

SPATIO-TEMPORAL AVAILABILITY OF EXPLOITABLE WATER RESOURCES FOR EFFICIENT USES IN BANGLADESH



By

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Declaration

I hereby declare that the work in this thesis has not been previously submitted to meet the requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the Thesis contains no material previously published or written by another person except where due reference is cited. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulations of CUET.

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Dedication

To Ma, Bubu, and Jagan, who saw me at my worst and still chose to love me
unconditionally.

List of Publications

Conference

- Chowdhury, P., & Mullick, R. A., 2025, Environmental Flow Requirements Assessments of Selected Rivers of Bangladesh, Proceedings of the International Conference on Emerging Technology for Sustainable Development (ICETSD-2025), JUST, Bangladesh.

Approval/Declaration by the Supervisor(s)

This is to certify that Priya Chowdhury has carried out this research work under my supervision and that she has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology so that she is qualified to submit the following Thesis in the application for the degree of MASTER of SCIENCE in Civil Engineering. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulations of CUET.

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Abstract

Bangladesh, a low-lying riparian country situated within the Ganges-Brahmaputra-Meghna Basin, comprises 7% of the total GBM catchment area. The country experiences abundant rainfall during the wet season; however, it encounters low rainfall and subsequent water scarcity in the dry season. Such an uneven distribution of water resources both spatially and temporally results pressure on the resource base. For an efficient management of the resource, the study aims to formulate an effective monthly water conservation strategy. The study estimated water demands across various sectors in Bangladesh, including domestic, industrial, irrigation, and environmental, while contrasting these with supply sources such as surface runoff, groundwater recharge, and transboundary inflows. The total annual water demand was calculated to be 1,017 BCM, while the renewable water availability amounted to 1,138 BCM, indicating no yearly water deficit. Nevertheless, the country-wide seasonal analysis indicated a distinct scenario. During the dry season, a deficit of 8 BCM was observed, whereas the other three seasons had a surplus of water. Analyses of individual basins revealed that all basins experienced water shortages throughout the dry season. Both the Ganges and Southeastern basins additionally faced deficits during the pre-monsoon, while the Meghna basin suffered even in the post-monsoon. To address the seasonal difference in water balance, the surplus water was evaluated for its potential monthly storage utilizing the mass curve method. The Storage to Allocation Ratios (SAR) were calculated as 0.345 for the Brahmaputra, 0.313 for the Meghna, 0.245 for the Ganges, and 0.077 for the Southeastern Basin, thereby highlighting the potential for the efficient utilization of available water resources. This methodology can be reproduced for any changes in future demand and supply to establish a monthly water conservation strategy.

বিমূর্ত

পানি প্রাকৃতিক সম্পদের একটি অত্যন্ত গুরুত্বপূর্ণ উপাদান, যা কৃষি, শিল্প, গৃহস্থালি জীবন ও পরিবেশসহ বিভিন্ন খাতে অপরিহার্য। বাংলাদেশ একটি নিম্নভূমি ও নদীবাহিত দেশ, যা গঙ্গা-ব্রহ্মপুত্র-মেঘনা অববাহিকার অন্তর্ভুক্ত এবং এই অববাহিকার মোট জলধারণ এলাকার ৭% জুড়ে রয়েছে। দেশে বর্ষা মৌসুমে প্রচুর বৃষ্টিপাত হয়; তবে বৃষ্টিপাতের স্থানিক ও কালের ব্যবধানজনিত কারণে শুষ্ক মৌসুমে পানি সংকট দেখা দেয়।

কার্যকর মাসভিত্তিক পানি সংরক্ষণ কৌশল প্রণয়নের উদ্দেশ্যে, এই গবেষণায় বাংলাদেশের চারটি প্রধান পানির চাহিদা — গৃহস্থালি, শিল্প, সেচ, ও পরিবেশগত প্রবাহ এবং তিনটি পুনর্নবীকরণযোগ্য পানির উৎস — পৃষ্ঠপ্রবাহ, ভূগর্ভস্থ পুনর্ভরণ, ও সীমান্ত পেরিয়ে আগত নদীর প্রবাহ — মূল্যায়ন করা হয়েছে।

সর্বমোট বাৎসরিক পানির চাহিদা নির্ধারণ করা হয়েছে ১,০১৭ বিলিয়ন ঘন মিটার (বিসিএম), যেখানে পুনর্নবীকরণযোগ্য পানির প্রাপ্যতা হয়েছে ১,১৩৮ বিসিএম, যা দেখায় যে বাৎসরিক পানি ঘাটতি নেই। তবে মৌসুমি বিশ্লেষণে অসাম্য ধরা পড়েছে — শুষ্ক মৌসুমে ৮ বিসিএম ঘাটতি, প্রাক-মৌসুমে ১৫২ বিসিএম, বর্ষায় ১১২ বিসিএম এবং পশ্চাৎ-মৌসুমে ১.৪২ বিসিএম উদ্বৃত্ত।

সবগুলো অববাহিকাই শুষ্ক মৌসুমে পানি ঘাটতির মুখোমুখি হয়েছে। গঙ্গা ও দক্ষিণ-পূর্ব পার্বত্য অববাহিকা প্রাক-মৌসুমে অতিরিক্ত ঘাটতির সম্মুখীন হয়েছে এবং মেঘনা অববাহিকা পশ্চাৎ-মৌসুমেও ঘাটতির শিকার হয়েছে। এর বিপরীতে, বর্ষা মৌসুমে সবগুলো অববাহিকায় যথেষ্ট পরিমাণে পানি উদ্বৃত্ত দেখা গেছে।

এই মৌসুমি অসমতা দূর করতে উদ্বৃত্ত পানি মাসভিত্তিক সংরক্ষণের সম্ভাব্যতা বিশ্লেষণ করা হয়েছে ম্যাস কার্ভ পদ্ধতি ব্যবহার করে। সংরক্ষণ থেকে বরাদ্দের অনুপাত (Storage to Allocation Ratio - SAR) নির্ধারণ করা হয়েছে: ব্রহ্মপুত্রের জন্য ০.৩৪৫, মেঘনার জন্য ০.৩১৩, গঙ্গার জন্য ০.২৪৫ এবং দক্ষিণ-পূর্ব পার্বত্য অববাহিকার জন্য ০.০৭৭, যা উপলব্ধ পানিসম্পদের দক্ষ ব্যবহারের সম্ভাবনা নির্দেশ করে। এই ফলাফলগুলো অববাহিকা-ভিত্তিক এবং টেকসই পানিসম্পদ ব্যবস্থাপনা নীতিমালার জন্য একটি বাস্তবভিত্তিক ভিত্তি সরবরাহ করে।

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Nomenclature

Symbols

ET_0	Reference evapotranspiration (mm/day)
Δ	The slope of saturation vapor pressure curve at mean air temperature (kPa/°C)
γ	Psychrometric constant = 0.054 (kPa/°C)
λ	Latent heat of vaporization = 2.45 MJ/kg
R_n	Net radiation (MJ/m ² -day)
G	Soil heat flux density (MJ/m ² -day)
U_2	Daily mean wind speed at 2m height (m/s)
e_s	Actual vapor pressure (kPa)
e_a	Saturation vapor pressure (kPa)
K_{time}	Unit conversion equal to 86400 for ET in mm/day
Q_a	Mean air density at constant pressure (kg/m ³)
c_p	Specific heat of the air (MJ/kg-°C)
r_a	Aerodynamic resistance (s/m)
r_s	Bulk specific resistance (s/m)
p	Mean annual percentage of daytime hours = 0.274
T_{mean}	Mean daily temperature (°C)
R_a	Extraterrestrial radiation (MJ/m ² -day)
T_{max}	Daily maximum temperature (°C)

$T_{\min}$	Daily minimum temperature (°C)
RH	Relative humidity (%)
P	Precipitation depth (inch)

Acronyms and Abbreviations

BWDB	Bangladesh Water Development Board
BARC	Bangladesh Agricultural Research Center
BMD	Bangladesh Meteorological Department
FAO	Food and Agricultural Organization
RMG	Readymade Garments
IRWR	Internal Renewable Water Resources
ERWR	External Renewable Water Resources
GBM	Ganges-Brahmaputra-Meghna Basin
BSFIC	Bangladesh Sugar and Food Industries Corporation
BBS	Bangladesh Bureau of Statistics
CSIRO	Commonwealth Scientific and Industrial Research Organization
DPHE	Department of Public Health Engineering
WASA	Water Supply and Sewerage Authority

Chapter 1: INTRODUCTION

1.1 BACKGROUND

Water is a vital component of natural resources and plays a crucial role in various sectors, including agriculture, industry, domestic use, commerce, navigation, and the environment, such as maintaining riverine ecological flows and supporting evapotranspiration (Ahmed & Roy, 2007). According to the Food and Agriculture Organization (FAO), total water resources are broadly categorized into two types: renewable and non-renewable. Renewable water resources are those replenished by the hydrological cycle, including surface and shallow groundwater. In contrast, non-renewable water resources primarily consist of deep aquifers with negligible recharge rates. A nation's total renewable water resources are composed of two key elements: Internal Renewable Water Resources (IRWR) and External Renewable Water Resources (ERWR). IRWR includes the long-term average annual flow of rivers and aquifer recharge resulting from precipitation within the country's territory, accounting for any overlap between surface and groundwater. ERWR refers to the inflow of water from transboundary rivers and aquifers, as well as shared water bodies located along national borders. The portion of renewable water resources that can be effectively utilized under existing conditions is termed Exploitable Water Resources. Typically, this value is significantly less than the total natural water resources, as not all sources, such as surface water, groundwater, and rainwater, are practically accessible or usable (FAO, 2014).

Bangladesh, located in the northeastern part of South Asia and bordered by the Bay of Bengal to the south, is a lower riparian country within the Ganges-Brahmaputra-Meghna (GBM) Basin. Most of its landmass is formed by the

alluvial deposits of these three major rivers, creating a vast, low-lying deltaic floodplain. Although Bangladesh lies at the heart of the GBM Basin, it contributes only 7% to the total catchment area. In contrast, India contributes 64%, China 18%, Nepal 9%, and Bhutan 3% (FAO, 2011). According to the Bangladesh Water Development Board (BWDB), approximately 236 rivers, including 57 transboundary ones, flow through the country during both summer and winter, collectively discharging about 1,222 million cubic meters of freshwater into the Bay of Bengal, excluding losses from evaporation, evapotranspiration, and deep percolation. Between 1980 and 2009, the combined mean annual discharge of the significant rivers was recorded at 981 cubic kilometers. However, during the dry season (November to April), the flow declines drastically, down to just 15% of the annual mean, with the Brahmaputra alone contributing around 75% of this reduced flow (CSIRO, 2014). Despite the transboundary rivers bringing nearly 1,000 billion cubic meters of water annually, this volume is insufficient to meet the country's dry season demands. This seasonal imbalance is primarily due to Bangladesh's downstream position relative to the Himalayan-originating rivers. Upstream water diversion, uncontrolled extraction, and river flow regulation by neighboring countries lead to excessive flooding during the monsoon and critically low flows in the dry months (Kolas et al., 2013).

Focusing on rainfall, Bangladesh receives an average annual precipitation of approximately 2,353 mm (Mohsenipour et al., 2020). However, during the dry season, the northwestern and southwestern regions experience significantly lower rainfall. This uneven distribution, coupled with the reduction in dry season river flows, leads to water scarcity, particularly in the northwestern part of the country (BWDB, 2020).

Seasonal flooding during the wet season and water scarcity in the dry season highlight the critical need for water storage to reduce pressure in subsequent seasons. While surface water and rainwater availability have been

discussed earlier, it is essential to focus on groundwater, which serves as the primary water source for both rural and urban populations across Bangladesh, excluding the hilly regions. In the northwest region, reliance on groundwater is particularly high, with up to 97% of cultivated land being irrigated from this source. Similarly, during 2009–10, groundwater supported 84% and 76% of irrigation needs in the central and southwest regions, respectively. In contrast, the northeast and southeast regions depend more on surface water, accounting for about 55% of irrigated areas (Chowdhury & Ward, 2004). Groundwater is mainly recharged by surface water; however, recharge activities are limited in many areas of Bangladesh. For instance, Dhaka city relies heavily on groundwater aquifers, which supply 87% of its total water needs. This dependency has led to an alarming decline in the water table, falling at a rate of 2.81 meters per year, far exceeding the recharge rate of 1.33 meters per year (Uddin & Baten, 2011). Such high stress, particularly in the northwest, is resulting in the overexploitation and depletion of deeper aquifers, emphasizing the urgent need for water storage infrastructure. Kaptai Lake, the largest artificial reservoir in Bangladesh, has a storage capacity of 6,500 million cubic meters and is currently used for hydroelectric power generation and recreational purposes (Suman et al., 2021). In conclusion, artificial reservoirs like this can not only help alleviate water scarcity but also serve as valuable sources for energy production.

The previous discussion covered the availability of water from various sources, including rainwater, groundwater, and surface water. This water is essential for multiple uses such as irrigation, domestic needs, industrial operations, and maintaining environmental flow. As an agriculturally dominant country, Bangladesh's water demand is primarily driven by irrigation, which constitutes most of the national water requirement. Other significant sectors that demand water include domestic and municipal use, industries, fisheries, navigation, evaporation, and environmental needs. While these sectors account

for a smaller portion of the total demand, their impact can be substantial, especially locally. In many instances, environmental water requirements are neglected, resulting in the drying up of natural rivers and wetlands during the dry season to fulfill the needs of other sectors. Thus, Bangladesh faces a dual water challenge: excessive flooding in the wet season and water scarcity in the dry season. This imbalance is mainly due to the country's predominantly flat topography, which causes monsoon floodwaters to quickly drain into the Bay of Bengal.

This study aims to quantify the seasonal availability of renewable water resources across four major basins, and the sectoral water demands throughout the year. The findings will help determine how much water must be stored each season to address water scarcity and promote more sustainable water use practices. As a result, it would be useful for water policymakers to make quantitative decisions about storing excess water during the wet season, which can be utilized during the dry season.

1.2 CONTEXT

Bangladesh, as a lower riparian country of the Ganges-Brahmaputra-Meghna (GBM) River Basin- the world's third-largest freshwater outlet to the oceans faces complex challenges due to the seasonal nature of both transboundary streamflow and internal rainfall (Chowdhury & Ward, 2004). The Ganges River typically experiences an initial surge in streamflow beginning in May, peaking between July and August. In contrast, the Brahmaputra and Meghna Rivers witness their first floods from July to August, followed by a second, less intense flood in September (Chowdhury & Sato, 1996). Rainfall patterns reflect similar seasonality, with over 89% of annual precipitation occurring between May and October. Spatial variability is also significant: the northwest region receives a mean annual precipitation of about 1,527 mm, while the northeast sees up to 4,197 mm (Shahid, 2012).

These hydrological characteristics indicate that while water is abundant during the wet season, it becomes scarce for the remainder of the year. Furthermore, this abundance is unevenly distributed, with the northwest being the driest and the northeast the wettest. A significant portion of the excess water during the wet season drains out through the Meghna estuary without being utilized.

This study aims to estimate the monthly water demand across four major basins in Bangladesh and assess water availability from various sources during the same period. The findings will help quantify the spatial and temporal dimensions of water scarcity, assisting policymakers in making informed decisions about storing surplus wet-season water for use during the dry months. As a result, the risk of unsustainable practices to meet the water deficit during the dry period will be reduced.

1.3 AIM AND OBJECTIVES

This study aims to investigate an efficient water conservation strategy in a monthly timestep considering all the water demands and supply across four major hydrological basins of Bangladesh: the Ganges, Brahmaputra, Meghna, and Southeastern Hill basins. The specific objectives of this study are:

- To assess the monthly domestic, industrial, irrigation, and environmental water demand across four major hydrological basins in Bangladesh.
- To quantify the renewable water resources, including surface runoff, groundwater recharge, and transboundary river flow, for each month across all basins.
- To quantify the water surplus and deficit for each month within each basin and to identify an efficient water conservation strategy for individual basin.

1.4 SCOPE OF THE STUDY

This study evaluates the monthly water balance across Bangladesh's four major hydrological basins: the Ganges, Brahmaputra, Meghna, and Southeastern Hill, covering the entire country. It assesses both water demand and availability to highlight spatial and seasonal disparities.

Water demand is estimated for domestic, industrial, agricultural (irrigation), and environmental sectors. Domestic and industrial demands are based on 2021 population and production data. Irrigation demand is calculated using the CROPWAT model with 2021 crop data, 2011–2021 climate averages, and FAO soil maps. Environmental flow needs are estimated by a hydrological method using 1990–2021 discharge data. Water supply includes transboundary inflows, surface runoff, and groundwater recharge. Transboundary flow is based on 2011–2021 river discharge at entry points. Surface runoff is estimated using the rational method with 10-year rainfall data and runoff coefficients from land cover maps derived from Sentinel-2 imagery. Groundwater recharge is calculated using the water balance method and evapotranspiration data from BARC.

The study computes net monthly water balances, identifies shortages, and suggests basin-specific storage allocation ratios to conserve excess wet-season water for dry-season use, supporting efficient water management in Bangladesh.

1.5 THESIS OUTLINE

This thesis is organized into six chapters, each covering a key aspect of the research.

Chapter One provides the introduction and background of the study. It outlines the research problem, defines the main objectives, and establishes the scope of the study. This chapter also highlights the existing gaps in knowledge and explains the rationale for conducting this research.

Chapter Two presents a comprehensive review of existing literature related to water demand and supply components. It covers the background of each demand type (domestic, industrial, irrigation, environmental), water sources (surface runoff, groundwater recharge, transboundary flow), and relevant studies conducted in Bangladesh. The chapter also discusses the methods used in previous research, the challenges faced, and the specific gaps in estimation for the Bangladeshi context.

Chapter Three describes the methodology adopted in this study. It begins with an overview of the study area and a detailed description of each basin. This chapter then outlines the data sources, the methods used for estimating each component of water demand and availability, and the overall procedure followed for analysis.

Chapter Four presents the results of the study through tables and graphical representations. It discusses the monthly water demand and supply variations, basin-wise analysis, and the resulting net water balance. In addition, it includes the estimation of the volume of water that should be conserved during the wet season to meet dry season demands.

Chapter Five focuses on a detailed discussion of the results for each basin. It analyses the findings in relation to the hydrological and topographical features of the basins and provides a comparative summary of the outcomes.

Chapter Six concludes the thesis by summarizing the key findings, outlining recommendations for future water resource planning, and discussing the limitations of the study.

Chapter 2: LITERATURE REVIEW

2.1 GENERAL

A comprehensive understanding of water demand and supply is a fundamental prerequisite for sustainable water resource management, particularly in balancing these two critical components. In Bangladesh, where water scarcity and abundance fluctuate seasonally and spatially, accurately estimating these parameters is essential for effective management. This literature review aims to provide a detailed description of each water demand and supply component, review estimation methods, explore existing literature specific to Bangladesh, identify gaps in current research, and establish a conceptual framework for the current study.

2.2 DOMESTIC WATER DEMAND

It is defined as the water needed for domestic consumption, including drinking, bathing, washing, gardening, and cooking. This demand depends on the volume of population, civilization, the level of services and utilities, and water availability. In some cases, it depends on the climatic conditions. In modern cities in the developed countries of the world, water use can vary from 500-800 liters per capita per day, whereas in developing countries of Asia, Africa, and Latin America, the domestic water demand is 50-100 liters per capita per day (BBS, 2019).

It is difficult to estimate exactly how much water will be needed for municipal water demand in the future. This is because residents of this area rely on both surface water and rainwater in addition to groundwater. Not every city in the country has access to a centralized water distribution system. In Bangladesh's four largest divisions (Dhaka, Chattogram, Khulna, and Rajshahi),

there are only four central water supply systems that collect their water mainly from rivers, and they only distribute it at a level that can't quite keep up with demand. The demand of the whole population of the corresponding cities can't even be met by these organizations. Deep tubewells, which are under the authority of the DPHE organization, are used by areas that are not served by central water supply systems to draw water from the ground. Rural residents use stored water from ponds and lakes for residential purposes only, not for drinking. So, it is quite difficult to estimate precisely how much water is required for domestic purposes in Bangladesh.

There are different guidelines on per capita consumption. The World Health Organization (WHO) gives guidelines for per capita consumption according to the availability of water sources near the house, which is shown in Table 2.1. Bangladesh National Building Code (BNBC) offers guidelines on per capita consumption (liters per capita per day) based on occupancy group and facilities, which is shown in Table 2.2.

Table 2.1 Domestic water consumption guideline (WHO)

Criteria	Demand
Water sources are several kilometers away	2-4 liters per day
Water sources up to 1 kilometer away	4-8 liters per day
Water next to the house	10-20 liters per day
Water in the home for the toilet, tap, shower	60-100 liters per day
Water in the home for toilet, bath, kitchen and laundry	100-250 liters per day

For Bangladesh, the International Training Network (ITN-BUET) has developed per capita consumption based on city types. According to Ahmed & Rahman (2007), the whole country has been divided into four categories: rural areas, upazila towns, zilla towns, and city corporations, and the consumption pattern has been shown in Table 2.3.

Table 2.2: Domestic water consumption (BNBC)

Occupancy group	For full facilities (lpcd)	For restricted facilities (lpcd)
Mess, hostels & boarding house	135	70
Minimum standard housing	-	70
Hotels or lodging house (per bed)	300	135
Hotel (up to 4 stars)	180	-
Hotel (up to 5 stars)	320	-

Table 2.3: Domestic water guideline (Ahmed & Rahman, 2007)

Area type	Demand (lpcd)
Rural area	50
Upazila town	100
Zilla town	120
City corporation	180

Despite the availability of different guidelines on per capita consumption based on various criteria, there is no comprehensive study on domestic water estimation for the entire country. While some literature has provided insights into water consumption, these studies remain limited in scope as they fail to incorporate the regional variations in water demand. This study aims to estimate the domestic water consumption for four basins of Bangladesh using Table 2.3 as it represents per capita consumption variations based on administrative boundaries. The output will provide valuable information on accurate water demand for sustainable water management.

2.3 INDUSTRIAL WATER DEMAND

Industrial water demand is defined as the water needed for industrial production, such as manufacturing, cooling, dying, and fire protection. Water consumption depends on the size of the industry as well as the economic growth. The management of water resources within the industrial sector holds significant importance in the context of Bangladesh. Industrial processes are distinguished

by their various inputs, such as raw materials, energy, and Labor, and outputs, including products, air and water emissions, refuse, and so forth (Mortier et al., 2007).

In Bangladesh, the primary manufacturing sectors are textiles, food products, and wearing apparel or readymade garments, with contributions of 27.66%, 20.38%, and 16.76%, respectively (BBS, 2019). The manufacturing sector accounts for around 22.63% of the Gross Domestic Product (GDP). The industry that has significantly contributed to the economy is readymade garments (RMG), which is currently the most significant contributor to Bangladesh's export earnings. Hence, exporting merchandise is one of Bangladesh's primary sources of revenue. Bangladesh ranks second in readymade garment exports, primarily to the EU and the USA. In the fiscal year 2021-22, the revenue generated from the Ready-Made Garments (RMG) industry amounted to 42,613.15 million USD, representing approximately 81.82% of the overall export earnings of this country (BBS, 2023). The export-oriented approach has been the driving force behind Bangladesh's economic growth, which has resulted in industries contributing significantly to the country's foreign exchange revenues. These industries, particularly textiles, pharmaceuticals, and information technology services, contribute to the nation's ability to finance essential imports and minimize trade imbalances through the revenue they create. This strengthens Bangladesh's total economic resilience, which is a positive outcome. The quick expansion of industrial sectors is accelerating Bangladesh's economic development. Also, more employment opportunities have arisen in Bangladesh due to the country's rapid industrialization. According to the preliminary report of the Labor Force Survey, 2022, the country's estimated total labor force (aged 15 and above) is 73.41 million. This figure comprises 47.48 million males and 25.93 million females. The Labor Force Survey of 2016-17 reported a total labor force of 63.5 million, with 43.5 million males and 20.0 million females (BBS, 2023). Industries not only

contribute to the economy but also play a catalytic role in the creation of new skills and technical developments. Investments in research and development have been motivated by the expansion of a variety of industries, which has resulted in the promotion of innovation and the enhancement of the nation's industrial capacities. Not only does the incorporation of contemporary technology increase productivity, but it also empowers Bangladesh to become a competitive competitor in the international market.

Water is an essential element of the production process. Almost every product requires water during production, either directly or indirectly. For example, food and beverage production frequently necessitates significant water use, involving activities such as cleaning, processing, and occasionally serving as a crucial component. Similarly, water is utilized in multiple phases of textile production, including cleansing, coloring, and finishing. In the pulp and paper industry, water is a crucial component. In cement, steel, and fertilizer production, water is an essential element that is used in the cooling process. This study focuses on water use in seven types of industries in Bangladesh, such as textile & RMG, leather, cement, steel, sugar, pulp & paper, and fertilizer. This section will discuss the production process and the contribution of water to the process occurring in the mentioned industries.

2.3.1 Textile and Readymade Garments Industry

From 1995 to 2009, Bangladesh increased the export of apparel to the U.S. from 2.8% to 5%; in Europe, the shift was from 3% to 4.7% (Gereffi & Frederick, 2010). Bangladesh is widely acknowledged as the second-largest global exporter of ready-made garments (RMG) (Hossain & Khan, 2017). The production of textiles is characterized by a lengthy process sequence that uses a lot of resources, including water, fuel, and various chemicals, and produces much waste. Water consumption in this industry can be as high as 200-250 m³/ton of cotton cloth (Restiani, 2016). In the case of Bangladesh, the major textile industries are based

on raw cotton. Among all the processes, slashing, bleaching, mercerizing, and dyeing are the steps directly involved with significant water consumption and wastewater generation. Approximately 85% of the water utilized and released by industries is during the wet processing phase. The estimated average water consumption per kilogram of fabric produced in factories in Bangladesh ranges from 250 to 300 liters. The global standard for fabric manufacture is 100 liters of water per kilogram, serving as a reference for comparison (Sagris et al., 2015).

2.3.2 Leather Industry

Leather is one of Bangladesh's most ancient sectors, holds a prominent position in the country's economy, and has an accredited global reputation (Khan, 2014). According to the Bureau of Manpower, Employment and Training (BMET), Bangladesh, the leather sector includes 220 tanneries, 3,500 SMEs, and 110 large firms (M. N. Islam, 2015). The Leather Goods & Footwear Manufacturer & Exporters Association (LFMEA) figured that Bangladesh produced approximately 300 million square feet of leather in 2016, and it was expected to have 35% production growth by the year 2021 (BBS, 2023).

2.3.3 Pulp and Paper Industry

At the government's initiative, the Karnaphuli Paper plant in Chittagong, a newsprint plant in Khulna, the North Bengal Paper Mill in Pabna, and a pulp mill in Sylhet were established after 1947. After Bangladesh entered the private sector, many paper mills opened, such as Sonali Paper Mill, Hashem Paper and Pulp Mill, Hossein Paper Mill, Magura Paper Mill, Bengal Paper Mill, Hakkani Paper Mill, Tongi Board Mill, Bashundhara Paper Mill, Meghna Paper Mill, etc. These sophisticated mills use imported pulp to make high-quality paper. Some mills recycle paper. Pulp is also made from jute and straw. All these mills produced 20000000 metric tons of pulp, paper, and newsprint products in 2022(BBS, 2023).

Different types of paper necessitate varying quantities of water. The Table 2.4 presents a concise overview of the water needs of paper production in North

America (Bryant et al., 1995). For each metric ton of paper produced, a substantial amount of water, ranging from 150 to 250 m³, is necessary in manufacturing paper and paper goods (Chaturvedi et al., 2006 ; Tewari et al., 2009). The water demand for imported pulp and wastepaper is 20-35 m³ /ton(Rahman & Kabir, 2010).

Table 2.4: Water requirements of different paper production (Chaturvedi et al., 2006; Tewari et al., 2009)

Types of paper	Water required (m ³ /ton)
Newsprints	6-12
Corrugating Medium	2-10
Fine Paper	5-10
Liner Board	2-10
Supercalendered Paper (SC)	10-15
Tissue Paper	10-15
Light Weight Coated Paper (LWC)	10-20
Multiply Board	8-15

2.3.4 Cement Industry

The cement industry is critical to the construction sector, serving as the foundation for development and urbanization on a global scale. Bangladesh's burgeoning cement industry has grown significantly over the past few decades. In recent years, Bangladesh has had over 35 active cement manufacturers, with a combined production capacity exceeding 50 million metric tons annually. The industry is primarily dominated by local players such as Shah Cement Industries Ltd., Heidelberg Cement Bangladesh Ltd., and Lafarge Holcim Bangladesh Ltd. Despite its smaller scale compared to global giants, the Bangladeshi cement industry has demonstrated remarkable growth, driven by increasing domestic demand for construction materials(Bangladesh Cement Manufacturers Association., 2023).

2.3.5 Sugar Industry

The sugar industry in Bangladesh is a vital part of the country's agro-industrial sector. It predominantly involves sugar production from sugarcane, with limited production from sugar beet. Both state-owned and private enterprises characterize this industry. The Bangladesh Sugar and Food Industries Corporation (BSFIC) oversees the state-owned sugar mills spread across the country. Currently, there are 15 state-owned sugar mills under BSFIC and a few private mills that contribute to the total production. However, the current sugar production only covers 5% of the total demand in Bangladesh (Rahman et al., 2016). Despite its potential, the sugar industry in Bangladesh faces several challenges. These include outdated machinery, inefficient production processes, and low productivity of sugarcane. Bangladesh's average sugarcane yield is relatively low compared to other sugar-producing countries, primarily due to traditional farming practices and a lack of modern agricultural techniques.

2.3.6 Fertilizer Industry

The fertilizer industry in Bangladesh is a cornerstone of the agricultural sector, ensuring the availability of essential nutrients required for crop production. This industry encompasses the production of various types of fertilizers, including urea, triple superphosphate (TSP), diammonium phosphate (DAP), and muriate of potash (MOP). The Bangladesh Chemical Industries Corporation (BCIC), a state-owned enterprise, is a major player in this sector, operating several large-scale fertilizer plants nationwide. Additionally, numerous private companies contribute to the production and distribution of fertilizers. Also, a large share of the demand is imported. In 2015-2016, the actual fertilizer consumption in Bangladesh was 2.64 million tons (Emerging Credit Rating Limited, 2017). One of the key aspects of Bangladesh's fertilizer industry is the government's heavy subsidy to make fertilizers affordable for farmers. This subsidy is crucial for maintaining agricultural productivity and ensuring food

security. However, the industry faces challenges such as dependency on imported raw materials, which makes it vulnerable to global market fluctuations. Furthermore, the industry needs technological advancements to improve production efficiency and reduce environmental impacts associated with fertilizer use.

According to the Food and Agriculture Organization (FAO), Bangladesh's estimated industrial water withdrawal in 2008 is 0.77 cubic kilometers. The country has an estimated 1.02 cubic kilometers of industrial water demand (Barua, et al., 2016). While these previous studies provide some insights into industrial water requirements, there is no extensive work on the overall industrial water demand in Bangladesh. Most existing studies focus on water requirements per unit production in different industries and water footprints of other industries, or they analyze the industrial wastewater characteristics. However, there is a remaining gap in the nationwide assessment of industrial water demand. This study bridges this gap by estimating industrial water demand using per-unit production data from different literature. Additionally, the findings will provide basin-wise water demand, which will assist policymakers in determining the water requirements for industrial growth and efficient and equitable water allocation across different regions of Bangladesh.

2.4 ENVIRONMENTAL WATER ASSESSMENT

Environmental flow or low flow requirement is the water flow to maintain a river's ecosystem. According to the Brisbane Declaration, E-flows are defined as "the quantity, the timing, and quality of water flow required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Arthington et al., 2018). It is also known as "environmental flow requirement (EFR)," "instream flow requirement (IFR)," "environmental flow," "environmental flow demand," "low flow demand," or "ecological flow requirement." The process of estimating e-flow requirements is

termed “environmental flow assessment (EFA)” (Karimi et al., 2012). E-flow assessment was first started in the United States of America in 1940, and it became more formal with documented techniques in the late 1970s. Outside the United States of America, the methodologies used to assess e-flow are not well documented. It received importance after the 1980s (Australia, England, New Zealand, etc.) in many countries, or later (Brazil, Japan, etc.). There is not well-published literature that only specifies environmental flow estimation and related issues (Tharme, 2003).

2.4.1 Importance of E-flow

Surface bodies such as rivers, wetlands, near-coast marine ecosystems, and estuaries serve humans in various ways, including providing potable water, fish, and fiber, as well as services such as water purification, flood mitigation, and recreational opportunities (Dyson et al., 2003). Water resource developments on rivers, such as dams, weirs, and abstractions, have been undertaken for human benefits, including irrigation, hydropower generation, and saving localities from major natural calamities, leading to river flow alterations.

Over 45,000 large dams have been built in more than 140 countries, with approximately 80,000 small dams worldwide. It is estimated that over 50% of the accessible surface water is regulated by humans, with projections indicating an increase to 70% by 2025 (Tharme, 2003). The construction of river impoundments affects the natural flow regime and the natural biodiversity-rich hotspots by reducing downstream water availability, altering seasonal flow patterns, and changing the flood frequencies (Suwal et al., 2020). Approximately 65% of aquatic ecosystems and river flows are under moderate to high threat due to climate change, dam construction, overfishing, and water pollution (Hairan et al., 2021). For instance, the Amazon basin has 416 commissioned and 334 planned hydroelectric power plants, which directly impact fish production by obstructing their migration routes (Hairan et al., 2021).

In Bangladesh, the construction of the Bangabandhu Jamuna Multi-purpose Bridge on the Jamuna River has significantly altered the river's morphology, increasing bar areas, leading to a reduction in fishing ground, causing erosion, and negatively impacting the economic status of fishermen (Islam et al., 2017). The Padma River, a major transboundary river and the natural breeding ground of Hilsa fish, has experienced a decline in fish populations due to the construction of the Farakka Barrage in 1975 (Islam, 2006). Similarly, the Teesta Barrage Irrigation Project, completed in 1998, has caused severe ecological and social challenges for the Teesta River (Mullick et al., 2010).

Although these hydraulic structures were built for more significant human benefits, they have severely impacted natural ecosystems (Karakoyun et al., 2018). The concept of minimum flow has been explored to maintain ecological and socioeconomic balance and conserve rare species in river ecosystems. Environmental flows aim to provide a flow regime that is sufficient in quantity and quality to sustain the health of river ecosystems.

2.4.2 Environmental Flow Assessment

The emergence of environmental flow leads to the development of methodologies to assess e-flows of surface water bodies. Several approaches, methods, and frameworks have been developed to set e-flows during the past 20 years. Still, there is no specific best approach or guideline for environmental flow assessment. Each method is only suitable for certain circumstances. The criteria for choosing a specific method to assess ecological flows are the types of rivers, increased cost, lack of important information, ecological importance, and severity of different resource development (Karimi et al., 2012). Most of the methods have been developed or applied in developed countries. Developing countries cannot establish new methodologies suitable for their environment and river systems due to knowledge gaps in e-flow, a lack of practice, and technical and institutional capacity.

About 207 methodologies to estimate environmental flow have been used in 44 countries (Tharme, 2003). He found that Australia and South Africa are among the most advanced countries due to the development and application of E-flows. Different methodologies are classified based on different criteria. Stalnaker et al. (1995) classified e-flow methodologies into two categories, namely incremental and standard-setting, considering the objectives of the decision-making process. The standard-setting method is called preliminary-level planning, in which the analyst is required to determine e-flow to guide the decision-making process. It includes hydrological methods and hydraulic methods of e-flow assessment. The incremental method is used in high-value projects where in-depth knowledge is required and a range of decision variables is available. Dyson et al. (2003) classified e-flow methodologies into look-up tables, desktop analysis, functional analysis, and habitat modeling. The look-up tables method is used for less important rivers where river flows are taken based on rules of thumb. Desktop analysis uses existing river flow data and fish data to estimate e-flow. The functional analysis aims to build a relationship between all aspects of the ecology of the river system and hydrology. Habitat modeling is the most difficult to use as it requires habitat data for specific freshwater species. Tharme (2003) classified all 207 methodologies into four major categories: hydrologic, hydraulic rating, habitat simulation, and holistic approach. There are different categorizations of e-flow assessment methodologies, three of which are shown in Table 2.5.

The classification by Tharme is the most logical and acceptable classification as it is based on the required input data, which may change over time (Tharme, 2003). A detailed description of these methodologies for assessing e-flow requirements is presented in the following sections.

