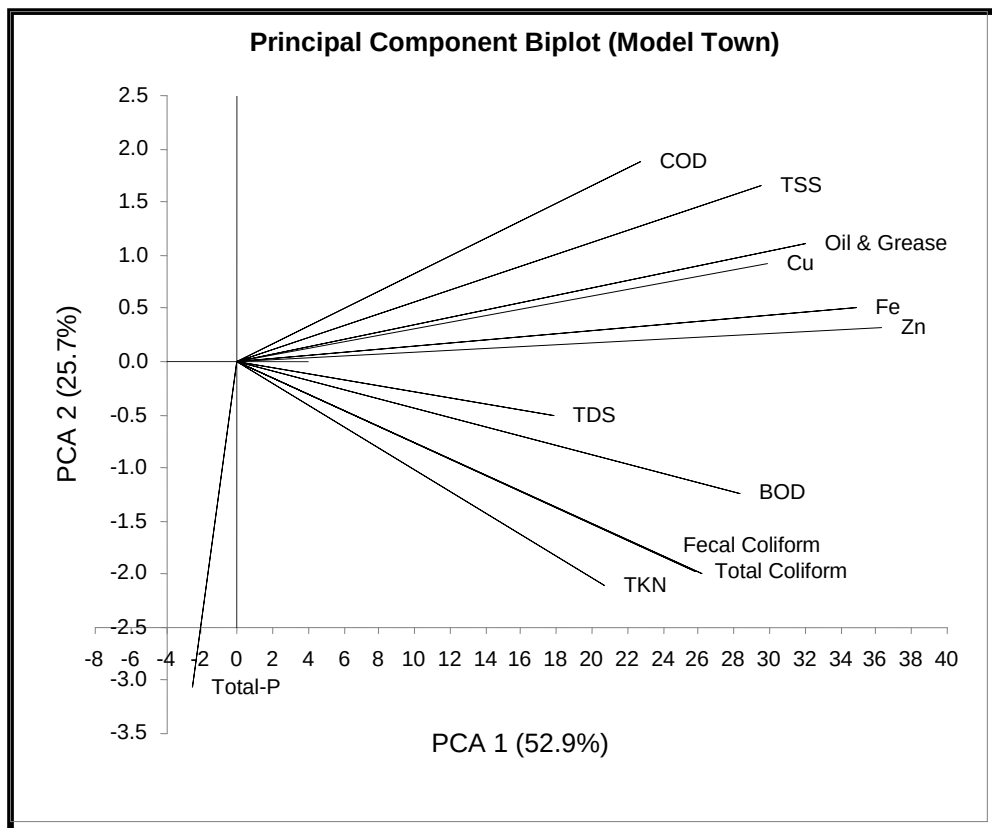


Figure 4.14: Biplot for Sub-watershed 1: Model Town

Subwatershed-2: Civil Lines (residential), Figure 4.15

- Total P and TKN are inversely correlated with each other as the two vectors form an almost 180° angle. TKN is mostly in dissolved form as shown by its correlation with TDS.
- COD and Oil and Grease constituents are particle bound as they are strongly correlated with each other and with the TSS.
- Among the heavy metals Cu and Zn are strongly correlated with TSS. However, Fe on the other hand shows weak correlation with the TSS in this catchment.
- Strong correlation among Total and Fecal counts for this residential sub-watershed, suggest fecal matter as the source of microbial contamination.

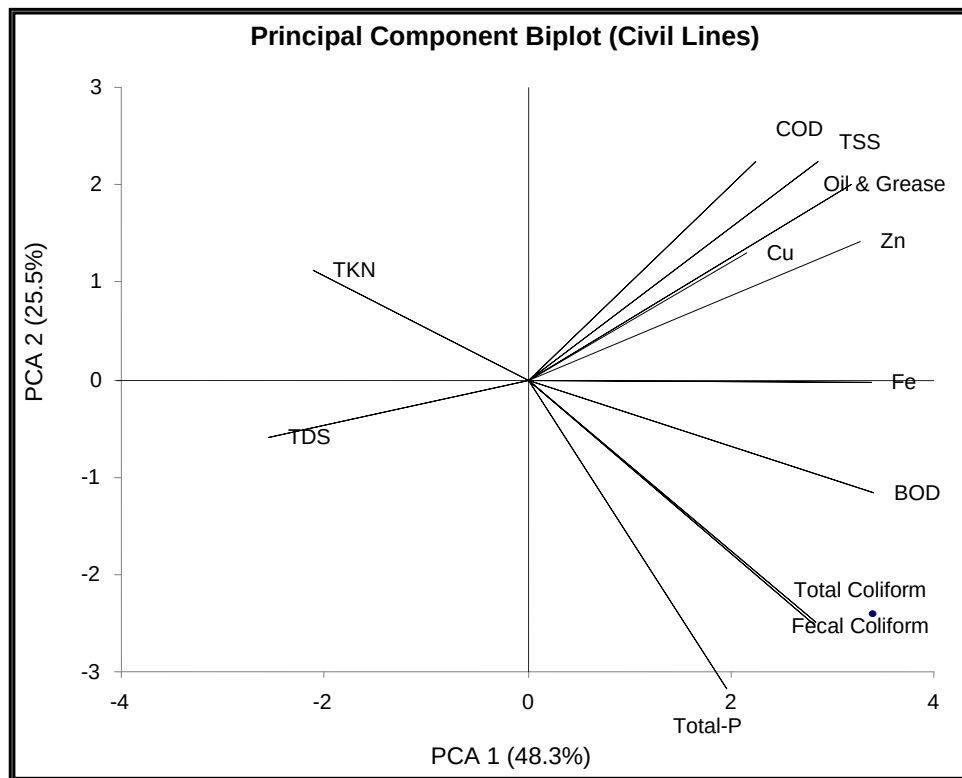


Figure 4.15: Biplot for Sub-watershed 2: Civil Lines

Subwatershed-3: Manjit Nagar (rural acreage-residential), Figure 4.16

- Most of the organic pollutants (especially COD), is not correlated with TSS. The correlation of BOD with TSS as compared to TDS indicates that most of the biodegradable organic matter is particle bound.
- Among the heavy metals, Cu and Fe are strongly correlated with TSS and must be mostly particle bound.
- Total Coliform and Fecal Coliform show strong correlation for this sub-watershed suggesting that the fecal matter is the source of microbial contamination.

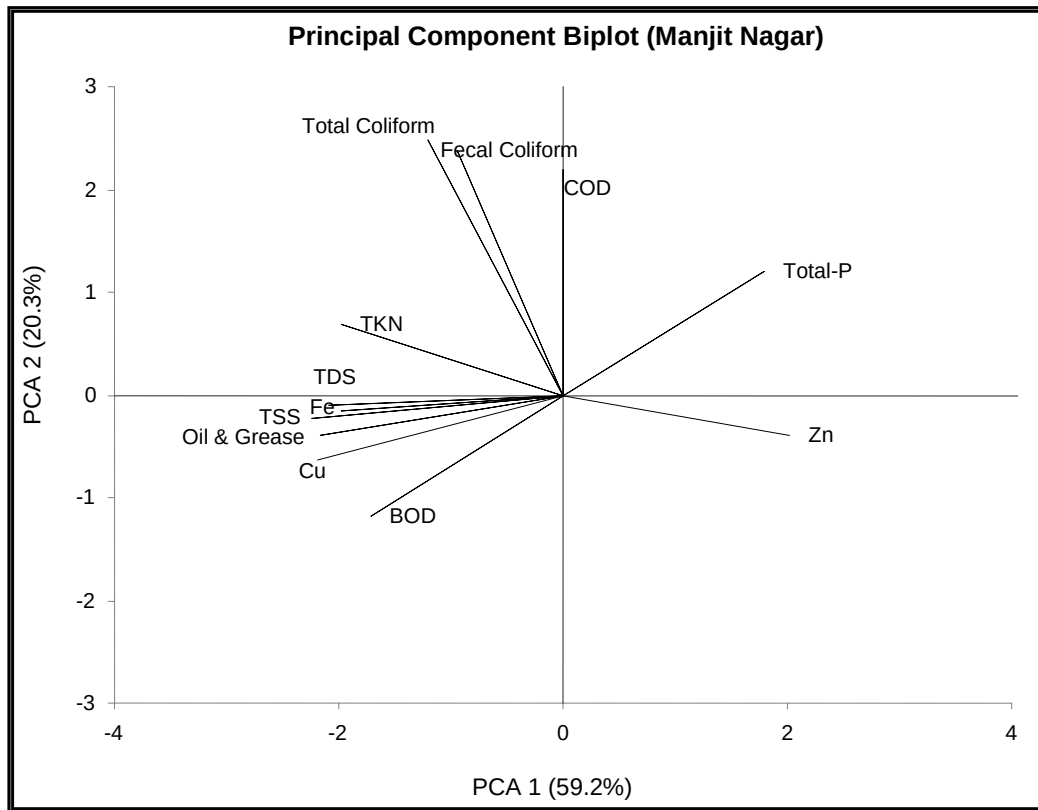


Figure 4.16: Biplot for Sub-watershed 3: Manjit Nagar

Subwatershed-4: Preet Nagar (mixed urban), Figure 4.17

- Total P and TKN are strongly correlated with each other and are inversely correlated with TSS indicating that most of the nutrients are in the dissolved form.
- BOD and Oil and Grease are strongly correlated with TSS and hence particle bound. Further, it also indicates that oil and grease are bio-degradable. COD on the other hand is not correlated to the TSS.
- Among the heavy metals Fe, Cu and Zn are strongly correlated with each other but not with TSS. Hence, heavy metals exist primarily in the dissolved form.
- Total Coliform and Fecal Coliform show strong correlation indicating fecal matter as the main source.