Table 2.5 : Three different classifications of e-flow assessment methodologies

Organization	Categorization of EFA	Sub-category	Example
(Tharme, 2003)		Hydrological index methods	Tennant Method
		Hydraulic rating methods	Wetted Perimeter Method
		Habitat simulation methodologies	IFIM
		Holistic approach	BBM DRIFT Expert Panel Benchmarking Methodology
(Dyson et al., 2003)	Methods	Look-up tables	Hydrological Ecological
		Desk-top analysis	Hydrological Hydraulic Ecological
		Functional analysis	BBM Expert Panel Assessment Method Benchmarking Methodology
		Habitat modeling	PHABSIM
	Approaches		Expert Team Approach Stakeholder Approach
	Frameworks		IFIM, DRIFT
(Brown and King, 2003)	Perspective approaches	Hydrological Index Methods	Tennant Method
		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert Panels	
		Holistic Approaches	BBM
	Interactive approaches		IFIM
			DRIFT

2.4.3 Hydrological Method

The hydrological method is the simplest method of estimating e-flows as it only requires historical streamflow data. To maintain the river's ecological health and fisheries, a portion or percentage of the flow is recommended for e-flow requirements. This method is generally used in the planning stage to get the preliminary idea of the minimum flow. The main goal is to sustain existing river ecology by maintaining a minimum flow, excluding factors such as habitat, water quality, temperature, and food. The most widely used hydrological methods are the Tennant method, the Flow Duration Curve method, the Constant Yield method, and the Range of Variability Approach.

The Tennant Method is the most widely used hydrological method because of its simple procedure. In this study, only the mean annual flow is considered for e-flow. Tennant examined 58 cross-sections of eleven streams in Montana, Nebraska, and Wyoming. He continued his studies for almost ten years and found that aquatic habitat conditions became the same in most streams, which carried the same proportion of flows. The stream width, water velocity, and depth increased when the flow increased from zero to 10%. He assumed that the water velocity and depth were degraded if the flow was less than 10% and 30% of the average flow as the baseflow regime. Tennant provided a guideline based on his experiment, which is shown in Table 2.6. This table classifies habitat quality into seven categories, from flushing to severe degradation, mainly describing the habitat quality for fish and aquatic life.

Table 2.6 : Percentage of MAF for various habitat quality (Tennant Method)

Habitat Quality	Percent of mean annual flow (MAF)	
	Low flow season	High flow season
Flushing or maximum	200	200
Optimum	60-100	60-100
Outstanding	40	60
Excellent	30	50

Good	20	40
Fair	10	30
Poor	10	10
Severe degradation	<10	<10

The flow duration curve method (FDC) is another hydrological method commonly applied worldwide. In this method, a flow duration curve is constructed, which gives the exceedance probability for different flows. It requires daily flow data for at least 20 years, recommending minimum flow for every month. According to this method, different exceedance percentiles have been considered to protect the river's ecology, such as the 90th percentile (equal flow or exceeded 90% of the time) for normal months and the 50th percentile for high flow months. To recommend the minimum flow, different countries have used different percentages. For instance, the 96th percentile has been used as minimum flow in New Zealand and Iowa state set at the 84th percentile (Bari et al., 2006). In Bangladesh, the 90th percentile is taken for the low-flow season, and the 50th percentile is taken for the high-flow season. Although this method requires only stream flow data, it is more accurate than other hydrological methods as it provides flow variability.

The constant yield method, developed in the USA, is suitable for unregulated streams with a catchment area greater than 130 km². In this method, at least 25 years of monthly hydrological data must be available, and 100% of the median monthly flow is taken as the minimum flow requirement. This method ensures a stable flow throughout the year, providing a consistent habitat for aquatic life (Khandaker & Rahman, 2020).

The range of variability approach (RVA) was introduced by Richter in 1996, which evaluates the natural variability of river flows. The RVA method was developed based on the indicators of hydrologic alteration (IHA) framework, which quantifies changes in flow regimes due to anthropogenic influences. Hydrologic alterations have been calculated by comparing two scenarios, pre-

impact and post-impact regimes. There are 32 IHA hydrological parameters, which are divided into five major groups: frequency, timing, duration, magnitude, and changing rate of flows, which are directly related to habitat suitability (Kumar & Jayakumar, 2018). This method can be applied to rivers where human intervention has been made and where pre-impact and post-impact data are available.

2.4.4 Hydraulic Rating Method

The hydraulic rating method estimates e-flows based on the changes in essential hydraulic variables (wetted perimeter and maximum depth), typically measured at single river cross-sections. It is assumed that maintaining an appropriate stream width or wetted perimeter is essential for sustaining river integrity and productivity in aquatic ecosystems (Tharme, 2003). E-flows are determined by plotting hydraulic variables against discharge and identifying the flow value near the curve breakpoint, which is considered optimal flow. The most applied hydraulic methodologies are the wetted perimeter method, R-2 Cross method, and WSP hydraulic simulation method.

2.4.5 Habitat Simulation Method

According to Tharme, the habitat simulation methodologies are the second largest hydrological environmental flow methodology globally. It provides more detailed and modeled analyses using the relationship between habitat and river discharge. These methods have been developed to provide e-flow requirements for target species. For a specific biota, the relationship between flow and habitat has been developed by linking the physical properties of rivers, such as depth, flow velocity, substratum composition, and cover. After developing simulated relationships, they are linked to river flow scenarios using suitability index curves. The traditional computer model called PHABSIM (Physical Habitat Simulation) uses a one-dimensional hydraulic model, which many countries, including France, Norway, and New Zealand, have adopted. The most applied

habitat simulation methodologies are the Usable Width Method, Weighted Usable Width Method, Preferred Area Method, and Instream Flow Incremental Methodology (IFIM).

2.4.6 Holistic Method

According to Tharme, holistic methods have contributed to the e-flow assessment over the last few decades. The researchers struggled to assess e-flows for conserving and sustaining whole river ecosystems rather than just focusing on a particular species. The holistic approach addresses the entire aquatic ecosystem, considering ecosystem components such as geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, invertebrates, and fish. This approach also includes evaluating mitigation measures, such as restoring longitudinal and lateral connectivity, providing fish passes, managing storage river levels, considering disturbance to flow regulation, etc. This method requires integrating vast amounts of data, stakeholder participation, and expert opinion. Still, many countries are using this method to save their ecosystems. Examples of these methods are the Building Block Method (BBM), DRIFT, and Ecotope Method.

2.4.7 Comparison Among Methodologies

Each method mentioned above requires different hydrological data, methodologies for assessing e-flow, ecological assumptions, and impact on river hydraulics. A comparison of these methods has been shown in Table 2.7. Hydrological methods are easy to use, requiring only flow data for at least 20 years and assuming a close relationship between natural flows and existing ecology.

Table 2.7: Selection criteria for different methodologies (Suwal et al., 2020)

Methods	Resolution level	Ecosystem	Time	Cost
Hydrologic	Very low/low	River	Short	Less
Hydraulic	Low	River	Short/ Long	Less/Medium

Habitat Simulation	Medium/ High	River	Medium/Long	Medium/High
Holistic	High	Wetland, Floodplains	Long	High

The hydraulic method assumes that biological productivity is directly related to the wetted area of the river. It requires cross-section and slope data, along with discharge data. The habitat simulation method is more suitable for situations with defined protection levels and transparent management goals. Holistic approaches require extensive data for various river components and provide mitigation measures for wetland protection. Among all these methods, there is no consideration for temperature, water quality, and a detailed understanding of the biological systems. Due to the diversity in river ecology, there is no single best approach to assess environmental flow. Different nations are developing many more methods that consider important aspects of available knowledge.

2.4.8 Environmental Flow Assessment in Bangladesh

In Bangladesh, rivers play a central role in the socio-economic and ecological framework. With a dense network of over 800 rivers, including major transboundary rivers such as the Ganges, Brahmaputra-Jamuna, and Teesta, the sustainability of these water bodies is crucial for maintaining biodiversity, ensuring water availability, and supporting the livelihoods of millions. Here, flood control and irrigation are significant aspects of water resources management, excluding minimum flow considerations.

Rahman (1998) determined low flow requirements for the Ganges River using the flow duration curve, constant yield, and Tennant methods. Zobeyer (2004) determined e-flow requirements for the Surma River using the PHABISM model for *Ghagot*, *Baghair*, and *Bacha* fish species. Bari et al. (2006) estimated minimum flow requirements for four rivers, such as Surma, Kushiya, Teesta, and Gorai, using three different methods, namely the hydrologic method, IFIM, and the Ecotope method. Saha (2007) assessed the instream flow requirements

for the Gorai River based on salinity intrusion and fish habitat considerations. Mullick et al. (2010) conducted a study to assess the e-flow requirements for the Teesta River using the Range of Variability Approach. Akter & Ali, (2012) assessed the instream flow for the Halda River using the Building Block Method. Sayed and Akter (2022) estimated low flow for the Padma River using HEC-RAS for discharge and water surface simulations at different stations. Chowdhury et al. (2024) conducted a study to assess environmental flow requirements for seven hydrological zones of Bangladesh using the Tennant Method.

Bangladesh has no standardized approach or comprehensive research framework for assessing environmental flow (E-flow). While some academic studies have explored E-flow requirements for specific rivers, there is a lack of scientifically validated guidelines considering the country's unique river ecology. Bangladesh also faces challenges in implementing E-flow regulations for effective water resources management.

Several researchers have estimated E-flow for individual or multiple rivers using various assessment methods. However, a broader analysis is needed. This study aims to address this gap by evaluating E-flow demand across four major river basins in Bangladesh using the Flow Duration Curve (FDC) method, providing a preliminary understanding of E-flow requirements at a national scale.

2.5 IRRIGATION WATER DEMAND

Agricultural water demand refers to the water required for agricultural purposes, including irrigation and livestock needs. However, in Bangladesh, the demand for livestock water is negligible compared to the demand for irrigation. Therefore, agricultural water demand is primarily considered as irrigation demand (Barua, et al., 2016). Agriculture plays a crucial role in Bangladesh's economy, contributing 18.6% to the national GDP and employing 45% of the total labor force. Around 85% of the population is directly or indirectly dependent on

agriculture (Islam et al., 2017). Given its significance, irrigated agriculture remains central to the country's agricultural development and food security. According to the Bangladesh Bureau of Statistics (2017), rice is the staple crop, covering 73.7% of the total cultivated land and for 93.4% of the total cereal production. The United Nations (2017) projected that Bangladesh's population will reach 185 million by 2030, requiring an estimated 12.4 million tons of rice to meet food demand (Mojid et al., 2020). As a result, irrigation will continue to play a critical role in food production, emphasizing the need for accurate estimation of irrigation water demand. This literature review will discuss the key parameters of irrigation water demand, various methodologies for estimating irrigation water demand, and the existing study of Bangladesh.

2.5.1 Evapotranspiration

Evaporation is the process by which liquid water transforms into vapor and is removed from surfaces such as lakes, rivers, soil, and vegetation. In contrast, transpiration refers to the vaporization of water from plant tissues, which is then released into the atmosphere. The combined effect of these two processes is known as evapotranspiration (ET). Evaporation from cropped soil depends on the fraction of solar radiation reaching the soil surface, as well as the availability of moisture in the topsoil. Several factors influence evapotranspiration, including weather conditions (solar radiation, air temperature, humidity, and wind speed) and crop-specific characteristics (crop type, variety, and growth stage). When estimating evapotranspiration, these factors must be considered. The evapotranspiration rate is typically expressed in millimeters per unit of time, representing the depth of water lost from a cropped surface due to evaporation and transpiration.

2.5.2 Reference Crop Evapotranspiration (ET_0)

Reference crop evapotranspiration, denoted as ET_0 , represents the evapotranspiration rate from a well-watered reference surface that is not limited

by water availability. The reference surface is defined as a hypothetical grass crop with a height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo of 0.23. It closely resembles an extensive area of green, well-watered grass of uniform height, actively growing and fully shading the ground. The only factors influencing ET_0 are climatic parameters (FAO, 1998).

Table 2.8: Indirect method of estimating reference evapotranspiration (A. Ali et al., 2025)

Model Type	Model Name	Equation	Equation no.
Combination based	Penman	$ET_0 = ((\Delta/(\Delta + \gamma))(R_n - G) + 6.43 (\Delta/(\Delta + \gamma)) (1 + 0.53u_2)(e_s - e_a))/\lambda$	(2.1)
	Penman-Monteith	$ET_0 = (\frac{\Delta(R_n - G) + K_{time} \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma (1 + \frac{r_s}{r_a})})/\lambda$	(2.2)
Temperature based	Blaney and Criddle	$ET_0 = p (0.46 T_{mean} + 8.13)$ $ET_0 = 25.4 (\frac{1.8T_{mean} + 32}{180}) * p$	(2.3)
	Hargreaves and Samani	$ET_0 = [0.0023R_a(T_{mean} + 17.8)((T_{max} - T_{min})^{0.5})]/\lambda$	(2.4)
	Schendel	$ET_0 = 16 \frac{T_{mean}}{RH}$	(2.5)
Mass transfer based	Penman	$ET_0 = 0.376 (e_s - e_a)u_2^{0.76}$	(2.6)
	Modified Penman	$ET_0(2.625 + 0.000479u_2)(e_s - e_a)$	(2.7)
	Meyer	$ET_0 = (3.75 + 0.503u_2)(e_s - e_a)$	(2.8)

There are two primary methods for estimating ET_0 : direct and indirect methods. The direct method involves using a lysimeter, an instrument that isolates soil volume with or without crops to measure actual evapotranspiration. In contrast, indirect methods estimate ET_0 based on meteorological data. Numerous estimation methods exist, as reviewed by (Ali et al., 2025) are summarized in. An Expert Consultation held in May 1990 recommended the FAO Penman-Monteith method as the standard approach for computing reference evapotranspiration. Studies have found that this method performs best in climates with moderate temperature and humidity (Ali et al., 2025).

2.5.3 FAO Penman Montieth Equation

Over the past 50 years, numerous methods have been developed worldwide to estimate ET_0 ; however, only a select few are listed in Table 2.8. Due to the need for a standardized approach, existing methods were evaluated, and a panel of experts recommended the Penman-Monteith equation as the new standard for reference evapotranspiration. The FAO Penman-Monteith can be derived as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + 900\gamma u_2 \left(\frac{e_d - e_a}{T + 273} \right)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2.9)$$

Where,

ET_0 = reference crop evapotranspiration (mm/d)

R_n = the net radiation flux density to the plant canopy ($\text{MJm}^{-2}\text{t}^{-1}$)

G = soil heat flux density ($\text{MJm}^{-2}\text{t}^{-1}$)

Δ = the slope of the saturation vapor pressure curve ($\text{kPa}^\circ\text{C}^{-1}$)

γ = the psychrometric constant ($\text{kPa}^\circ\text{C}^{-1}$)

e_d = the saturation vapor pressure at the dewpoint temperature (kPa)

e_a = the saturation vapour pressure at the current air temperature (kPa)

T = mean daily temperature ($^\circ\text{C}$)

u_2 = daily mean wind speed at 2 m height (m/sec)

2.5.4 Crop Coefficient (K_c)

The crop coefficient (K_c) represents the ratio of crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_0) and serves as a conversion factor to estimate ET_c from ET_0 . It is calculated as:

$$K_c = ET_c / ET_0 \quad (2.10)$$

The K_c value for a crop is determined experimentally and varies throughout its growth stages due to changes in vegetation and ground cover. To develop a crop-coefficient curve, only three key values are needed:

- Initial stage (K_c , ini)

- Midseason stage (K_c , mid)
- Late season stage (K_c , end)

Figure 2.1 represents a crop coefficient curve. Crop evapotranspiration differs from reference evapotranspiration due to variations in ground cover, canopy characteristics, and aerodynamic resistance between crops and the reference grass surface. These factors are integrated into the crop coefficient. Additionally, differences in evapotranspiration and transpiration between field crops and the reference grass surface can be represented using either a single crop coefficient (K_c) or divided into two components: the basal crop coefficient (K_{cb}), which represents transpiration under well-watered conditions and the soil evaporation coefficient (K_e), which accounts for evaporation from the soil surface.

$$K_c = k_{cb} + k_e \quad (2.11)$$

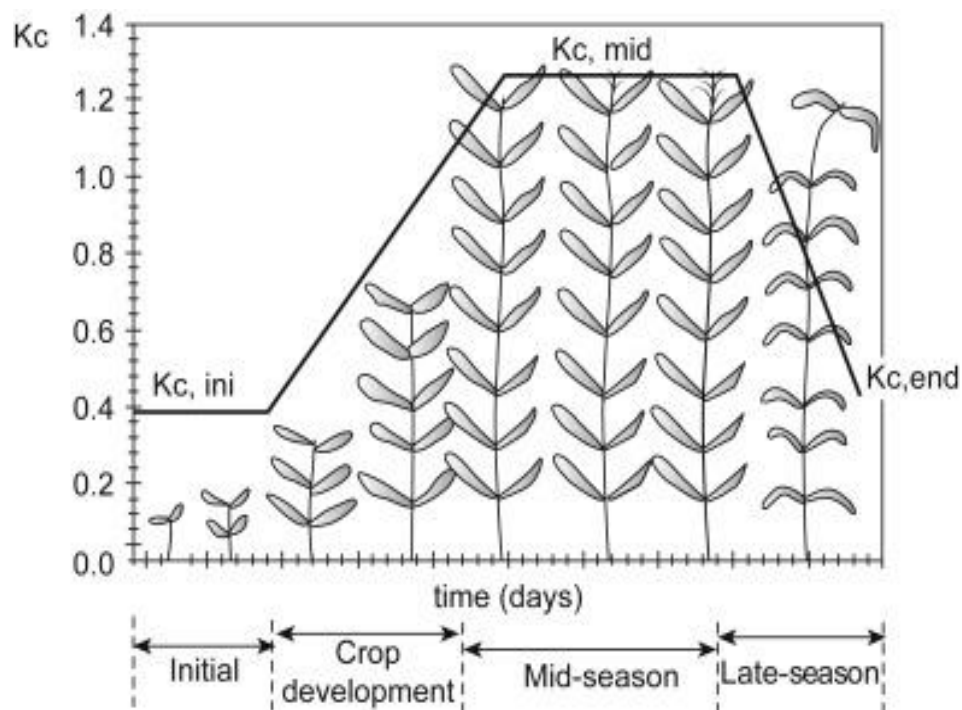


Figure 2.1: Crop coefficient curve (FAO, 1998)

2.5.5 Crop Water Requirements

Crop water requirements refer to the amount of water needed to compensate for losses due to evapotranspiration, ensuring optimal crop growth. These requirements vary based on factors such as climate, crop type, and growth stage (FAO, 1998). The crop water requirement can be determined using the following formula:

$$CWR_i = ET_{c,i} = \sum_{i=1}^m k_{c,i} \times ET_{0,i} \quad (2.12)$$

Where,

$ET_{c,i}$ = the crop water requirement (mm/day) for the i^{th} day,

$k_{c,i}$ = the crop coefficient for the i^{th} day

Irrigation water demand refers to the total amount of water needed to meet crop water requirements along with additional needs such as land preparation and leaching (FAO, 1989). The net irrigation water demand is the amount required specifically during the crop's growing period.

$$NIWR = \sum_{i=1}^m k_{c,i} \times ET_{0,i} + P_i - P_{e,i} + GW_{c,i} \quad (2.13)$$

Where NIWR is the net irrigation water requirement (mm/day), P_i represents percolation loss (mm), GW_c denotes groundwater contribution through capillary rise (mm), and P_e is the effective rainfall, calculated as the total water received minus surface runoff.

The gross irrigation water requirement (GIWR) is the total amount of water needed for a successful crop harvest, accounting for field application efficiency (E_a) and conveyance efficiency (E_c) of the irrigation system.

$$GIWR = \frac{NIWR}{E_a - E_c} \quad (2.14)$$

2.5.6 Methodologies of Irrigation Water Demand

Over the past few decades, irrigation has been the main source of water for agriculture. The crop water requirement (CWR) must be estimated accurately to ensure food security, maximize water efficiency, and minimize environmental effects. Several approaches are used to estimate irrigation water demand, such as empirical methods, analytical approaches, remote sensing-based approaches, simulation modelling approaches, and machine learning approaches (Dixit et al., 2024).

2.5.6.1 Empirical Method

Empirical approaches are statistical relationships between CWR and climatic parameters, which are not universally applicable worldwide, such as the Blaney-Criddle method and Hargreaves-Samani equations.

The Blaney-Criddle method estimates ET_0 based on temperature and sunshine hours from the arid western United States. The equation is as follows:

$$ET_0 = p (0.457 - T_{mean} + 8.128) \quad (2.15)$$

Where p is the mean daily percentage of annual sunshine hours, and T_{mean} is the mean daily temperature.

The Hargreaves and Samani method are considered the traditional method for estimating ET_0 as it considers radiation and temperature. The equation is as follows: where R_a is extraterrestrial radiation, T_c is the temperature, and T_R is the temperature range.

$$ET_0 = 0.0029 R_a (T_c + 20) T_R^{0.4} \quad (2.16)$$

2.5.6.2 Analytical Method

The analytical method applies the physical principles of soil-water balance, energy balance and plant physiology, such as the Penman-Monteith equation which is discussed in the earlier section.

2.5.6.3 Remote Sensing based Method

This method uses satellite data on vegetation indices, soil moisture, temperature, and evapotranspiration to estimate CWR. The rapid advancement of remote sensing technology has accurately calculated crop water requirements (Sun et al., 2024). With this method, the evapotranspiration is estimated from models such as SEBAL (Surface Energy Balance Algorithm for Land). Precipitation data from satellite images is used to estimate effective rainfall.

2.5.6.4 Simulating Model Method

With advancements in technology, equations for estimating crop evapotranspiration and effective rainfall have been integrated into crop growth simulation models such as CROPWAT, AquaCrop, SWAT, and WEAP. AquaCrop, developed by the Food and Agriculture Organization (FAO), combines agronomic principles with detailed soil and climate data to simulate crop growth, predict evapotranspiration rates, and optimize irrigation scheduling. Similarly, CROPWAT, also developed by FAO, utilizes the Penman-Monteith equation to estimate crop water requirements and guide irrigation scheduling based on climate, crop, and soil characteristics (Archana et al., 2024). In this study, CROPWAT is used to estimate irrigation water demand, which will be discussed in the following section.

2.5.6.5 Machine Learning Method

As the volume of climate and agricultural data continues to grow, machine learning has emerged as a promising tool for future food production. Recently, big data technologies and high-performance computing models, such as Artificial Neural Networks (ANN), have advanced the ability to predict crop

yields, soil properties, and various irrigation water quality parameters. These methods are also being utilized to forecast irrigation water demand, helping to manage water resources at national, provincial, and state levels.(Emami et al., 2022).

2.5.7 CROPWAT Software

Developed by the Food and Agriculture Organization (FAO), this software estimates crop water and irrigation requirements. It also provides irrigation scheduling for various management conditions and water supply schemes tailored to different cropping patterns. The FAO 56 Penman-Monteith equation is employed to estimate crop evapotranspiration. The program incorporates four methods for calculating effective rainfall: the USDA Soil Conservation method, fixed percentage, FAO/AGLW method, and the empirical method. Among these, the USDA Soil Conservation method is the most widely used worldwide, as outlined below:

$$P_e = P_{total} \left(\frac{125 - 0.2P_{total}}{125} \right) \text{ for } P_{total} < 250 \text{ mm} \quad (2.17)$$

$$P_e = (125 + 0.1P_{total}) \text{ for } P_{total} > 250 \text{ mm} \quad (2.18)$$

The input of this software includes climate data, rainfall data, soil data, and crop data, which are tabulated in .

Table 2.9.

Table 2.9: CROPWAT data requirement

Name	Required data
Climatic data	Minimum Temperature (°C)
	Maximum Temperature (°C)
	Humidity (%)
	Wind Speed (km/day)
	Sunshine hours (hour)
Rainfall data	Monthly rainfall (mm)
Crop data	Crop planting date (dd/mm)

	Crop stages (initial, development, mid-season, late season)
	(days)
	Rooting depth (m)
	Critical depletion (fraction)
	Crop coefficient (initial, mid, end)
	Crop height (m)
	Total available soil moisture (mm/meter)
	Maximum rain infiltration rate (mm/day)
	Maximum rooting depth (cm)
	Initial soil moisture depletion (%)
Soil data	Initial available soil moisture (mm/meter)

2.5.8 Irrigation Water Demand in Bangladesh

As an agricultural country, the irrigation water requirement assessment is vital for irrigation and water resources management planning. Many researchers in this country have estimated crop water requirements for different crops.

Masum et al. (2014) analyzed the irrigation water requirements for wheat in the Rajshahi district using the FAO Penman-Monteith method from 2002 to 2011. The study found that the highest evapotranspiration occurred in 2004, while the lowest was recorded in 2011. It was also observed that wheat requires more water during the vegetative and mid-season stages.

Rahman et al. (2016) assessed the irrigation water demand for maize under different tillage groups and irrigation schedules. The experiment was carried out during the Rabi season at the Bangladesh Agricultural Research Institute (BARI) in Gazipur. The reference evapotranspiration for maize was estimated using CROPWAT software. It was found that the combination of minimum tillage with two-time irrigation optimized water resources in Bangladesh during the dry season.

Islam et al. (2017) estimated the irrigation water requirements for selected crops (rice, wheat, pepper, sugarcane, and banana) in three major districts (Dinajpur, Rangpur, and Saidpur) in the Northwestern region of Bangladesh using the CROPWAT 8.0 model. The study found that rice had the highest water

requirement, followed by wheat, pepper, and sugarcane. The evaporative demand was highest from April to November.

Hasan et al. (2019) focused on the shift from groundwater to surface water for irrigation, addressing the growing problem of groundwater depletion in northern Bangladesh. Using the Blaney-Criddle formula, the study estimated the seasonal consumptive use requirement (mm) for rice grown in Natore, Rajshahi. The results showed that irrigation was not needed between June and September due to high rainfall, and harvesting rainwater using ponds could contribute up to 5% of the consumptive use.

Sen et al. (2019) estimated the actual crop water requirements and supplemental irrigation needs for the high-yielding Aman rice variety BR11 in the Rajshahi and Rangpur districts of northern Bangladesh. The study utilized the FAO Penman-Monteith method to estimate reference crop evapotranspiration at different growth stages, with the analysis covering a period of 20 years.

Mojid et al. (2020) analyzed the irrigation water requirements for eight major crops (Aus, Aman, Boro, vegetables, mustard, sugarcane, wheat, and potato) and six cropping patterns in the Bogra and Rajshahi districts from 1985 to 2013. Using the CROPWAT model, the study found that crop water requirements generally decreased, except during a few months, and that water requirements increased as rainfall increased.

Haque & Chowdhury (2020) analyzed the trends in irrigation water requirements in the Halda River basin over a 27-year period. In this study, reference crop evapotranspiration was estimated using the FAO Penman-Monteith method, and net irrigation water demand was calculated for Boro rice, mustard, and maize. The analysis, conducted using the Mann-Kendall method, revealed an increasing trend in net irrigation water demand.

Amin et al. (2021) estimated the irrigation requirements and schedules for rice in four southeastern districts (Comilla, Brahman Baria, Chandpur, and Feni) by integrating 30 years of climate and rainfall data into the CROPWAT 8.0 model. The study found that Boro rice required more irrigation than any other variety of rice.

Prattoyee et al. (2021) estimated the irrigation water demand and scheduling for Boro rice grown in Rajshahi using the CROPWAT 8.0 and CLIMWAT 2.0 models. The study found that the net irrigation water demand for Boro rice showed an increasing trend, influenced by factors such as wind speed, humidity, rainfall, and evapotranspiration.

Akter et al. (2023) estimated the irrigation water demand for chickpeas in the Gazipur and Rajshahi districts using soil-moisture balance models. This three-year study (2015-2018) found that chickpeas required 92-98% less water than rice, making them a viable alternative for cultivation in water-scarce areas.

The existing literature on agricultural water demand in Bangladesh offers valuable insights into crop-specific water requirements; however, most studies focus on specific crops or regions, resulting in gaps in comprehensive analysis across all districts. Additionally, many studies have primarily concentrated on staple crops like rice, wheat, and sugarcane, with limited attention given to a wider range of crops. To address these gaps, this study will provide valuable information by estimating monthly irrigation water demand for 35 crops, integrating 11 years (2010-2021) of climate and precipitation data into the CROPWAT model for all districts of Bangladesh.

2.6 SURFACE RUNOFF

The hydrologic cycle is a vital system comprising several key components, including evaporation, transpiration, infiltration, percolation, groundwater recharge, and precipitation. Surface runoff is the result of rainfall. While the

hydrological cycle may seem straightforward, its processes are intricate and dynamic. Water evaporates from oceans, and trees release water vapor through transpiration, creating clouds through atmospheric circulation. This water returns to the land as precipitation, which is intercepted by vegetation and trees, leading to runoff across the land surface. Surface runoff is the portion of rainfall that flows over the land surface and drains from a catchment area.

A watershed refers to the area of land where all water flows into a specific stream at a designated location. Within this system, rainfall serves as the input, and runoff is the output, which is measured at the watershed's outlet (Satheeshkumar et al., 2017).

In Bangladesh, surface runoff is the primary source of water, making accurate runoff estimation essential for managing water supplies, rainwater harvesting, reservoirs, and flood forecasting. Various factors influence runoff, including rainfall intensity, duration, soil type, land use, land cover, topography, and drainage characteristics.

There are three primary methods for estimating surface runoff: the empirical method, the conceptual model (e.g., the NAM Model), and the physically based model (e.g., the HEC-HMS Model). This review examines these methods, their applications, limitations, and relevance to Bangladesh's unique hydrological conditions.

2.6.1 Empirical Method

Empirical methods for estimating surface runoff rely on existing hydrological data and are tailored to specific regions. Researchers have developed these rainfall-runoff relationships through extensive field measurements and statistical analysis, making them practical for areas where detailed hydrological data is limited. These formulas establish a direct link between rainfall and runoff, often incorporating additional parameters to account for climatic conditions and catchment characteristics (Kanji, 2024). Some

of the key empirical formulas used in different regions of Bangladesh are discussed below.

2.6.1.1 Rational Method

The Rational Formula is a widely used empirical method for estimating stormwater runoff in relatively simple watersheds with areas not exceeding 30 acres (Helles & Mogheir, 2023). Originally developed by Emil Kuichling, it was first applied in 1889. This method is commonly utilized to estimate the peak runoff in small catchments and to determine the design flood for various hydraulic structures (Sabzevari et al., 2024). It is regarded as a conceptual model that simplifies catchment behaviour by simulating the conversion of rainfall into runoff (PJ, 2018). The following equation determines the maximum runoff:

$$Q = CIA \quad (2.19)$$

In this equation, **Q** represents the peak runoff (m³/day), **I** denote the rainfall intensity (m/day), **C** is the runoff coefficient, and **A** refers to the catchment area (m²). However, the Rational Formula is based on certain assumptions and has several limitations, as outlined by Helles & Mogheir (2023):

1. The rainfall intensity and rate are assumed to be uniform and evenly distributed across the entire watershed for the duration of the rainfall event.
2. The runoff coefficient (**C**) is considered constant throughout the entire rainfall period.
3. All surface runoff is assumed to reach the designated outlet point, disregarding any flow diversion in different directions.
4. The peak runoff occurs when the entire watershed contributes to the flow simultaneously.
5. The method does not account for initial losses due to infiltration, percolation, or seepage.

6. The time of concentration is regarded as a critical factor in determining rainfall intensity in this approach.

The runoff coefficient is a crucial parameter in the Rational Formula, representing the dimensionless ratio of rainfall that converts into runoff. Its value is influenced by factors such as land use and land cover, soil type, rainfall intensity, rainfall duration, and vegetation cover. The runoff coefficient is expressed as:

$$C=R/P \quad (2.20)$$

Where:

C = Runoff coefficient

R = Runoff depth (m)

P = Precipitation (m)

The runoff depth is determined by dividing the runoff volume by the catchment area. In watersheds with diverse land-use types, the weighted average runoff coefficient is used to represent the overall runoff behaviour of the area.

$$C_w = \frac{\sum(C_i \times A_i)}{\sum(A_i)} \quad (2.21)$$

Where,

C_w = weighted average runoff coefficient

C_i = Runoff coefficient of land use i

A_i = Area of land use i.

Rainfall intensity (I) refers to the rate at which rain falls over a specific area within a given period, typically expressed in mm/h or inches/h. It is influenced by the return period, meaning that for a given rainfall event, a more extended return period corresponds to a higher rainfall intensity. Additionally, as the duration of rainfall increases, the average rainfall intensity decreases. The relationship between rainfall duration, intensity, and return period is represented by a set of curves known as Intensity-Duration-Frequency (IDF)

curves. According to the TxDOT Hydraulic Design Guidelines, an empirical formula for IDF curves is given as:

$$i = \frac{b}{(t_c + d)^e} \quad (2.22)$$

Where,

i = design rainfall intensity (in/h)

t_c = time of concentration (min)

b, d, e = regional parameters.

The time of concentration (t_c) refers to the duration required for water from the most distant point in a watershed to reach its outlet. It is influenced by factors such as watershed size and shape, slope, surface roughness, land use, and rainfall intensity. If the selected storm duration exceeds the time of concentration, rainfall intensity decreases, resulting in a lower peak discharge than the optimal value when using the rational method. Conversely, if the storm duration is shorter than t_c , not all areas of the catchment will contribute to runoff. Therefore, the rainfall duration is typically set equal to the time of concentration (Thompson, 2006).

2.6.1.2 SCS-CN Method

Developed by the Soil Conservation Service (SCS) of the USA in 1969, the SCS-CN method is a simple, reliable, and widely used approach for estimating direct runoff. Its popularity stems from its simplicity, flexibility, and reliance on a single parameter—the curve number (CN). The method is based on the water balance equation, which states that total rainfall is the sum of direct surface runoff, cumulative infiltration, and initial abstraction (Muthu & Santhi, 2015). The equation for surface runoff is given by:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad (2.22)$$

Where,

Q = Accumulated runoff or rainfall excess (mm)

P = Rainfall depth (mm)

I_a = Initial abstraction (mm)

S = Potential maximum retention (mm)

Parameter S is influenced by the soil-vegetation-land use characteristics of the catchment, as well as the antecedent soil moisture conditions immediately preceding the rainfall event. To simplify its application, the SCS expresses S in terms of a dimensionless parameter known as the curve number (CN) as:

$$S = \frac{25400}{CN} - 254 \quad (2.23)$$

The Curve Number (CN) can be obtained from the SCS Hydrology Handbook (NEH-4), Section 4. It is influenced by factors such as soil type, land use, land cover, and antecedent soil moisture conditions. According to the SCS classification, soils are categorized into four hydrological soil groups.

2.6.2 Physical-Based Model

The HEC-HMS model, a physically based hydrological model, is used to simulate rainfall-runoff by incorporating the physical characteristics of a catchment. The choice of modelling method within HEC-HMS depends on the desired output and the availability of data. Researchers have explored the most suitable applications of this model under different conditions (Sahu et al., 2020). It includes various equations for assessing losses, runoff, routing, and rainfall-runoff simulations (Modi et al., 2017). Ranjan & Singh (2022) applied the HEC-HMS model and ArcGIS to estimate runoff for the Punpun River basin. Additionally, the HEC-HMS model can be used for streamflow forecasting, with calibration possible using hourly data and the model's built-in auto-calibration techniques.

2.6.3 Irrigation Water Demand in Bangladesh

Bangladesh has a subtropical monsoon climate with distinct seasonal variations. Around 80% of the total annual rainfall occurs during the monsoon season, while the dry season sees little to no rainfall. Numerous researchers have estimated the runoff in different basins across the country using various methods, which are discussed further.

Sifa et al. (2024) estimated runoff in northeastern Bangladesh (Sylhet, Sunamganj, Habiganj, and Maulvi Bazar) using the GIS-based Soil Conservation Service Curve Number (SCS-CN) method. Analyzing precipitation data from 2009 to 2018, they observed a linear relationship between average rainfall and simulated runoff.

Mitu et al. (2019) developed a rainfall-runoff model for northeastern Bangladesh using the Soil and Water Assessment Tool (SWAT), calibrated with the SWAT_CUP SUFI-2 algorithm. The model was utilized to estimate runoff and predict future flood events.

Nur et al. (2022) developed a calibrated model using HEC-HMS and ArcGIS to generate runoff from ungauged rainfall data for the Khowai River Basin in Bangladesh. Rainfall data from 2000 to 2005 were sourced from APHRODITE's website. The study identified the time of concentration and storage coefficient as key parameters influencing the simulated runoff.

Munna et al. (2024) estimated runoff for the Sylhet city canal systems using the EPA Stormwater Management Model (SWMM) with meteorological data from 1975 to 2019. The generated model can evaluate the performance of drainage systems and assess the effectiveness of existing canal drainage infrastructure.

Aziz et al. (2023) estimated surface runoff for the Padma River basin using the SCS-CN method in GIS. Analyzing daily runoff data from 2010 to 2020, they

found that the average annual runoff was 409.67 mm, with a mean monthly runoff of 34 mm.

Aziz et al. (2023) estimated runoff for the Dakatia River Basin in Bangladesh using the SCS-CN method. Using satellite-based rainfall data from 2010 to 2020, the study determined that the average annual runoff for the basin was 579 mm.

Roy et al. (2021) developed a runoff model for the Surma River Basin using hydrological and meteorological data from 1996 to 2012. A regression model was created in Microsoft Excel Solver, incorporating eleven hydrological and meteorological parameters. The study found that the basin is particularly sensitive to three key factors: rainfall, sunshine hours, and vapor pressure.

The existing literature on runoff estimation for Bangladesh has assessed runoff for various river basins and specific regions using different models, including SWAT, HEC-HMS, SWMM, and the SCS-CN method. However, a nationwide runoff assessment remains unexplored. Moreover, these studies have employed complex hydrological models, which limit their applicability for broader assessments. To address the gap, this study aims to assess runoff for the entire country using the rational method, based on 10 years' average precipitation data. The rational method was selected because it is relatively simple to apply and suitable for large-scale analysis, providing a general estimate of surface runoff.

2.7 GROUNDWATER RECHARGE

Groundwater recharge refers to the process through which water from the Earth's surface infiltrates down into underground aquifers. This recharge typically occurs when rainfall, surface water, or other water sources seep through various soil layers to reach the aquifer (Olabiya et al., 2024). The process is influenced not only by natural factors such as climate change but also by human

activities, particularly groundwater extraction (Shamsudduha et al., 2011). Recharge can occur naturally through interception and percolation, or it can be enhanced artificially using methods such as recharge basins, infiltration basins, and rainwater harvesting systems.

2.7.1 Importance of Groundwater Recharge

Groundwater makes up nearly 99% of the Earth's total freshwater resources. With the global population steadily increasing, the demand for freshwater is rising accordingly. Currently, over two billion people worldwide rely on groundwater as their primary source of freshwater (Mahmud et al., 2023). Groundwater supports not only domestic needs but also plays a vital role in the agricultural and industrial sectors. In many countries, approximately 50% of groundwater is used for agriculture, while around 20% is allocated for domestic purposes. As a result, overexploitation of groundwater resources is becoming increasingly common to meet growing demands (Meherin, 2024).

Groundwater recharge mechanisms are essential for replenishing aquifer levels and ensuring efficient water supply, particularly in regions facing water scarcity (Olabiyi et al., 2024). Recharge not only supports long-term water sustainability but also helps maintain healthy aquatic ecosystems. During dry periods, groundwater contributes baseflow to rivers and ponds, sustaining surface water bodies and supporting biodiversity by providing critical habitats for aquatic life. Moreover, groundwater recharge plays a key role in mitigating natural disasters such as droughts by storing excess water during wet seasons for use during dry periods. Recharge zones also function as natural filters, removing pollutants from surface water before it enters the aquifer, thereby improving groundwater quality (Olabiyi et al., 2024). Therefore, groundwater recharge is fundamental to the sustainable development and management of water resources, offering ecological, social, and environmental benefits.

2.7.2 Types of Groundwater Recharge

Groundwater recharge has been classified in various ways by different researchers. Based on the sources of recharge, it is categorized into three types: direct recharge, indirect recharge, and localized recharge (Meherin, 2024). When classified according to the quantity of recharge, three types are identified: net groundwater recharge, potential recharge, and rejected recharge (Shamsudduha et al., 2011). Additionally, based on the recharge mechanisms, groundwater recharge is broadly divided into two main types: natural recharge and artificial recharge (Olabiyi et al., 2024). The definitions and explanations of these types of groundwater recharge are provided in Table 2.10.

Table 2.10: Groundwater Recharge classification definition

Groundwater recharge types	Definition
Direct recharge	Water from precipitation or irrigation directly infiltrates the soil and percolates down to the underground aquifer
Indirect recharge	Surface water contributes to groundwater recharge by percolating into the subsurface through riverbeds, stream channels, or other surface pathways.
Localized recharge	Recharge occurs in specific low-lying areas, such as depressions or ponds, where water accumulates and infiltrates into the ground.
Net or actual recharge	The actual volume of water that infiltrates into the subsurface and contributes to a measurable rise in groundwater levels.
Potential recharge	The total amount of water that could potentially infiltrate into the aquifer under ideal conditions, assuming no limiting factors.
Rejected recharge	The portion of water that is available for recharge but cannot infiltrate due to the saturation of soil or aquifer layers.
Natural recharge	Groundwater recharge occurs through natural processes such as rainfall infiltration, river seepage, and soil moisture percolation.
Artificial recharge	Groundwater recharge is enhanced through various human activities, including methods such as recharge basins, check dams, retention ponds, and infiltration wells.

2.7.3 Mechanisms of Groundwater Recharge

Before estimating groundwater recharge for any specific location, it is crucial to understand the underlying recharge mechanisms relevant to that area (Mahmud et al., 2023). The primary processes contributing to groundwater recharge include infiltration, percolation, surface water interaction, and direct recharge events such as flooding and snowmelt (Olabiyi et al., 2024). Following rainfall or irrigation, a portion of the water is absorbed to fulfill the soil moisture deficit and is subsequently lost to the atmosphere through evapotranspiration. The remaining water percolates downward through the soil profile, eventually reaching the aquifer and contributing to recharge.

However, not all infiltrated water reaches the water table. Some water may become trapped within impermeable or semi-permeable layers that have low hydraulic conductivity. In such cases, the trapped water may move laterally toward surface depressions or ponds, where it can evaporate without contributing to the aquifer (Meherin, 2024).

Precipitation levels also significantly influence groundwater recharge. In humid regions, where annual rainfall exceeds potential evapotranspiration, consistent recharge is typical. In contrast, arid and semi-arid regions experience limited recharge, as rainfall is typically lower than potential evapotranspiration (Mahmud et al., 2023). Additionally, surface water bodies, such as rivers, can recharge adjacent aquifers through permeable riverbanks, surrounding soils, and porous rock formations. These interconnected mechanisms collectively play a crucial role in maintaining groundwater levels and ensuring the long-term sustainability of this vital resource.

2.7.4 Factors Affecting Groundwater Recharge

Groundwater recharge is influenced by a range of factors, each of which can independently or collectively impact the recharge process. These factors include climate change, land use and land cover, vegetation, topography, soil texture and structure, soil moisture, and the properties of underlying geological materials. Consistent rainfall supports steady groundwater recharge, whereas rising temperatures can increase evaporation rates, thereby reducing the amount of surface water available for infiltration. Urban development further exacerbates this issue by introducing impervious surfaces such as roads and buildings, which limit infiltration and significantly reduce recharge potential. Additionally, soil textural characteristics such as porosity and pore size distribution affect the soil's water-holding capacity, which in turn influences the rate and extent of groundwater recharge.

2.7.5 Groundwater Recharge Estimation Method

Groundwater recharge estimation techniques are classified into various types based on hydrological sources and methodologies used by different researchers. These methods can be broadly categorized into two main approaches: direct and indirect. The direct method involves physical procedures, such as lysimeters, and chemical procedures, including the chemical mass balance (CMB) approach. Different types of these methods are discussed in this section. Numerous methods are employed to achieve the best result, as a single approach can be ineffective. The uncertainties in each method lead to an increase in the application of multiple approaches, which makes the recharge more reliable. The selection of the estimation method relies not only on data availability (topography, vegetation, soil type, and hydrology) but also on the sources and mechanisms. However, the availability of data is the prime factor here (Kanoua & Merkel, 2015).

2.7.5.1 *Lysimeter Method*

It is a widely used direct method for estimating groundwater recharge, in which all physical water balance components—such as rainfall, evapotranspiration, soil moisture change, and irrigation—are measured (Ali & Mubarak, 2017). The method involves filling containers with different types of soil, with or without vegetation, to simulate natural conditions. Recharge is then estimated using the following equation:

$$P + I + SM_i = ET + R + SM_f \quad (2.24)$$

Here,

P = precipitation

I = Irrigation

SM_i = initial soil moisture

SM_f = final soil moisture

R = recharge

This method is not ideal for capturing spatial variability and may produce results that differ from actual conditions. Additionally, it is expensive, challenging to set up, and requires high maintenance. Water may also seep through the sidewalls, which can reduce the overall efficiency and accuracy of the method (Meherin, 2024).

2.7.5.2 *Water Balance Method*

It follows a residual approach to the water balance equation, considering changes in soil water storage across the entire unsaturated zone. It accounts not only for variations in soil moisture but also includes the runoff component. (Mahmud et al., 2023). The following equation is used to estimate recharge:

$$R = P - ET_a - R \pm \Delta S \quad (2.25)$$

Here, R represents recharge (mm), P is precipitation (mm), ET refers to actual evapotranspiration, and S denotes the change in soil moisture. Since soil

moisture change is not typically included in the water balance method, it can be omitted, and the recharge can be expressed as:

$$R = P - ET_a - R \quad (2.26)$$

The accuracy of this method largely depends on the precise measurement of other components involved in the equation, such as runoff and actual evapotranspiration. It is considered reliable in humid regions, where precipitation exceeds evapotranspiration, providing sufficient water for percolation into aquifers. However, in arid and semi-arid regions, where precipitation is significantly lower than evapotranspiration, special precautions must be taken, as limited water availability reduces the potential of recharge. In such cases, careful measurement and adaptation are essential. Hendrickx (1992) proposed four key guidelines for modifying the water balance method in these environments:

1. The method should be applied over short time intervals, such as 10 days, 15 days, or one month.
2. Real-time values of rainfall and evapotranspiration should be used instead of long-term averages.
3. A long-term dataset is essential to account for significant climatic variability.
4. The outcome should not be a single annual recharge rate; instead, it should indicate a range of potential recharge values for the area.

2.7.5.3 Water Table Fluctuation Method

The Water Table Fluctuation (WTF) method is one of the most widely used techniques due to its simplicity and suitability for validating or comparing with other methods and simulation models. Although it is an indirect approach, fluctuations in the groundwater table directly reflect recharge events. The method is based on the principle that infiltrating water causes a measurable rise

in the water table (Ali & Mubarak, 2017). This technique has been in use since the 1920s. Recharge is calculated using the following equation:

$$R = S_y \frac{dh}{dt} \quad (2.27)$$

Where R is the recharge (m/day), S_y represents the specific yield of the soil, dh is the change in water table elevation (m), and dt is the time interval (days). Specific yield is defined as the volume of water released from an unconfined aquifer by gravity drainage per unit area per unit decline in the water table. Estimating this value typically requires a pumping test (Mahmud et al., 2023).

This method is influenced by several factors, including inflow and outflow to or from the aquifer, aquifer type, specific yield, and the areal extent of the aquifer. It is only applicable to unconfined aquifers due to the immediate response of the water level to recharge and the direct relationship between the water table fluctuations and the volume of recharge.

2.7.5.4 Empirical Method

The precipitation cannot fully percolate into the groundwater aquifer because of evaporation, transpiration, and surface runoff. The empirical formula was developed for different location based on their weather pattern and the soil characteristics. Following are the empirical formula developed for humid tropical climate such as India, presented in Table 2.11.

Table 2.11: Summary of empirical methods to assess groundwater recharge

Formula name	Equation	Remarks	Reference	Equation no
Chaturvedi	$R_e = 2.0 (P - 15)^{0.4}$	P (inch)	(R. S. Chaturvedi, 1973)	(2.28)
Modified Chaturvedi	$R_e = 1.35 (P - 14)^{0.5}$	P (inch)	(C. P. Kumar & Seethapathi, 2002)	(2.29)

Sehgal	$R_e = 2.5 (P - 0.6)^{0.5}$	P (inch)	(M. H. Ali & Mubarak, 2017)	(2.30)
Krishna	$R_e = 0.25 (P - 400)$	600<P<1000 P (mm)	(Krishna Rao, 1970)	(2.31)
Kirchner	$R_e = 0.12 (P - 20)$	P (mm)	(Kirchner et al., 1991)	(2.32)
Bredenkamp	$R_e = 0.32 (MAP - 360)$	P(mm), MAP	(Bredenkamp et al., 1995)	(2.33)
Bhattacharjee	$R_e = 3.47(P - 38)^{0.5}$	P (cm)	(Praveen & Krishnaiah, 2017)	(2.34)
Kumar	$R_e = 0.63 (P - 15.28)^{0.76}$	P (inch)	(C. P. Kumar & Seethapathi, 2002)	(2.35)
Maxey-Eakin	$R_e = P * a$	P (mm), a = 20%	(Maxey & Eakin, 1949)	(2.36)

2.7.6 Groundwater Recharge Estimation in Bangladesh

Since the 1970s, researchers in Bangladesh have been working to estimate groundwater recharge in shallow aquifers using various approaches and datasets. The first estimation of potential groundwater recharge was conducted by the International Bank for Reconstruction and Development (IBRD), based on the difference between effective rainfall and evapotranspiration. In 1982, the United Nations Development Program (UNDP) carried out a more detailed study, estimating potential recharge from excess precipitation after accounting for surface runoff and potential evapotranspiration. Subsequently, in 1983, the Bangladesh Water Development Board (BWDB), in collaboration with the UNDP, provided a more refined estimate of potential recharge for the northwestern and north-central regions of Bangladesh, excluding rejected recharge (Shamsudduha et al., 2011).

Ali et al. (2019) estimated annual groundwater recharge in the Ishwardi district of Bangladesh using both the Tracer Method and the Water Balance Method. The study covered the years 2017 and 2018, comparing the outcomes of the two methods to evaluate their reliability. The findings indicated that the modified Water Balance Method produced more accurate and reliable results for the study area.

Kanoua & Merkel, (2015) assessed groundwater recharge in Titas Upazila of Bangladesh using the Water Table Fluctuation (WTF) method and the Water Balance Method. Recharge was estimated separately for monsoon and non-monsoon seasons using long-term monthly average climatic data. The results showed that the Water Balance Method estimated recharge as 984 mm/a, 459 mm/a, and 396 mm/a for different conditions, while the WTF method yielded a significantly lower estimate of 230 mm/a. The study emphasized the need for extra caution when estimating recharge during the wet season.

Islam et al. (2023) analyzed trends in maximum and minimum groundwater depths for four locations in the Pabna and Rangpur districts, using rainfall and groundwater level data from 1989 to 2017. The study identified years of both positive and negative recharge and observed a linear relationship between rainfall and groundwater recharge in both regions.

Rushton et al. (2020) estimated potential groundwater recharge using a daily soil water balance approach, based on over two years of monitoring groundwater levels, rainfall, temperature, and irrigation pumping hours.

Islam & Imran (2019) identified potential natural groundwater recharge zones in Dhaka city, Bangladesh, using satellite imagery, GIS techniques, and factors such as topography, soil type, slope, land use/land cover, drainage density, and clay layer thickness. The results showed that only 0.94% of the area was classified as 'Very Good' and 26.87% as 'Good', indicating that a combined 27.81% of the study area is suitable for groundwater recharge.

Adhikary (2014) estimated groundwater recharge for Kushtia district, Bangladesh, using a modified version of the Water Table Fluctuation (WTF) method, suitable for areas with limited data availability. This approach required only monthly rainfall and weekly groundwater level data. The study found that the annual recharge for Kushtia Upazila from 1992 to 2007 was 1,413 mm.

Ali et al. (2022) estimated groundwater recharge at two locations in Rajshahi district—Nachol and Niamatpur—using the tracer technique, the Water Table Fluctuation (WTF) method, and the Water Balance method. Their results indicated that the tracer technique was the most reliable for this study area, with recharge estimates ranging from 125.1 mm to 210 mm across the different methods.

Tithi & Bari (2024) estimated groundwater recharge in Godagari, northern Bangladesh, for the period 1991 to 2022 by developing a model using the Soil and Water Assessment Tool (SWAT). The simulated model demonstrated satisfactory performance, with recharge estimates ranging from 83.89 mm to 194.78 mm.

Joy et al., (2024) delineated potential groundwater recharge zones in the Bogra district using remote sensing data, the ArcGIS platform, and the Analytical Hierarchy Process (AHP). The results indicated that 89.62% of the study area falls within zones of good groundwater recharge potential.

Jahan et al. (2015) analyzed groundwater recharge trends in the northwestern region of Bangladesh, highlighting the rate of decline over successive 12-year periods. The study found a general decreasing trend in recharge rates, though the extent of decline varied across different locations. It specifically focused on shallow and unconfined aquifers.

Pial & Khan (2022) analyzed groundwater potential zones in Bishwamvarpur Upazila, Bangladesh, using remote sensing data, ArcGIS, and

the integration of the Analytical Hierarchy Process (AHP). The study identified three potential zones: 10.7% as good, 79.6% as moderate, and 9.6% as poor.

Adham et al. (2010) analyzed the potential for groundwater recharge in the Barind Tract (Rajshahi district) of Bangladesh using geographic information systems (GIS) and remote sensing techniques. The results indicated that only 8.6% of the precipitation could percolate into the groundwater aquifer.

Over the decades, researchers in Bangladesh have employed various methods to estimate groundwater recharge, including the water balance method, water table fluctuation method, tracer techniques, GIS-AHP, and SWAT models. However, most of these studies have been limited to specific locations or regions, with a noticeable gap in national-scale assessments. Additionally, only a few have utilized long-term datasets or analyzed seasonal variations in groundwater recharge. Addressing these limitations, the present study employs the water balance method, utilizing ten years of climate data to estimate groundwater recharge nationwide, providing valuable insights into regional and seasonal patterns.

2.8 TRANSBOUNDARY FLOW

Transboundary flow refers to the movement of water across political boundaries, primarily between nations that share common river basins. Bangladesh, bordered by India on three sides and Myanmar on the fourth, shares several rivers with its neighbouring countries. According to the Ministry of Water Resources, Bangladesh is interlaced by 230 rivers, 57 of which are transboundary. Of these, 54 rivers are shared with India, while the remaining three are shared with Myanmar.

In addition to surface water, transboundary flows also influence groundwater resources. Since Bangladesh shares river basins with its

neighbouring countries, it is also likely to share transboundary aquifers, further emphasizing the importance of cooperative water management across borders.

2.8.1 Importance of Transboundary River Flow in Bangladesh

Rivers in Bangladesh are vital sources of freshwater and provide essential ecosystem services. They offer a wide range of benefits, including supporting livelihoods, agriculture, biodiversity, and overall environmental balance. When managed effectively, rivers can become instruments for regional cooperation by enabling neighbouring countries to share their benefits.

Bangladesh, situated downstream of the Ganges-Brahmaputra-Meghna (GBM) river system, receives substantial surface water flows generated upstream. However, these flows significantly decline during the dry season, leading to acute water shortages.

Transboundary rivers contribute approximately 1,010 billion cubic meters of water annually, forming the largest share of Bangladesh's water resources (Ahmed, 2013). These flows are crucial for meeting growing irrigation, domestic use, and environmental sustainability demands.

Therefore, understanding and managing transboundary flows is essential. A cooperative approach between upstream and downstream countries sharing the same river basins can lead to mutual benefits and sustainable water resource management.

2.8.2 Transboundary Flow Estimation Method

Estimating transboundary flow is a complex process that involves accounting for multiple hydrological components, including surface water inflow from upstream regions, runoff generated within the basin, subsurface flows, and groundwater base flow. Various methods exist to estimate transboundary flow, ranging from direct measurement techniques to advanced modelling approaches. Remote sensing and Geographic Information Systems

(GIS) offer effective tools for estimating transboundary flow across river systems by integrating spatial and hydrological data.

One of the most straightforward approaches is to estimate river discharge at the point where the river enters from a neighbouring country. However, establishing and maintaining discharge monitoring stations on all transboundary rivers is often challenging, particularly for developing countries like Bangladesh, due to the high costs and technical requirements associated with such infrastructure.

2.8.3 Challenges in Using Discharge Data for Flow Estimation

While using discharge data offers certain advantages, obtaining such data from the precise point of river entry into the country is often challenging, leading to data inconsistencies. The Bangladesh Water Development Board (BWDB) provides discharge data for primary and significant rivers; however, data for smaller tributaries are generally unavailable, as these are not routinely monitored.

Another challenge lies in the limited data-sharing practices among countries that share river basins. This lack of cooperation contributes to discrepancies and complications in accurately estimating water flow and availability. Establishing effective transboundary data-sharing mechanisms is essential to addressing these issues. Enhanced collaboration would benefit all involved nations by promoting more accurate assessments and sustainable water resource management.

2.9 SUMMARY

This literature review examined existing research on water demand and supply estimation, focusing on key components such as irrigation, domestic, industrial, and environmental flow (E-flow) requirements for water demand and transboundary flow, surface runoff, and groundwater recharge for water supply.

Various methods for estimating these components were explored, from traditional techniques to more modern approaches.

Research specific to Bangladesh has shown some progress at the district and regional levels in estimating water resources, yet challenges persist in accurately measuring seasonal and spatial variations. This review emphasizes the need for national-scale studies to assess water demand and available water resources spatially and temporally, providing valuable insights for water balance studies and sustainable water resource management.

Additionally, several gaps in the literature were identified, including limited research on industrial water demand, crop-specific irrigation water demand, and water balancing on a national scale within Bangladesh's hydrological context. These gaps form the basis for the current study, which aims to develop a framework for storage capacity estimation and water conservation planning by considering all water demand and supply components.

Chapter 3: METHODOLOGY

3.1 STUDY AREA

Bangladesh, located in South Asia, is positioned between 20°30' and 26°40' north latitude and 88°03' and 92°40' east longitude. The country encompasses approximately 147,570 square kilometers and features one of the world's largest and most active delta systems. It shares its borders with India to the east, west, and north, while Myanmar lies to the southeast, and the Bay of Bengal forms its southern boundary. The terrain is predominantly flat, with hilly regions concentrated in the southeastern and northeastern areas. The country experiences a subtropical monsoon climate characterized by four distinct seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and Dry season (December-February).

According to the Food and Agriculture Organization (FAO) Aquastat Report 2011, the average annual rainfall is 2320 mm, about 80% of which happens during the monsoon season. Monsoon-induced flooding affects 20% to 25% of the country's total area, contributing positively to agriculture, ecology, and the environment. However, excessive flooding beyond this threshold results in significant direct and indirect damage, causing economic losses and disruptions to local communities.

The river system is primarily composed of the Ganges, Brahmaputra, and Meghna rivers, along with their tributaries and distributaries (Figure 3.1). According to the Bangladesh Water Development Board (BWDB), the country has 405 rivers, of which 57 are transboundary, three of which originate from Myanmar. Bangladesh is mainly divided into four major river basins: the Ganges, the Brahmaputra, the Meghna, and the Southeast Hill basin (Figure 3.2). The

basin fraction for each district has been estimated using the ArcGIS georeferencing tool. The basin fraction for each basin is shown below.

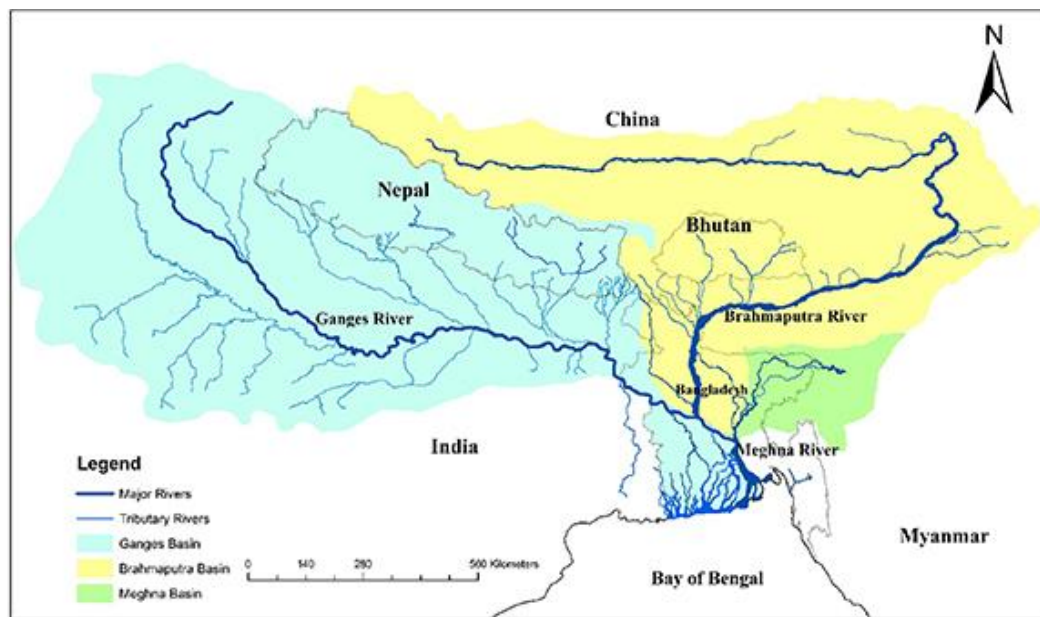


Figure 3.1: Ganges, Brahmaputra and Meghna River basin (Alamgir et. al., 2024)

3.1.1 The Ganges Basin

The Ganges River originates in the Himalayan Mountains and enters Bangladesh approximately 50 km downstream of Farakka. Its principal tributaries, including the Mahananda, Punarbhava, Atrai, and Karotoya, originate in India and join the Ganges on its left side. After merging with the Brahmaputra River, it is renamed the Padma River, which later joins the Meghna River before finally discharging into the Bay of Bengal. The Ganges Basin spans India, China, Nepal, Bhutan, and Bangladesh, with 4% of the basin located within Bangladesh, covering approximately 32% of the country's total area. It is estimated that almost 75 million people live in this basin. According to the FAO Report (2011), the annual flow of the Ganges Basin from India to Bangladesh is approximately 525.02 km³. The basin fraction of each district of this basin is shown in Table 3.1.

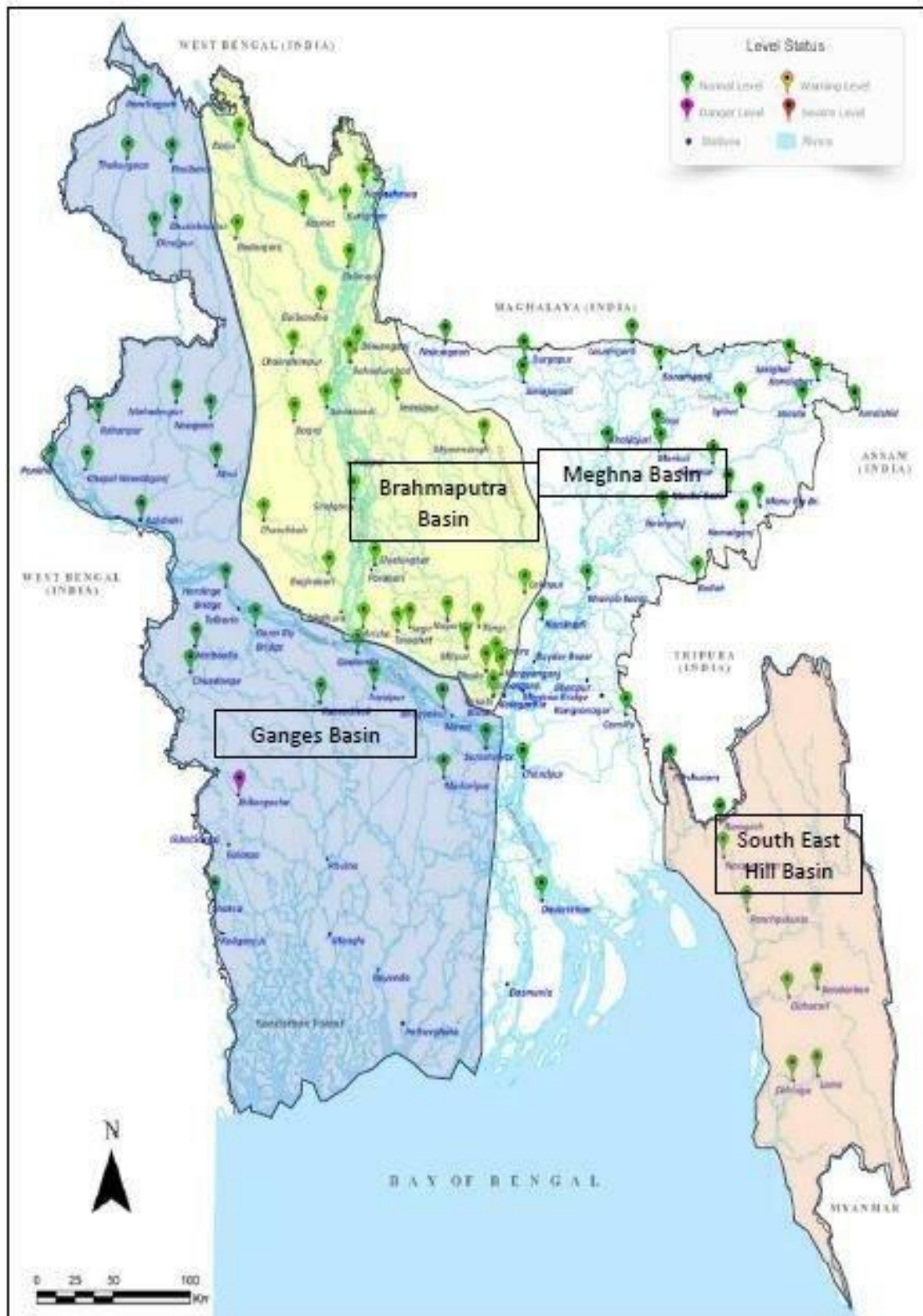


Figure 3.2: Basin map of Bangladesh (BWDB, 2020)

Table 3.1: District-wise basin area percentage of the Ganges Basin

District Name	Basin Fraction (%)	District Name	Basin Fraction (%)
Barguna	100	Barisal	75
Jhalokati	100	Patuakhali	46
Pirojpur	100	Dhaka	15
Faridpur	100	Gopalganj	100
Madaripur	100	Manikganj	17
Munshiganj	46	Rajbari	100
Shariyatpur	80	Bagerhat	100
Chaudanga	100	Jessore	100
Jhenaidaha	100	Khulna	100
Kushtia	100	Magura	100
Meherpur	100	Narail	100
Satkhira	100	Bogra	10
Chapainawabganj	100	Joypurhat	72
Naogaon	100	Natore	55
Pabna	38	Rajshahi	100
Dinajpur	83	Nilphamari	37
Panchagarh	100	Thakurgaon	100

3.1.2 The Meghna Basin

The Meghna River Basin covers an area of 82,000 km², with 57% located in India and 43% in Bangladesh. Originating from the hilly regions of eastern India, the Meghna River divides into two streams—Surma and Kushiya—before entering Bangladesh, where it spans 24% of the country's total area. These two streams later merge to form the Lower Meghna, among the world's largest river systems, serving as the confluence of three major rivers: Ganges, Brahmaputra, and Meghna. According to FAO (2011), the annual flow of the Meghna Basin from India to Bangladesh is approximately 48.36 km³. The population of this basin is almost 69 million. The distribution of the basin across different districts is illustrated in Table 3.2.

Table 3.2 : Percentage of the Meghna basin area by district

District Name	Basin Fraction (%)	District Name	Basin Fraction (%)
Barisal	25	Bhola	100
Patuakhali	54	Brahmanbaria	100
Chandpur	100	Chattogram	7
Comilla	100	Feni	35

Lakshmipur	100	Noakhali	97
Kishoreganj	88	Munshiganj	28
Mymensingh	33	Narayanganj	43
Narsinghdi	74	Netrokona	100
Shariyatpur	20	Sherpur	54
Habiganj	100	Maulvi bazar	100
Sunamganj	100	Sylhet	100

3.1.3 The Brahmaputra Basin

The Brahmaputra River originates from the northern Himalayan slope in China. This river is classed as a braided channel while it flows eastward, turning south, it enters India. After flowing for about 480 km, it turns westward and enters Bangladesh. From 543400 km² basin area, Bangladesh only covers 7% of this basin area. The Brahmaputra basin covers 27% of the whole country. It is estimated that almost 75 million people live in this basin. When the Brahmaputra River meets the Ganges River, the stream is called the Jamuna River in Bangladesh. The basin fraction for each district of the Brahmaputra basin is shown in Table 3.3.

Table 3.3 : Percentage of Brahmaputra basin area by district

District Name	Basin Fraction (%)	District name	Basin Fraction (%)
Dhaka	85	Gazipur	100
Jamalpur	100	Kishoreganj	12
Manikganj	83	Munshiganj	26
Mymensingh	67	Narayanganj	57
Narsinghdi	26	Sherpur	46
Tangail	100	Bogra	90
Joypurhat	28	Natore	45
Pabna	62	Sirajganj	100
Dinajpur	17	Gaibandha	100
Kurigram	100	Lalmonirhat	100
Nilphamari	63	Rangpur	100

3.1.4 The Southeastern Hill Basin

The area outside the Ganges-Brahmaputra-Meghna Basin is known as the Southeastern Hill Basin, home to approximately 19 million people. Covering 16,140 square kilometers, this basin also forms part of Bangladesh's coastal

region. Its major rivers include Karnaphuli, Sangu, Matamuhuri, and Halda. The Sangu and Matamuhuri Rivers originate in Myanmar, carrying transboundary water into Bangladesh. The distribution of the basin across different districts is illustrated in

Table 3.4.

Table 3.4 : District-wise percentage coverage of the Southeastern Hill Basin

District Name	Basin Fraction (%)	District Name	Basin Fraction (%)
Bandarban	100	Chattogram	93
Cox's Bazar	100	Feni	65
Khagrachari	100	Noakhali	3
Rangamati	100		

3.2 METHODOLOGY

Bangladesh, a variety of freshwater sources, including surface water, groundwater, and stormwater. According to the Bangladesh Water Act 2013, the Government of Bangladesh owns available water on behalf of its population. So, the local government is responsible for providing water to the stakeholders. For metropolitan cities (Dhaka, Chattogram, Khulna, and Rajshahi), water is collected and treated from the available sources, such as surface water and groundwater, by the Water Supply and Sewerage Authority (WASA). In other main cities, safe water is ensured by the Department of Public Health Engineering (DPHE) by providing guidelines for tubewell digging, rainwater harvesting, and pump installation. In short, except in hilly areas, people rely primarily on groundwater in rural and urban areas for domestic, agricultural, and industrial use. Due to improper implementation of water rules and regulations, people use groundwater in an undocumented manner, which leads to water stress in some areas. Also, the shortage of documentation leads to inappropriate estimation of existing water scenarios. In this study, the work has been divided into three significant steps, presented in Figure 3.3. Firstly, the

water demand has been determined. In the second stage, the available water was calculated, and lastly, the regional water balance was calculated for every basin.

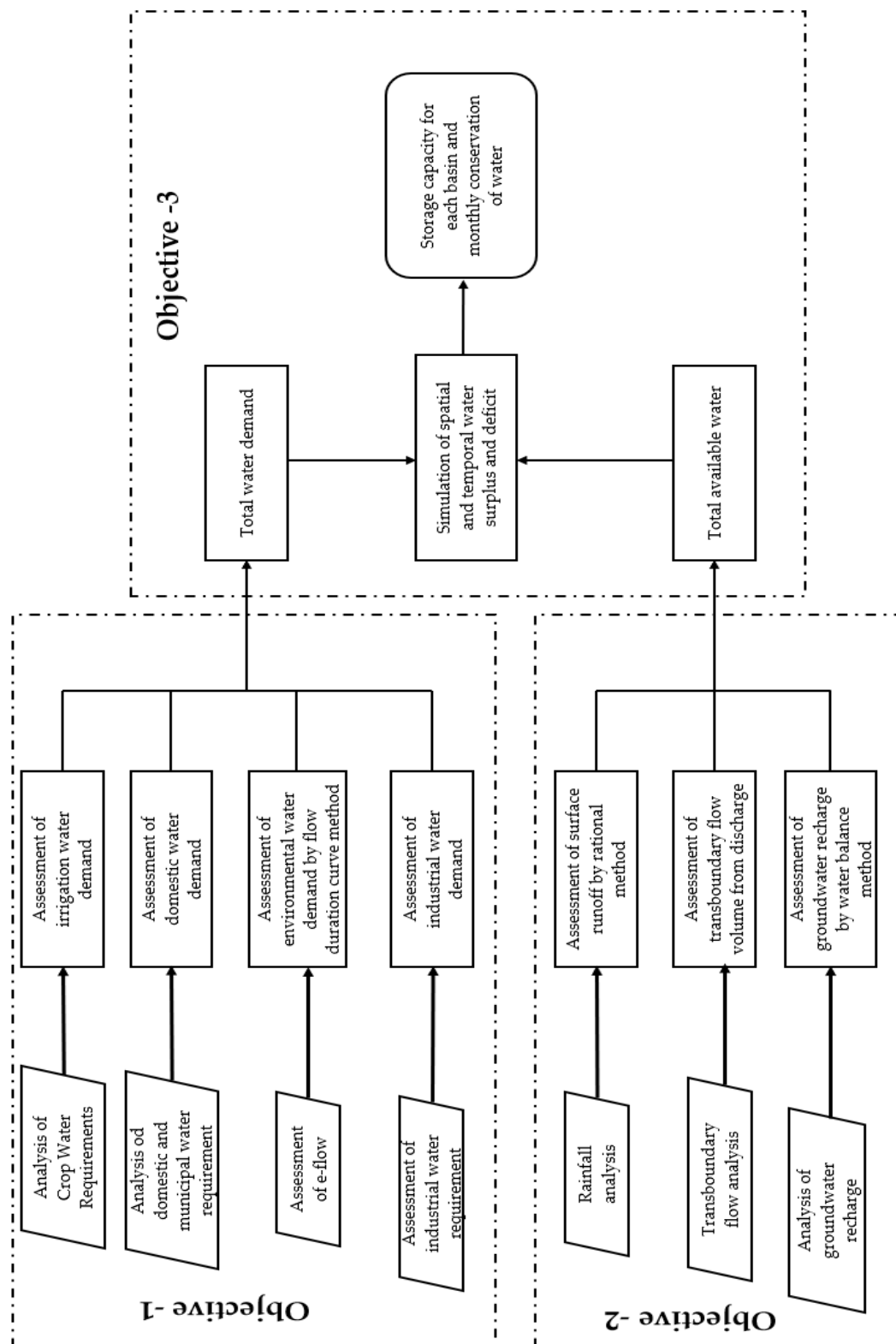


Figure 3.3: Schematic flowchart of the study's methodological approach

3.3 WATER DEMAND

Water is required for every purpose from the beginning to the end of the day. The water demand in Bangladesh is driven by various sectors, reflecting the diverse needs of its population and economy. Understanding the water demand of these sectors is crucial for effective water resources management. However, the major demand sector implies domestic, industrial, agricultural, and environmental water requirements, which have been addressed in this study. These four types of demand will be calculated using different methodologies for four river basins.