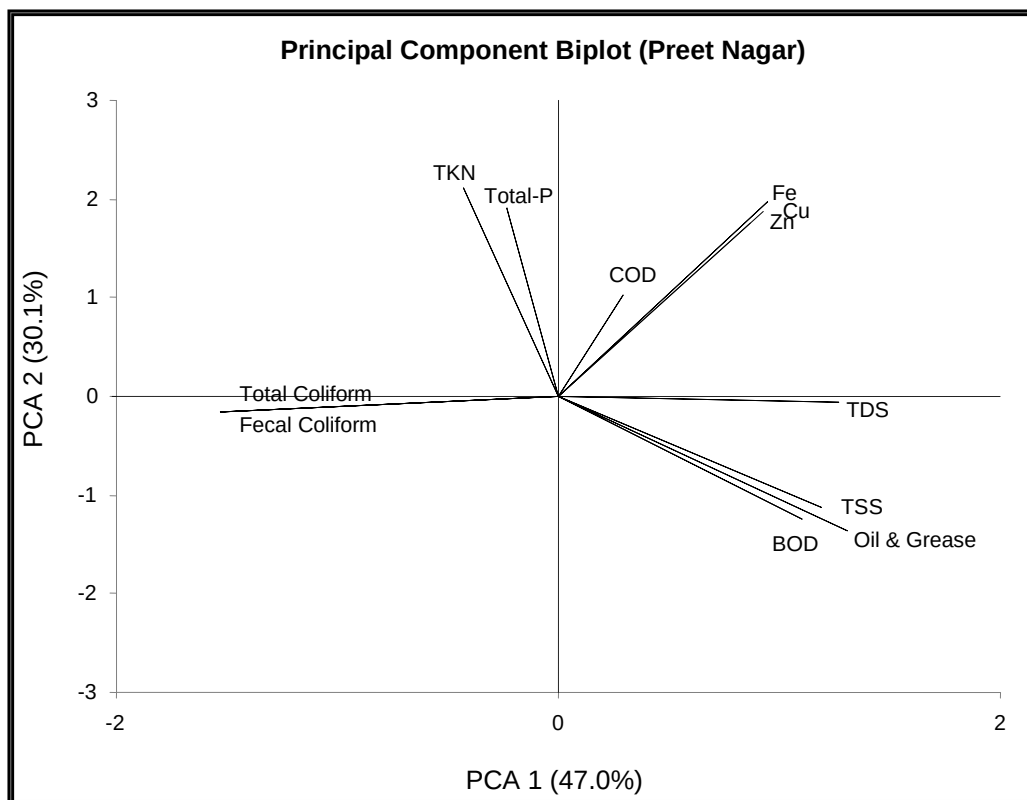


Figure 4.17: Biplot for Sub-watershed 4: Preet Nagar

Subwatershed-5: Bus Stand (heavily travelled urban), Figure 4.18

- COD shows strong correlation with TSS and hence can be concluded as particle bound whereas BOD is mostly in dissolved form as inferred from its strong correlation with TDS.
- Total Coliform and Fecal Coliform show weak correlation suggesting that the source of microbial contamination is not just the fecal matter.

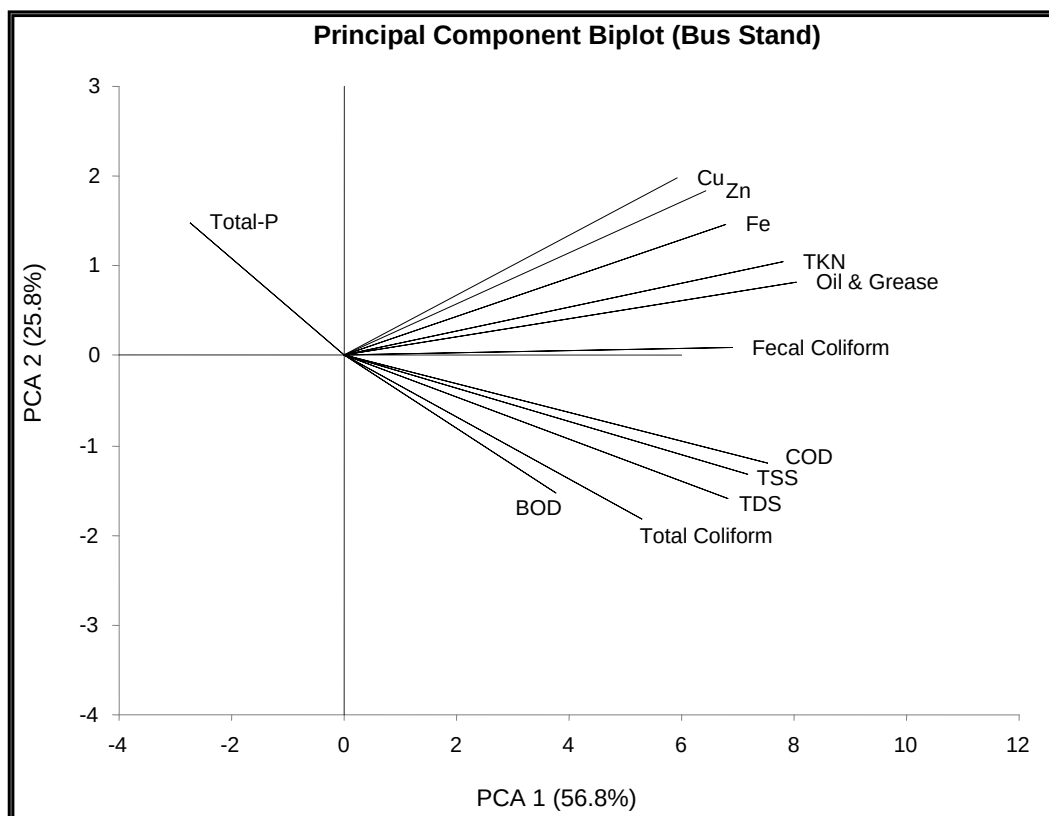


Figure 4.18: Biplot for Sub-watershed 5: Bus Stand

From a management perspective, the results indicate that mere provision of structural stormwater improvement measures, such as detention basins or sediment traps, can be effective in removing SS, COD and Heavy metals to a significant extent. But these may not necessarily be effective in removing certain other pollutants such as TKN, Total P and Coliform bacteria. The structural measures to be adopted should thus depend on the targeted pollutants.

Inter-parameter relationships can appreciably guide in making decisions on the minimum number and type treatment units required for treating the stormwater to the desired quality. For establishing the inter-parameter relationships among different parameters correlations among the parameters for each of the sub-watersheds were also studied. The correlation matrices obtained from such studies are given in Appendix D. Key results obtained from the parameter correlation studies and the PCA are shown in Table 4.19. Based on the correlations observed, it can be postulated that removal of TSS, Oil and Grease, BOD and Iron from stormwater can also effectively take care of the rest of the parameters.

The parameters mentioned in the Table 4.19 have been selected on the basis of the following two criteria.

- Table 4.19 includes only those parameters whose values exceeded the permissible limits and which had higher non compliance frequency (Table 4.9). Reason for such inclusion is that only these may require treatment as priority pollutants.
- Based on the inter-parameter relationships, established through correlation and PCA, the included parameters are grouped together into more than one group in the table. For example in case of the Model town sub-watershed, COD, TSS, and Oil & Grease are interrelated as shown by the vectors in the PCA. The correlations observed were $r=0.858$ for COD-TSS, $r=0.972$ for TSS-O&G and $r=0.844$ for COD-O&G. Similarly, for civil

lines sub-watershed, the correlations observed for BOD-Total Coliform-Fecal Coliform were: $r=0.853$ for BOD-TC, $r=0.868$ for BOD-FC and $r=0.998$ for TC-FC. PCA results were also found confirming these inter-parameter relationships. Similar findings were observed for the other sub-watersheds.

Thus both the factors PCA and Correlation studies were taken into account while deciding on the treatment scheme and parameters to be targeted. Further an assumption can be made that from among the groups including TSS, if TSS is removed in the stormwater treatment system the other parameters of the group will also get coincidentally removed.

Table 4.19: Inter-parameter relationships established among different parameters

Sub-watershed	Inter-parameter Relationships	Postulations
Model Town	1. COD – TSS – Oil and Grease	Removal of TSS, Coliform count, Fe and Oil and grease will eventually take care of the rest of the significant parameters such as BOD and COD. Due to their association with the parameters mentioned above, these parameters will also eventually get removed. TSS removal will result in the removal of COD as most of it is in the particle bound form
	2. Zn – Fe – Cu	
Civil Lines	1. BOD – TC – FC	Treatment Scheme designed should have provision for the removal of Organics, TSS, Fe and Coliform. Rest of the parameters, are not in significant proportions for this sub-watershed and will be reduced co-incidentally to lower levels. The difference in the parameters as observed in the first case could be attributed to the difference land use characteristics of the sub-watersheds.
	2. COD – TSS – Oil and Grease	
	3. Zn – Fe – Cu	
Manjit Nagar	1. TSS – Oil and Grease	Treatment unit should be designed for the removal of TSS, Oil and grease, Fe and Coliform count.
	2. Oil and Grease – Fe – Cu	
	3. TC – FC	
Preet Nagar	1. BOD – TSS – Oil and Grease	For Preet Nagar Sub-watershed treatment system should be designed for the removal of TSS, Coliform and Heavy metals. Rest of the parameters will get reduced co-incidentally in account with their inter-parameter relationship with the parameters addressed.
	2. TC – FC	
	3. Zn – Fe – Cu	
Bus Stand	1. COD – TSS	Taking into account the significant parameters along with the inter-parameter relationships obtained, the treatment scheme should be designed for BOD, TSS, Oil and Grease, Fe and Coliform removal.
	2. Oil & Grease – TKN – Zn – Fe – Cu	

4.5 Experimental stormwater treatment system

Keeping in mind the stormwater characteristics, the pollution parameters that require treatment and inter-parameter relationships, an experimental 3-stage multi-grade up-flow roughing filter (Figure 4.19 and Figure 4.20) was fabricated for the stormwater treatment.