3.3.1 Domestic Water Demand

The domestic water demand is determined by multiplying per capita water consumption by population data (Equation 3.1). District-wise population data for 2021 was obtained from the Population and Housing Census Report published by the Bangladesh Bureau of Statistics (BBS). The district populations were then aggregated to estimate the basin population based on the basin percentages of each district, as presented in Table 3.5.

$$\text{Domestic water demand} = \text{Per capita consumption} * \text{Population} \quad (3.1)$$

According to Table 2.3, per capita consumption is categorized into four groups. Since population data is available at the district level, a per capita consumption of 120 liters per capita per day is assigned to district or Zilla towns. For Bangladesh's 12 city corporations, a higher per capita consumption of 180 liters per capita per day is considered. After estimating district-wise water demand, it is converted into basin-wise demand using the basin fraction or percentage of each district.

Table 3.5: Population statistics of four river basins (BBS, 2021)

Basin Name	Total Population
The Ganges Basin	50,173,434
The Meghna Basin	45,636,323
The Brahmaputra Basin	54,974,638
The Southeastern Hill Basin	14, 374,222

3.3.2 Industrial Water Demand

Bangladesh has different types of industries. This study focuses on seven key sectors: textile, steel, fertilizer, sugar, cement, paper, and leather. The industrial water demand is calculated by multiplying per-unit water consumption by total production, as outlined in Equation 3.2.

$$\text{Industrial water demand} = \text{water used per unit} * \text{Total production} \quad (3.2)$$

Industrial production data for various industries has been obtained from the Industrial Production Statistics (IPS) reports published by the Bangladesh Bureau of Statistics (BBS), as presented in Table 3.6.

Table 3.6: Annual production of selected industries in Bangladesh (BBS, 2021)

Types of industry	Products	No of industries reported	Production unit	Production (2021)
Steel	Iron & steel (M.S. products)	-	MT	41075
Fertilizer	Fertilizer	7	MT	1175986
Sugar	Sugar	16	MT	47104
Paper	Pulp, paper, and newsprint	3	MT	170326
Leather	Tanning and Finishing	175 and EPB	Square meters	18093000
Textile	Weaving of textile	15	Meter	42030000

Textile	Dying, bleaching and finishing	19	Meter	145083000
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The per-unit water requirement data has been sourced from existing literature. Numerous studies have been conducted on the industrial sector in both Bangladesh and other countries. Given the similarities in geological and economic conditions between Bangladesh and India, some data has been adopted from Indian research due to the unavailability of equivalent data specific to Bangladesh. Table 3.7 shows the variation of water requirements in several industrial sectors collected from different literature.

Table 3.7 : Literature-based industrial water requirements by sector

Industry type	Reference	Country	Water requirement for each production
Pulp and paper	(Rahman & Kabir, 2010)	Bangladesh	20-35 m ³ /ton for paper production from imported pulp and wastepaper
Pulp and paper	(Chaturvedi et al., 2006)	India	200 m ³ /ton
Pulp and paper	(Tewari et al., 2009)	India	150-250 m ³ /ton
Sugar	(Rasul et al., 2006)	Bangladesh	1.25 tons of water per ton of cane processed
Leather	(Paul et al., 2017)	Bangladesh	40 m ³ water for 255 kg finished leather
Leather	(Saha & Azam, 2021)	Bangladesh	About 60 m ³ of water is required to process one ton of hides and skins
Leather	(Sundar et al., 2001)	India	40-45 L water/kg raw hide or skin
Cement	(Hosseinian & Nezamoleslami, 2018)	Iran	2.126 m ³ /ton cement production
Fertilizer	(Fiamelda et al., 2020)	Indonesia	12.8 m ³ /ton of urea
Textile	(Restiani, 2016)	India	200-250 m ³ / ton of cotton cloth

To estimate basin-wise industrial demand, the labor force has been considered, as basin-specific industrial production data is unavailable. The assumption was made on the basis that the presence of industries is generally indicated by labor-intensive districts. Bangladesh has divided into eight divisions- Dhaka, Chattogram, Barisal, Khulna, Mymensingh, Rangpur, Rajshahi and Sylhet. The Bangladesh Bureau of Statistics (BBS) publishes the Bangladesh Labor Force Survey (LFS) annually for each division. Table 3.8 presents the

percentage distribution of industrial workers across different divisions in Bangladesh for the year of 2021. According to the LFS data, Dhaka is the largest industrial zone, employing the highest number of workers, followed by Chattogram as the second largest industrial zone.

Table 3.8: Distribution of industrial labor force by division in Bangladesh

Division	Worker percentage (%)
Barisal	5.08
Chattogram	16.87
Dhaka	26.98
Khulna	11.18
Mymensingh	6.94
Rajshahi	14.06
Rangpur	12.75
Sylhet	6.14

To convert the demand from division wise to basin wise, it is necessary to determine the basin fraction for each division. Using the ARCGIS tool, the area of each division has been calculated out, and the corresponding basin percentage of each division has been determined and presented in the following Table 3.9. The monthly variations is assumed to be uniform over a year.

Table 3.9: Percentage of basin area covered within each division

Division	Ganges Basin (%)	Meghna Basin (%)	Brahmaputra Basin (%)	Southeastern Hill Basin (%)
Barisal	55.85	44.15	0	0
Chattogram	0	36.58	0	63.42
Dhaka	37.03	19.64	43.33	0
Khulna	100	0	0	0
Mymensingh	0	46.69	53.31	0
Rajshahi	58.01	0	41.99	0
Rangpur	40.89	0	59.11	0
Sylhet	0	100	0	0

3.3.3 Environmental Water Demand

Bangladesh is a riverine country with 405 flowing rivers, including 57 transboundary rivers, as reported by the Bangladesh Water Development Board (BWDB). Among these, surface water discharge data is available from 179 river

stations, while 411 stations for monitoring water levels. Due to the unavailability of historical discharge data for every river, this study considers only the major rivers in each basin.

The study area for this study is categorized into major river systems: the Ganges River system, the Brahmaputra River system, and the Meghna River system. For the Meghna River system, the Kushiya, Surma-Meghna, and Dhalai rivers are included. The Brahmaputra River system includes the Dholeswari, Dudhkumar, Teesta, and Brahmaputra rivers, while the Ganges River system consists of the Padma, Gorai, and Mohananda rivers. Additionally, for the Eastern Hill basin, the Sangu and Halda rivers have been considered for assessment.

Daily discharge data for the selected rivers have been obtained from the Bangladesh Water Development Board (BWDB) from 1990 to 2021. A summary of the data collection status is presented in Table 3.10.

Table 3.10: Summary of collected river discharge data

Basin	River Name	River station	Station ID	Data type and frequency	Data year
The Ganges Basin	Ganges-Padma	Hardinge Bridge	SW90	Daily Discharge	1990-2021
	Gorai-Madhumati	Gorai Railway Bridge	SW99	Daily Discharge	1990-2021
	Mohananda	Chapainawabganj	SW211.5	Daily Discharge	1990-2021
The Brahmaputra Basin	Dholeswari	Jagir_Dholeswari	SW68.5	Daily Discharge	1990-2021
	Dudhkumar	Pateswari	SW81	Daily Discharge	1990-2021
	Teesta	Kaunia	SW294	Daily Discharge	1990-2021
	Teesta	Dalia	SW291.5R	Daily Discharge	1990-2021
	Brahmaputra-Jamuna	Bahadurabad_Transit	SW46.9L	Daily Discharge	1990-2021
The Meghna Basin	Kushiya	Sheola	SW173	Daily Discharge	1990-2021
	Surma-Meghna	Kanaighat	SW266	Daily Discharge	1990-2021

	Surma-Meghna	Sylhet	SW267	Daily Discharge	1990-2021
	Dhalai	Kamalganj	SW67	Daily Discharge	1990-2021
The Eastern Hill Basin	Halda	Panchpukuria	SW119.1	Daily Discharge	1990-2021
	Sangu	Bandarban	SW247	Daily Discharge	1990-2021

To estimate the environmental flow (E-flow) requirements for each river, a Flow Duration Curve (FDC) was constructed for every month using the collected daily discharge data. The daily discharge values were arranged in descending order, with the highest value assigned rank one. The exceedance probability for each value was then calculated using Equation 3.3, which represents the percentage of time a specific flow is equalled or exceeded.

$$P = m/(n + 1) * 100 \quad (3.3)$$

Here, P denotes the exceedance probability, m is the rank of each discharge value, and n is the total number of available discharge records. After computing the exceedance probabilities, a flow duration curve was developed for each month at every station, plotting the exceedance probability on the x-axis and streamflow on the y-axis. Key exceedance percentiles—50th, 75th, and 90th—were extracted from these curves. In this study, E-flow requirements were determined for different seasons in Bangladesh:

- 90th percentile for dry season (December-January)
- 50th percentile for monsoon (June – September)
- 75th percentile for pre-monsoon (February-May) and post-monsoon (October-November).

A sample Flow Duration Curve demonstration for January in the Padma River is presented in Figure 3.4.

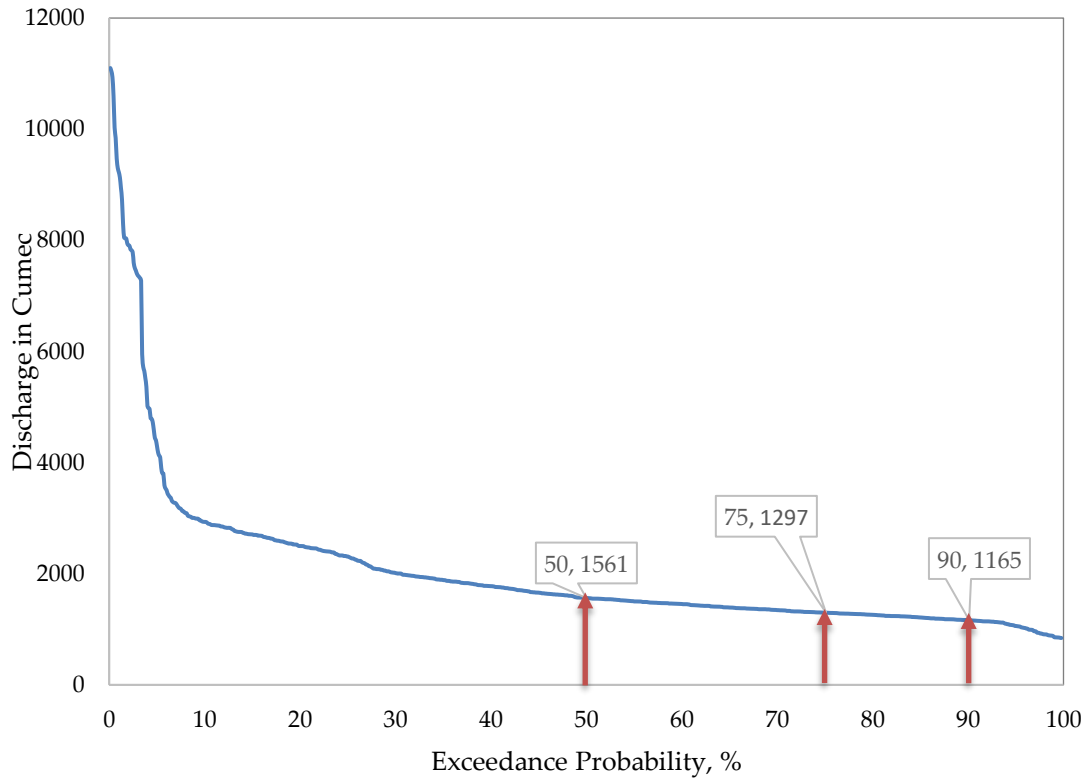


Figure 3.4: January flow duration curve for the Padma River

3.3.4 Irrigation Water Demand

Bangladesh is an agricultural country, where irrigation plays a key role in crop cultivation. Crop water requirement refers to the amount of water needed for a crop from land preparation to the maturity stage. In this study, the crop water requirements for each crop, along with the total of the individual crop water requirements (CWR), represent the net irrigation water requirement for a specific district.

3.3.4.1 Data Collection

Before estimating the CWR, data collection has been completed. A study was conducted across 64 districts to assess the total irrigation demand for the entire country. According to the Bangladesh Meteorological Department (BMD), there are 35 meteorological stations in Bangladesh, as shown in Table 3.11.

Table 3.11 : List of meteorological stations in Bangladesh

Station	Latitude (N)	Longitude (E)	Elevation (m)
Dhaka-41923	23.78	90.38	8.45
Tangail-41909	24.25	89.93	10.20
Faridpur-41939	23.6	89.85	8.10
Madaripur-41939	23.17	90.18	7.00
Mymensingh-41886	24.73	90.42	18.00
Chattogram-41978	22.22	91.8	5.50
Sandwip-41964	22.48	91.43	2.10
Sitakunda-41965	22.63	91.7	7.30
Rangamati-41966	22.63	92.15	68.89
Cumilla-41933	23.43	91.18	7.50
Chandpur-41941	23.23	90.7	4.88
M. Court-41953	22.87	91.1	4.87
Feni-41943	23.03	91.42	6.40
Hatiya-41963	22.45	91.1	2.44
Cox's Bazar-41992	21.45	91.97	2.10
Kutubdia-41989	21.82	91.85	2.74
Madaripur-41939	23.17	90.18	7.00
Srimangal-41915	24.3	91.73	21.95
Sylhet-41891	24.9	91.88	33.53
Bogura-41883	24.85	89.37	17.90
Dinajpur-41863	25.65	88.68	37.58
Ishrudi-41907	24.15	89.03	12.90
Rajshahi-41895	24.37	88.7	19.50
Rangpur-41859	25.73	89.27	32.61
Sayedpur-41858	25.75	88.92	39.60
Chaudanga-41926	23.65	88.82	11.58
Jessore-41936	23.2	89.33	6.10
Khulna-41947	22.78	89.53	2.10
Mongla-41958	22.47	89.6	1.80
Satkhira-41946	22.72	89.08	3.96
Barisal-41950	22.72	90.37	2.10
Bhola-41951	22.68	90.65	4.30
Khupupara-41984	21.98	90.23	1.83
Patuakhali-41960	22.33	90.33	1.50
Teknaf-41998	20.87	92.3	5.00
Ambagan-41938	22.35	91.82	33.20

The crop evapotranspiration was calculated using the FAO Penman-Monteith method for all 35 stations by the Bangladesh Agricultural Research Council (BARC) dataset. The decade-wise reference crop evapotranspiration and actual crop evapotranspiration have been collected from their database. Daily precipitation data have been collected from the Bangladesh Meteorological

Department (BMD). Additionally, crop data, irrigated area, and the crop calendar have been sourced from the Statistical Yearbook of Bangladesh 2021, published by BBS.

Soil data for Bangladesh has been obtained from the Harmonized World Soil Database (HWSD), developed by IIASA and FAO in July 2008, with its latest update in 2013. The primary objectives of HWSD are to enhance the quantity and quality of available soil data by capturing information at a 1 km grid cell resolution and to harmonize and expand soil attribute details, such as texture and composition, with collected soil data. A summary of the data collection is presented in Table 3.12.

Table 3.12 : Summary of data used for assessing irrigation water demand

Data type	Data frequency	Data year	Source
Reference Crop Evapotranspiration	Decade (every 10 days)	2010-2021	Bangladesh Agricultural Research Council (BARC)
Regional Soil Texture Map	-	-	Harmonized World Soil Database v2.0
Precipitation	Daily	2010-2021	Bangladesh Meteorological Department (BMD)
District-wise Crop Irrigated area	Yearly	2021	Statistical Yearbook of Bangladesh, 2021
Crop Planting date	-	-	Yearbook of Agricultural Statistics, 2021
Crop-coefficient, Crop height, Crop Growth Stage	-	-	Food and Agricultural Organization (FAO)
Soil Properties	-	-	Food and Agricultural Organization (FAO)

3.3.4.2 Data Processing

As meteorological data was available for only 35 stations, climatic data for every district of Bangladesh are needed. To convert the reference crop

transpiration, zonal statistics method was applied and for precipitation the Theissen Polygon Method in the Geographic Information System (ARCGIS 10.8).

The reference crop evapotranspiration (ET_0) for each station has been calculated on a monthly basis by summing the three decade-wise values for each month. The 10-year average for each month was then determined. After obtaining the monthly ET_0 values, these data, along with the latitude and longitude of the stations, were organized in an Excel file. In ArcGIS, this Excel file and the district shapefile of Bangladesh were imported with the correct coordinate system. First, a raster file was generated from the point values of the stations using the Inverse Distance Weighting (IDW) interpolation method. The raster map for Bangladesh was then extracted from the generated surface. Using the “Zonal Statistics as Table” tool under the Spatial Analyst toolbox in ArcGIS, statistical measures for each district in Bangladesh were obtained. This process was repeated for each month, and the corresponding raster files are presented in Figure 3.5. It can be concluded from the map that the lowest ET_0 is observed in the winter season (December- February) due to lower temperatures, and the peak value is expected in the Pre-monsoon season (March-May) due to high temperatures and solar radiation.

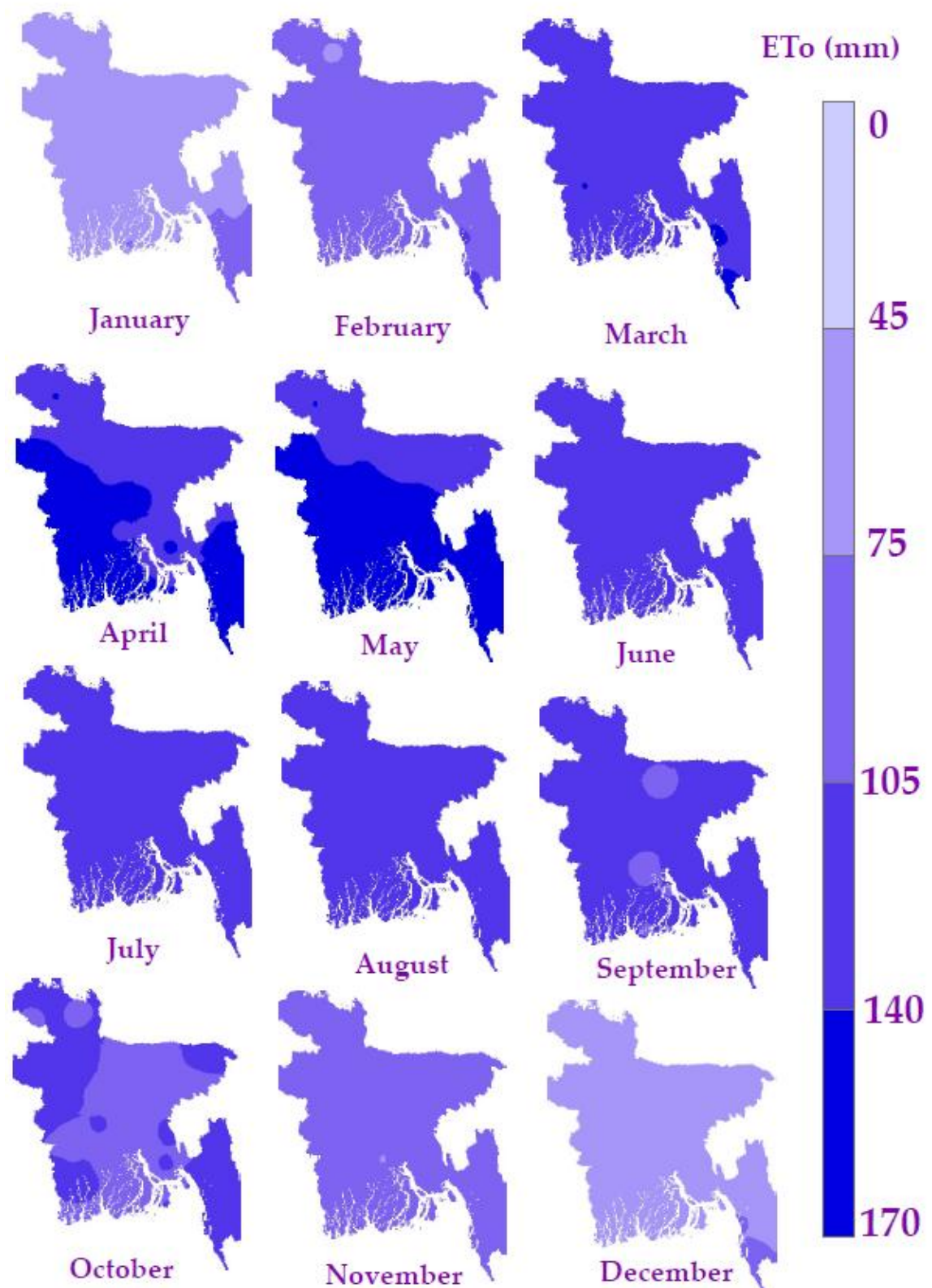


Figure 3.5 : Spatial Distribution of Monthly Reference Crop Evapotranspiration (ET_0) in Bangladesh

The Thiessen Polygon Method was employed to process rainfall data for each district. Initially, daily rainfall data were aggregated into monthly values, and a 10-year average for each month was calculated. These values, along with the latitude and longitude of the rainfall stations, were compiled into an Excel file. This file was then imported into ArcGIS and converted into a point shapefile. Using the Thiessen Polygon Method, 35 polygons were generated around the points and clipped to fit within Bangladesh's boundaries.

The resulting rainfall distribution for the twelve months is illustrated in Figure 3.6. From this figure, it is evident that low rainfall occurs during the dry season (January–March), followed by heavy monsoon rains from April to May. A regional variation in precipitation is also observed, with the southeastern and northeastern regions receiving significantly higher rainfall during the monsoon, while the northwestern region experiences comparatively lower rainfall.

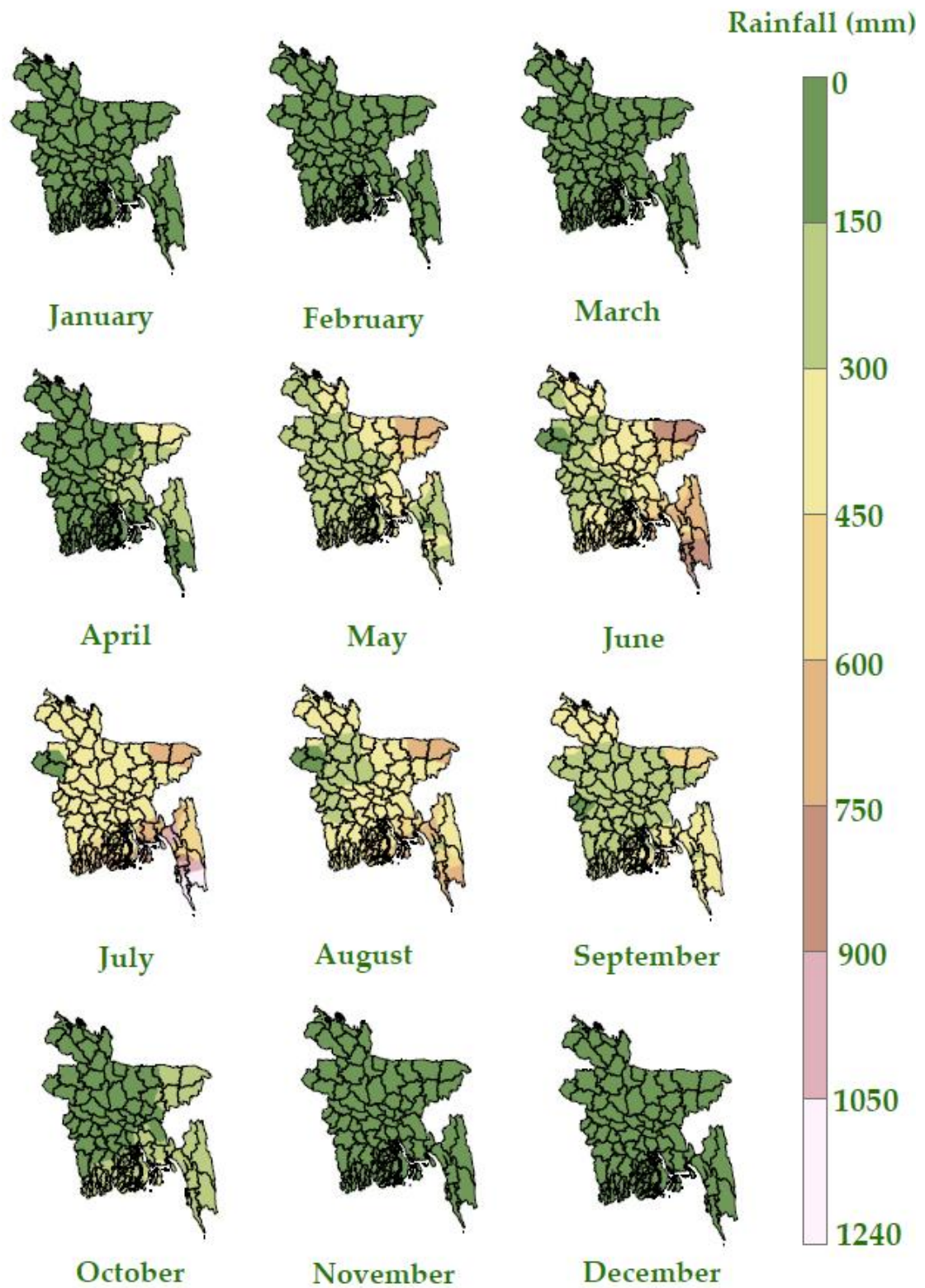


Figure 3.6: Monthly average precipitation distribution in Bangladesh

A soil map of Bangladesh was developed using the global dataset from the Harmonized World Soil Database, incorporating the country's boundary. The FAO classifies soils into 26 major groups, further detailed into subunits. For Bangladesh, four primary soil groups have been identified: Fluvisol (sandy-loamy), Gleysol (clayey to loamy), Acrisol (loamy), and Cambisol (clayey). The soil group distribution across the country is illustrated in Figure 3.7. Additionally, to facilitate interpretation, a chart summarizing the total coverage area of each soil type is presented in Table 3.13. The soil properties parameters have been collected from the FAO for every district of Bangladesh.

Table 3.13: Classification and description of soil types on the map

Soil name	Acrisol	Cambisol	Gleysol	Fluvisol	Nitosol	Histosol	Regosol
Notation on map	Af, Ao	Bd, Be, Bh	Gc, Gd, Ge	Jc, Je, Jt	Nd	Od	Rd
% of total area	4.3%	15.67%	62.67%	11.15%	3.61%	2.55%	0.04%

In Bangladesh, the Bangladesh Bureau of Statistics (BBS) publishes agricultural reports under the Yearbook of Agricultural Statistics. This report includes a crop calendar and district-wise irrigated areas for various crops. To meet crop data requirements, key crops have been selected based on their irrigated area. Crop coefficients for the initial, mid-season, and late-season growth stages have been sourced from the FAO for each crop, as presented in Table 3.14.

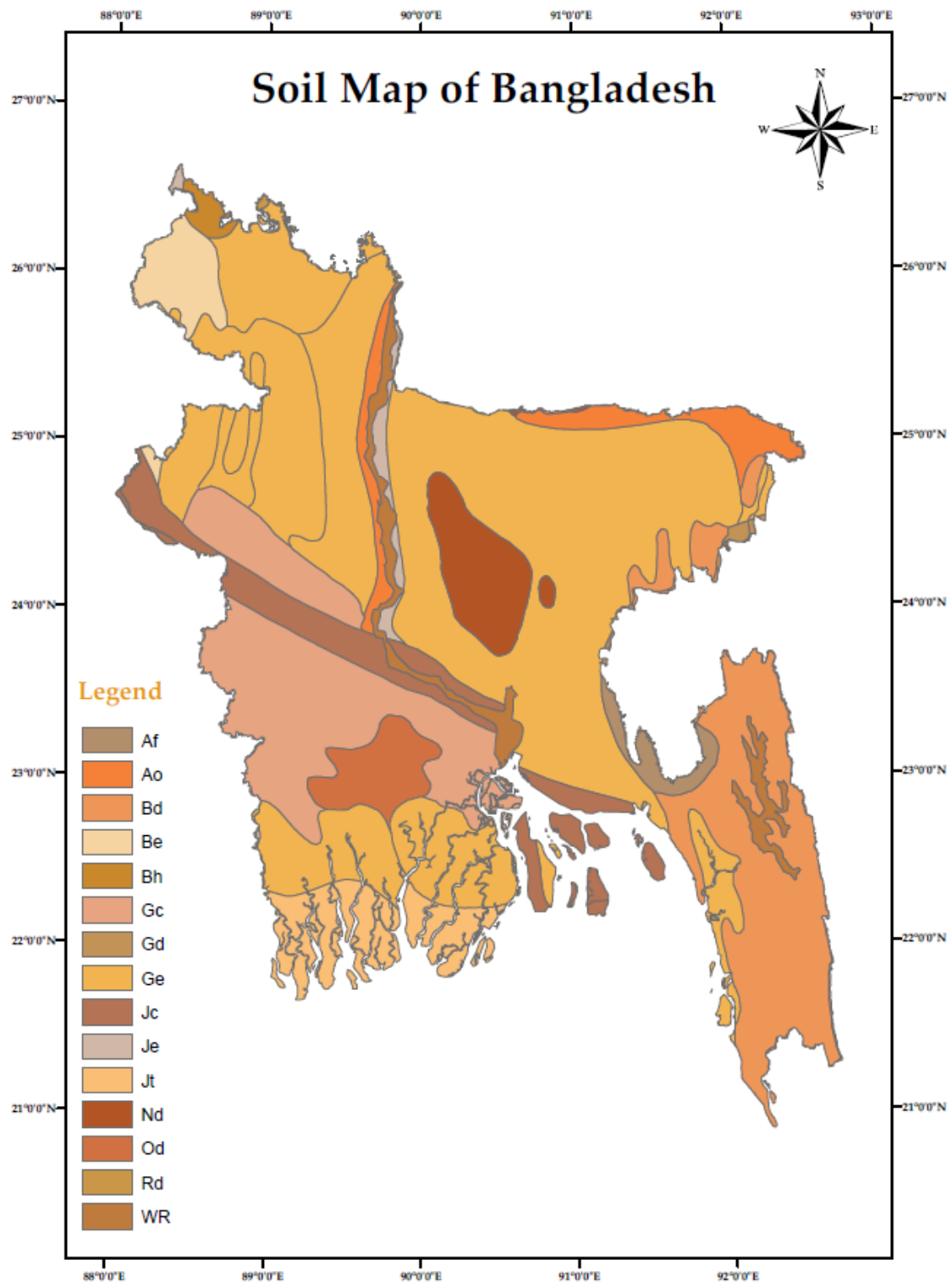


Figure 3.7 : Soil classification map of Bangladesh

Table 3.14: Crop types and their characteristics used in the study

Crop name	Total irrigated area (ha)	Planting date	Total
Aush rice	1225290.5	Mid-March to Mid-April	150
Aman rice	5427701	End June to Early September	150
Boro rice	3708225	December to Mid-February	150
Wheat	340285.5	November to December	130
Maize (Rabi)	397328.06	Mid-October to Late December	125
Gram	4457.70	Mid-August to Mid-September	110
Lentil	145208.84	Mid-October to Mid-November	110
Green Gram	45164.87	Mid-October to Late-November	110
Kheshari	171768.74	Mid-October to Late-December	110
Coriander	3505.44	October to December	95
Turmeric	26425.04	Mid-April to Mid-June	300
Onion	199846.69	October to Mid-December	150
Garlic	72533.96	Mid-October to Mid-December	140
Radish	27079.06	Mid-August to Early October	95
Tomato	29548.19	Mid-August to Late-November	145
Ginger	9720.67	Mid-March to Mid-May	270
Sugarcane	75043.32	Early Mid-October to Mid-	365
Cauliflower	22754.62	Late-October to Mid-November	95
Cabbage	21919.88	Late-October to Mid-November	165
Cucumber	10306.19	Late-October to Mid-November	95
Rape & Mustard	330127.38	Mid-October to Mid-November	110
Sweet Potato	27728.08	Mid-September to Mid-December	130
Potato	188722.69	Mid-September to November	130
Jute	285286.63	Early-March to Mid-April	120
Banana	29650.03	Mid-January to Mid-March	330
Mango	118548.11	Mid-April to Mid-June	365
Papaya	4191.29	Mid-June to End-August	315
Watermelon	19976.47	Mid-October to Mid-January	120
Jackfruit	23024.81	Mid-April to Mid-June	300
Kharif-Brinjal	23024.81	October to Mid-November	95

3.3.4.3 Estimation of Crop Water Requirement

The crop water requirement was estimated using the CROPWAT model after collecting all necessary data. A flowchart illustrating this model is provided in Figure 3.8. The model calculates crop water requirements using a specific equation (3.4), with calculations performed for each 10 days (decade). For consistency, all months were assumed to have 30 days, divided into three decades of 10 days each.

$$CWR = ET_0 * K_c \quad (3.4)$$

To determine the monthly agricultural water demand in terms of volume, the following equation was used, where A represents the crop irrigated area and CWR denotes the crop water requirement.

$$Volume = \sum_{i=1}^{12} CWR * A \quad (3.5)$$

The crop water requirements (volume) for 30 crops have been estimated for each district by multiplying the cultivated area by the required water depth. The district-wise, crop-specific irrigated area has been obtained from the Yearbook of Agricultural Statistics. Once the district-wise monthly water demand was obtained, it was converted into basin-wise demand by applying the basin fraction of each district, ensuring an accurate representation of water needs at the basin level.

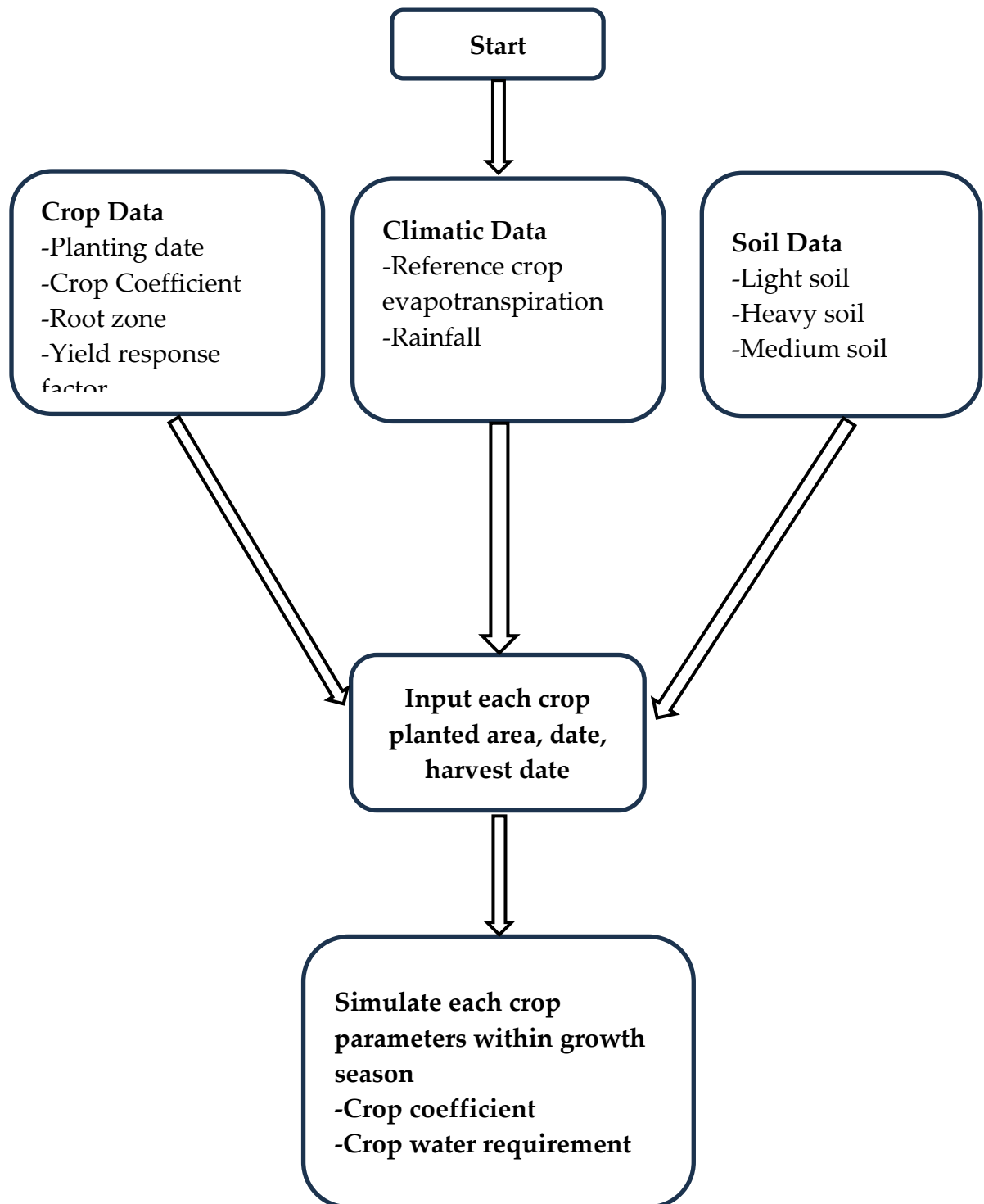


Figure 3.8 : Schematic diagram of the CROPWAT model

3.4 WATER SUPPLY

As a riverine country, Bangladesh has diverse freshwater sources, including surface water, groundwater, and rainwater. The country experiences seasonal variations, with abundant water during the monsoon and scarcity in the dry season. This section will discuss the water supply from these different sources.

3.4.1 Surface Runoff

Surface runoff is the portion of rainfall that flows over the land surface and discharges into streams, rivers, lakes, or other water bodies. The rainfall-runoff process is complex and influenced by various meteorological factors. Extreme rainfall can lead to severe flooding. Estimating runoff is crucial for understanding freshwater availability and potential water harvesting. In this study, the Rational Method is used to determine the peak or maximum runoff, providing an estimate of the available water. A flowchart to estimate surface runoff is represented in Figure 3.9.

3.4.1.1 Watershed Data Preparation

To apply the rational formula, the watershed must first be identified. In this study, sub-basin layers for Bangladesh were obtained from HydroBASINS, a sub-product of HydroSHEDS, developed by the World Wildlife Fund (WWF) in collaboration with the European Commission's Joint Research Centre (JRC).

HydroBASINS provides vectorized polygon layers representing global catchment boundaries. These layers were derived from gridded HydroSHEDS core data at a 15-arc-second resolution. The key advantage of this dataset is its ability to divide basins into 12 levels of nested sub-basins, ranging from regional scale to smaller watersheds. At the first level, a basin is split into two sub-basins when two river branches meet, provided each upstream area is at least 100 km². The Pfafstetter Coding System (PCS) is used to systematically group and label these nested sub-basins, ensuring a structured hierarchy. Shapefiles for levels 1

to 12 for each continent are available for download in a single zipped file from the HydroBASINS website (www.hydrosheds.org/products/hydrobasins).

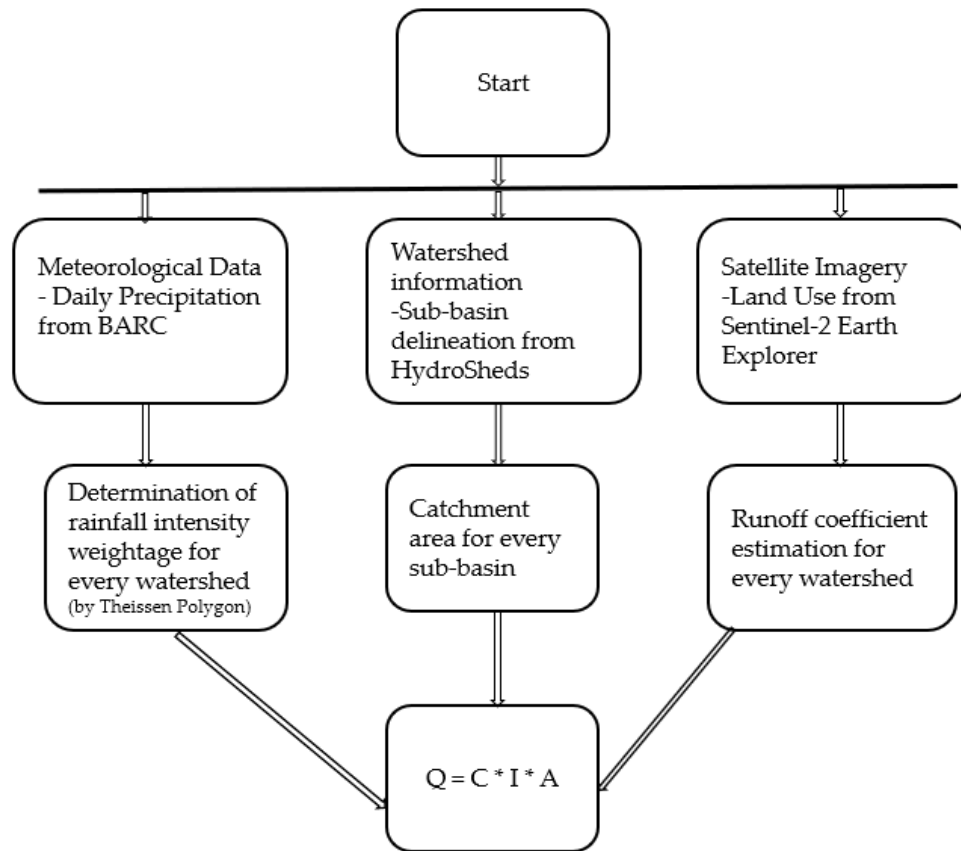


Figure 3.9 : Schematic workflow for estimating surface runoff

In this study, Level 6 of the nested sub-basins of Asia was selected to maintain a moderate number of catchments within each basin. The watershed delineation for Bangladesh was extracted from the continental watershed map by clipping the relevant region. Subsequently, a basin-wise delineated map for Bangladesh was created, as shown in Figure 3.10. The analysis revealed that:

- The Ganges Basin contains 20 sub-basins.
- The Meghna Basin consists of 11 sub-basins.
- The Brahmaputra Basin comprises 10 sub-basins.
- The Southeastern Basin includes six sub-basins.

The watershed area for each sub-basin was determined from the attribute table of these maps.

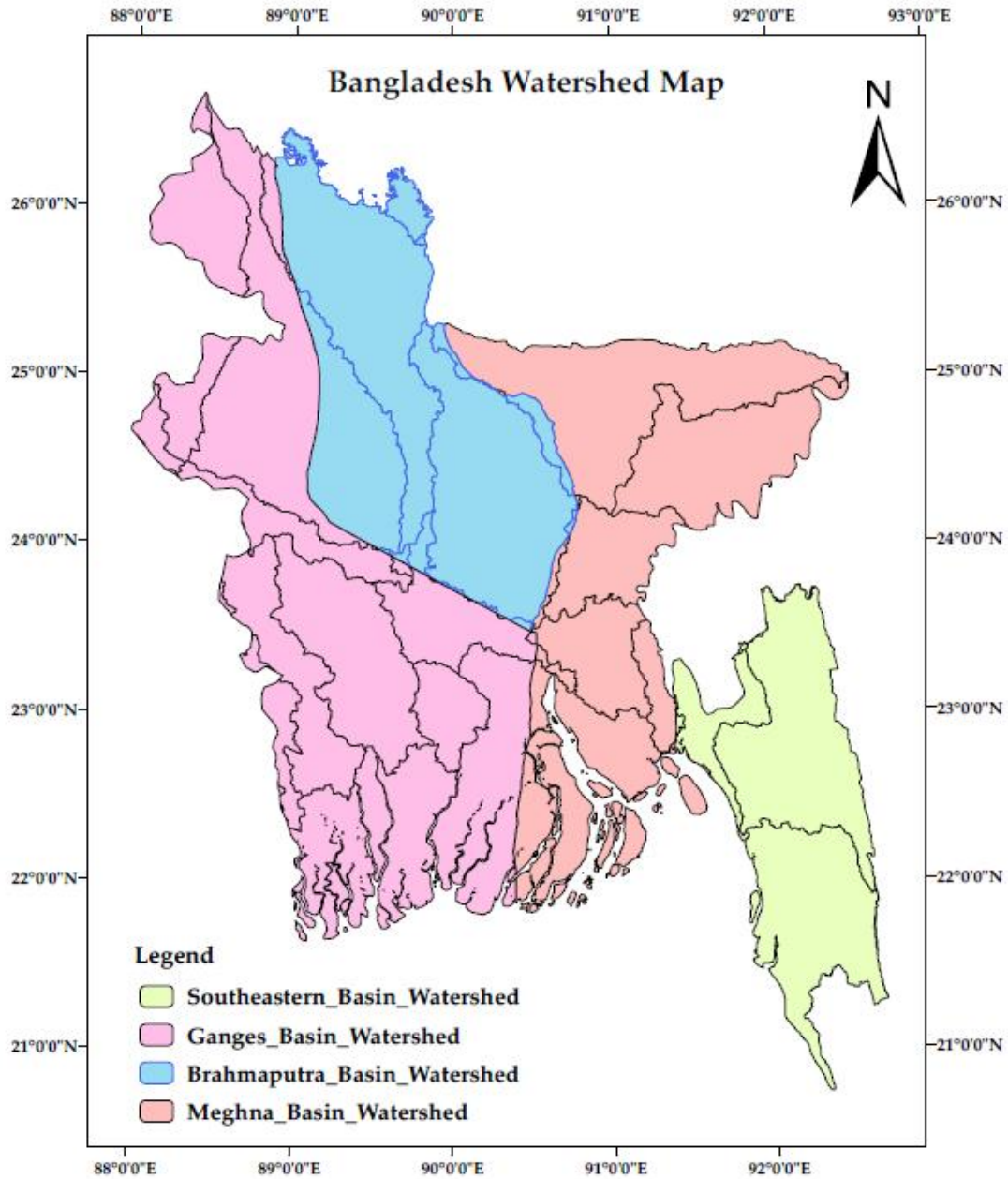


Figure 3.10: Hydrological watershed delineation of Bangladesh

3.4.1.2 *Precipitation Data Preparation*

To estimate rainfall intensity, daily rainfall data from 2010 to 2021 were collected from the Bangladesh Meteorological Department (BMD) for 35 stations,

as listed in Table 3.11. The Thiessen Polygon Method, described in section 3.3.4.2, was used to determine the average monthly rainfall for each watershed. Rainfall intensity refers to the amount of rainfall per unit of time. The monthly rainfall was converted into rainfall intensity (mm/h) by dividing it by the corresponding time period, ensuring a uniform estimate of rainfall intensity.

3.4.1.3 Land Use Data Preparation

In the rational method, the runoff coefficient is a crucial parameter. To estimate this coefficient, the land use land cover of the catchment area must be considered, as it directly influences the runoff coefficient. The Land Use Land Cover (LULC) map used for this study was obtained from the Sentinel-2 Land Use Land Cover map, derived from ESA's Sentinel-2 L2A imagery at a 10m resolution. This global LULC map, covering the years 2017-2024, was developed using Microsoft's Planetary Computer. Each year's map was generated through a collaboration between Impact Observatory's deep learning AI land classification model and Esri. The map provides annual land cover classifications, which are grouped into nine key thematic classes, as outlined in Table 3.15.

Table 3.15: Description of LULC classes derived from Sentinel-2 data

Class Name	Description
Water	Rivers, lakes, oceans, ponds, flooded salt pans
Trees	Wooded vegetation, mangroves, clusters of dense tall vegetation
Flooded Vegetation	Flooded mangroves, wetlands, seasonal flood areas
Crops	Agricultural fields
Build Area	Houses, pavement, impervious infrastructures
Bare Ground	Dry lands, sand dunes, exposed rock or soil, dried lake beds
Snow	Glaciers, snow fields
Clouds	Area covered by the clouds at the time of observations
Rangeland	Open grassland, golf courses/lawns

The LULC map for 2021 was downloaded from the ArcGIS Living Atlas website (<https://livingatlas.arcgis.com/landcoverexplorer>). After downloading

the data, the individual tiles were merged into a single layer. Using the 'Mask Extracting' tool in ArcGIS, the LULC map of Bangladesh was created, as shown in Figure 3.10.

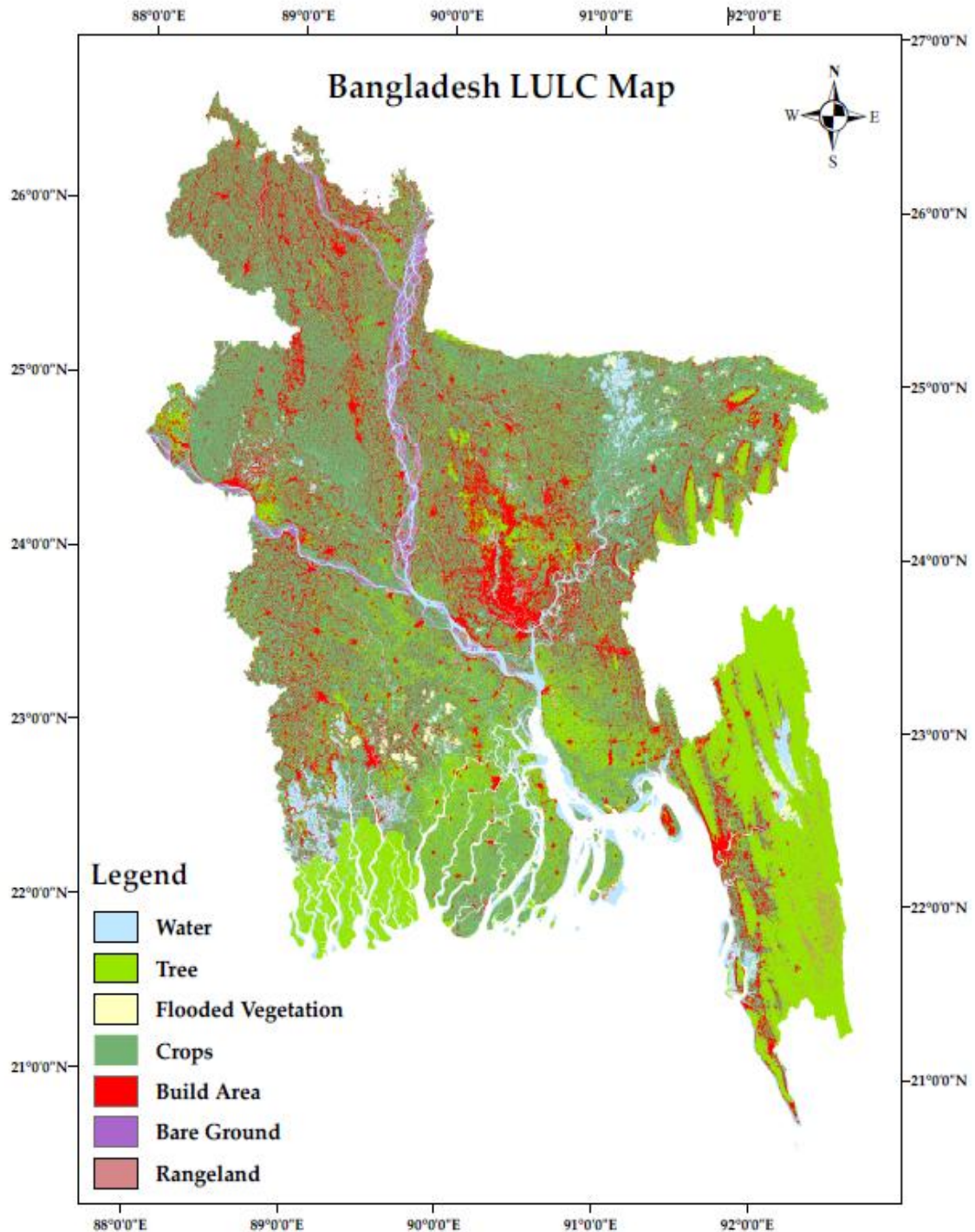


Figure 3.11: LULC Map of Bangladesh Based on Satellite Imagery

To determine the weighted runoff coefficient, the LULC map for each watershed was analyzed to identify the classifications and their corresponding areas. The weighted runoff coefficient was calculated using Equation 2.21. The runoff coefficient values for each classification type were obtained from Ramachandra et al. (2014), as presented in Table 3.16.

Table 3.16: Runoff coefficients by land cover classification

Classification Name	Runoff Coefficient, C
Water	1.0
Trees	0.1
Flooded Vegetation	0.15
Crop	0.5
Build Area	0.9
Bare land	0.6
Rangeland	0.15

3.4.1.4 Direct Runoff Estimation

To estimate the peak runoff the rational method is used. After getting the rainfall intensity, runoff coefficient and the catchment area the runoff for each watershed has been computed using the following equation:

$$Q = \frac{C \times I \times A}{360} \quad (3.6)$$

Here,

Q = peak runoff, m³/s

C = weighted runoff coefficient

I = Rainfall Intensity (mm/h)

A = catchment area, ha

As each basin has several sub-basins the monthly direct runoff has been obtained from the summation of all sub-basins. The monthly runoff volume was found out by multiplying with the time period.

3.4.2 Groundwater Recharge

Groundwater recharge is the downward movement of water from the surface into an aquifer. This study adopts the Water Balance Method to estimate groundwater recharge across four major basins of Bangladesh. The method is chosen for its simplicity and effectiveness in providing a preliminary understanding of both the amount and pattern of groundwater (GW) recharge.

A simplified form of the Water Balance Method to estimate the GW recharge was used:

$$P = R + RO + AET + SM \quad (3.7)$$

Here, P is the precipitation (mm), AET represents the actual evapotranspiration (mm), R represents the recharge (mm), the RO is runoff (mm), and SM is the change in soil moisture (mm). Neglecting the change in soil moisture, the GW recharge can be estimated from:

$$R = P - RO - AET \quad (3.8)$$

This study applies a modified approach by Hendrickx (1992) to overcome certain limitations of the basic water balance method. This modification enables more accurate monthly groundwater recharge estimation using 10 years of climatic data.

3.4.2.1 Data Preparation and Estimation

Precipitation data have been prepared for each of the watersheds, as discussed in Section 3.3.1.2 of the study.

The runoff is calculated using the rational method:

$$Q \text{ (mm)} = C * P \text{ (mm)} \quad (3.9)$$

Here,

C = Runoff coefficient (values compiled in Table 3.16)

P = precipitation (mm)

Runoff for each watershed is calculated, and the total runoff per basin is obtained by summing the runoff values of all watersheds within each basin.

3.4.2.2 *Actual Evapotranspiration (AET)*

The actual evapotranspiration (AET) is estimated by using the **Grindley Method** (Grindley, 1967) under the following two criteria:

1. When $P > PET$, then $AET = PET$
2. If $P < PET$, then $AET = P + f (PET - P)$

Here,

PET = potential evapotranspiration (mm)

f = Slope of the drying curve (PET vs AET), commonly taken as 0.1.

The potential evapotranspiration PET data for 35 climatic stations were collected from the BARC website. To estimate PET for each watershed, the Inverse Distance Weighted (IDW) method and the Zonal Statistics tool were applied. Monthly PET values were then used to estimate AET using the Grindley method.

3.4.2.3 *Recharge Estimation*

After obtaining the necessary inputs (precipitation, runoff, and AET) for each watershed, monthly groundwater recharge is estimated using:

$$R = P - RO - AET \quad (3.10)$$

To calculate the **total recharge volume**, the following equation is used:

$$R (volume) = \sum_{i=1}^n R_i * A_i \quad (3.11)$$

Here,

R_i = Recharge in the i^{th} watershed

A_i = Area of the i^{th} watershed

N = Total number of watersheds

3.4.3 **Transboundary Flow**

The estimation of transboundary or international river flows was carried out using the available discharge data sourced from monitoring stations. For each

hydrological basin under study, a representative transboundary river was selected based on having at least 10 years of continuous and reliable discharge records. This threshold was set to ensure the consistency and accuracy of flow estimations over a significant period.

Only four monitoring stations were ultimately selected for analysis in the Meghna Basin. This limitation was due to a lack of observed discharge data at several other stations and the absence of any discharge monitoring system on many rivers in the region.

Although the Karnaphuli River is recognized as one of the most important rivers in the Southeastern Basin due to its hydrological and socio-economic significance, it could not be included in the analysis. This was solely due to the unavailability of reliable discharge data for the river during the study period, which made it unsuitable for inclusion based on the selection criteria.

Furthermore, some stations were selected even though they are situated a considerable distance from the rivers' entry points into Bangladesh. The rationale behind this choice is that these stations—such as SW6.9L, SW90, and SW247—are located at strategic confluence points where several tributaries join before flowing further into the country. Therefore, these stations provide a more integrated measure of transboundary flow from multiple upstream sources.

All discharge data used in this study were obtained from the Bangladesh Water Development Board (BWDB), the primary national organization responsible for hydrological monitoring and data management. Detailed information regarding the selected monitoring stations, including their river names, locations, and periods of data availability, is presented in Table 3.17. Figure 3.12 represents the location map of those stations for Bangladesh.

After acquiring the daily discharge data for each selected river, the data were processed to compute the monthly average flow for each river. This step was essential to reducing daily variability and obtaining a more stable and representative estimate of river flow patterns over time.

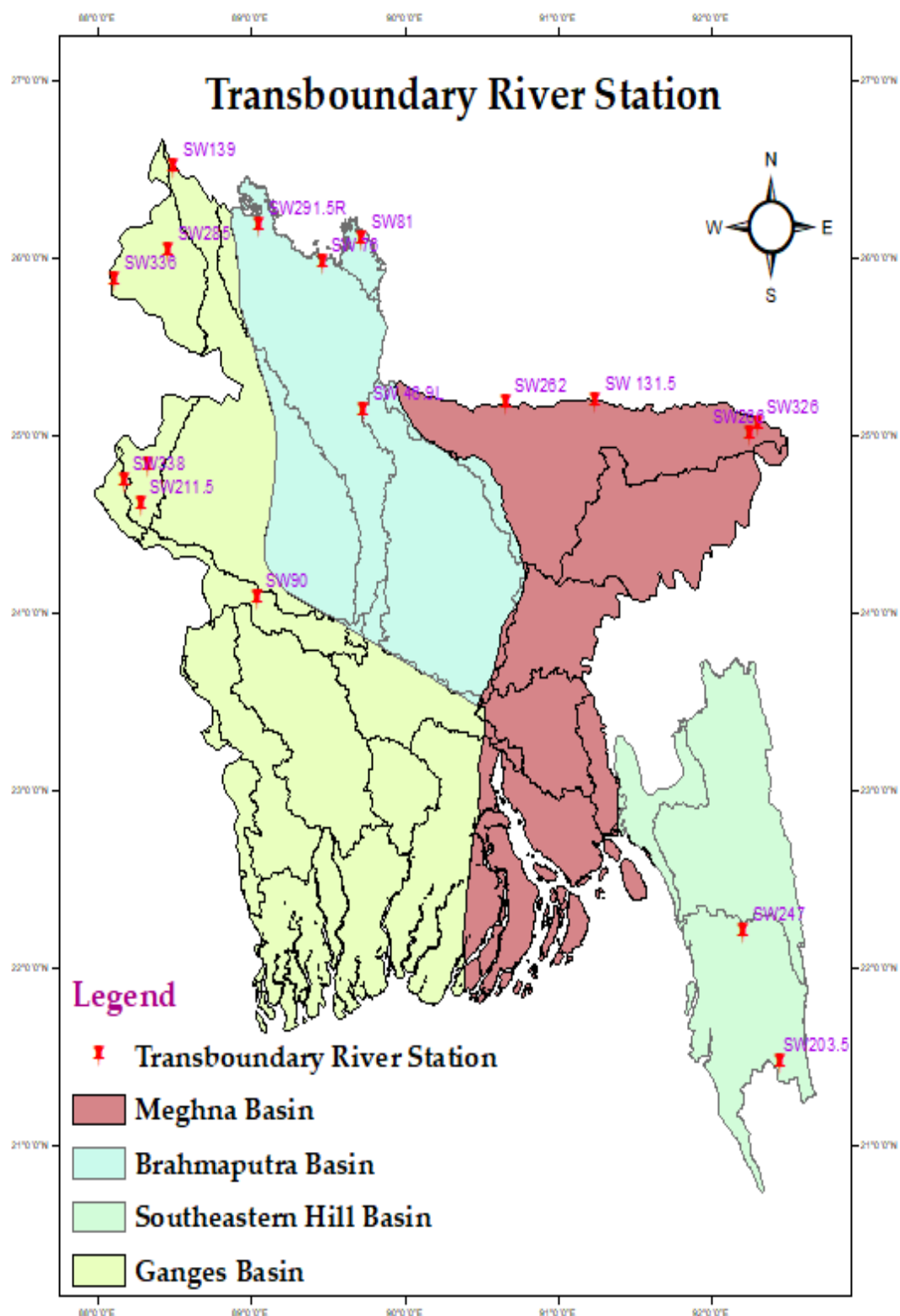


Figure 3.12: Locations of transboundary river discharge monitoring stations

Table 3.17 : Summary of transboundary river discharge data sources and characteristics

Basin	River Name	Station ID	Data type and frequency	Data year
The Ganges Basin	Ganges-Padma	SW90	Daily Discharge	2010-2021
	Punarbhaba	SW238	Daily Discharge	2010-2021
	Pagla	SW338	Daily Discharge	2010-2021
	Karatoa-Atrai	SW139	Daily Discharge	2010-2021
	Nagar (NW border)	SW336	Daily Discharge	2010-2021
	Tangon	SW285	Daily Discharge	2010-2021
	Mohananda	SW211.5	Daily Discharge	2010-2021
The Brahmaputra Basin	Dharla	SW76	Daily Discharge	2010-2021
	Dudhkumar	SW81	Daily Discharge	2010-2021
	Teesta	SW291.5R	Daily Discharge	2010-2021
	Brahmaputra-Jamuna	SW46.9L	Daily Discharge	2010-2021
The Meghna Basin	Someswari	SW262	Daily Discharge	2010-2021
	Jadukata	SW131.5	Daily Discharge	2010-2021
	Surma-Meghna	SW266	Daily Discharge	2010-2021
	Lubachara	SW326	Daily Discharge	2010-2021
Southeastern Hill Basin	Matamuhuri	SW203.5	Daily Discharge	2010-2021
	Sangu	SW247	Daily Discharge	2010-2021

To determine the flow volume, the average discharge values were multiplied by the corresponding time period, converting the rate of flow (typically expressed in cubic meters per second) into a volume (cubic meters). Specifically, for each month, the flow volume was calculated by multiplying the average discharge by the total number of seconds in that month.

Once the monthly flow volumes for individual rivers were estimated, the values corresponding to rivers within the same basin were aggregated. This summation provided the total transboundary flow volume entering each basin from upstream sources.

3.5 POTENTIAL STORAGE CAPACITY ESTIMATION

Excess water can be stored in a reservoir to ensure a consistent water supply throughout the year and to manage seasonal fluctuations in water availability and demand. The minimum amount of water required to prevent scarcity during the dry season is referred to as the potential Storage capacity. To account for the

seasonal variations in water abundance and shortages, the cumulative mass balance approach was employed to estimate the potential Storage capacity. This method considers monthly changes in supply and demand, ensuring that the storage design aligns with temporal patterns.

3.5.1 Net Water Balance

Water surplus refers to the amount of water remaining after meeting all the required water demands, indicating excess supply over demand. Conversely, the water deficit occurs when the available water supply is insufficient to fulfill the total demand, signifying a shortage. The water surplus or deficit is determined using the following equation:

$$\text{Net Balance} = \text{Water Supply} - \text{Water Demand} \quad (3.12)$$

In this context, a positive result indicates a water surplus, meaning the water supply exceeds the demand. A negative result, on the other hand, signifies a water deficit, where the demand surpasses the available supply.

In this study, the monthly water surplus or deficit was calculated after estimating both the total water supply and the total water demand for each basin.

3.5.2 Cumulative Balance

The monthly net water balance and the cumulative balance for the year were calculated. This cumulative value shows how water surpluses and shortages evolve, indicating the amount of water stored and required each month. The cumulative balance is calculated using the following equation:

$$\text{Cumulative Balance}_n = \sum_i^n \text{Supply}_i - \text{Demand}_i \quad (3.13)$$

3.5.3 Mass Curve Formation

After calculating the cumulative balance, a mass curve was created by plotting the cumulative balance over time for each basin. Time, typically

measured in months, is represented on the x-axis, while the cumulative balance is plotted on the y-axis. The mass curve illustrates the fluctuations in water storage over time. The lowest point on this curve indicates the minimum storage level needed to prevent reservoir depletion. The minimum capacity for the Storage was determined from the mass curve of each basin.

3.6 MONTHLY CONSERVATION OF WATER

According to the Garg (2005), it's recommended to allocate 30% of live storage as dead storage to ensure a balanced approach to storage management. Once the minimum Storage capacity for the year is determined, it is increased by 30% and 50% to account for variable inflows and outflows. In this study, 50% increment is introduced as a conservative estimate to consider additional water losses such as evaporation as well as to conserve more water for future uncertainties. Additionally, the Storage's capacity may need to be adjusted to meet future demand increases due to population growth and the impact of climate change. The required storage volume was calculated as follows:

$$\text{Storage Volume} = 1.5 * \text{minimum Storage capacity} \quad (3.14)$$

$$\text{Storage Volume} = 1.3 * \text{minimum Storage capacity} \quad (3.15)$$

A Storage Allocation Ratio (SAR) was introduced to develop the monthly water allocation strategy and determine the amount of water that should be stored each month. The ratio is defined as:

$$\text{Storage Allocation Ratio (SAR)} = \frac{\text{Storage Volume}}{\text{Total Annual Surplus}} \quad (3.16)$$

The SAR was applied to estimate the monthly storage for each basin using the following equation:

$$\text{Monthly Storage} = \text{Monthly Surplus} * \text{SAR} \quad (3.17)$$

3.7 SUMMARY

This chapter outlines the methodology adopted for estimating each component of water demand and supply in the study. Domestic water demand was calculated using population data, while industrial water demand was derived from secondary sources in the literature. Environmental water demand was estimated using the flow duration curve method, and irrigation water demand was assessed through the CROPWAT model. On the supply side, surface runoff was determined using the rational method, transboundary inflow was estimated based on flow discharge data, and groundwater recharge was calculated via the water balance method. The chapter also presents all underlying assumptions, the rationale behind method selection, and the equations applied for each estimation. The adopted approach ensures consistency across datasets and supports the integration of multiple sources to develop a comprehensive water balance model for the study area.

Chapter 4: RESULTS and DISCUSSION

This chapter represents the research results aimed at estimating the water balance and providing the storage capacity for each basin. The study considers four significant water demands (domestic, industrial, environmental flow, and irrigation) and three primary water supply sources (transboundary flow, surface runoff, and groundwater flow). Additionally, this chapter outlines the monthly storage allocation for each basin. Each section addresses a specific aspect of water demand and supply, followed by the corresponding results, offering insights into the dynamics of storage estimation. This analysis will highlight the significance of each parameter and contribute to the discussion of its implications.

4.1 WATER DEMAND

This study estimates four types of water demand—domestic, industrial, agricultural, and environmental flow—for each basin across four seasons: pre-monsoon, monsoon, post-monsoon, and dry season. The monthly variations in each demand have been calculated and expressed in Million Cubic Meters (MCM).

4.1.1 Domestic Water Demand

Domestic water demand solely depends on the population and per capita water requirements. As population growth continues, the demand for freshwater for daily use is expected to rise accordingly. In this study, the demand is initially calculated daily and then converted to a monthly basis by multiplying by the number of days in a month. Therefore, the demand for the months having the same number of days is similar, except for February, which has 28 days, resulting in a slightly lower total demand. Table 4.1 presents the monthly variations in

domestic water demand across different basins. The total domestic water demand for the country in 2021 has been found as 8,460.754 MCM.

A graphical representation of the demand has been demonstrated in Figure 4.1. The figure illustrates that the Brahmaputra Basin has the highest domestic water demand, reaching 3,002.202 MCM, whereas the Southeastern Hill Basin has the lowest demand at 816.345 MCM.

Table 4.1: Basin-wise estimates of domestic water demand

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	199.764	254.982	194.506	69.333
	April	193.320	246.756	188.232	67.097
	May	199.764	254.982	194.506	69.333
Monsoon	June	193.320	246.756	188.232	67.097
	July	199.764	254.982	194.506	69.333
	August	199.764	254.982	194.506	69.333
	September	193.320	246.756	188.232	67.097
Post-monsoon	October	199.764	254.756	194.506	69.333
	November	193.320	246.756	188.232	67.097
Dry season	December	199.764	254.756	194.506	69.333
	January	199.764	254.756	194.506	69.333
	February	180.432	230.306	175.683	62.624

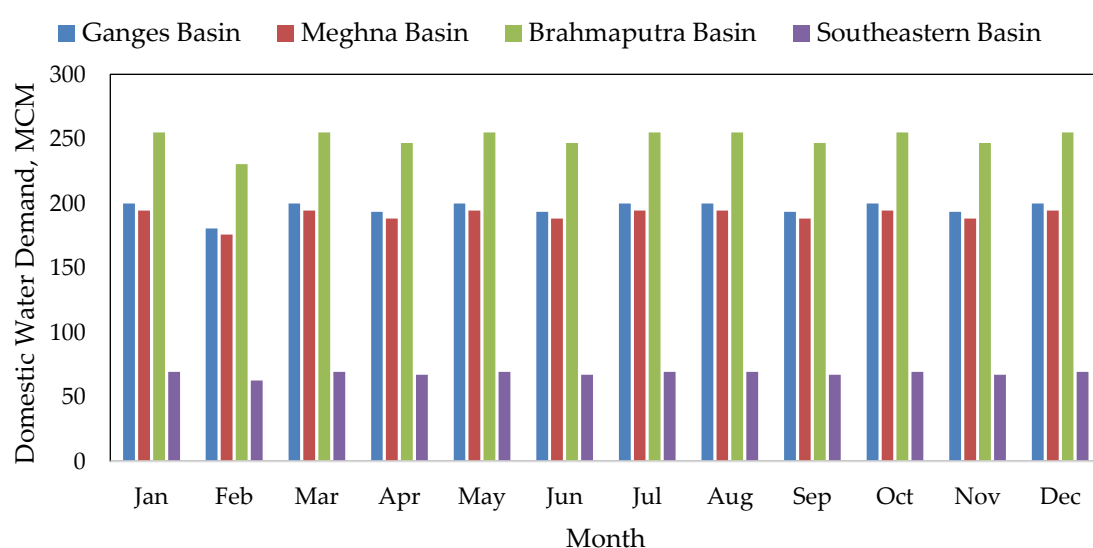


Figure 4.1: Monthly domestic water demand in selected basins

Due to its large population and extensive coverage across Bangladesh, the Brahmaputra Basin accounts for approximately 35% of the total domestic water demand. In comparison, the Ganges and Meghna Basins, which cover nearly equal areas, contribute around 28% and 27%, respectively. The Eastern Hill Basin, with the smallest coverage, accounts for only 8% of the total demand. No seasonal variations were spotted in the result, as the demand estimation did not count any seasonal variability of per capita consumption.

4.1.2 Industrial Water Demand

In this study, the industrial water demand was estimated using production data from the Bangladesh Bureau of Statistics (BBS) and the water requirements per unit production from different literature. The annual industrial water demand of significant industries of the country was first calculated for the whole country and presented in Table 4.2.

Table 4.2: Estimated industrial water demand by sector

Industry Type	Water requirements per unit of production (m ³ /ton)	Water demand (m ³)
Pulp and paper	30	1063240
Cement	2.126	44412352.60
Steel	1.25	513393.75
Sugar	28.4	1337753.6
Leather	60	1459907.74
Textile	227	24735051.45
Fertilizer	12.8	16592654.43

Table 4.3: River basin-wise industrial water demand estimates

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	3.87	2.39	2.99	1.11
	April	3.87	2.39	2.99	1.11

	May	3.87	2.39	2.99	1.11
	June	3.87	2.39	2.99	1.11
Monsoon	July	3.87	2.39	2.99	1.11
	August	3.87	2.39	2.99	1.11
	September	3.87	2.39	2.99	1.11
	October	3.87	2.39	2.99	1.11
Post-monsoon	November	3.87	2.39	2.99	1.11
	December	3.87	2.39	2.99	1.11
Dry season	January	3.87	2.39	2.99	1.11
	February	3.87	2.39	2.99	1.11

A visual representation of industrial water demand across all basins has been shown in Figure 4.2. The monthly industrial water demand is assumed to be uniform throughout the year for each basin. No seasonal variations had been assumed for demand calculation due to the unavailability of required data. Several factors influence this demand, including the number of workers, production levels, industry types, and per-unit water requirements.