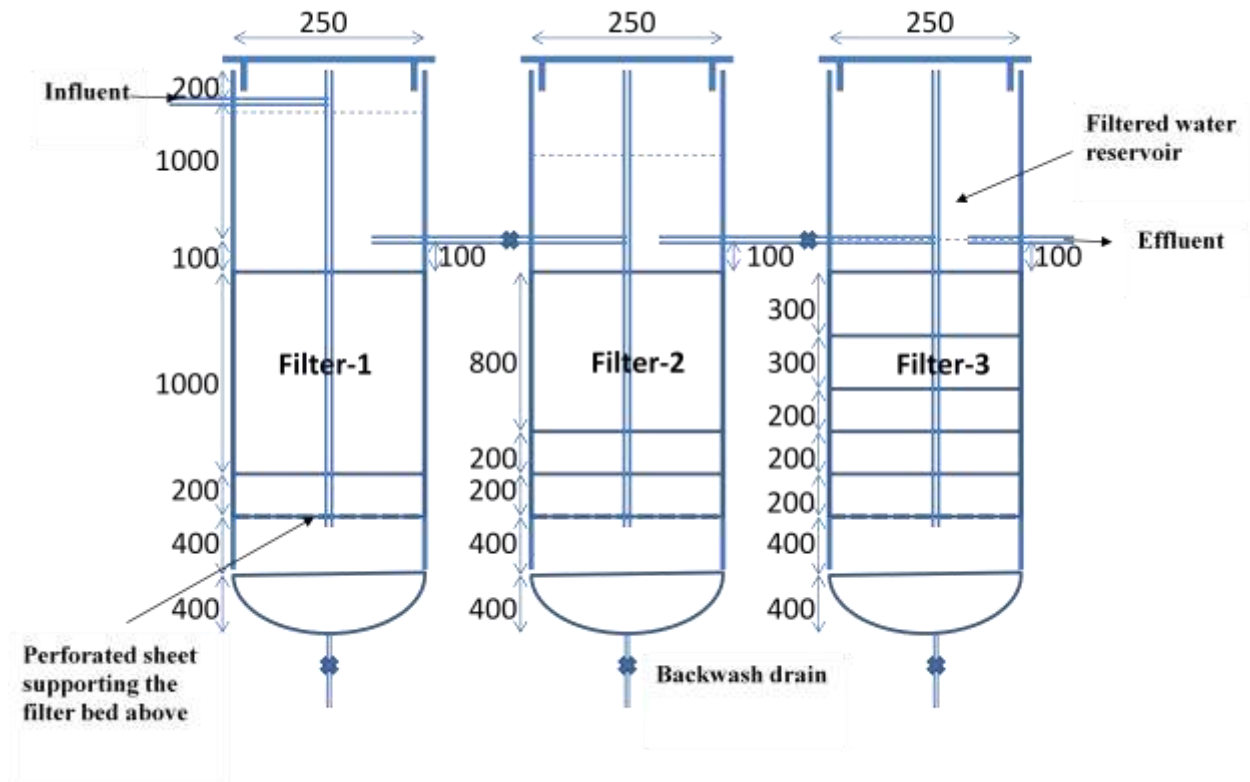


Figure 4.19: 3-stage multi-grade up-flow roughing filter

Profile of the filter beds and head loss occurring at 5 m/hr filtration rate in the clean filter are given in Table 4.20. Head loss through the clean filter amounted to about 0.2377m. Besides these losses, other minor losses occurring in the filters (Friction loss across pipes, Entry, Exit and Diversion losses) were estimated as 0.00085m.

Table 4.20: Profile of the up-flow 3-stage multi-grade roughing filter

Head loss through Filter	Particle Size	Multi-grade Filter-1		Multi-grade Filter-2		Multi-grade Filter-3	
		Bed Depth (m)	Head Loss (m)	Bed Depth (m)	Head Loss (m)	Bed Depth (m)	Head Loss (m)
	10-20 mm	0.2	0.001	0.2	0.001	0.2	0.001
	5-10 mm	1	0.009	0.2	0.002	0.2	0.002
	2.5-5 mm			0.8	0.029	0.2	0.007
	1.25-2.5 mm					0.3	0.042
	0.675-1.25 mm					0.3	0.142



Figure 4.20: 3-stage multi-grade up-flow roughing filter installed

The treatment system was first run on tap water and maintained filled with tap water. During the rainfall events, the system was run on the accumulated stormwater. After running at the constant flow rate (5m/hr) for over one hour duration, stormwater samples were collected from both the inlet and the outlet and analyzed for BOD₅ at 20°C, COD, TSS, TDS, Turbidity, and Total and Fecal coliform count. Selection of the above parameters was based on the criteria that only those parameters which frequently exceeded the permissible limits were included. Analysis of the other parameters that were already within the limits of safe disposal was avoided. Only one exception to this criterion was Fe. Since iron is mostly particle bound, and since it will be removed along with the TSS, iron was not monitored. Instead TSS was monitored. Turbidity has been an additional parameter monitored in addition to the earlier list.

The treatment system was run during three storm events (on 18th August, on 5th September and on 22nd September, 2013), and the monitoring results are given in the Table 4.21.

Table 4.21: Results of analysis and removal efficiency of experimental stormwater treatment system

Parameter	1st Storm Event			2nd Storm Event			3rd Storm Event		
	Inlet	Outlet	Removal efficiency	Inlet	Outlet	Removal efficiency	Inlet	Outlet	Removal efficiency
BOD (mg/L)	9.2	0.7	92.4%	12.2	0.8	93.4%	22.5	1.2	94.7%
COD (mg/L)	128	40	68.7%	112	28	75.0%	240	46	80.8%
TSS (mg/L)	345	35	89.8%	384	23	94.0%	434	30	93.1%
TDS (mg/L)	215	240	---	312	196	30.5%	332	210	36.7%
Turbidity (NTU)	1180	40	96.6%	1266	22	98.3%	1572	18.6	98.8%
Total Coliform (MPN/100 mL)	430000	2400	99.4%	530000	1300	99.7%	730000	940	99.9%
Fecal Coliform (MPN/100 mL)	230000	750	99.7%	240000	310	99.9%	310000	70	99.9%

Removal efficiencies greater than 90% were observed for BOD, TSS, Turbidity and Coliform count. The overall removal efficiencies were observed to increase with the successive storm events. Residual water left in the filter and the accumulated suspended solids might have resulted in the bio-film development and this might have been improving the treatment efficiencies over the successive rainfall events. In the actual stormwater treatment system running of grey water in the intervening periods of rainfall events was assumed to keep the developed bio-film viable and result in better removal efficiencies especially for BOD, COD and Coliform count.

4.6 Sub-watershed level stormwater management system conceptualized

The urban stormwater management system conceptualized has three core functions: collection, treatment and disposal of stormwater. The system in addition to the stormwater will also be handling the grey water of the sub-watershed. The treated water will be disposed off through reuse as reclaimed water and through groundwater recharging.

4.6.1 Collection system

Stormwater generated in the sub-watershed will flow as sheet flow for the first few meters distance then as shallow concentrated flow and enter the storm sewer inlet. If gutters are provided then the stormwater flow will be through gutters prior to entry into the storm sewer inlets. The storm sewer inlets are connected to the storm sewer through catch basins. The sewer inlet with bar screen or grating will remove larger particles like leaves, rags, etc from the stormwater. Catch basins will help in the removal of grit and floating material from the stormwater. Grey water will also be allowed to enter the storm sewers. Storm sewers are designed to carry the grey water during dry weather at above the self cleansing velocity and the stormwater during wet weather at below the erosion velocity. The storm sewer can have a

composite cross-section of semicircular bottom section and a wider trapezoidal section above (Figure 4.21). Bottom of the trapezoidal section can slope towards the semicircular section.

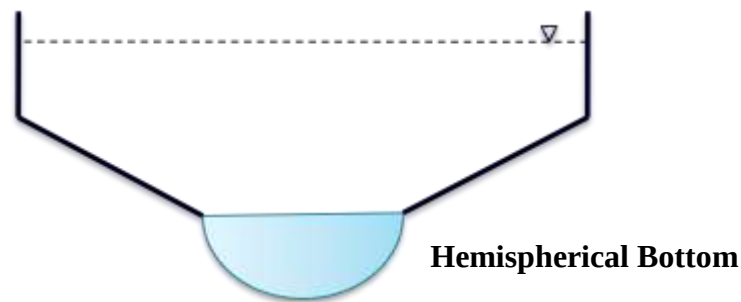


Figure 4.21: Sewer cross section of the collection system

Under normal conditions (dry weather conditions) treated water will be held in storage and will be pumped and supplied as reclaimed water to the nearby areas for reuse.

Under wet weather conditions the treated water will be overflowing the storage provided and entering the recharge well through a micro-filter or slow sand filter. Stormwater diversion would be provided for the case when combined stormwater and grey water flow is beyond the capacity of the system.

4.6.2 Treatment system

The stormwater treatment system included the following units:

1. Bar Screen/Grate Inlet
2. Cyclone De-gritter
3. Up flow Anaerobic Reactor (similar to a UASB pond)
4. Multistage multi-grade roughing filter
5. Filtered water storage facility
6. Micro-filter or Slow sand filter
7. Recharge well

Different units of the treatment system can be sized to handle the expected stormwater flows at 90 percentile rainfall event. Provisions may be made at the grate inlet for diverting and

transporting out the excess stormwater flows. Filtered water storage facility can be sized to store the expected maximum grey water flows. Hydraulic design of the treatment system may be such that the up-flow anaerobic reactor and the multi-grade roughing filter beds will remain submerged in water and no pumping is required for the stormwater and/or grey water to flow through the treatment system. The stormwater treatment system conceptualized for the urban sub-watersheds is schematically shown in Figure 4.22.

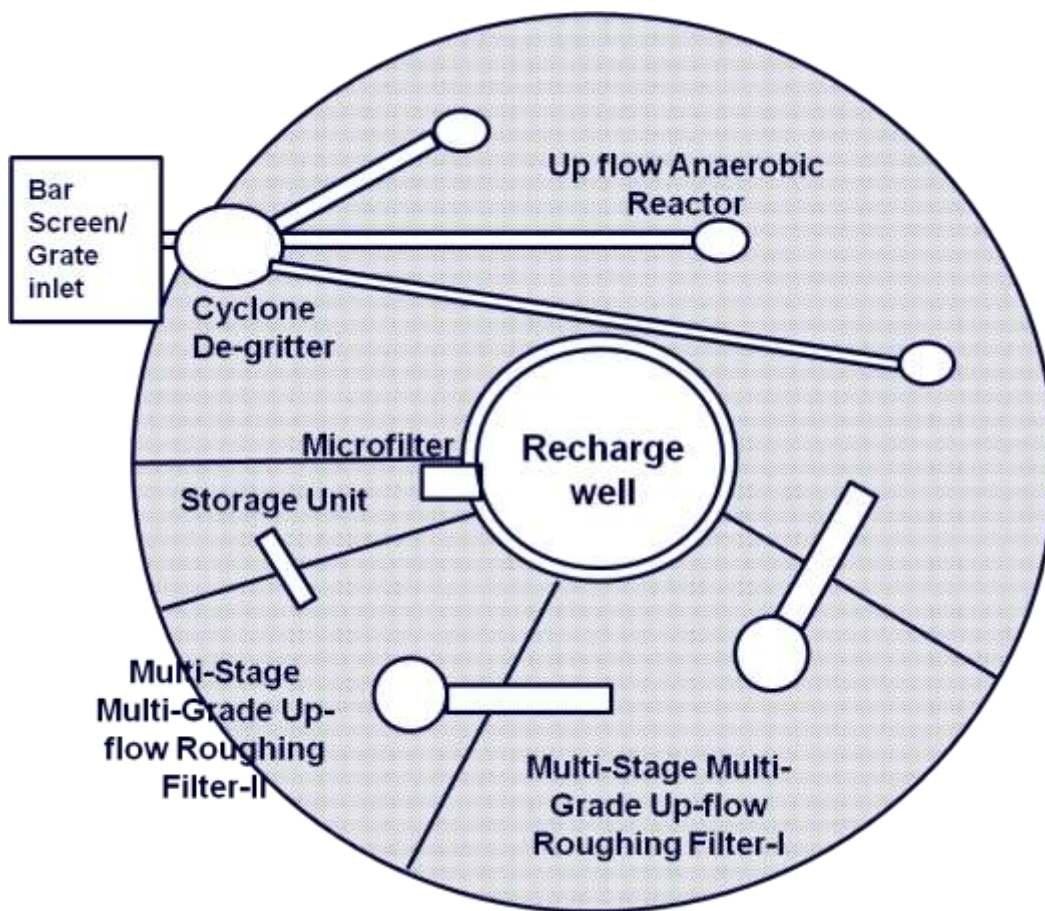


Figure 4.22: Stormwater treatment system

4.6.3 Disposal System

The treated water collected into the storage facility can be pumped and reused as reclaimed water. Treated water overflowing the storage facility can be disposed off through groundwater recharging. The overflowing water may be finally filtered through a micro-filter or slow sand filter and then allowed into a recharge well for groundwater recharging. All the units of the stormwater treatment system may be arranged peripheral to the recharge well. The micro-filter/slow sand filter may be provided over the recharge well.