The graph indicates that the Ganges Basin had the highest industrial water demand, reaching 46.5 MCM, which accounts for approximately 37% of the total demand. The Brahmaputra Basin ranked second, contributing 28.9% of the total demand, mainly due to the high number of labourers in the Dhaka division, which spans both the Ganges and Brahmaputra basins. In contrast, the Eastern Hill Basin recorded the lowest industrial water demand at 13.3 MCM.

It is seen that the estimated total industrial water demand for 2021 was about 124 million cubic meters. According to the worker percentage and basin fraction, the gross water demand has been transformed into division-wise demand and then converted into the basin demand, which has been presented in Table 4.3.

Table 4.3: River basin-wise industrial water demand estimates

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre- monsoon	March	3.87	2.39	2.99	1.11
	April	3.87	2.39	2.99	1.11
	May	3.87	2.39	2.99	1.11
Monsoon	June	3.87	2.39	2.99	1.11
	July	3.87	2.39	2.99	1.11
	August	3.87	2.39	2.99	1.11
	September	3.87	2.39	2.99	1.11
Post- monsoon	October	3.87	2.39	2.99	1.11
	November	3.87	2.39	2.99	1.11
Dry season	December	3.87	2.39	2.99	1.11
	January	3.87	2.39	2.99	1.11
	February	3.87	2.39	2.99	1.11

A visual representation of industrial water demand across all basins has been shown in Figure 4.2. The monthly industrial water demand is assumed to be uniform throughout the year for each basin. No seasonal variations had been assumed for demand calculation due to the unavailability of required data. Several factors influence this demand, including the number of workers, production levels, industry types, and per-unit water requirements.

The graph indicates that the Ganges Basin had the highest industrial water demand, reaching 46.5 MCM, which accounts for approximately 37% of the total demand. The Brahmaputra Basin ranked second, contributing 28.9% of the total demand, mainly due to the high number of labourers in the Dhaka division, which spans both the Ganges and Brahmaputra basins. In contrast, the Eastern Hill Basin recorded the lowest industrial water demand at 13.3 MCM.

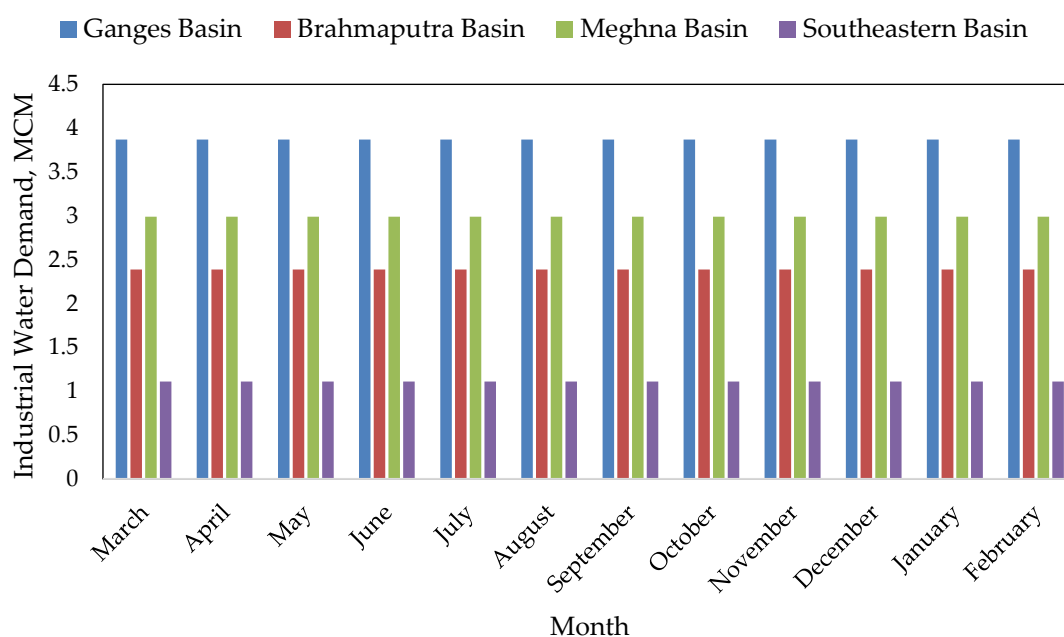


Figure 4.2 : Monthly industrial water demand for selected basins

4.1.3 Environmental Flow Demand

To estimate the environmental flow requirements for all basins, flow duration curves were constructed for each month at every river station, as illustrated in Figure 4.3, and Figure A.1-Figure A.11, where the flow duration curves for all 12 months are compiled. From these graphs, discharge values for the 50%, 75%, and 90% percentiles were determined for each river. As initially explained, Q50 corresponds to the monsoon period, Q75 represents the pre- and post-monsoon periods, and Q90 is for the dry season. The monthly variations in environmental flow requirements are summarized in Table 4.4.

The flow duration curve method reveals the seasonal variations in environmental flow demand. The table presents these variations for each river, indicating that the minimum flow is highest during the monsoon season compared to other seasons. Conversely, the minimum flow requirement is also the lowest when river discharge is at its lowest during the dry season.

Table 4.4: Required environmental flow volumes for selected rivers

River Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sangu	2.81	2.33	2.74	2.60	5.12	61.06	127.72	136.24	80.29	31.36	12.6	1.43
Dhaleswari	2.74	2.63	2.27	2.02	1.67	14.12	22.31	25.96	25.96	21.58	3.1	2.98
Dudhkumar	90.2	73.38	74.39	97.28	160.33	550.92	1057.51	838.91	782.49	320.19	196.27	109.35
Padma	1165.88	759.90	712.21	617.17	908.11	2911.70	16802.28	31342.19	28532.70	10392.45	4496.57	2036.54
Gorai	9.35	1.76	6.43	6.09	24.72	274.46	2159.71	3214.11	2984.58	952.23	278.13	36.26
Halda	4.18	2.13	3.03	5.94	18.56	74.65	94.19	86.27	78.98	33.85	17.77	6.41
Kushiyara	94.54	71.92	75.74	145.44	357.55	1305.73	1558.28	1511.51	1321.24	555.04	240.73	129
Mohananda	27.81	18.41	14.70	10.51	14.25	93.15	583.60	945.62	943.30	339.53	92.39	40.18
Meghna	7.26	4.40	6.96	24.72	174.62	1217.13	1369.35	1286.73	1089.91	271.52	62.18	13.33
Surma	6.13	4.60	5.53	21.45	170.15	1147.05	1382.41	1332.54	1095.90	254.13	37.58	9.43
Teesta	31.90	16.99	36.83	100.94	295.69	1324.89	2168.58	2007.36	1487.99	551	240.51	103.54
Dhalai	5.66	4.69	16.18	16.32	16.77	17.95	17.46	17.63	17.62	16.82	16.53	7.98
Brahmaputra	4235.04	3447.89	4071.17	6500	12416.78	30146.99	46316.08	40932.83	37522.02	19040.26	9296.32	5165.21

The environmental flow requirement for each basin has been estimated by summing the flows of all major rivers within the basin area, as presented in Table 4.5. Furthermore, transboundary flows from major rivers such as the Ganges and Brahmaputra contribute to this increase, as the entire South Asian region experiences intense monsoon rainfall during this period. The excessive precipitation in the country and its neighbouring areas leads to a substantial rise in monsoon flow, resulting in higher environmental flow requirements.

Additionally, a graphical representation of the demand is provided in Figure 4.4. Both the table and graph indicate that flow requirements are highest during the monsoon season. This is primarily due to the heavy rainfall the country experiences from June to September, which significantly increases river discharge. Furthermore, transboundary flows from major rivers such as the Ganges and Brahmaputra contribute to this increase, as the entire South Asian region experiences intense monsoon rainfall during this period. The excessive precipitation in both the country and its neighboring areas leads to a substantial rise in monsoon flow, resulting in higher environmental flow requirements.

The environmental flow requirement during the pre-monsoon period gradually increases from March to May, except in the Ganges Basin. This rise is primarily due to snowmelt, which contributes to increased river flow in most basins. Additionally, early rainfall during this period adds to river discharge, though it remains lower than during the monsoon season. An exception is observed in the Ganges Basin in April, where the average discharge of the Padma River is slightly lower than in March, leading to a deviation from the overall increasing.

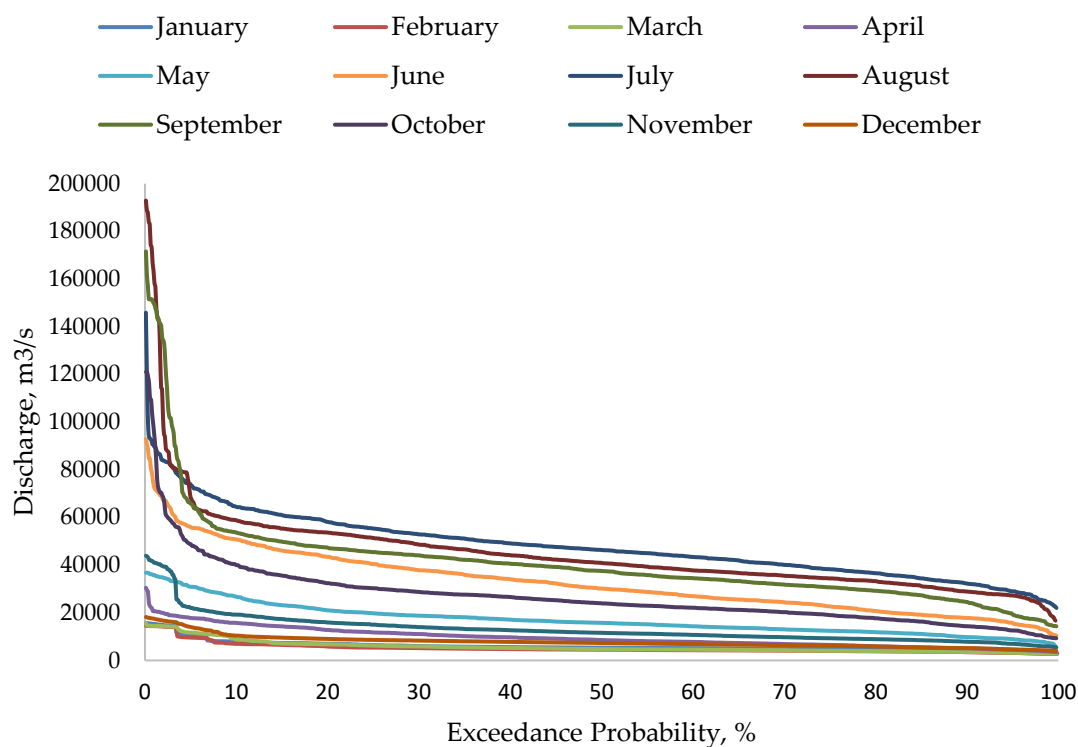


Figure 4.3: Flow duration curve development for Brahmaputra River (46.9L)

Table 4.5: Required monthly environmental flow volumes for every basin

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre- monsoon	March	1964.15	11208.19	279.62	15.45
	April	1642.74	17367.01	538.95	22.11
	May	2536.66	25640.89	1925.98	63.42
Monsoon	June	7997.41	81069.88	9558.92	351.75
	July	45496.51	130576.31	11590.78	594.35
	August	90372.85	114249.43	11111.10	595.96
	September	80431.03	114249.43	9135.92	412.80
Post- monsoon	October	31294.97	101670.24	2939.54	174.66
	November	12615.48	53281.48	925.37	78.73
Dry season	December	5659.39	25236.22	427.85	21.00
	January	3222.21	11677.51	304.23	18.72
	February	1887.14	8566.12	207.12	10.75

During the post-monsoon season, the significant decrease in rainfall leads to a decline in river discharge. Additionally, as the monsoon recedes, groundwater seepage increases, influencing the base flow of rivers and further reducing environmental flow requirements compared to the monsoon season. In the dry season, river streamflow experiences a sharp decline due to minimal rainfall across the country. Furthermore, the high evaporation rate and increased irrigation water demand further reduce the available flow, resulting in the lowest environmental flow requirements of the year.

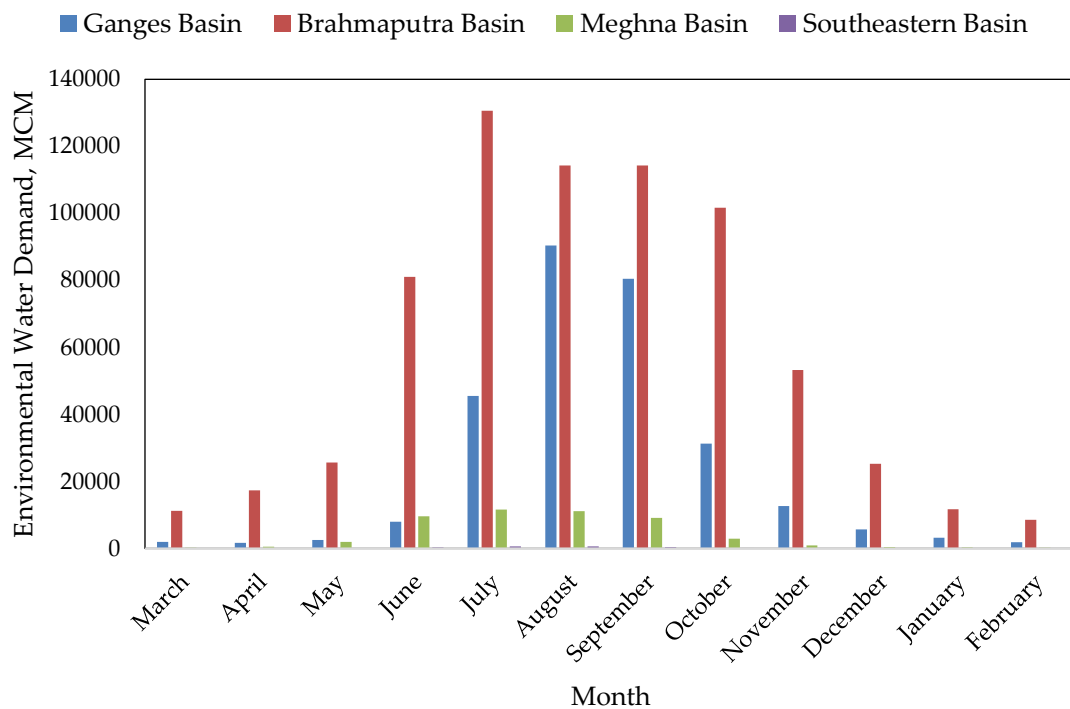


Figure 4.4: Comparative environmental flow demand by basins

Among the four basins, the Brahmaputra Basin has the highest environmental flow demand, followed by the Ganges and Meghna Basins. The Brahmaputra Basin covers a vast area, and the Brahmaputra River carries the highest discharge among all rivers in Bangladesh, even maintaining a relatively high flow during the dry season. A similar trend is observed in the Ganges Basin, as the Ganges River is also a high-energy river, making it the second highest in

terms of flow demand. In contrast, the Southeastern Hill Basin has the lowest environmental flow requirement due to the lower discharge of its rivers, which carry significantly less water compared to the other basins.

4.1.4 Irrigation Water Demand

To estimate the irrigation water demand, CROPWAT has been used. The estimated monthly irrigation water demand for each basin is presented in Table 4.6. The total irrigation water demand of Bangladesh for 2021 was approximately 76,760 million cubic meters.

From the table it is evident that, the Ganges Basin had the highest water demand accounting for 28522.512 MCM, followed by the Brahmaputra Basin (24370.956 MCM) and the Meghna Basin (19893.475 MCM). The Southeastern Basin had the lowest demand accounting for 4062.215 MCM in 2021.

Table 4.6 : Estimated irrigation water demand for each basin

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	8407.79	6864.64	5222.35	1365.97
	April	3306.87	2168.60	1550.51	429.21
	May	1023.56	485.45	528.93	227.36
Monsoon	June	2614.76	2129.40	2220.14	552.22
	July	150.38	111.84	89.41	21.73
	August	0.644	1.24	0.48	0.00
	September	179.94	396.71	226.36	2.84
Post-monsoon	October	387.40	162.37	109.93	25.04
	November	5888.21	6611.29	5707.77	752.72
Dry season	December	994.069	1063.16	469.01	46.86
	January	2104.93	1545.85	1219.52	178.29
	February	3463.97	2830.42	2459.07	458.97

A graphical representation of irrigation water demand is illustrated in Figure 4.5. The figure clearly shows that during the pre-monsoon season, water demand gradually increased, particularly in March and April. This rise can be attributed to high evapotranspiration rates, irrigation requirements for summer crops (Boro rice), and limited rainfall. In the monsoon season, water demand reached its lowest point in August, primarily due to heavy rainfall and

waterlogged fields, which reduced the need for irrigation. As the post-monsoon season began, water demand started to rise again. This increase was driven by soil moisture depletion, winter crop cultivation (such as vegetables), and lower rainfall. The highest water demand was recorded in the dry season, as this period coincided with the full growth stage of winter vegetables and an absence of rainfall, making irrigation essential for sustaining crop production.

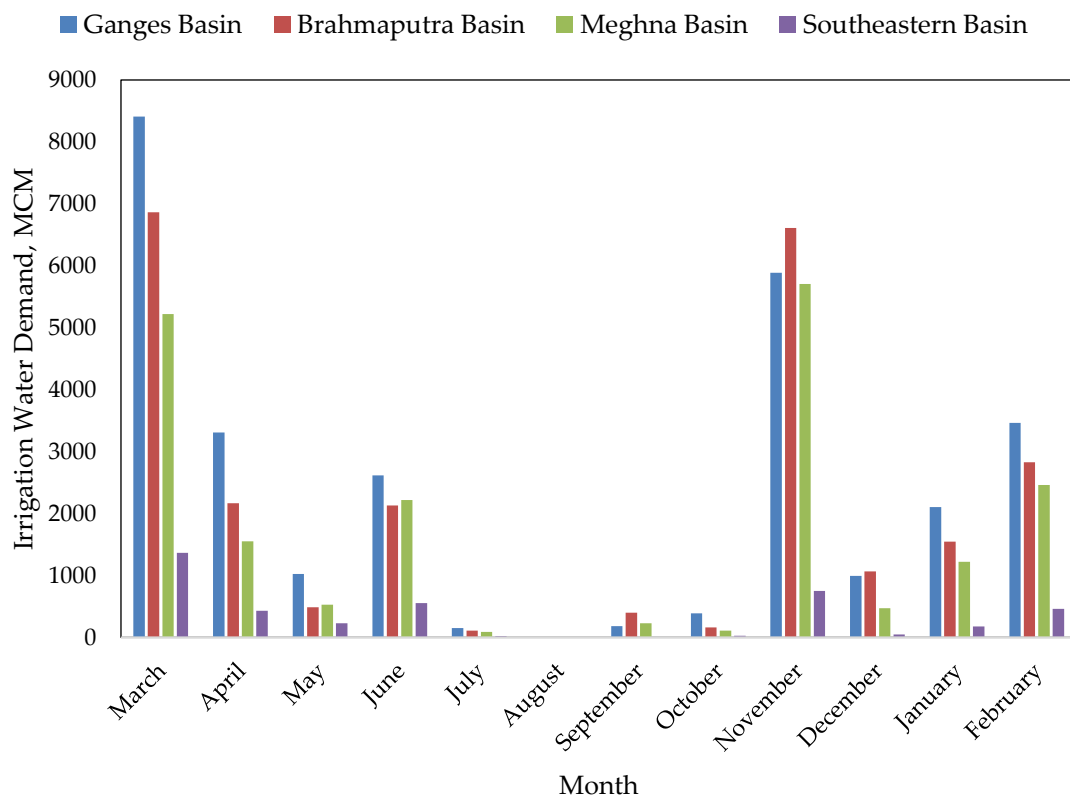


Figure 4.5: Monthly irrigation demand estimates for each basin

4.2 WATER SUPPLY

This study assesses three types of water supply sources of Bangladesh: Surface runoff from the rainfall, transboundary flow from transboundary rivers, and the groundwater recharge. As the water demand has been calculated for four seasons, similarly, the water supply across four major basins of Bangladesh has been computed for four seasons, such as pre-monsoon, monsoon, post-monsoon, and dry season.

4.2.1 Surface Runoff

The surface runoff, a potentially exploitable water source from precipitation, was estimated using the rational method. The runoff coefficient, a key parameter, was determined based on LULC data for each watershed. Table 4.7 presents the runoff volume across the four major basins. In 2021, Bangladesh generated approximately 118,384 MCM of runoff. The Ganges Basin, receiving the highest precipitation, recorded the most significant runoff volume, followed by the Ganges and Brahmaputra Basins. In contrast, the Southeastern Basin exhibited the lowest runoff volume due to its comparatively lower precipitation intensity.

Table 4.7: Monthly runoff volume variation in the basins

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	609.51	464.97	839.61	178.72
	April	2126.30	2086.00	3582.56	631.13
	May	4833.92	4384.92	6251.36	1255.22
Monsoon	June	6620.88	6166.87	7767.62	3587.22
	July	8955.74	5271.05	7871.29	3036.06
	August	7273.29	4953.74	6732.57	2375.24
	September	5999.71	4608.22	5306.28	1743.02
Post-monsoon	October	3029.79	1984.15	2860.98	1073.66
	November	525.67	159.23	458.52	140.94
Dry season	December	141.38	79.45	190.42	35.64
	January	182.84	92.40	96.79	32.51
	February	454.16	263.27	334.95	60.61

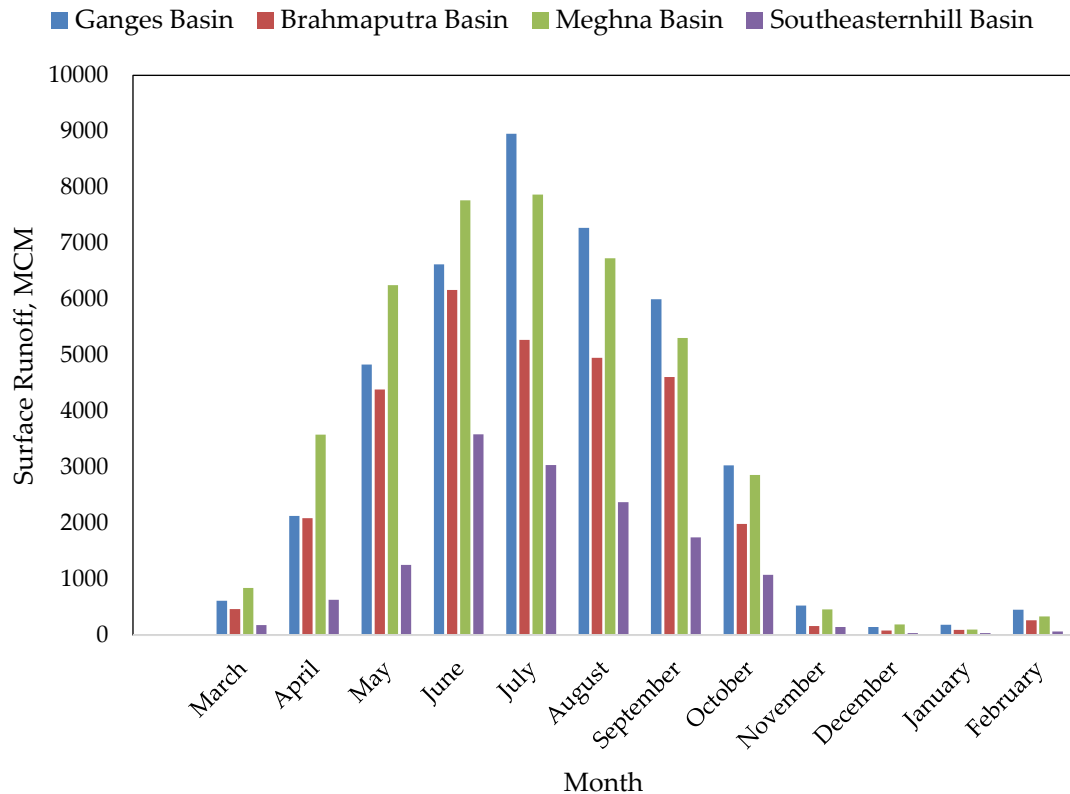


Figure 4.6: Monthly surface water runoff volume across the basin

Figure 4.6 presents a graphical representation of surface runoff volume. The runoff volume gradually increases during the pre-monsoon season, reaching its peak in the monsoon months, with the highest runoff observed in July. This variation is directly influenced by the rainfall received in the catchment area. As the monsoon retreats, the reduction in rainfall leads to a gradual decline in runoff, reaching minimal levels during the dry season.

Despite experiencing heavy monsoon rainfall, the Meghna Basin recorded the second-largest runoff volume among the four basins. This is because the Ganges Basin, with its larger catchment area, responds more gradually, accumulating higher runoff. Additionally, although the Meghna and Brahmaputra Basins receive substantial rainfall, their significant forest cover enhances infiltration, reducing direct runoff. In contrast, agricultural fields,

particularly in the Ganges Basin, become saturated quickly during the monsoon, contributing to sharp runoff peaks from June to August.

4.2.2 Groundwater Recharge

In this study, groundwater recharge was estimated using the Water Balance Method, which relies heavily on the precise calculation of other components of the water balance equation, particularly runoff and actual evapotranspiration. Based on ten years of climatic data, the monthly groundwater recharge volumes for the four major river basins of Bangladesh are presented in Table 4.8.

Table 4.8: Estimated monthly groundwater recharge for each basin

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	-1251.58	-813.96	-1167.87	-398.43
	April	-2525.00	-2176.04	-775.79	-557.31
	May	-2681.35	-1000.88	2594.19	1013.73
Monsoon	June	1686.49	1106.99	6192.21	9450.01
	July	5240.79	397.23	6016.45	7968.61
	August	2872.57	108.04	4621.76	5381.19
	September	1185.85	311.10	2913.62	3442.38
Post-monsoon	October	-1851.99	-1764.38	-165.38	1271.78
	November	-876.03	-407.73	-683.55	-278.02
	December	-464.76	-262.54	-401.66	-181.41
Dry season	January	-519.47	-280.99	-344.59	-192.86
	February	-856.05	-496.25	-610.95	-246.26

Analysis of the table reveals that total groundwater recharge is highest in the Southeastern Hill Basin, showing a significant positive value of 26,674 MCM,

followed by the Meghna Basin with 18,188 MCM. This high recharge can be attributed to the substantial rainfall these basins receive throughout the year, particularly during the monsoon season, which contributes to greater aquifer replenishment than abstraction. In the Southeastern Hill Basin, the hilly topography and highly permeable soil facilitate rapid infiltration and percolation of precipitation, enhancing groundwater recharge. The steep slopes and dense forest cover further aid in directing surface runoff toward streams or enabling it to be quickly absorbed into subsurface layers. Similarly, the Meghna Basin consists of floodplains and alluvial soils, which are naturally highly permeable, allowing both rainwater and river water to seep easily into aquifers.

In contrast, the Ganges and Brahmaputra Basins exhibit negative total groundwater recharge. These basins are densely populated and highly dependent on groundwater for irrigation, especially during the dry and pre-monsoon seasons. Although some recharge occurs during the monsoon, it is insufficient to offset the high volume of groundwater abstraction, resulting in a net deficit. Additionally, increasing urbanization in these regions contributes to the spread of impermeable surfaces, which restrict water infiltration and further reduce recharge potential, ultimately leading to negative groundwater balances.

Figure 4.7 illustrates the monthly and seasonal variations in groundwater recharge volumes across Bangladesh's four major river basins, measured in million cubic meters (MCM). The graph clearly shows that groundwater recharge is highly seasonal, with the monsoon period (June to September) being the primary contributor to positive recharge. During these months, intense rainfall promotes infiltration, leading to aquifer replenishment. In contrast, the pre-monsoon and dry seasons are marked by negative recharge values, reflecting a period dominated by groundwater withdrawal.

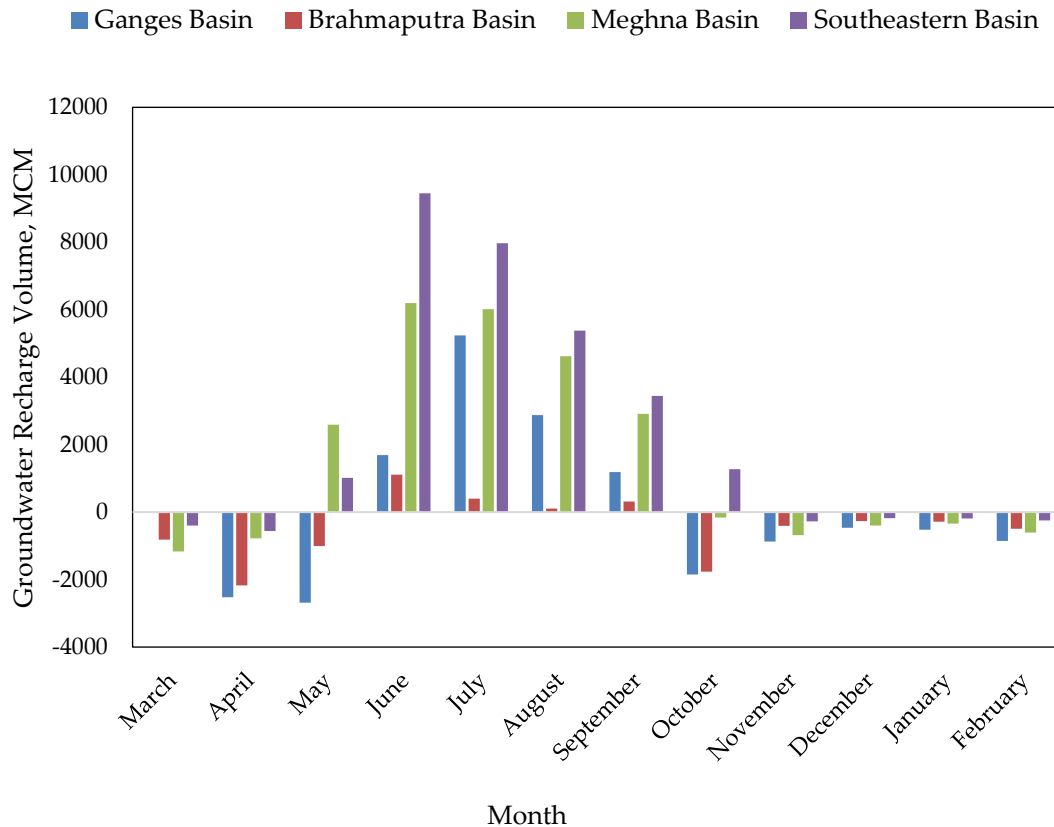


Figure 4.7: Estimated monthly groundwater recharge across basins

This trend is primarily due to low rainfall, high evapotranspiration rates, and intensive irrigation activities, particularly for Boro rice cultivation, which collectively lead to a decline in groundwater levels during these months. The post-monsoon season marks the beginning of a decline in groundwater recharge as rainfall decreases while water withdrawal continues.

This monthly variation in recharge highlights an imbalance in groundwater management, where aquifers are increasingly stressed to meet growing water demands, particularly in intensively used basins such as the Ganges and Brahmaputra. This pattern necessitates the urgent need for improved groundwater governance, including strategies such as Managed Aquifer Recharge (MAR), to promote long-term sustainability and resilience of groundwater resources.

4.2.3 Transboundary Flow

In this study, the estimation of transboundary flow has been conducted for each basin using discharge data spanning more than 10 years. Bangladesh receives nearly 1000 billion cubic meters of transboundary flow annually, a value close to the estimated flow volume provided by the Ministry of Water Resources, confirming the validity of the results. The monthly transboundary water flow across the four basins of Bangladesh is presented in Table 4.9, and Figure 4.8 illustrates the seasonal variations in Bangladesh's transboundary flow.

Table 4.9: Transboundary flow volume across basins

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	2794.68	11765.12	72.61	17.28
	April	2561.68	19286.02	661.78	21.20
	May	3817.67	38044.85	1771.31	39.69
Monsoon	June	10167.69	76773.80	3381.11	416.30
	July	54557.77	128025.33	4142.41	657.73
	August	89601.97	111633.99	4487.28	506.67
	September	83738.77	99976.47	3240.29	325.14
Post-monsoon	October	47363.11	62925.86	1933.83	217.86
	November	16993.78	27493.01	449.48	58.58
Dry season	December	10017.48	17728.13	109.36	28.07
	January	5657.95	13463.84	77.00	23.28
	February	3326.35	9846.37	46.96	16.40

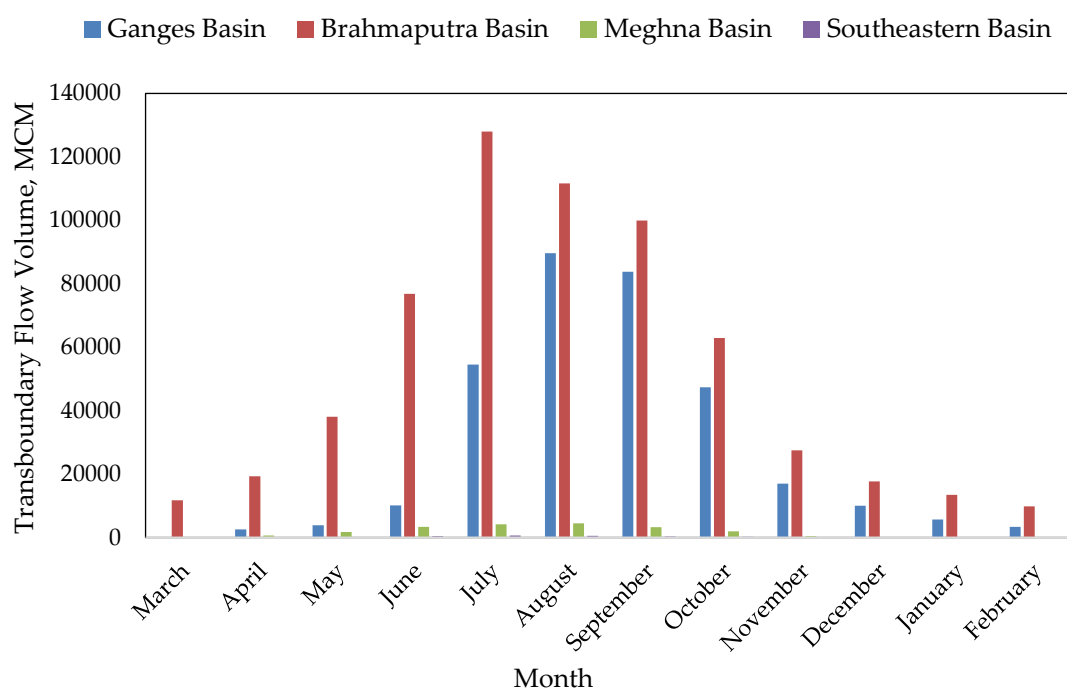


Figure 4.8: Monthly variation of transboundary flow across four basins

From Figure 4.8, it is evident that, among the four basins, the Brahmaputra Basin contributes the most water, followed by the Ganges and Teesta Basins. Ganges and Teesta rivers, however, are highly regulated through dams and barrages upstream, particularly by India, which significantly controls their flow, resulting in lower flow volumes. In contrast, the Brahmaputra has fewer major upstream water control measures, allowing more water to flow into Bangladesh.

While the GBM (Ganges-Brahmaputra-Meghna) system is the major water system, the Brahmaputra stands out as the most uninterrupted upper stretch. Several factors influence the seasonal variability in transboundary flow volumes across all basins. During the monsoon, South Asia experiences heavy rainfall, which feeds the rivers and increases their discharge. Conversely, in the dry season, there is a natural decline in discharge due to limited precipitation in the region, reducing the upstream flow. In the pre-monsoon season, the flow volume is the lowest due to minimal to no rainfall. Additionally, the water stored in the river systems from the previous monsoon season has already been depleted, naturally reducing the flow volume. Each basin shows a strong monsoonal

dependence on its flow pattern, with over 70-80% of the annual flow occurring during the monsoon season.

Focusing on the Ganges Basin, the Ganges Water Sharing Treaty between India and Bangladesh guarantees Bangladesh a minimum flow of 35,000 cusecs (991 MCM/month) during alternate periods, depending on the available flow. The low dry season flows in the Ganges Basin align with this regulated water release.

The Southeastern Hill Basin shows the lowest transboundary flow due to the smaller catchment area of the rivers in this basin compared to the others. The terrain in this basin is hilly and mountainous, which results in fast-flowing rivers that are often steep and narrow. Additionally, the Southeastern Hill Basin has fewer major transboundary rivers, which contribute a small amount of water to the overall flow.

In conclusion, effective water management among the shareholders of the same river basins is essential to ensure the distribution of water and sustainable water resources.

4.3 POTENTIAL STORAGE CAPACITY

The Storage capacity for each basin was estimated using the mass curve approach, a widely recognized method in water resources planning. The process began by calculating the monthly net water balance, obtained by subtracting the total water demand from the total water supply for each month. This step helps identify the periods of water surplus and deficit.

Following this, the cumulative water balance was computed by successively adding the net balances over the year. This cumulative data was used to generate the mass curve for each basin, which was further used to

estimate the minimum Storage capacity for each basin. The description of every step involved is discussed in the following sections.