Line diagram of the conceptualized stormwater management system, including the treatment and disposal components is shown in Figure 4.23.

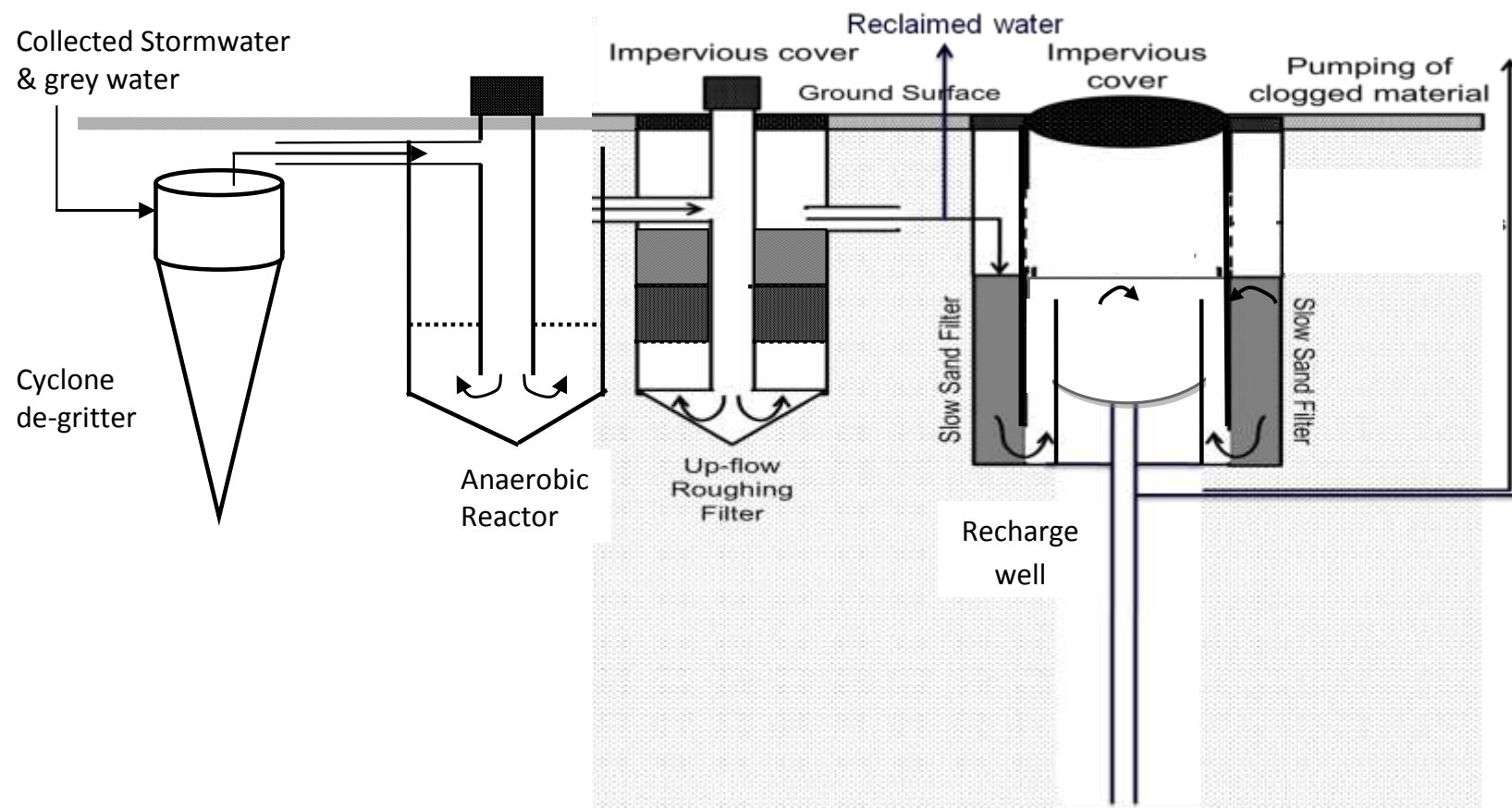


Figure 4.23: Conceptualized sub-watershed level stormwater management system

4.6.3.1 Protocol for the design of Recharge wells

Design of the recharge well can follow the protocol stated below. Based on this protocol, a recharge well has been designed for the Civil Lines sub-watershed (details are given in Appendix E).

Step 1: Collection of background information

Following data is required and was collected for one of the sub-watershed

- a) 90 percentile storm hydrograph for the sub-watershed
- b) Soil profile information (strata chart)
- c) Saturated hydraulic conductivity of the strata, in which the stormwater will be released (the most permeable layer nearest to the soil surface).
- d) Initial saturated thickness of the aquifer, if water is not present in the aquifer the distance between the top of the impervious layer below the aquifer to the top of the aquifer layer is taken as thickness of the aquifer.
- e) Depth to the aquifer
- f) Type of aquifer (confined or unconfined)
- g) Storativity
- h) Capillary rise

Step 2: Determination of Recharge rate Q_r

Average flow rate of stormwater for a 90 percentile rainfall event was taken as the designed recharge rate. At this recharge rate all the stormwater can be disposed off by the end of the rainfall event and stormwater flooding will be very limited and to a tolerable short duration. Recharge rate of $76 \text{ m}^3/\text{hr}$ was estimated for the civil lines sub-watershed.

Step 3: Estimation of Mound Height

Rise of water level in recharge well for unconfined aquifer due to artificial recharge was estimated from the following analytical quadratic equation (Patel et al., 2011)

$$h_o^2 = -\frac{PL^2}{k} + \frac{2q_oL}{k} + h_n^2 \quad (4.1)$$

Where,

h_o is rise of water level above aquifer base (m).

k is co-efficient of permeability (m/sec)

L is influence zone or radius of spread (m)

P is amount of rainfall (m/sec)

q_o is underground flow per unit aquifer-width (m^3/sec)

h_n = Height of natural Ground Water Table (G.W.T.)

Since, it is difficult to determine radius of influence L because of the sensitivity of permeability factor k . Hence radius of spread was assumed to be 30 m for recharge well with open bottom and no perforations and 70 m for open bottom perforated pipe. These assumed values were taken from the study done by Patel et al. (2011).

Step 4: Determination of the maximum allowable depth of the recharge well

The maximum allowable depth of the recharge well was obtained by subtracting mound height and the capillary rise from the actual depth of the aquifer.

Step 5: Determination of the diameter of the Recharge well

Recharge rate Q_r by a constant recharge head in borehole is directly proportional to the diameter of the recharge well and the co-efficient of permeability of the concerned strata (Patel et al.,

2011). The relationship between the recharge rate and diameter of the recharge well is described by the following equation:

$$Q_r = 2.75 \times d \times h \times k \quad (4.2)$$

Where,

d is the diameter of the recharge well (m)

h is the fixed depth or minimum depth of the recharge well (m)

Chapter-5

Conclusions and Future Research

5.1 Conclusions

The influence of rainfall and catchment characteristics on urban stormwater quality and quantity has been studied. An attempt was made to use the quality and quantity assessments of stormwater in the design of decentralized (sub-watershed level) urban stormwater management systems.

Stormwater characterization studies indicated that BOD, COD, TSS, Oil and Grease, Total Coliforms, Fecal Coliforms, Lead and Iron are the important pollution parameters of stormwater and these should be the focus of the stormwater management efforts.

Urban stormwater quality significantly varied with the sub-watersheds and was influenced by the watershed characteristics. The stormwater quality was also found influenced by the rainfall events and the antecedent dry days. At the sub-watershed level, the stormwater quality was closely related with the size of the rainfall event and with the antecedent dry period. Predictive modeling and assessment of the stormwater quality was found possible at the urban sub-watershed level.

Stormwater flows from the urban sub-watershed were quantified through assessing the effective rainfall depths and stormwater management systems were planned for handling the stormwater flows from 90 percentile rainfall events.

Peak runoff rates were supposed to be used for the design of stormwater collection system and the rainfall events with 2-year return period were to be used as the design rainfall events. Assessment of peak runoff rates and design of the stormwater collection system have however been treated as beyond the scope of this work.

For sustainability and the viability of especially the stormwater treatment system, management of grey water and urban stormwater together in a single system was proposed.

A sub-watershed level urban stormwater management system comprising of a stormwater-grey water collection system, a stormwater-grey water treatment system and a groundwater recharge system has been proposed for playing a key role in the sustainable urban water management.

A compound drain/sewer comprised of a bottom semi-circular section and a top trapezoidal section to convey only grey water during dry weather and both stormwater and grey water during wet weather was proposed for the stormwater-grey water collection system.

The treatment system comprised of a cyclone de-gritter, a UASB pond and an up-flow multi-grade filter was considered sufficient to treat the stormwater. By pass and diversion provision was suggested for handling the excess stormwater during the extreme rainfall events. Provisions were suggested for pumping and reusing of the treated water as reclaimed water. Only the excess treated water (available during the wet weather) was supposed for disposal (after filtering through a micro-filter/slow sand filter) through groundwater recharging. However sizing and design of the micro-filter/slow sand filter was considered as beyond the scope of the work.

Groundwater recharging with the treated effluents through injecting the latter into the sub-surface unconfined or unsaturated shallow aquifer was suggested and a protocol for the design of

the recharge well was developed. The entry of untreated stormwater into the recharge well was eliminated both through physical layout and hydraulic design of the stormwater treatment and disposal system.

In essence this research work, for Ph.D., has come out with a model for the decentralized urban stormwater management that supports and can be integrated with the sustainable urban water management system. This model, at the maximum, with minor modifications, can be used for the management of stormwater for sustainability in other sub-watersheds of Patiala city and in other urban human settlements.

5.2 Future Research

The drainage system (proposed under the new urban sub-watershed level storm water management system) for the collection and conveyance of stormwater – grey water is sufficiently different from the conventional sewerage system. There is a need to work on the design, construction and maintenance of this drainage system prior to the implementation. Further, a demonstration and/or experimental system for the urban stormwater – grey water handling and management is in fact needed for fully understanding the problems associated with and for appreciating the feasibility of the new system proposed.

The research study used grab sampling as the preferred mode in place of composite sampling in accordance with the requirement of the study which involved first collection of the entire stormwater and then its treatment followed by final disposal. However composite sampling provides variation of stormwater quality with time. This can strengthen the relationship studies involving rainfall characteristics, land use and stormwater quality characteristics. Therefore future work in this area is recommended.

Regression models developed (for the characterization of storm water) used only Antecedent Dry Days (ADD) and average rainfall depth as variables. This made the models sub-watershed specific. Generic regression models for the characterization of the storm water can be developed through a third variable 'the urban sub-watershed characteristics' variable in form of sub-watershed index.

Water quality standards for the treated effluent to use as reclaimed water and to dispose through groundwater recharging are not available and they should be developed and prescribed for the implementation of the proposed urban sub-watershed level storm water management system.

Slow sand filter proposed for use in the proposed urban sub-watershed level stormwater management system has larger foot print. Further, use of micron filter as an alternative to the slow sand filter in the passive storm water management system should be thoroughly investigated.

During the design of recharge well, it was felt that not much of the details are provided with regard to the quality of treated water to be considered before recharging. The recharge well designs are far too generic and need to be according to the type and characteristics of the wastewater to be considered for recharge. Current study designed the groundwater recharge system taking into account both the quantity and quality of stormwater. Similar studies for other types of wastewater could be undertaken in future providing the complete solution to the problem.

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Appendix-A

Physical Survey information sheet for sub-watersheds

Junction location:

Longitude:	Code:
Latitude:	Location identification (descriptive):
Altitude:	

Roads forming the Junction

Road-1:	Road-5:
Road-2:	Road-6:
Road-3:	Road-7:
Road-4:	

Land use

Rank the land use:

Residential:	Commercial:	Institutional:	Industrial:	Agricultural:
Other land use (specify):				

Intensity of urbanization/development

Very high intensity (>90%):	High intensity (70-90%):	Moderate intensity (30-70%):
Low intensity (10-30%):	Poorly developed (<10%):	

Typical Land use of the plots (indicate as %; should total to 100%)

% impervious cover:	% natural plants and landscaping:
% grass cover:	% bare soil:
	% tree canopy:

Roads (drive way)

Road number and name	Mud road	Metal road	Concrete road	Tar road				
				<20 feet	20-30 feet	30-60 feet	Multilane	Highway
1								
2								
3								
4								
5								
6								
7								

Road sides

Road number and name	Mud/bricklined/paved/grass covered	Width (negligible/<3 feet/3-6 feet, >6 feet)	Hedged/planted trees/other	Littered/silted/eroded	Open defecation/urination
1					
2					
3					
4					
5					
6					
7					

Utilities and services coverage (rank more than one are used)

Water supply

Municipal:	Local:	Household:
------------	--------	------------

Sewerage system

Municipal:	Local:	On-site:	No system:
------------	--------	----------	------------

MSW management system

Collection bins in place:	No proper arrangement for collection:
Arrangement for transport:	No proper arrangement for transport:

Pollution sources (indicate number wherever feasible)

	Road-1	Road-2	Road-3	Road-4	Road-5	Road-6	Road-7	Remarks	
Workshops:									
Petrol pumps:									
Cattle keeping:									
Poultry forms:									
Slums:									
Open defecation:									
Open urination:									
MSW dump:									
Construction waste dump:									
Cow dung dumps:									
Stormwater flooding:									
Municipal Sewage flooding:									
Overflowing sewer manholes:									
Open discharge of sewage:									
Other (specify):									

Storm water drainage details

Drinage facilities (give separately for each of the roads)

Road Number and name	No difined facility	Road side storm drains	Storm sewers	Combined sewers
1				
2				
3				
4				
5				
6				
7				

Stormwater flow patterns (give separately for each of the roads)

Road number and name	Direction of stormwater flow		Flooding with storm water during			Entry of storm water into sewers	
	Towards junction	Away from junction	low rain (<10mm)	moderate rain (10-25)	heavy rain (>25mm)	Intentional	Unintentional

Fate of the stormwater of the area

Does stormwater cause problematic stagnation on roads?
When such problematic stagnation last occurred?
What problems were actually faced during such flooding
How long the flooding problem persisted?

How frequently such problematic stagnation occurs?

Even when a moderate rainfall occurs	During rainy season of every year	Once in a few years from persistent rains	Once in many years when exceptionally heavy rains occur

Where the rain water goes from your area?

Rain water was never a problem and do not know where it goes	
Rain water goes into a localized pit or pond or underground tank specially created for the purpose	
Stagnates and lost through percolation and evaporation	
Goes to nearby drain (specify the drain)	
Goes to nearby depression or toba (specify)	

If rainwater is a problem what you think can be done to take care of the problem?

--

Name of the surveyor:

--

Date:

Signature:

Appendix-B

WinTR55 software interface for calculating the Weighted Curve Numbers

Figure B1: Weighted CN for Model Town Sub-watershed

Land Use Details

Sub-area Name:

Land Use Categories: ☒ Urban Area ☐ Developing Urban ☐ Cultivated Agriculture ☐ Other Agriculture ☐ Arid Rangeland

Area (Acres) for Hydrologic Soil Groups

Cover Description	Condition	A	CN	B	CN	C	CN	D	CN
FULLY DEVELOPED URBAN AREAS (Veg Estab.)									
Open space (Lawns, parks etc.)									
Poor condition; grass cover < 50%		68		79		86		89	
Fair condition; grass cover 50% to 75%		49	0.315	69		79		84	
Good condition; grass cover > 75%		39		61		74		80	
Impervious Areas:									
Paved parking lots, roofs, driveways		98		98	0.854	98		98	
Streets and roads:									
Paved; curbs and storm sewers		98		98		98		98	
Paved; open ditches (w/right-of-way)		0.470	83		89		92		93
Gravel (w/ right-of-way)		76	0.251	85		89		91	
Dirt (w/ right-of-way)		0.210	72		82		87		89
Urban Districts									
	Avg % Imperv								
Commercial & business	85		89		92		94		95
Industrial	72		81		88		91		93
Residential districts (by average lot size)									
	Avg % Imperv								
1/8 acre (town houses)	65		77		85		90		92
1/4 acre	38		61		75		83		87

Project Area(ac): Summary Screen: ☒ Off ☐ On Sub-Area Area (ac): Weighted CN:

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Figure B2: Weighted CN for Civil Lines Sub-watershed

Land Use Details

Sub-area Name:

Land Use Categories: ☒ Urban Area ☐ Developing Urban ☐ Cultivated Agriculture ☐ Other Agriculture ☐ Arid Rangeland

Area (Acres) for Hydrologic Soil Groups

Cover Description	Condition	A	CN	B	CN	C	CN	D	CN
FULLY DEVELOPED URBAN AREAS (Veg Estab.)									
Open space (Lawns, parks etc.)									
Poor condition; grass cover < 50%			68		79		86		89
Fair condition; grass cover 50% to 75%			49		69		79		84
Good condition; grass cover > 75%			39	2.352	61		74		80
Impervious Areas:									
Paved parking lots, roofs, driveways			98		98	2.295	98		98
Streets and roads:									
Paved; curbs and storm sewers			98		98		98		98
Paved; open ditches (w/right-of-way)		1.095	83		89		92		93
Gravel (w/ right-of-way)			76	0.923	85		89		91
Dirt (w/ right-of-way)		1.176	72		82		87		89
Urban Districts									
	Avg % Imperv								
Commercial & business	85		89		92		94		95
Industrial	72		81		88		91		93
Residential districts (by average lot size)									
	Avg % Imperv								
1/8 acre (town houses)	65		77		85		90		92
1/4 acre	38		61		75		83		87

Project Area(ac): Summary Screen: ☒ Off ☐ On Sub-Area Area (ac): Weighted CN:

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Figure B3: Weighted CN for Manjit Nagar Sub-watershed

Land Use Details

Sub-area Name:

Land Use Categories: ☒ Urban Area ☐ Developing Urban ☐ Cultivated Agriculture ☐ Other Agriculture ☐ Arid Rangeland

Area (Acres) for Hydrologic Soil Groups

Cover Description	Condition	A	CN	B	CN	C	CN	D	CN
FULLY DEVELOPED URBAN AREAS (Veg Estab.)									
Open space (Lawns, parks, etc.)									
Poor condition; grass cover < 50%			68		79		86		89
Fair condition; grass cover 50% to 75%			49		69		79		84
Good condition; grass cover > 75%			39	1.520	61		74		80
Impervious Areas:									
Paved parking lots, roofs, driveways			98		98	1.000	98		98
Streets and roads:									
Paved; curbs and storm sewers			98		98		98		98
Paved; open ditches (w/ right-of-way)		0.466	83		89		92		93
Gravel (w/ right-of-way)		76		0.090	85		89		91
Dirt (w/ right-of-way)		0.770	72		82		87		89
Urban Districts									
Commercial & business	Avg % Imperv: 85		89		92		94		95
Industrial	72		81		88		91		93
Residential districts (by average lot size)									
1/8 acre (town houses)	Avg % Imperv: 65		77		85		90		92
1/4 acre	38		61		75		83		87

Project Area(ac): Summary Screen: ☒ Off ☐ On Sub-Area Area (ac): Weighted CN:

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Figure B4: Weighted CN for Preet Nagar Sub-watershed

Land Use Details

Sub-area Name:

Land Use Categories: ☒ Urban Area ☐ Developing Urban ☐ Cultivated Agriculture ☐ Other Agriculture ☐ Arid Rangeland

Area (Acres) for Hydrologic Soil Groups

Cover Description	Condition	A	CN	B	CN	C	CN	D	CN
FULLY DEVELOPED URBAN AREAS (Veg Estab.)									
Open space (Lawns, parks etc.)									
Poor condition; grass cover < 50%			68		79		86		89
Fair condition; grass cover 50% to 75%			49	0.220	69		79		84
Good condition; grass cover > 75%			39		61		74		80
Impervious Areas:									
Paved parking lots, roofs, driveways			98		98	0.800	98		98
Streets and roads:									
Paved; curbs and storm sewers			98		98		98		98
Paved; open ditches (w/right-of-way)		0.180	83		89		92		93
Gravel (w/ right-of-way)			76	0.130	85		89		91
Dirt (w/ right-of-way)		0.150	72		82		87		89
Urban Districts									
Commercial & business	Avg % Imperv	85			92		94		95
Industrial		72			88		91		93
Residential districts (by average lot size)									
1/8 acre (town houses)	Avg % Imperv	85			85		90		92
1/4 acre		38			75		83		87