4.3.1 Net Water Balance

Water surplus and deficit for each basin to gain insight into the water scarcity and abundance throughout the year. Table 4.10 presents the monthly basin-wise distribution of water surplus and deficit.

Table 4.10: Monthly water balance: surplus and deficit

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	-8422.97	-6914.67	-5954.52	-1654.30
	April	-2983.82	-589.36	1188.46	-424.51
	May	2206.39	15044.59	7965.05	1947.42
Monsoon	June	7665.69	598.63	5371.24	12481.36
	July	22903.78	2747.48	6153.06	10975.88
	August	9170.71	2187.13	4533.14	7596.70
	September	10116.16	2579.09	1907.28	5026.69
Post-monsoon	October	16654.90	9443.82	1383.07	2293.16
	November	-2057.46	-4852.74	-6599.32	-978.16
Dry season	December	2836.99	1811.24	-1195.64	-256.01
	January	-209.442	-206.08	-1891.46	-404.53
	February	-2610.96	-2016.43	-3073.31	-702.69

The table clearly shows that there is a water surplus during the monsoon season, as this period brings increased runoff, transboundary flow, and groundwater recharge. The negative values indicate water deficits during the dry season, primarily due to high irrigation demands. The highest water deficit occurs in March, mainly due to the cultivation of Boro rice, a dominant crop during this time. A water deficit is also observed in November, as most winter

crops are planted, leading to increased water demand and contributing to water scarcity.

While Bangladesh experiences both water scarcity and abundance throughout the year, the overall water balance remains positive, indicating that water is available. However, effective management of water distribution is crucial to mitigating water scarcity.

4.3.2 Cumulative Water Balance

The cumulative water balance for each month has been estimated by adding the water balance of the previous month to the net water balance. Table 4.11 represents the cumulative water balance across four basins.

Table 4.11: Cumulative water balance analysis

Season	Month	Ganges Basin (MCM)	Brahmaputra Basin (MCM)	Meghna Basin (MCM)	Southeastern Hill Basin (MCM)
Pre-monsoon	March	-8422.97	-6914.67	-5954.52	-1654.30
	April	-11406.79	-7504.03	-4766.06	-2078.80
	May	-9200.40	7540.55	3198.99	-131.39
Monsoon	June	-1534.71	8139.18	8570.23	12349.97
	July	21369.07	10886.66	14723.29	23325.86
	August	30539.77	13073.80	19256.43	30922.55
	September	40655.94	15652.89	21163.71	35949.25
Post-monsoon	October	57310.84	25096.71	22546.78	38242.41
	November	55253.38	20243.97	15947.46	37264.25
Dry season	December	58090.38	22055.21	14751.82	37008.24
	January	57880.94	21849.13	12860.36	36603.71
	February	55269.98	19832.69	9787.05	35901.02

4.3.3 Mass Curve Formation

A Mass curve represents the cumulative water balance plotted over time, providing insight into the temporal distribution of surplus and deficit. Based on the cumulative water balance calculated in the previous section, mass curves have been developed for all four basins and are presented in Figure 4.9.

These curves are particularly useful for reservoir planning, as they provide the maximum storage requirement needed to bridge the gap between the excess water and water shortage. By analyzing the lowest point, the minimum storage capacity can be determined.

4.3.4 Minimum Storage Capacity

After generating the mass curve (cumulative balance plot) for each basin, the maximum negative cumulative balance was identified. This value represents the minimum required potential storage capacity for each basin, the minimum storage volume necessary to meet water demands during periods of shortage. The need for this storage arises primarily due to consecutive months of water deficit. Ensuring this volume is available helps prevent seasonal water scarcity. Table 4.12 presents the estimated minimum storage capacities for each basin.

From the table, it is evident that the Ganges Basin requires the highest storage capacity, while the Southeastern Hill Basin requires the least. This variation is closely linked to basin size and the extent of water shortage. The Ganges Basin experiences the highest annual deficit, thus demanding greater storage whereas the Southeastern Hill Basin, being the smallest in all basins and with lower water demand, shows the least requirement for storage capacity.

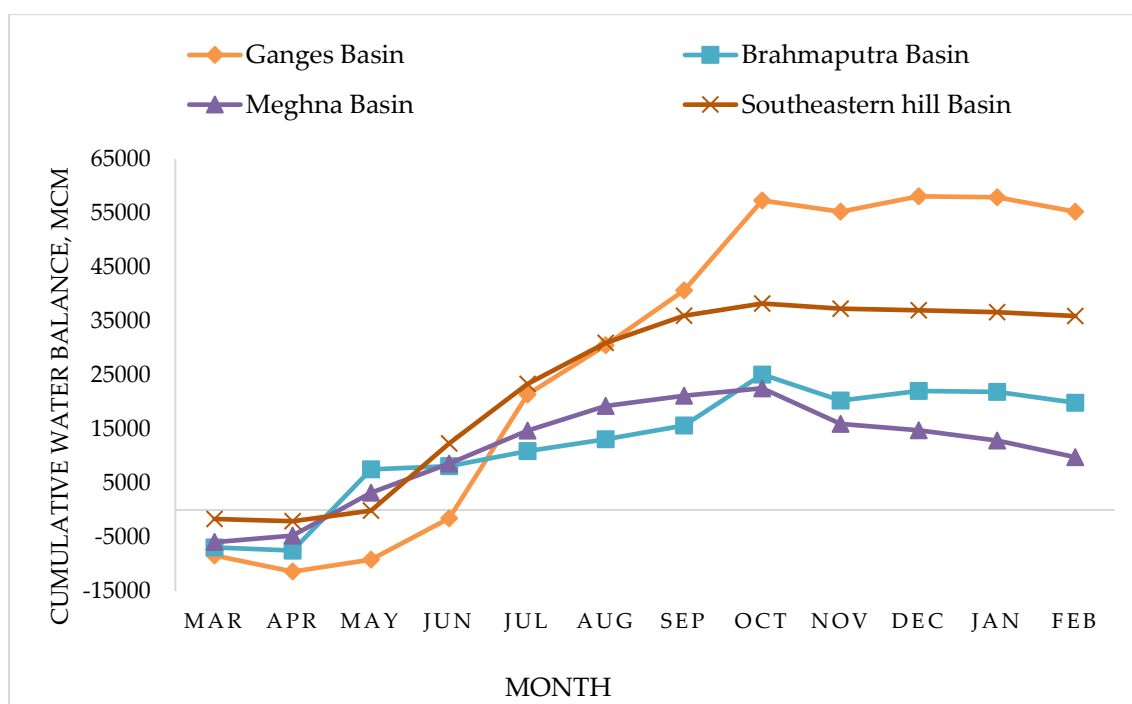


Figure 4.9: Comparative mass curve profiles of four basins

Table 4.12: Basin-wise minimum storage capacities

Basin name	Minimum storage capacity (MCM)
Ganges Basin	11407
Brahmaputra Basin	7505
Meghna Basin	6000
Southeastern Hill Basin	2100

4.4 MONTHLY CONSERVATION OF WATER

To distribute water evenly from the months of excess water to the months of water scarcity, a storage allocation ratio was determined. Firstly, the required storage capacity has been increased to 30% and 50% of the minimum required capacity. The Storage to Allocation Ratio (SAR) has been determined from the required Storage capacity and the total excess water throughout the year. Table

4.13 represents the required storage capacity and storage to allocation ratio across four basins.

Table 4.13: Storage-to-allocation ratios with estimated required storage capacity

Basin name	Required storage capacity (MCM) (30%)	Required storage capacity (MCM) (50%)	Storage to Allocation Ratio (SAR) (30%)	Storage to Allocation Ratio (SAR) (50%)
Ganges Basin	14830	17200	0.216	0.249
Brahmaputra Basin	9760	11300	0.299	0.345
Meghna Basin	7800	9000	0.286	0.313
Southeastern Hill Basin	2730	3200	0.068	0.077

With this allocation ratio, the excess water from May to October has been identified to be stored to avoid water shortages, as presented in Table 4.14. The data presented in the table indicate that the utilization of both increments yields the requisite potential storage capacity. The 50% increment presents a more prudent strategy considering differential losses. This study recommends adopting a 50% increase in minimum required storage capacity to enhance water conservation efforts, thus ensuring improved readiness for any rise in demand.

Table 4.14: Required monthly conservation storage capacities

Month	Ganges Basin (MCM)		Brahmaputra Basin (MCM)		Meghna Basin (MCM)		Southeastern Hill Basin (MCM)	
	30%	50%	30%	50%	30%	50%	30%	50%
percentage								
May	480	550	4510	5192	2280	2495	140	150
June	1660	1910	180	207	1540	1682	850	965
July	4950	5704	840	950	1760	1927	750	846
August	1980	2284	660	755	1300	1420	520	585
September	2190	2520	780	890	550	600	350	388
October	3600	4150	2850	3260	400	435	160	177

4.5 DISCUSSION

This chapter presents the results of each component assessed across the four major hydrological basins of Bangladesh: the Ganges, Brahmaputra, Meghna, and Southeastern Hill basins. Monthly water demand and availability have been illustrated through graphical representations, highlighting significant spatial and temporal variations. The findings reveal that irrigation constitutes the highest share of water demand, followed by environmental flow requirements. Water demand peaks during the dry months, while water availability is predominantly concentrated during the wet season. This imbalance between supply and demand varies across both time and region. To address this disparity, the study introduces a storage allocation ratio, estimating the volume of excess wet-season water that should be conserved to meet the requirements of the dry season. This strategic estimation offers practical guidance for developing basin-specific storage and water management plans.

4.5.1 Ganges Basin

The Ganges basin illustrates seasonal variability in water demand and availability, driven by its diverse geographical features, topography, and climatic conditions. It is the largest of the four principal basins in Bangladesh. It is predominantly characterized by flat terrain with limited drainage capacity and low natural water retention, primarily due to the presence of sandy loam soils. The basin has a high population density and is extensively used for agricultural purposes. Rainfall distribution across the basin is highly uneven, with some areas receiving minimal precipitation and others experiencing substantial rainfall.

Water demand peaks during the monsoon season, particularly in August, primarily due to environmental water requirements necessary to maintain ecological integrity and support aquatic ecosystems. Long and wide stream channels further necessitate base flow maintenance, especially in downstream regions. Beyond the monsoon period, significant water demand is observed in

March and November, predominantly for irrigation purposes. This period is crucial due to the unavailability of sufficient water. March corresponds to the peak of Boro rice cultivation, while November corresponds to winter vegetable farming, both of which are highly water-intensive.

Conversely, water availability is maximized during the monsoon season, with July recording the highest supply due to intense rainfall, increased surface runoff, transboundary inflows, and potential groundwater recharge. In contrast, the dry season is marked by minimal water availability, leading to a substantial water deficit.

To mitigate the seasonal imbalance between water demand and supply, an estimated storage capacity of 17,200 million cubic meters (MCM) is required for the Ganges Basin. Analysis of storage allocation suggests that approximately 25% of the surplus water generated during the wet season should be retained for use during dry periods, while the remaining 75% may be safely released to natural watercourses or the ocean. Notably, given its contribution to peak water inflows within the basin, July represents the optimal month for water conservation.

4.5.2 Brahmaputra Basin

The Brahmaputra basin has diverse topography, ranging from steep upstream Himalayan regions to relatively flat terrain in the downstream stretches. The basin falls within a subtropical monsoon climatic zone, experiencing high annual precipitation, particularly in June, which coincides with increased river discharge and surface runoff. The topographical gradient facilitates rapid overland flow, significantly contributing to surface runoff volumes.

During the monsoon season, total water demand peaks, predominantly driven by environmental flow requirements in major rivers such as the Teesta and the Brahmaputra. These flows are essential for maintaining ecological balance. The natural hydrological regime of the Brahmaputra River, which

remains unaltered mainly by infrastructure such as dams or reservoirs, results in high discharge levels from July to September, corresponding to the highest environmental flow demand among all river basins in Bangladesh. Irrigation water demand is most prominent during the pre-monsoon (March) and post-monsoon (November) periods. This pattern aligns with the agricultural calendar, particularly for Boro rice cultivation and winter cropping, which require supplemental irrigation due to limited rainfall during these months. Moreover, the Brahmaputra Basin records the highest domestic water demand among all basins, attributed to its high population density.

On the supply side, the basin benefits from the highest transboundary water flow, as it receives substantial inflows from neighbouring countries through its extensive river networks. However, groundwater recharge is the lowest among all four basins, owing to the predominance of pervious surface soils, which limit retention. Recharge activity is mostly confined to the monsoon period, from June to September.

To mitigate seasonal variations between demand and supply, a storage capacity of 11,300 MCM has been estimated using the mass curve method. Based on a Storage to Allocation Ratio (SAR) of 0.345, it is recommended that approximately 34.5% of excess water from the wet season be conserved for use during dry months, while the remaining volume can be safely released into natural systems. Among the monsoon months, May exhibits the highest surplus water, making it the most suitable period for conservation interventions.

4.5.3 Meghna Basin

The Meghna basin, situated in the northeastern region of Bangladesh, receives the highest annual rainfall in the country. Areas such as Sylhet and Sree Mangal are among the wettest zones, primarily influenced by the subtropical monsoon climate and the orographic lifting of moist air masses along the hilly

terrain. This topographical feature significantly enhances precipitation in the basin.

The total water demand in the Meghna Basin exhibits marked seasonal variation, with the peak occurring during the monsoon months, predominantly driven by environmental water requirements. In August, this demand alone surpasses 11,000 MCM, the highest among all months. However, due to its comparatively smaller area than the Ganges and Brahmaputra basins, the overall demand remains lower.

In terms of water supply, the basin experiences maximum groundwater recharge due to intense rainfall and high soil permeability. The highest water availability is observed in June and July, coinciding with peak rainfall, substantial surface runoff, and notable transboundary inflows.

Despite the high rainfall, the water balance reveals a significant deficit during the dry months, particularly in March and November, due to increased irrigation demand. To mitigate these imbalances, a storage capacity of 9,000 MCM has been estimated using the mass curve approach. Based on the storage to allocation ratio (SAR) of 0.313, approximately 31.3% of monsoon surplus water should be conserved for use during water-scarce periods. May and July have been identified as the most suitable months for water conservation due to their substantial surplus volumes.

4.5.4 Southeastern Hill Basin

This basin is the smallest among all the major basins in Bangladesh and is in the southeastern region of the country. It is characterized by hill ranges and narrow valleys, with steep slopes and undulating terrain that distinguish it from the relatively flatter landscapes of other basins. This basin encompasses the Chittagong Hill Tracts, including districts such as Bandarban, Khagrachari, and Rangamati.

Due to its smaller population and limited agricultural activity, the total water demand in this basin remains relatively low. The number of rivers in the region is also limited, and these rivers exhibit lower flow volumes compared to those in the Ganges, Brahmaputra, and Meghna basins. Water demand peaks in March, driven by irrigation requirements, while August shows zero irrigation demand, as extensive rainfall during this month sufficiently meets crop water needs.

From the supply perspective, this basin records the highest groundwater recharge among all basins in Bangladesh, sustained throughout the monsoon season and extending into October. Despite this, the transboundary flow contribution remains minimal due to the limited number of transboundary rivers. Additionally, lower evaporation rates in the region result in less negative groundwater flow values during the dry season compared to other basins.

While the basin experiences water deficits during the dry and pre-monsoon periods, it also shows the highest water surplus during the monsoon season. To manage this seasonal imbalance, a storage capacity of 3,200 MCM has been estimated using the mass curve approach. With a Storage to Allocation Ratio (SAR) of 0.077, only 7.7% of the surplus water needs to be stored to ensure adequate supply during dry months. Despite receiving the highest monsoonal inflow relative to its demand, the storage requirement remains the lowest due to limited dry season water needs. June stands out as the month with the highest surplus volume and the largest amount of conserved water for future use.

4.6 CONCLUDING SUMMARY

The subsequent section presents the concluding summary of the findings of this study:

- The Brahmaputra basin experiences the highest domestic water demand because of its substantial population.

- Industrial water demand peaks in the Ganges basin due to high industrial labor concentration.
- The demand for environmental flow is at its peak in the Brahmaputra basin due to the highest discharge recorded in the Brahmaputra River.
- The demand for irrigation water is highest in the Ganges basin, driven by expansive irrigation fields, larger basin sizes, and increased evaporation.
- The southeastern basin shows minimal water demand, attributable to its smaller area, restricted irrigation land, abundant rainfall, and reduced river discharge.
- The Meghna basin experiences the highest volume of surface runoff due to heavy and frequent rainfall.
- Groundwater recharge has not been observed in the Ganges basin, and there is evidence of groundwater overexploitation in the Brahmaputra basin. In contrast, the southeastern basin exhibits the greatest potential for groundwater recharge.
- The Brahmaputra basin exhibits the highest transboundary flow volume, attributed to its extensive upstream catchment area.
- The water deficit occurs during the dry season, while a surplus is observed in the monsoon season. Even the Meghna basin faced water scarcity in the pre-monsoon season.
- A 50% increment has been chosen over a 30% increase due to a more water-conservative approach with the minimum storage capacity.
- The annual surplus of water supply is thirty-two times the deficit, only the deficit amount needs to be retained and the remaining surplus can be discharged to the sea. Dredging of the river bed can preserve some excess water in the natural stream, that indicates an efficient use of water resources for the country as a whole.

Chapter 5: CONCLUSION

5.1 GENERAL

The water demand and supply scenario in Bangladesh presents a complex and challenging situation that requires sustainable solutions. With a rapidly growing population, urbanization and industrialization the demand for water has surged, placing significant pressure on the available water resources. Bangladesh faces various issues such as over extraction of groundwater, impacts of climate change, changes in precipitation patterns and the sea level rise.

From this study, it can be concluded that water resources have become inadequate and scarce in the dry season. As for the wet season, the surplus water is available after fulfilling the existing demand. Excessive extraction of groundwater in the dry season causes the lowering of the groundwater level which will cause the unavailability of groundwater. Without an adequate water supply, industries and agricultural firms that rely heavily on groundwater may be forced to close, resulting in a national disaster as workers become unproductive and fisheries may be destroyed.

In Bangladesh, the water sector receives the least attention from the Government. To alleviate Bangladesh's water stress, the government must prioritize and implement water management strategies. It is necessary to understand the water shortage and surplus to build a sustainable water supply. The deficit during the dry season can be reduced by utilizing the water surplus. Furthermore, the reserve water can be used to generate electricity as well as for recreational purposes. This study provides the base for sustainable water use and management-related planning, projection, and action.

5.1.1 Key Findings

From the water balance study of Bangladesh, the key findings are summarized as follows:

1. **Spatial variation across basins:** Bangladesh's four major hydrological basins—Brahmaputra, Ganges, Meghna, and the Southeastern Hill basin—exhibit distinct topographic and hydrological characteristics. These differences are crucial in shaping the seasonal dynamics of water demand, availability, and storage capacity in each region.
2. **Seasonal trends in water demand:** The total water demand has been assessed at approximately 1017 BCM, with the environmental flow (E-flow) requirements constituting the largest portion at 931 BCM. This is followed by irrigation needs, which account for 77 BCM, domestic consumption at 8.5 BCM, and industrial usage at 0.2 BCM. While the E-flow demand is the highest, it is influenced by the trends in water availability. The demand for irrigation water is particularly critical, especially during the dry season when it is most essential.
3. **Patterns of water supply:** Bangladesh has approximately 1138 BCM of renewable water resources, comprising surface runoff volume represented by 128 BCM, groundwater recharge volume indicated by 39 BCM, and transboundary flow volume denoted by 970 BCM. Each of these components follows seasonal trends influenced by rainfall, as they rely entirely on precipitation.
4. **Water deficit and water surplus:** The annual water surplus has been identified at 1748 BCM, while a deficit is noted only at 54 BCM, indicating an absence of water stress across the country. Nonetheless, an analysis of seasonal water balance reveals that water deficits are present in each basin during the dry season, specifically in the Ganges basin and

southeastern basin during the pre-monsoon season, as well as in the Meghna basin during the post-monsoon season.

5. **Storage capacity and allocation ratio:** The estimated storage requirement is highest in the Ganges basin and lowest in the Southeastern Hill basin. However, when comparing storage to allocation ratios, the Brahmaputra basin has the highest, while the Southeastern Hill basin has the lowest.
6. **Optimal months for water conservation:** In order to optimize the use of excess water during the dry season, the monthly water conservation requirements have been determined based on an analysis of the average demand and supply over an eleven-year period. The months of May and June are particularly highlighted as optimal for implementing water conservation initiatives, as all basins generally exhibit a surplus during this time.

5.1.2 Limitations of the Study

Despite providing insights on water demand, water availability, and storage requirements across four major basins, this study has several limitations:

1. In terms of industrial water demand, the primary data had not been identified. The industrial water requirements at different stages were not clearly defined.
2. For transboundary river flow, only the discharge data for rivers with available information were considered, potentially leading to underestimation.
3. This study assumes that current water use patterns remain relatively constant. It does not consider the potential impacts of climate change, urbanization, or future population growth.

5.1.3 Practical Implications

This study comprehensively estimates water demand and availability across all major river basins of Bangladesh, offering valuable insights for policymakers and water resource planners.

Sector-Specific Water Demand: The analysis identifies the water requirements for key sectors such as domestic, industrial, agricultural (irrigation), and environmental flow, which will assist policymakers in developing targeted water allocation strategies.

Environmental Flow Requirements: The study highlights the minimum environmental flow needed to sustain the ecological health of major rivers, contributing to effective river basin management and ecosystem preservation.

Renewable Water Availability: The assessment of basin-wise water availability estimates renewable and exploitable water resources, aiding in sustainable planning and development of surface and groundwater use.

Storage Capacity Planning: This study estimates the required storage capacity for each basin using the mass curve approach. It helps policymakers understand how much surplus water needs to be conserved to offset seasonal deficits, especially during dry months. This method applied in this study can also identify the storage capacity for any year, considering the changed water demand and supply.

Mitigating Seasonal Water Stress: These findings support the formulation of integrated water resource management (IWRM) strategies to minimize seasonal water stress while ensuring the sustainable fulfillment of water demands across all sectors.

5.1.4 Recommendation for Further Study

In this study, the simplest method requiring the least data has been selected. However, several recommendations can be made for further research:

1. For industrial water demand, collecting real-time data from various industries will help more accurately reflect the actual scenario.
2. For environmental flow demand, alternative approaches such as hydraulic methods can be considered for more precise results. The Range of Variability Approach (RVA) may offer better outcomes in rivers with hydraulic alterations.
3. For the water balance analysis, including other hydrological components such as evaporation, infiltration, and subsurface baseflow, could provide a complete and more accurate picture.
4. Further studies can also explore the feasibility of storage capacity in each basin and evaluate the suitability of the proposed storage.

References

- Adham, M. I., Jahan, C. S., Mazumder, Q. H., Hossain, M. M. A., & Haque, A. M. (2010). Study on Groundwater Recharge Potentiality of Barind Tract, Rajshahi district, Bangladesh Using GIS and Remote Sensing technique. *Journal of the Geological Society of India*, 75(2), 432–438. <https://doi.org/10.1007/s12594-010-0039-3>
- Ahmed, F., & Rahman, M. (2007). *Water Supply and Sanitation* (Third). ITN-Bangladesh.
- Ahmed, T. (2013). Transboundary Flow and Water Management in Bangladesh. *Water Resources in South Asia: Conflict to Cooperation*.
- Akter, A., & Ali, M. H. (2012). Environmental Flow Requirements Assessment in the Halda River, Bangladesh. *Hydrological Sciences Journal*, 57(2), 326–343. <https://doi.org/10.1080/02626667.2011.644242>
- Akter, F., Prattoyee, F. T., Hossain, Md. A., Rannu, R. P., Murad, K. F. I., & Hossain, Md. S. (2023). Irrigation Requirement for Chickpea Cultivation in Gazipur and Rajshahi Districts of Bangladesh. *Journal of Bangladesh Agricultural University*, 21(3), 343. <https://doi.org/10.5455/jbau.154395>
- Ali, A., Haq, Z., & Khurram Sheraz, E. Dr. (2025). Review on Estimation and Forecast of Reference Evapotranspiration. *International Journal of Agriculture and Sustainable Development*.
- Ali, M. H., & Mubarak, S. (2017). Approaches and Methods of Quantifying Natural Groundwater Recharge – A Review. *Asian Journal of Environment & Ecology*, 5(1), 1–27. <https://doi.org/10.9734/AJEE/2017/36987>
- Ali, M. H., Zaman, M. H., Islam, M. A., & Biswas, P. (2019). Estimation of Groundwater Recharge Using Tracer and Water Balance Method, Bangladesh. *Journal of Agricultural Engineering*, 42/AE(Number 1), 75–82.
- Ali, Md. H., Hasanuzzaman, Md., Islam, Md. A., & Biswas, P. (2022). Groundwater Recharge Estimation at Barind Area, Bangladesh for Sustainable Groundwater Management: Application of Multiple Methods. *European Journal of Environment and Earth Sciences*, 3(6), 23–29. <https://doi.org/10.24018/ejgeo.2022.3.6.312>
- Amin, R. Al, Hossain, M. B., & Yunus, A. (2021, March). Estimation of Crop Water Requirements and Irrigation Scheduling of Rice in South-Eastern Region of Bangladesh Using FAO-CROPWAT 8.0. *Proceedings of the 5th International Conference on Advances in Civil Engineering (ICACE 2020)*.
- Archana, K., Reddy, S. R., Vengala, J., & Nayak, A. K. (2024). Optimization of Irrigation Requirements for the Markonahalli Command Area Using the

- SWAT Model. *Journal of Engineering (United Kingdom)*, 2024. <https://doi.org/10.1155/je/8480722>
- Arthington, A. H., Bhaduri, A., Bunn, S. E., Jackson, S. E., Tharme, R. E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A. C., Kendy, E., McClain, M. E., Poff, N. L. R., Richter, B. D., & Ward, S. (2018). The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). In *Frontiers in Environmental Science* (Vol. 6, Issue JUL). Frontiers Media S.A. <https://doi.org/10.3389/fenvs.2018.00045>
- Aziz, Md. T., Islam, Md. R., Kader, Z., Imran, H. M., Miah, M., Islam, Md. R., & Salehin, M. (2023). Runoff Assessment in the Padma River Basin, Bangladesh: a GIS and RS Platform in the SCS-CN Approach. *Journal of Sedimentary Environments*, 8(2), 247–260. <https://doi.org/10.1007/s43217-023-00133-x>
- Bangladesh Cement Manufacturers Association. (2023). *Overview of Cement Industry*.
- Barua, S., Barua, A., & Mullick, Md. R. A. (2016). *Renewable Water Resources and an Overall Water Demand Availability Analysis for Bangladesh*.
- BBS. (2019). *Survey of Manufacturing Industries*.
- BBS. (2023). *Statistical Yearbook of Bangladesh*.
- Bredenkamp, D., Botha, L. J., Van Tonder, G. J., & Janse Van Rensburg, H. (1995). *Manual on Qualitative Estimation of Groundwater Recharge and Aquifer Storativity, Based on Practical Hydrological Methods*.
- Bryant, P. S., Malcolm, E. W., & Woitkovich, C. P. (1995). Pulp and Paper Mill Water Use in North America. *Environmental Conference Proceedings*.
- BWDB. (2020). *Annual Flood Report. Flood Forecasting and Warning Centre. Bangladesh Water Development Board*.
- Chaturvedi, G., Jain, R. K., Singh, K., & Kulkarni, A. G. (2006). *Indian Paper Industry- Growth and Prospects*.
- Chaturvedi, R. S. (1973). *A Note on the Investigation of Groundwater Resources of Uttar Pradesh*.
- Chowdhury, M., & Sato, Y. (1996). Flood Monitoring in Bangladesh: Experience from Normal and Catastrophic Floods. *Journal of Japanese Association of Hydrological Sciences*, 26, 152–241.
- Chowdhury, MD. R., & Ward, N. (2004). Hydro-Meteorological Variability in the Greater Ganges–Brahmaputra–Meghna Basins. *International Journal of Climatology*, 24(12), 1495–1508. <https://doi.org/10.1002/joc.1076>
- Dixit, S., Singh, V. K., Shivam, Ankit, Roshan, V. K., Tiwari, S. N., Mathur, A., Akram, M., & Ali, K. (2024). Comprehensive Review of Crop Water Requirement Estimation Techniques: Approaches, Challenges, and Future Directions. *International Journal of Environment and Climate Change*, 14(11), 664–670. <https://doi.org/10.9734/ijecc/2024/v14i114576>
- Dyson, Megan., Bergkamp, G. J. Jacobus., & Scanlon, John. (2003). *Flow : the Essentials of Environmental Flows*. IUCN--the World Conservation Union.

- Emami, M., Ahmadi, A., Daccache, A., Nazif, S., Mousavi, S. F., & Karami, H. (2022). County-Level Irrigation Water Demand Estimation Using Machine Learning: Case Study of California. *Water (Switzerland)*, 14(12). <https://doi.org/10.3390/w14121937>
- Emerging Credit Rating Limited. (2017). *Fertilizer Industry of Bangladesh Volume-I*.
- FAO. (2011). *Ganges-Brahmaputra-Meghna Basin*.
- FAO. (2014). *Country Survey on Water Use for Agriculture and Rural Development*. Rome: FAO.
- Fiamelda, L., Suprihatin, & Purwoko. (2020). Analysis of Water and Electricity Consumption of Urea Fertilizer Industry: Case Study PT. X. *IOP Conference Series: Earth and Environmental Science*, 472(1), 012034. <https://doi.org/10.1088/1755-1315/472/1/012034>
- Garg, S. K. (2005). *Irrigation Engineering and Hydraulic Structures* (2nd Edition).
- Gereffi, G., & Frederick, S. (2010). *The Global Apparel Value Chain, Trade and the Crisis: Challenges and Opportunities for Developing Countries*.
- Grindley, J. (1967). The Estimation of Soil Moisture Deficits. *Meteorological Magazine*, 97–108.
- Hairan, M. H., Jamil, N. R., Azmai, M. N. A., Looi, L. J., & Camara, M. (2021). Environmental Flow Assessment of a Tropical River System Using Hydrological Index Methods. *Water (Switzerland)*, 13(18). <https://doi.org/10.3390/w13182477>
- Haque, M. P., & Chowdhury, S. M. K. H. (2020). Trend of Irrigation Water Requirement in Halda River Basin of Bangladesh. *Journal of Science Technology and Environment Informatics*, 10(1), 673–684. <https://doi.org/10.18801/jstei.100120.68>
- Hasan, M. R., Nuruzzaman, M., & Mamun, A. Al. (2019). Contribution of Rainwater to the Irrigation Requirement for Paddy Cultivation at Tanore Upazila in Rajshahi, Bangladesh. *Air, Soil and Water Research*, 12. <https://doi.org/10.1177/1178622119837544>
- Helles, Z., & Mogheir, Y. (2023). Quantification of Surface Runoff Using Different Methods (Case Study: Waqf Infiltration Basin in the Gaza Strip). *Israa University Journal of Applied Science*, 7(1), 1–26. <https://doi.org/10.52865/FJTA8487>
- Hendrickx, J. M. H., & Walker, G. R. (1992). Recharge of Phreatic Aquifers in Semi Arid Areas. In *Journal of Environmental Quality* (Vol. 21, Issue 3). Wiley. <https://doi.org/10.2134/jeq1992.00472425002100030036x>
- Hossain, L., & Khan, M. S. (2017). Blue and Grey Water Footprint Assessment of Textile Industries of Bangladesh. *Fifth International Conference on Chemical Engineering (ICChE 2017) Energy, Environment and Sustainability*.
- Hosseini, S. M., & Nezamoleslami, R. (2018). Water Footprint and Virtual Water Assessment in Cement Industry: A Case Study in Iran. *Journal of Cleaner Production*, 172, 2454–2463. <https://doi.org/10.1016/j.jclepro.2017.11.164>

- Islam, M. A., & Imran, A. H. (2019). *Identification of Potential Zones for Natural Groundwater Recharge in Dhaka City of Bangladesh*.
- Islam, M. N. (2015). *Leather Sector and Tannery Industry in Bangladesh: Bureau of Manpower Employment and Training*.
- Islam, M. R., Mizan, M. H., Akter, M., & Zakaria, G. (2017). Assessment of Crop and Irrigation Water Requirements for Some Selected Crops in Northwestern Bangladesh. *Global Journal of Science Frontier Research*.
- Islam, M. T., Hossain, M. B., Roy, D., Mahmud, M. N. H., Paul, P. L. C., Yesmin, M. S., & Kundu, P. K. (2023). Behaviour of Groundwater Table with Rainfall in North-West Region of Bangladesh. *Bangladesh Rice Journal*, 25(2), 85–95. <https://doi.org/10.3329/brj.v25i2.62710>
- Islam, R., Islam, M. N., & Islam, M. N. (2017). Impacts of Bangabandhu Jamuna Multi-purpose Bridge on the Dynamics of Bar Morphology at the Jamuna River in Bangladesh. *Modeling Earth Systems and Environment*, 3(3), 903–925. <https://doi.org/10.1007/s40808-017-0342-8>
- Jahan K, Nowreen S, & Hossain S. (2015). *Trends of Groundwater Recharge in North West Region of Bangladesh using Groundwater Table Fluctuation Method*.
- Joy, M. N. H., Mumu, E. J., Muzahid, A. H. N., & Jahan, M. (2024, December). GIS and RS-Based Delineation of Groundwater Recharge Potential Zones in Bogra Using AHP. *7th International Conference on Advances in Civil Engineering (ICACE 2024)*. <https://www.researchgate.net/publication/390119794>
- Kanji, S. (2024). A Review of Empirical Methods for Runoff Estimation and Their GIS Applications. *International Journal for Research in Applied Science and Engineering Technology*, 12(1), 141–152. <https://doi.org/10.22214/ijraset.2024.57889>
- Kanoua, W., & Merkel, B. J. (2015). Groundwater recharge in Titas Upazila in Bangladesh. *Arabian Journal of Geosciences*, 8(3), 1361–1371. <https://doi.org/10.1007/s12517-014-1305-2>
- Karakoyun, Y., Dönmez, A. H., & Yumurtacı, Z. (2018). Comparison of Environmental Flow Assessment Methods with a Case Study on a Runoff River-Type Hydropower Plant Using Hydrological Methods. *Environmental Monitoring and Assessment*, 190(12). <https://doi.org/10.1007/s10661-018-7107-3>
- Karimi, S. S., Yasi, M., & Eslamian, S. (2012). Use of Hydrological Methods for Assessment of Environmental flow in a River Reach. *International Journal of Environmental Science and Technology*, 9(3), 549–558. <https://doi.org/10.1007/s13762-012-0062-6>
- Khan, W. (2014). Leather Industry in Bangladesh: Opportunities and Challenges. *American Journal of Trade and Policy*, 1(3), 119–126. <https://doi.org/10.18034/ajtp.v1i3.373>
- Khandaker, F., & Rahman, M. A. (2020, February). Assessment of Environmental Flow Requirement of Teesta River by Hydrological Methods. *5th*

- International Conference on Civil Engineering for Sustainable Development (ICCESD 2020).*
- Kirchner, J., Van Tonder, G., & Lukas, E. (1991). *The Exploitation Potential of Karoo Aquifers.*
- Kolas, A., Barkved, L. J., Bhattacharjee, J., Edelen, K., Hoelscher, K., Holen, S., Jahan, F., Jha, H. B., & Mikilan, J. (2013). *Water Scarcity in Bangladesh: Transboundary Rivers Conflict and Cooperation. PRIO Report.*
- Krishna Rao, P. R. (1970). *Hydrometeorological Aspects of Estimating Groundwater Potential.*
- Kumar, A. U., & Jayakumar, K. V. (2018). Assessment of Environmental Flows Using Hydrological Methods for Krishna River, India. *Advances in Environmental Research*, 7(3), 161–175. <https://doi.org/https://doi.org/10.12989/aer.2018.7.3.161>
- Kumar Adhikary, S. (2014). *Estimating Shallow Groundwater Recharge from Precipitation and Water Level Observations.* <https://www.researchgate.net/publication/269463008>
- Kumar, C. P., & Seethapathi, P. V. (2002). Assessment of Natural Groundwater Recharge in Upper Canal Command area. *Journal of Applied Hydrology*, 15(4), 12–20.
- Mahmud, M. N. H., Roy, D., Paul, P. L. C., Hossain, M. B., Yesmin, M. S., Kundu, P. K., & Islam, M. T. (2023). Natural Groundwater Recharge: A Review on the Estimation Methods. *Bangladesh Rice Journal*, 25(2), 45–56. <https://doi.org/10.3329/brj.v25i2.62706>
- Masum, A. Al, Biswas, R., Opu, R. K., & Islam, S. (2014). Irrigation Water Requirement Estimation for Wheat by FAO Penman-Monteith Method: A Case Study of Barind Area. *International Journal of Advanced Research.*
- Meherin, N. (2024). *Comparative Evaluation of Groundwater Recharge Estimation Methods- A Review.*
- Mitu, K. A., Hossain, M. M., Chikita, K. A., & Hossain, M. S. (2019). *Development of Rainfall-Runoff Model for Northeast Region of Bangladesh.*
- Modi, P., Ghasidas Vishwavidyalaya, G., Rao Chintalacheruvu, M., & Kale, R. V. (2017). RAINFALL-RUNOFF SIMULATION USING HEC-HMS MODEL FOR SUTLEJ RIVER BASIN, INDIA. <https://www.researchgate.net/publication/337108135>
- Mohsenipour, M., Shahid, S., Ziarh, G. F., & Yaseen, Z. M. (2020). Changes in monsoon rainfall distribution of Bangladesh using quantile regression model. *Theoretical and Applied Climatology*, 142(3–4), 1329–1342. <https://doi.org/10.1007/s00704-020-03387-x>
- Mojid, M. A., Shibly, F. Y., & Acharjee, T. K. (2020). Trends of Water Requirements of Major Crops and Cropping Patterns in Bogura and Rajshahi Districts of Bangladesh. *Agricultural Science*, 2(1), p170. <https://doi.org/10.30560/as.v2n1p170>