Project Area(ac): Summary Screen: ☒ Off ☐ On Sub-Area Area (ac): Weighted CN:

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Figure B5: Weighted CN for Bus Stand Sub-watershed

Land Use Details

Sub-area Name:

Land Use Categories: ☒ Urban Area ☐ Developing Urban ☐ Cultivated Agriculture ☐ Other Agriculture ☐ Arid Rangeland

Area (Acres) for Hydrologic Soil Groups

Cover Description	Condition	A	CN	B	CN	C	CN	D	CN
FULLY DEVELOPED URBAN AREAS (Veg Estab.)									
Open space (Lawns, parks etc.)									
Poor condition; grass cover < 50%			68		79	0.290	86		89
Fair condition; grass cover 50% to 75%			49		69		79		84
Good condition; grass cover > 75%			39		61		74		80
Impervious Areas:									
Paved parking lots, roofs, driveways			98		98	1.490	98		98
Streets and roads:									
Paved; curbs and storm sewers			98		98		98		98
Paved; open ditches (w/right-of-way)			83	2.830	89		92		93
Gravel (w/ right-of-way)			76		85	4.550	89		91
Dirt (w/ right-of-way)			72	0.690	82		87		89
Urban Districts									
	Avg % Imperv								
Commercial & business	85		89		92		94		95
Industrial	72		81		88		91		93
Residential districts (by average lot size)									
	Avg % Imperv								
1/8 acre (town houses)	85		77		85		90		92
1/4 acre	38		61		75		83		87

Project Area(ac): Summary Screen: ☒ Off ☐ On Sub-Area Area (ac): Weighted CN:

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Appendix-C

Characterization results for Individual Storm Events

Table C1: Stormwater Characterization Results of Sub-watershed 1 (Model Town)

S. No.	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TDS (mg/l)	Oil & Grease (mg/l)	TKN (mg/l)	Total- P (mg/l)	Total Coliform (MPN/100ml)	Fecal Coliform (MPN/100ml)	Zn (ppm)	Cd (ppm)	Ni (ppm)	Pb (ppm)	Fe (ppm)	Cu (ppm)
1	14.8	264	160	44	213	9.1	0.50	930000	430000	0.98	<0.01	<0.30	<0.05	54.2	0.26
2	7.8	256	124	23	145	8.4	0.52	430000	93000	0.44	<0.01	<0.30	<0.05	20.9	0.12
3	15.5	120	70	21	76	10.4	0.61	43000	4300	0.41	<0.01	<0.30	<0.05	19.0	0.14
4	16.8	180	57	41	69	9.0	0.60	930000	430000	0.30	<0.01	<0.30	<0.05	17.2	0.16
5	28.8	226	135	25	155	10.2	0.46	75000	43000	1.08	<0.01	<0.30	<0.05	74.8	0.32
6	31.0	240	141	42	203	11.2	0.65	1000000	4600000	1.20	<0.01	<0.30	<0.05	68.2	0.24
7	15.0	200	107	23	132	7.9	0.50	240000	93000	0.42	<0.01	<0.30	<0.05	18.9	0.10
8	6.9	89	35	20	53	6.5	0.42	15000	2400	0.24	<0.01	<0.30	<0.05	12.2	0.07
9	38.5	325	158	52	280	13.5	0.75	1500000	4600000	1.85	<0.01	<0.30	<0.05	105.2	0.65
10	21.5	275	174	47	224	10.2	0.53	1000000	430000	1.10	<0.01	<0.30	<0.05	59.5	0.30
11	8.6	140	50	21	82	8.9	0.58	43000	4600	0.44	<0.01	<0.30	<0.05	19.4	0.12
12	25.0	235	137	32	198	10.8	0.63	4600000	460000	1.18	<0.01	<0.30	<0.05	63.4	0.22

Table C2: Stormwater Characterization Results of Sub-watershed 2 (Civil Lines)

S. NO.	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TDS (mg/l)	Oil & Grease (mg/l)	TKN (mg/l)	Total-P (mg/l)	Total Coliform (MPN/100ml)	Fecal Coliform (MPN/100ml)	Zn (ppm)	Cd (ppm)	Ni (ppm)	Pb (ppm)	Fe (ppm)	Cu (ppm)
1	12.5	78	45	23	8.2	9.6	0.62	150000	93000	0.31	<0.01	<0.30	<0.05	11.2	0.08
2	13.0	72	38	19	7.9	9.2	0.61	43000	9300	0.29	<0.01	<0.30	<0.05	8.3	0.05
3	10.5	64	19	19	4.2	8.1	0.71	15000	4300	0.25	<0.01	<0.30	<0.05	7.5	0.04
4	9.5	60	11	33	2.1	10.5	0.65	43000	15000	0.2	<0.01	<0.30	<0.05	7.0	0.05
5	17.3	68	32	20	6.8	8.6	0.83	24000000	10000000	0.31	<0.01	<0.30	<0.05	13.4	0.07
6	10.0	62	23	18	5.5	9.2	0.62	2400000	430000	0.34	<0.01	<0.30	<0.05	12.6	0.09
7	11.5	69	29	16	5.8	8.1	0.52	430000	93000	0.25	<0.01	<0.30	<0.05	7.3	0.04
8	5.4	52	9	15	2.0	7.8	0.35	15000	9300	0.19	<0.01	<0.30	<0.05	5.4	0.03
9	28.5	108	68	41	12.5	12.3	0.84	43000000	15000000	0.55	<0.01	<0.30	<0.05	22.0	0.19
10	13.2	74	48	25	9.0	10.2	0.65	240000	93000	0.35	<0.01	<0.30	<0.05	13.6	0.11
11	10.4	66	18	20	3.9	9.4	0.63	24000	4600	0.28	<0.01	<0.30	<0.05	6.4	0.05
12	11.2	61	27	19	6.8	8.2	0.61	1500000	430000	0.35	<0.01	<0.30	<0.05	11.5	0.07

Table C3: Stormwater Characterization Results of Sub-watershed 3 (Manjit Nagar)

S. No.	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TDS (mg/l)	Oil & Grease (mg/l)	TKN (mg/l)	Total- P (mg/l)	Total Coliform (MPN/100ml)	Fecal Coliform (MPN/100ml)	Zn (ppm)	Cd (ppm)	Ni (ppm)	Pb (ppm)	Fe (ppm)	Cu (ppm)
1	16.8	148	129	52	43.2	10.4	0.71	930000	93000	0.78	<0.01	<0.30	<0.05	38.2	0.10
2	19.5	152	111	47	30.3	10.1	0.63	430000	43000	1.22	<0.01	<0.30	<0.05	39.3	0.09
3	17.3	128	60	33	17.5	10.2	0.73	240000	43000	1.08	<0.01	<0.30	<0.05	36.4	0.08
4	16.0	108	43	34	11.1	9.6	0.83	150000	24000	1.50	<0.01	<0.30	<0.05	32.5	0.03
5	22.8	45	125	49	41.2	10.9	0.66	93000	7500	0.38	<0.01	<0.30	<0.05	37.3	0.11
6	19.9	153	113	47	32.9	11.3	0.72	1500000	930000	0.30	<0.01	<0.30	<0.05	37.5	0.09
7	17.8	132	103	43	27.3	10.2	0.61	430000	46000	1.15	<0.01	<0.30	<0.05	36.4	0.07
8	8.3	42	31	22	10.0	8.2	0.52	10000	4300	0.26	<0.01	<0.30	<0.05	19.8	0.03
9	29.3	198	187	73	78.0	13.3	0.93	2400000	930000	1.69	<0.01	<0.30	<0.05	48.6	0.24
10	19.8	152	135	54	45.4	10.8	0.73	1000000	460000	0.37	<0.01	<0.30	<0.05	40.2	0.10
11	15.4	124	62	31	17.2	9.7	0.43	43000	4600	0.90	<0.01	<0.30	<0.05	34.5	0.09
12	20.9	144	120	49	37.0	11.1	0.70	2400000	460000	0.29	<0.01	<0.30	<0.05	36.4	0.08

Table C4: Stormwater Characterization Results of Sub-watershed 4 (Preet Nagar)

S. No.	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TDS (mg/l)	Oil & Grease (mg/l)	TKN (mg/l)	Total- P (mg/l)	Total Coliform (MPN/100ml)	Fecal Coliform (MPN/100ml)	Zn (ppm)	Cd (ppm)	Ni (ppm)	Pb (ppm)	Fe (ppm)	Cu (ppm)
1	12.5	128.0	71.2	23.9	18.3	10.50	0.879	43000	23000	0.49	<0.01	<0.30	<0.05	23.50	0.10
2	12.0	112.0	50.5	24.8	9.5	8.96	0.764	9300	2300	0.57	<0.01	<0.30	<0.05	21.44	0.13
3	14.3	192.0	69.5	22.1	16.3	4.48	0.590	23000	9300	0.54	<0.01	<0.30	<0.05	18.40	0.08
4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
5	15.0	30.0	73.2	25.6	19.7	5.25	0.650	43000	15000	0.29	<0.01	<0.30	<0.05	12.66	0.07
6	9.5	96.0	45.3	19.3	8.2	8.66	0.750	930000	240000	0.30	<0.01	<0.30	<0.05	11.60	0.05
7	11.4	108.0	59.0	24.8	14.5	6.65	0.680	230000	43000	0.50	<0.01	<0.30	<0.05	18.50	0.11
8	4.2	31.0	29.0	19.6	5.2	4.20	0.460	4600	2300	0.21	<0.01	<0.30	<0.05	8.90	0.03
9	24.5	210.0	96.0	46.0	26.0	11.20	1.120	2300000	460000	0.94	<0.01	<0.30	<0.05	32.90	0.22
10	13.7	133.0	65.0	28.6	19.5	9.80	0.780	46000	24000	0.52	<0.01	<0.30	<0.05	26.50	0.20
11	14.5	87.5	34.0	22.0	6.5	5.60	0.640	10000	4300	0.47	<0.01	<0.30	<0.05	15.40	0.07
12	10.2	110.0	52.0	21.1	12.1	8.80	0.770	1000000	240000	0.30	<0.01	<0.30	<0.05	11.40	0.06

*Sample for the 4th event could not be obtained for this sub-watershed

Table C5: Stormwater Characterization Results of Sub-watershed 5 (Bus Stand)

S. No.	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TDS (mg/l)	Oil & Grease (mg/l)	TKN (mg/l)	Total- P (mg/l)	Total Coliform (MPN/100ml)	Fecal Coliform (MPN/100ml)	Zn (ppm)	Cd (ppm)	Ni (ppm)	Pb (ppm)	Fe (ppm)	Cu (ppm)
1	25.8	288	227	26	113	11.2	0.83	240000	43000	2.20	<0.01	<0.30	<0.05	109.1	0.98
2	35.5	368	320	52	94	10.4	0.63	4300000	150000	1.34	<0.01	<0.30	<0.05	30.3	0.47
3	35.5	280	239	29	85	10.1	0.97	93000	15000	1.79	<0.01	<0.30	<0.05	45.2	0.85
4	32.5	264	192	32	80	10.3	0.85	43000	15000	1.64	<0.01	<0.30	<0.05	40.2	0.69
5	33.0	368	308	50	121	11.6	0.66	240000	150000	2.53	<0.01	<0.30	0.28	180.0	1.13
6	38.5	380	325	54	143	12.2	0.86	4600000	2400000	2.63	<0.01	<0.30	<0.05	150.6	1.25
7	32.4	305	250	36	96	10.6	0.62	2300000	150000	1.30	<0.01	<0.30	<0.05	29.2	0.41
8	15.7	146	98	24	29	8.0	0.48	24000	10000	0.94	<0.01	<0.30	<0.05	24.5	0.31
9	42.0	476	448	95	241	15.7	0.98	43000000	2400000	2.89	<0.01	<0.30	0.35	207.2	1.39
10	32.9	321	268	46	123	11.6	0.85	460000	93000	1.98	<0.01	<0.30	<0.05	98.6	0.88
11	24.5	254	149	26	75	9.8	0.59	46000	15000	1.04	<0.01	<0.30	<0.05	28.7	0.39
12	34.9	383	324	54	137	12.1	0.86	9300000	460000	2.49	<0.01	<0.30	<0.05	135.2	1.05

Appendix-D

Correlation matrices of five sub-watersheds for establishing inter-parameter relationships

Table D1: Correlation Matrix for Model Town Sub-watershed

	BOD	COD	TSS	TDS	Oil & Grease	TKN	TP	Total Coliform	Fecal Coliform	Zn	Fe	Cu
BOD	1.000	0.061	0.271	0.250	0.334	0.832	0.157	0.621	0.634	0.756	0.807	0.736
COD		1.000	0.858	0.383	0.844	0.283	-0.466	0.266	0.259	0.568	0.524	0.422
TSS			1.000	0.250	0.972	0.089	-0.466	0.319	0.316	0.824	0.762	0.642
TDS				1.000	0.433	0.034	0.254	0.509	0.518	0.355	0.281	0.302
Oil & Grease					1.000	0.171	-0.274	0.494	0.493	0.851	0.760	0.617
TKN						1.000	0.465	0.638	0.648	0.571	0.553	0.419
Total-P							1.000	0.627	0.627	-0.199	-0.303	-0.465
Total Coliform								1.000	1.000	0.566	0.460	0.200
Fecal Coliform									1.000	0.574	0.470	0.215
Zn										1.000	0.977	0.872
Fe											1.000	0.938
Cu												1.000

Table D2: Correlation Matrix for Civil Lines Sub-watershed

	BOD	COD	TSS	TDS	Oil & Grease	TKN	TP	Total Coliform	Fecal Coliform	Zn	Fe	Cu
BOD	1.000	0.489	0.569	-0.328	0.618	-0.403	0.700	0.853	0.868	0.421	0.576	0.159
COD		1.000	0.963	-0.259	0.883	-0.068	-0.127	0.014	0.039	0.441	0.258	0.230
TSS			1.000	-0.428	0.974	-0.150	-0.096	0.128	0.140	0.648	0.448	0.389
TDS				1.000	-0.588	0.827	-0.168	-0.196	-0.175	-0.735	-0.433	-0.211
Oil & Grease					1.000	-0.276	-0.037	0.212	0.216	0.759	0.534	0.422
TKN						1.000	-0.580	-0.389	-0.386	-0.376	-0.258	0.119
Total-P							1.000	0.883	0.894	0.021	0.354	-0.113
Total Coliform								1.000	0.998	0.320	0.658	0.238
Fecal Coliform									1.000	0.287	0.627	0.200
Zn										1.000	0.856	0.793
Fe											1.000	0.863
Cu												1.000

Table D3: Correlation Matrix for Manjit Nagar Sub-watershed

	BOD	COD	TSS	TDS	Oil & Grease	TKN	Total-P	Total Coliform	Fecal Coliform	Zn	Fe	Cu
BOD	1.000	-0.519	0.617	0.534	0.574	0.702	-0.706	-0.003	0.193	-0.703	0.489	0.673
COD		1.000	0.014	0.030	-0.086	-0.084	0.036	0.648	0.415	0.208	0.306	-0.083
TSS			1.000	0.978	0.981	0.669	-0.748	0.454	0.236	-0.725	0.833	0.887
TDS				1.000	0.963	0.582	-0.641	0.475	0.230	-0.658	0.739	0.777
Oil & Grease					1.000	0.655	-0.669	0.398	0.161	-0.745	0.757	0.886
TKN						1.000	-0.433	0.604	0.695	-0.976	0.524	0.727
Total-P							1.000	-0.027	0.070	0.406	-0.904	-0.839
Total Coliform								1.000	0.875	-0.540	0.385	0.285
Fecal Coliform									1.000	-0.589	0.162	0.134
Zn										1.000	-0.484	-0.753
Fe											1.000	0.879
Cu												1.000

Table D4: Correlation Matrix for Preet Nagar Sub-watershed

	BOD	COD	TSS	TDS	Oil & Grease	TKN	Total-P	Total Coliform	Fecal Coliform	Zn	Fe	Cu
BOD	1.000	-0.033	0.868	0.696	0.838	-0.684	-0.542	-0.810	-0.811	0.136	0.115	0.136
COD		1.000	0.032	0.360	-0.099	-0.046	-0.099	-0.164	-0.161	0.747	0.537	0.229
TSS			1.000	0.549	0.990	-0.420	-0.224	-0.693	-0.671	0.054	0.223	0.000
TDS				1.000	0.566	-0.083	0.037	-0.850	-0.852	0.237	0.396	0.616
Oil & Grease					1.000	-0.376	-0.171	-0.637	-0.615	-0.064	0.152	-0.053
TKN						1.000	0.977	0.236	0.255	0.155	0.462	0.377
Total-P							1.000	0.124	0.149	0.118	0.500	0.366
Total Coliform								1.000	0.999	-0.598	-0.637	-0.677
Fecal Coliform									1.000	-0.603	-0.624	-0.684
Zn										1.000	0.873	0.813
Fe											1.000	0.845
Cu												1.000

Table D5: Correlation Matrix for Bus Stand Sub-watershed

	BOD	COD	TSS	TDS	Oil & Grease	TKN	Total-P	Total Coliform	Fecal Coliform	Zn	Fe	Cu
BOD	1.000	0.523	0.576	0.658	0.169	0.097	0.035	0.625	0.582	-0.004	-0.035	0.042
COD		1.000	0.983	0.955	0.701	0.638	-0.643	0.746	0.570	0.392	0.538	0.301
TSS			1.000	0.921	0.650	0.562	-0.577	0.757	0.546	0.336	0.466	0.264
TDS				1.000	0.557	0.512	-0.644	0.767	0.560	0.248	0.398	0.161
Oil & Grease					1.000	0.987	-0.165	0.452	0.780	0.878	0.874	0.829
TKN						1.000	-0.162	0.360	0.747	0.911	0.909	0.855
Total-P							1.000	-0.328	0.159	0.080	-0.206	0.239
Total Coliform								1.000	0.694	-0.001	0.025	-0.041
Fecal Coliform									1.000	0.585	0.471	0.602
Zn										1.000	0.956	0.985
Fe											1.000	0.898
Cu												1.000

Table D6: Combined Correlation Matrix for Five Sub-watersheds

	BOD	COD	TSS	TDS	Oil & Grease	TKN	Total-P	Total Coliform	Fecal Coliform	Zn	Fe	Cu
BOD	1.000	-0.650	0.303	0.203	0.046	0.020	-0.247	0.901	0.907	0.318	0.639	0.581
COD		1.000	0.391	0.027	0.479	0.335	0.024	-0.555	-0.562	0.216	-0.053	-0.068
TSS			1.000	0.369	0.915	0.268	-0.630	0.534	0.508	0.596	0.716	0.502
TDS				1.000	0.389	0.846	-0.103	0.297	0.304	0.412	0.446	0.303
Oil & Grease					1.000	0.292	-0.481	0.386	0.374	0.683	0.686	0.507
TKN						1.000	0.293	-0.013	0.020	0.541	0.402	0.396
Total-P							1.000	-0.466	-0.392	0.175	-0.132	0.178
Total Coliform								1.000	0.996	0.454	0.775	0.637
Fecal Coliform									1.000	0.503	0.803	0.689
Zn										1.000	0.910	0.942
Fe											1.000	0.945
Cu												1.000

Appendix-E

Stormwater management system for the Civil Lines sub-watershed

Table E1: Input information taken for design of the units of the treatment system

S.No.	Information	Value	Comments
1	Design storm event runoff rate	204.25 m ³ /hr	Total runoff volume of 817 m ³ is generated for Civil Lines sub-watershed during 70 mm rainfall event (90 percentile event) for assumed duration of 4 hrs
2	Peak grey water generation rate	4.6 m ³ /hr	Total population of the sub-watershed is around 300. Daily grey water generation rate is 1.125 m ³ /hr

Table E2: Design and dimensional details of different units of the treatment system for Civil Lines sub-watershed

S. No.	Design Parameters/ Units	Value	Comments
1	Cyclone de-gritter	-	Designed dimensional details are provided in Figure E2
2	Up-flow Anaerobic Reactor (Area)	100 m ²	Up-flow velocity is taken as 0.7 m ³ /hr.
3	Multi-stage multi-grade up-flow roughing filter-I (Area)	35 m ²	Up-flow velocity in this unit is taken as 2 m ³ /hr
4	Multi-stage multi-grade up-flow roughing filter-II (Area)	17.5 m ²	Up-flow velocity in this unit is taken as 4 m ³ /hr
5	Storage unit (Area)	4.6 m ²	Calculated on the basis of peak grey water generation.
6	Total area of the System	170 m ²	Includes area of the treatment unit as well as recharge well

Figure E1 shows the stormwater treatment and disposal system along with the design details.