- Mortier, R., Block, C., & Vandecasteele, C. (2007). Water Management in the Flemish Steel Industry: The Arcelor Gent Case. *Clean Technologies and Environmental Policy*, 9(4), 257–263. <https://doi.org/10.1007/s10098-007-0102-y>
- Mullick, M. R. A., Babel, M. S., & Perret, S. R. (2010). Flow Characteristics and Environmental Flow Requirements for the Teesta River, Bangladesh. *International Conference on Environmental Aspects of Bangladesh, Japan*.
- Munna, G. M., Hasan, M. M., Alam, M. J. Bin, Uddin, M. M., Rahman, M. S., Nury, A. H., & Islam, S. (2024). Modeling Flow of the Major Canals of Sylhet City Using the EPA SWMM Runoff Model. *Water Practice and Technology*, 19(3), 887–899. <https://doi.org/10.2166/wpt.2024.038>
- Muthu, A. C. L., & Santhi, M. H. (2015). Estimation of Surface Runoff Potential using SCS-CN Method Integrated with GIS. *Indian Journal of Science and Technology*, 8(28). <https://doi.org/10.17485/ijst/2015/v8i28/83324>
- Nur, F., Mohib, K. M., Toma, U. T., Khandaker, F., Rozario, P. M., Bari, M. S., Anjum, N., & Khandakar, F. (2022). *Rainfall-Runoff Simulation of Khowai River Basin Using HEC-HMS Model*.
- Olabiyyi, W., Frank, E., Joyce, J., & Joyce, S. (2024). *Groundwater Recharge Mechanisms*. <https://www.researchgate.net/publication/385791183>
- Paul, H., Antunes, P., Covington, A. D., Evans, A. D., & Phillips, P. S. (2017). Bangladeshi Leather Industry: An Overview of Recent Sustainable Developments. *Journal- Society of Leather Technologists and Chemists*.
- Pial, M. A. M., & Khan, T. I. (2022). Analyzing Groundwater Potential Zones Using AHP, RS and GIS Techniques in Bishwamvarpur Upazila, Bangladesh. *Sust Journal of Science and Technology*, 32, 10–29.
- PJ, J. (2018). Evaluation of the Conceptual Basis of the Rational Method. *International Journal of Hydrology*, 2(6). <https://doi.org/10.15406/ijh.2018.02.00145>
- Prattoyee, F. T., Hasan, F. R. M. R., Nahid, I. K., & Faruq, M. O. (2021). Modelling Net Irrigation Water Requirements and Irrigation Scheduling of Boro Rice Using FAO-CROPWAT 8.0 and CLIMWAT 2.0: A Case Study of Rajshahi Regions, Bangladesh. *Journal of Global Ecology and Environment*, 13(2), 1–11.
- Praveen, G. D., & Krishnaiah, C. (2017). Comparative Analysis of Empirical Models Derived Groundwater Recharge Estimation in Venkatapura Watershed, Karnataka . *International Journal of Research and Scientific Innovation IV (VIS)*.
- Rahman, M. S., Khatun, S., & Rahman, M. K. (2016). Sugarcane and Sugar Industry in Bangladesh: An Overview. *Sugar Tech*, 18(6), 627–635. <https://doi.org/10.1007/s12355-016-0489-z>
- Rahman, Md. M., & Kabir, K. B. (2010). Wastewater Treatment Options for Paper Mills Using Recycled Paper/Imported Pulps as Raw Materials: Bangladesh Perspective. *Chemical Engineering Research Bulletin*, 14(1). <https://doi.org/10.3329/cerb.v14i1.5236>

- Rahman, Md., Mahmud, Md., Ferdous, H., Sultana, N., & Sayed, A. (2016). Assessment of Irrigation Water Requirement of Maize Crop for Different Tillage Practices in Bangladesh. *American Journal of Experimental Agriculture*, 10(5), 1–10. <https://doi.org/10.9734/ajea/2016/21654>
- Ramachandra, T. V., Nagar, N., Vinay, S., & Aithal, B. H. (2014). Modelling hydrologic regime of Lakshmanatirtha watershed, Cauvery river. *2014 IEEE Global Humanitarian Technology Conference - South Asia Satellite, GHTC-SAS 2014*, 64–71. <https://doi.org/10.1109/GHTC-SAS.2014.6967560>
- Ranjan, S., & Singh, V. (2022). HEC-HMS based rainfall-runoff model for Punpun river basin. *Water Practice and Technology*, 17(5), 986–1001. <https://doi.org/10.2166/wpt.2022.033>
- Rasul, M. G., Faisal, I., Masud, M., & Khan, K. (2006). Environmental Pollution Generated from Process Industries in Bangladesh . *International Journal of Environment and Pollution*, 28(2).
- Restiani, P. (2016). *Water Governance Mapping Report: Textile Industry Water Use in India Focus on the Faridabad-Ballabgarh Textile Cluster in the State of Haryana*.
- Roy, B., Rahman, A., & Dollan, I. J. (2021). Development of a Regression Model for Runoff of Surma River by Multiple Regression Analysis. *Proceedings of 5th International Conference on Advances in Civil Engineering (ICACE 2020)*.
- Rushton, K. R., Zaman, M. A., & Hasan, M. (2020). Monitoring Groundwater Heads and Estimating Recharge in Multi-Aquifer Systems Illustrated by an Irrigated Area in North-West Bangladesh. *Sustainable Water Resources Management*, 6(2). <https://doi.org/10.1007/s40899-020-00382-y>
- Sabzevari, T., Haghighi, A. T., Ghadampour, Z., Petroselli, A., & Namazi, H. (2024). Estimation of Regional Design Runoff Coefficient in the Rational Method. *Iranian Journal of Science and Technology - Transactions of Civil Engineering*, 48(1), 467–482. <https://doi.org/10.1007/s40996-023-01286-5>
- Sagris, T., Abbott, J., Arup, O., Songa, P., Hennayake, M., & Görlitz, S. (2015). *An Analysis of Industrial Water Use in Bangladesh with a Focus on the Textile and Leather Industries*. 2030 Water Resources Group.
- Saha, B., & Azam, F. A. Bin. (2021). Probable Ways of Tannery's Solid and Liquid Waste Management in Bangladesh – An Overview. *Textile & Leather Review*. <https://doi.org/10.31881/TLR.2020.25>
- Satheeshkumar, S., Venkateswaran, S., & Kannan, R. (2017). Rainfall–Runoff Estimation Using SCS–CN and GIS Approach in the Pappiredipatti Watershed of the Vaniyar Sub Basin, South India. *Modeling Earth Systems and Environment*, 3(1). <https://doi.org/10.1007/s40808-017-0301-4>
- Sen, R., Karim, N., Islam, M., Rahman, M., & Adham, A. (2019). Estimation of Actual Crop Evapotranspiration and Supplemental Irrigation for Aman rice Cultivation in the Northern Part of Bangladesh. *Fundamental and Applied Agriculture*, 0, 1. <https://doi.org/10.5455/faa.34264>
- Shahid, S. (2012). *Rainfall Variability and Changes in Bangladesh during the Last Five Years*. In *Rainfall: Behavior, Forecasting and Distribution*.

- Shamsudduha, M., Taylor, R. G., Ahmed, K. M., & Zahid, A. (2011). The impact of intensive Groundwater Abstraction on Recharge to a Shallow Regional Aquifer System: Evidence from Bangladesh. *Hydrogeology Journal*, 19(4), 901–916. <https://doi.org/10.1007/s10040-011-0723-4>
- Sifa, S. F., Nila, A. A., Hossain, A., & Hayat, T. (2024). Rainfall-Runoff Estimation in the North-Eastern Region of Bangladesh Using SCS-CN Method. *The Dhaka University Journal of Earth and Environmental Sciences*, 12(2), 83–96. <https://doi.org/10.3329/dujees.v12i2.73165>
- Stalnaker, C., Lamb, B., Henriksen, J., Bovee, K., & Bartholow, J. (1995). *The Instream Flow Incremental Methodology*.
- Suman, K. H., Hossain, M. S., Salam, M. A., Rupok, Q. S. S., & Haque, M. N. (2021). Production Trends, and Challenges for Biodiversity Conservation and Sustainable Fisheries Management of Kaptai Lake, the Largest Reservoir in Bangladesh. *Asian Fisheries Science*, 34(2). <https://doi.org/10.33997/j.afs.2021.34.2.004>
- Sun, J., Chen, L., Qi, P., & Zhang, G. (2024). *Agricultural Irrigation Water Requirement and Its Response to Climatic Factors Based on Remote Sensing and Single Crop Coefficient Method*. <https://doi.org/10.21203/rs.3.rs-4293162/v1>
- Sundar, J., Ramesh, R., Rao, P. S., Saravanan, P., Sridharnath, B., & Muralidharan, C. (2001). Water Management in Leather Industry. *Journal of Scientific and Industrial Research*, 60.
- Suwal, N., Kuriqi, A., Huang, X., Delgado, J., Młyński, D., & Walega, A. (2020). Environmental Flows Assessment in Nepal: The Case of Kaligandaki River. *Sustainability (Switzerland)*, 12(21), 1–23. <https://doi.org/10.3390/su12218766>
- Tewari, P. K., Batra, V. S., & Balakrishnan, M. (2009). Efficient water use in industries: Cases from the Indian agro-based pulp and paper mills. *Journal of Environmental Management*, 90(1), 265–273. <https://doi.org/10.1016/j.jenvman.2007.09.001>
- Tharme, R. E. (2003). A global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers. *River Research and Applications*, 19(5–6), 397–441. <https://doi.org/10.1002/rra.736>
- Thompson, D. B. (2006). *The Rational Method* *. <http://manuals.dot.state.tx.us/dynaweb/colbridg/hyd>
- Tithi, S. A., & Bari, Md. N. (2024). *Groundwater Recharge Modeling at Godagari using the Soil and Water Assessment Tool (SWAT)*. <https://doi.org/10.21203/rs.3.rs-5338641/v1>
- Uddin, A. A., & Baten, M. A. (2011). *Water Supply of Dhaka City: Murky Future Page*. Dhaka: Unnayan Onneshan.

Appendices

Appendix A: Flow Duration Curve

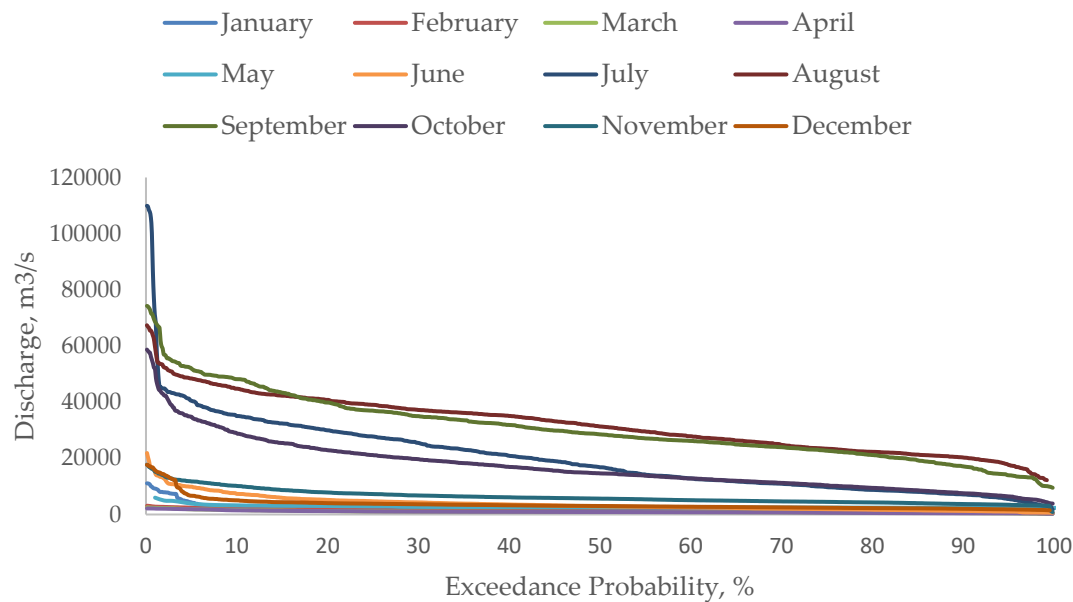


Figure A.1: Flow duration curve for SW 90

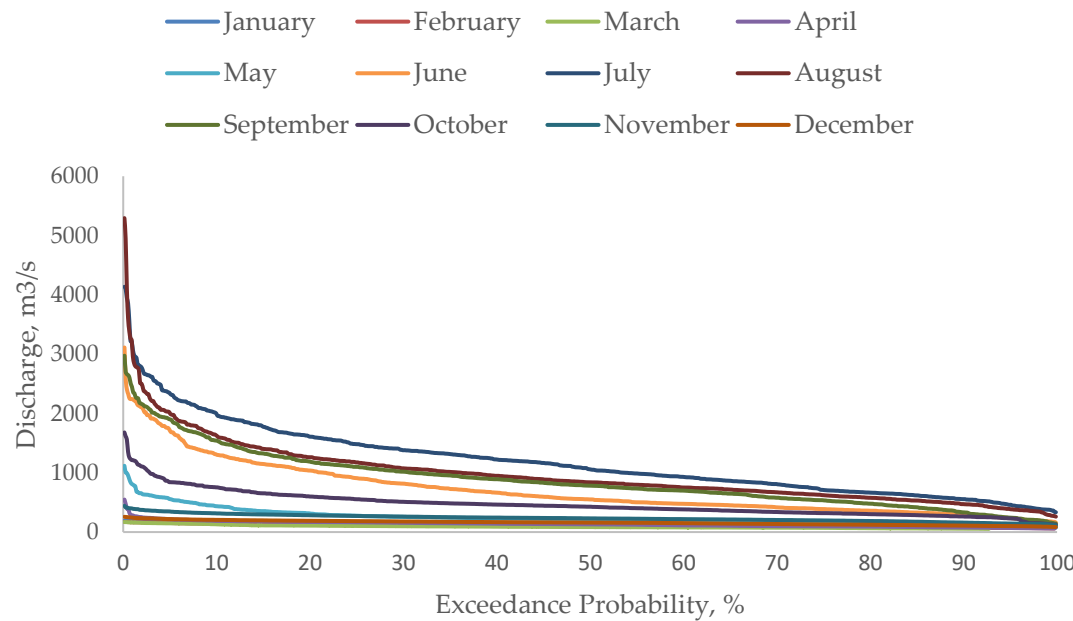


Figure A.2: Flow duration curve for SW 81

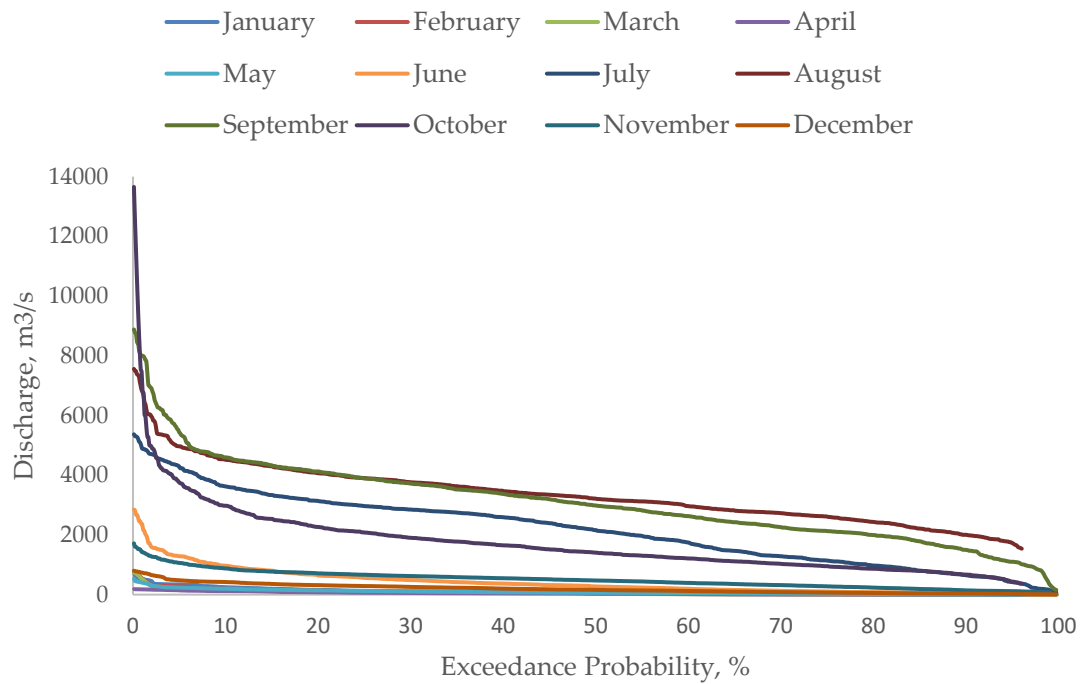


Figure A.3: Flow duration curve for SW 99

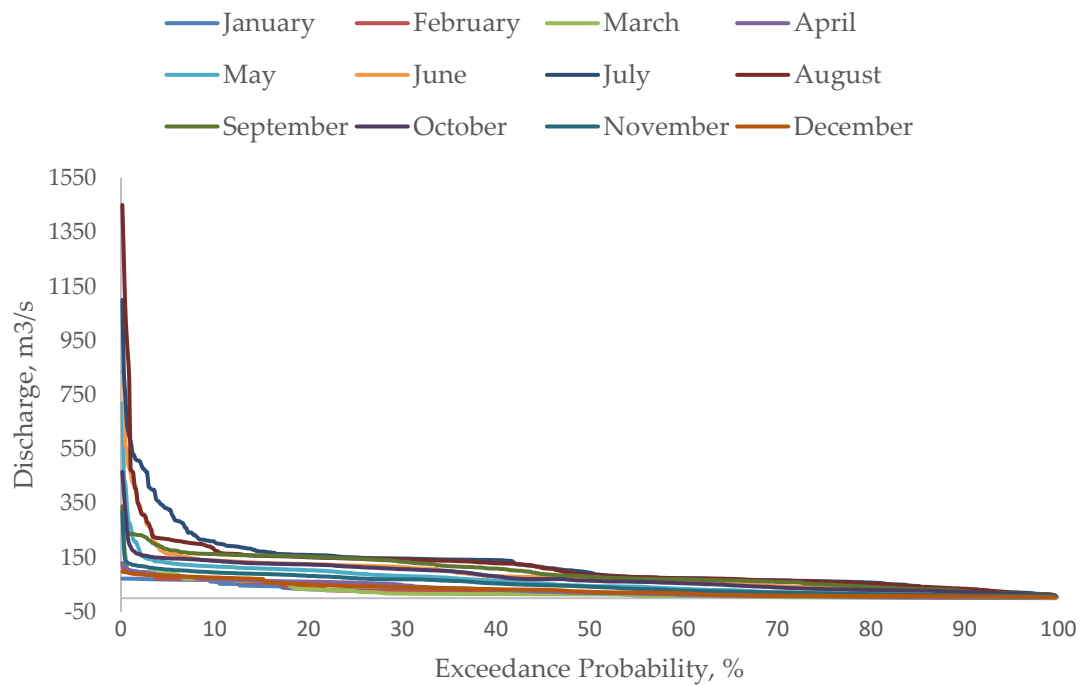


Figure A.4: Flow duration curve for SW 119.5

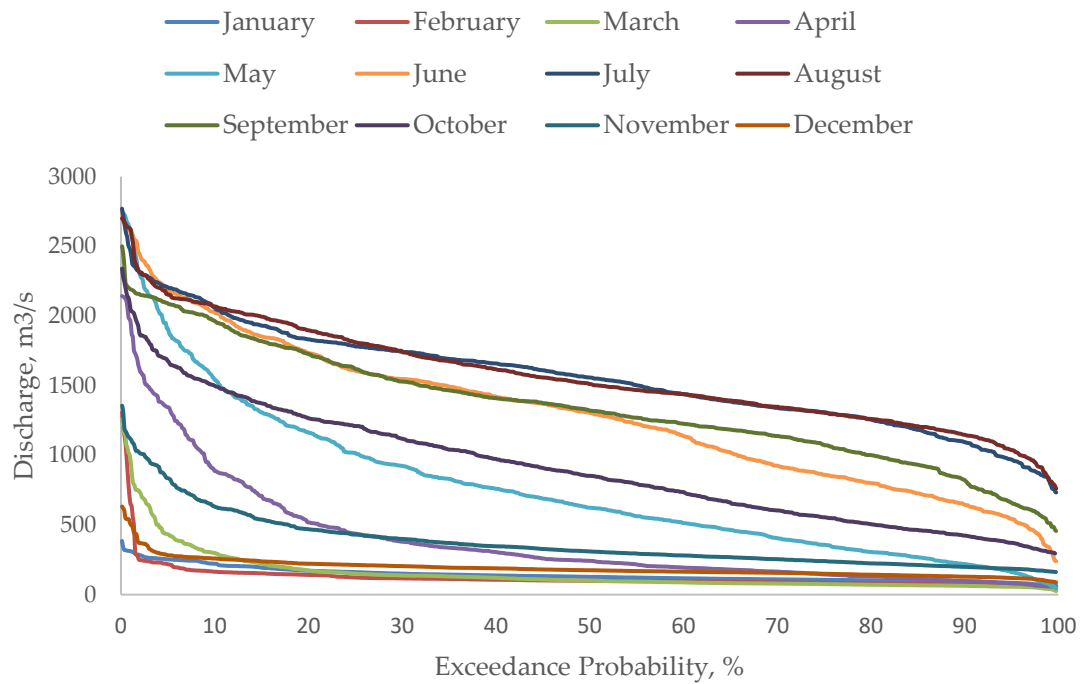


Figure A.5: Flow duration curve for SW 173

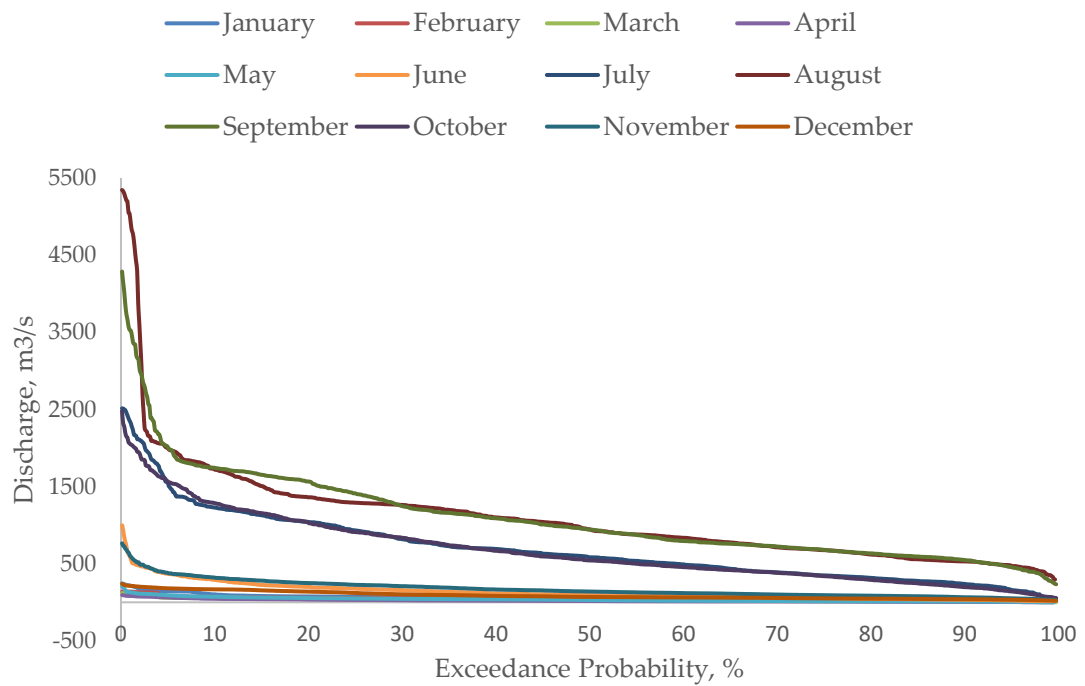


Figure A.6: Flow duration curve for SW 211.5

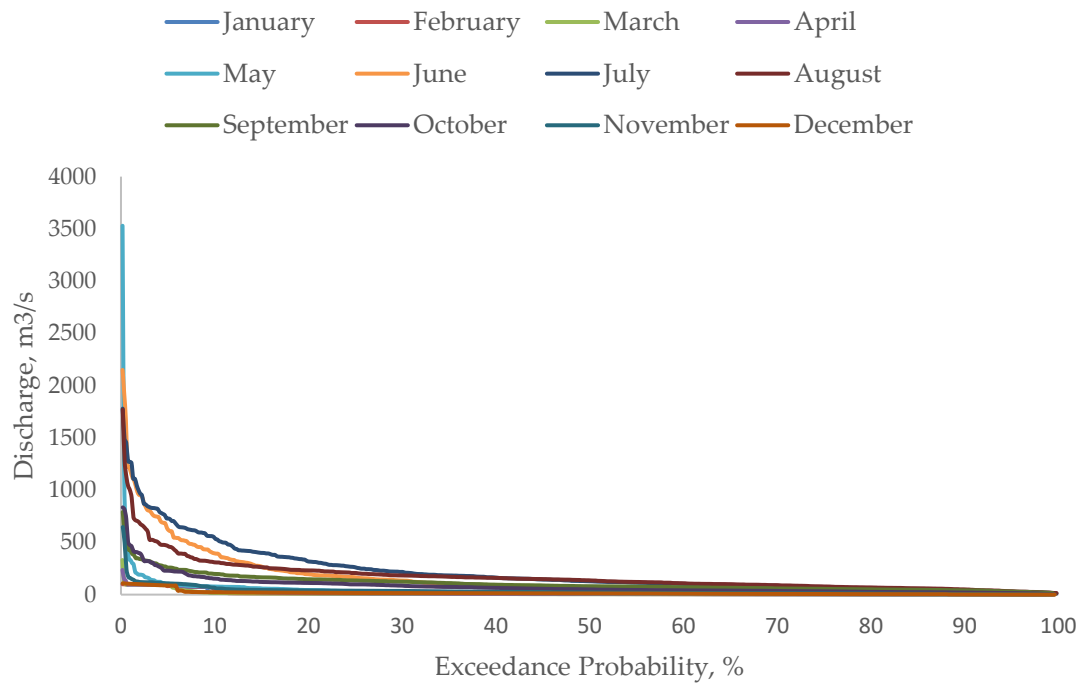


Figure A.7: Flow duration curve for SW 247

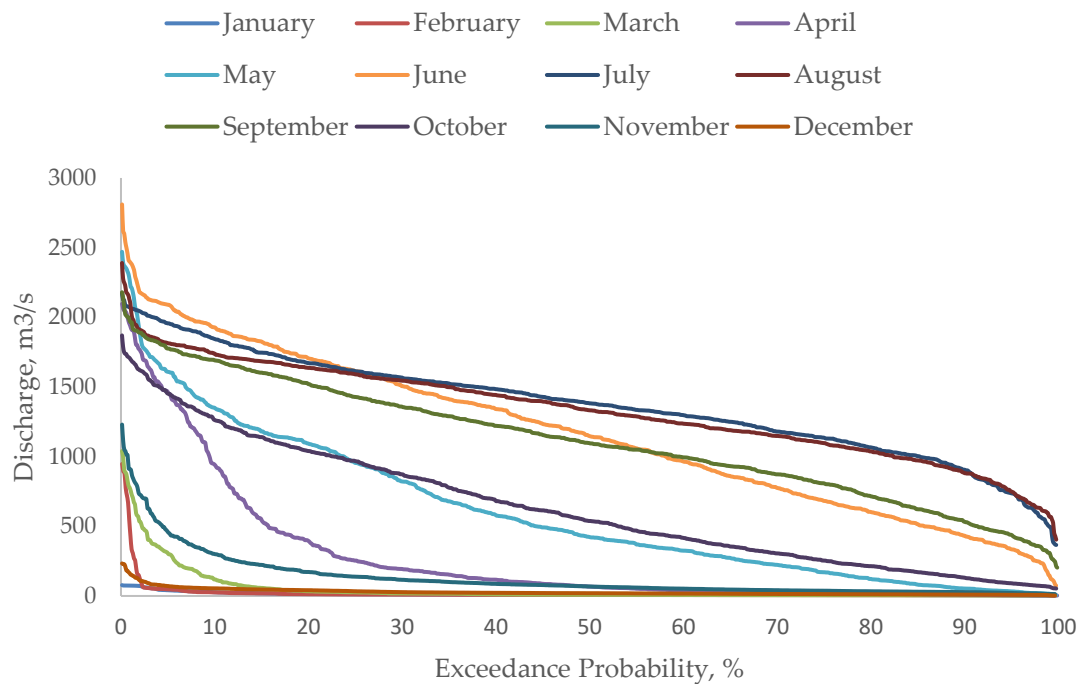


Figure A.8: Flow duration curve for SW 266

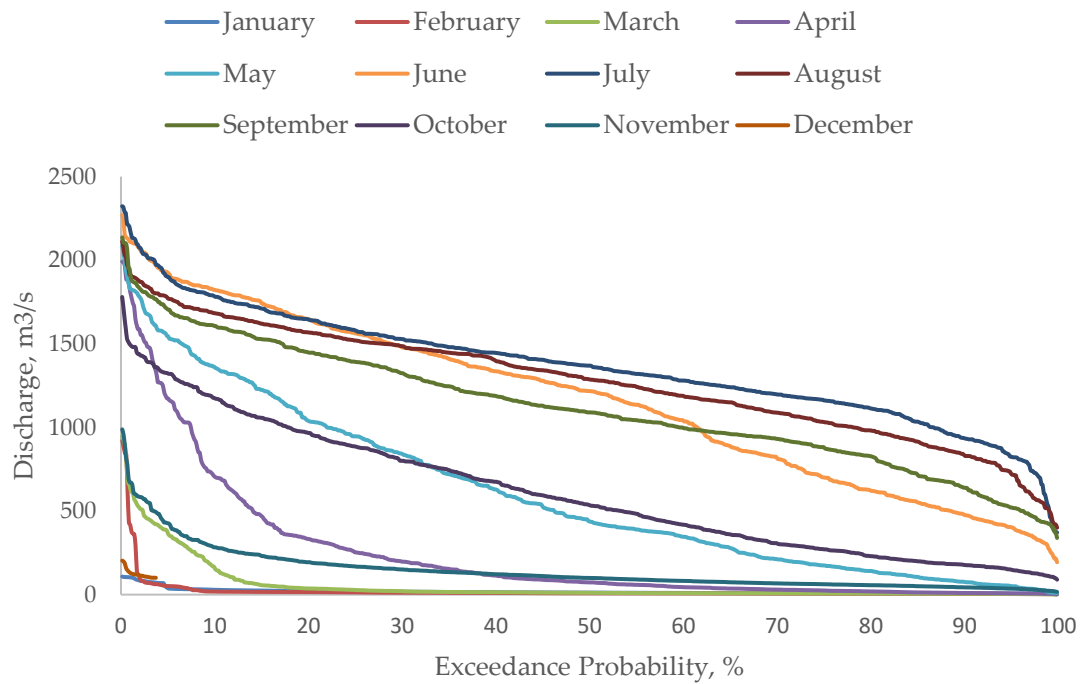


Figure A.9: Flow duration curve for SW 267

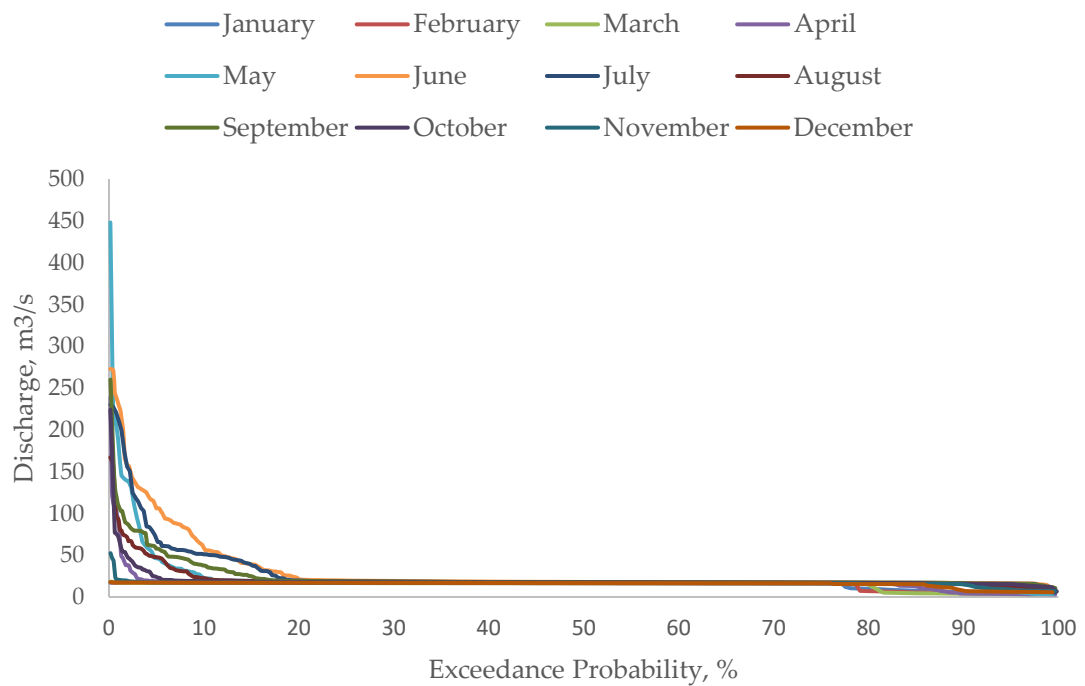


Figure A.10: Flow duration curve for SW 67

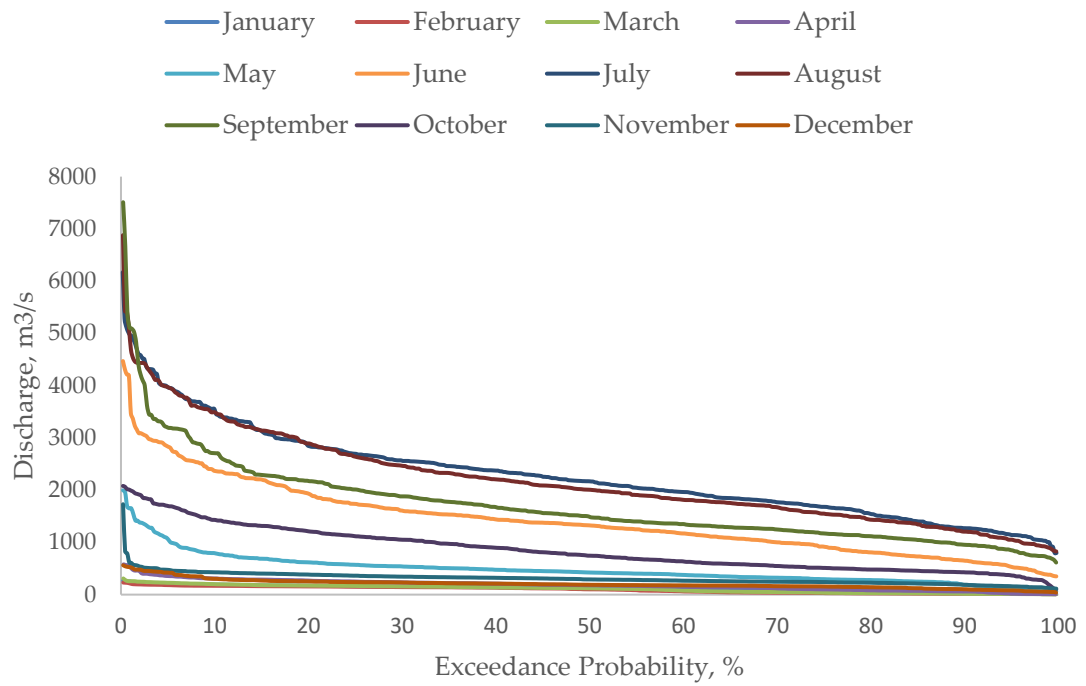


Figure A.11: Flow duration curve for SW 294

final draft

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