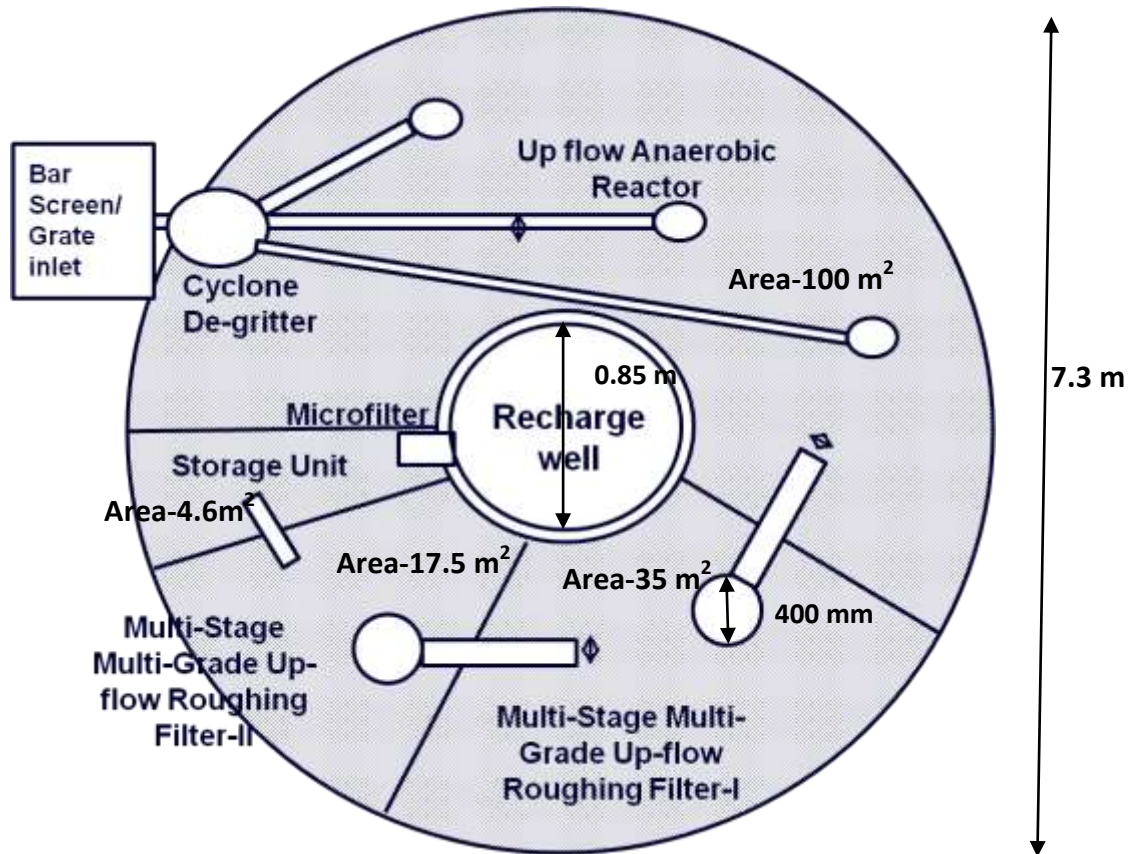
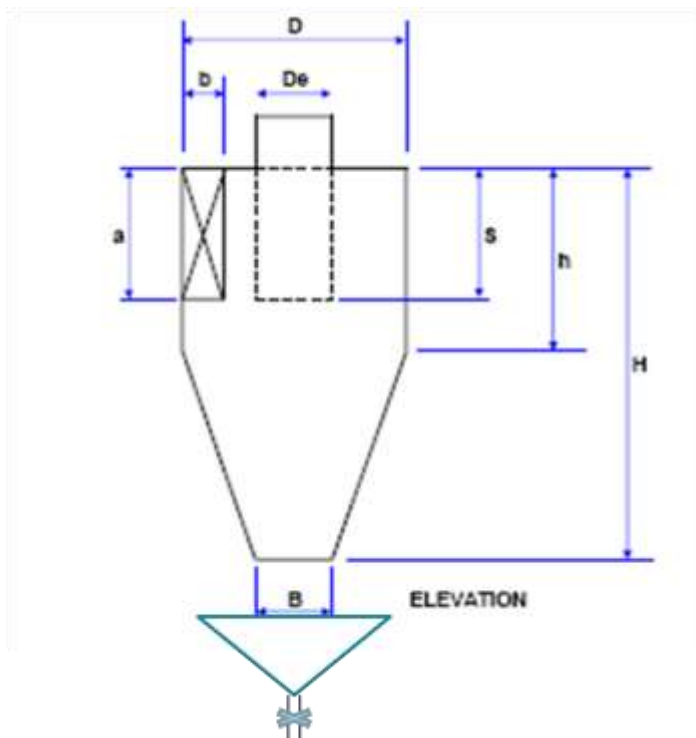


Figure E1: Stormwater Treatment and Disposal System



Diameter	D	mm	200
Inlet height	a	mm	50
Inlet width	b	mm	40
Outlet length	S	mm	200
Outlet diameter	De	mm	80
Cylinder height	h	mm	200
Overall height	H	mm	800
Under flow dia	B	mm	50

Figure E2: Design details of the cyclone de-gritter

For designing the recharge well for one of the sub-watershed i.e. Civil Lines soil profile or strata chart was required as the base input. The following Figure E3 gives the soil strata chart of Civil lines, Patiala.

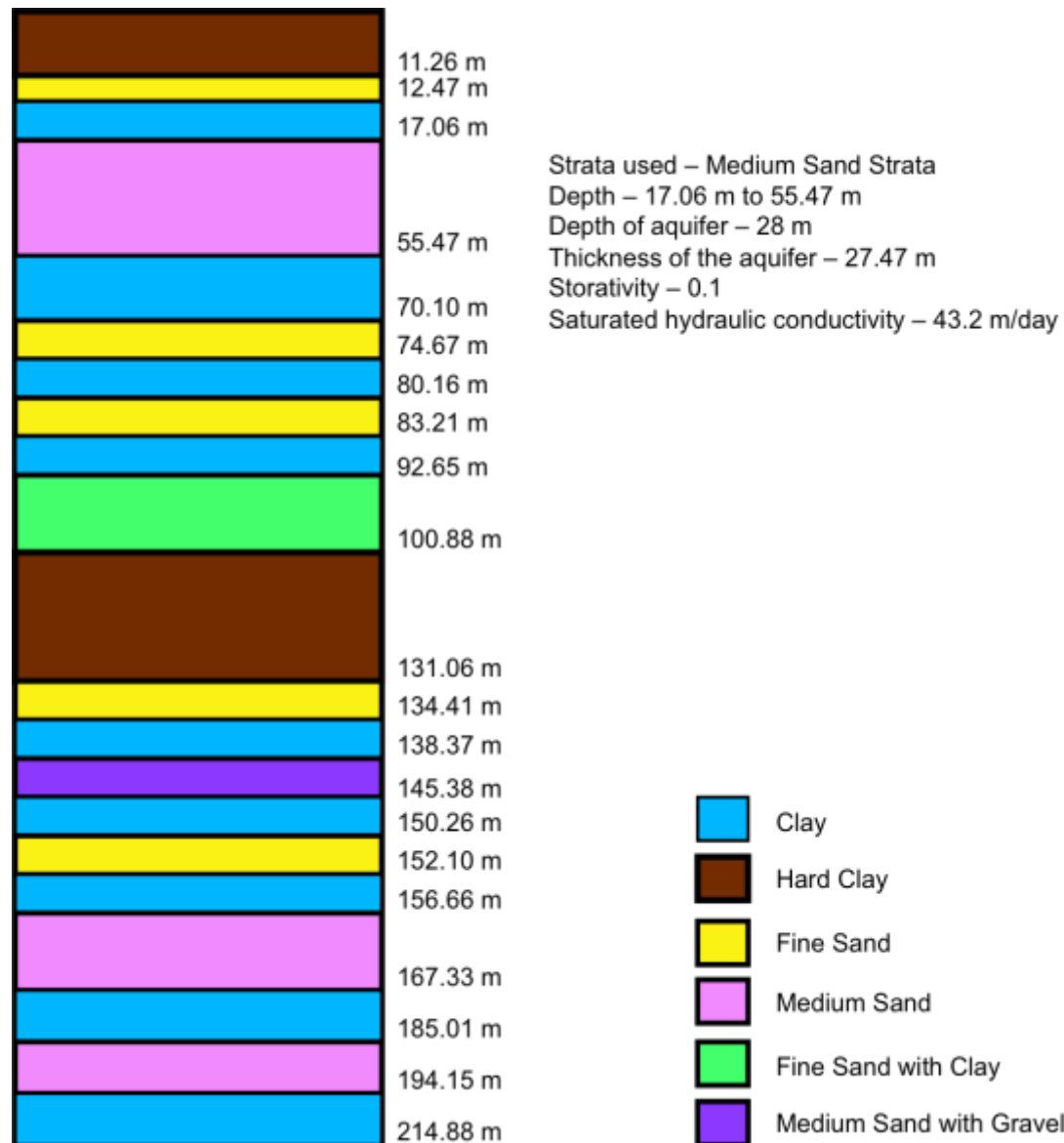


Figure E3: Soil strata chart for Civil lines, Patiala

Strata chart provided the information on strata to be used for recharging, nature of soil, storativity of the permeable layer and saturated hydraulic conductivity of the aquifer. Table E3 provides the required information for the design of recharge well; their values have been

calculated or obtained based on literature survey and comments on the values taken have been mentioned in the table itself.

Table E3: Values of the required information for design purpose

S. No.	Information	Value	Comments
1	Design infiltration rate	76.22 m ³ /hr	The average flow rate was 98 m ³ /hr. Since 1 hr of flooding is tolerated after the rain stops the infiltration rate is taken as 76.22 m ³ /hr
2	Depth to the aquifer	28 m	Information was obtained from the water supply department
3	Initial saturated thickness of the aquifer	27.47 m	
4	Strata used for recharge	Medium sand	Maximum hydraulic conductivity strata nearest to the soil surface
5	Saturated hydraulic conductivity	43.2 m/day	Since medium sand strata was used for recharge purpose the value was obtained from the literature
6	Type of aquifer	Unconfined	
7	Storativity	0.1	Since the aquifer is of unconfined type
8	Capillary rise	0.246 m	From literature for medium sand strata

Based on the above information obtained and using the protocol developed, the recharge well was designed and the design parameters are listed in Table E4.

Table E4: Values of design parameters used in the design of recharge well

S. No.	Design Parameter	Value
1	Diameter of the recharge well	0.85 m
2	Maximum allowable depth	26.21 m
3	Fixed depth of the recharge well	18 m
4	Mound height at fixed depth	1.28 m
5	Capillary rise	0.246 m
6	Rate of infiltration	75.93 m ³ /hr
7	Rate of percolation	25.42 m/hr