Water Footprint in the Context of Urban Water Management: Challenges and Opportunities

by

ALIK BANERJEE
201821004

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY
to

DHIRUBHAI AMBANI INSTITUTE OF INFORMATION AND COMMUNICATION TECHNOLOGY

December, 2023

Declaration

I hereby declare that

i) the thesis comprises of my original work towards the degree of Doctor of Philosophy at Dhirubhai Ambani Institute of Information and Communication Technology and has not been submitted elsewhere for a degree,

ii) due acknowledgment has been made in the text to all the reference material used.

Alik Banerjee

Certificate

This is to certify that the thesis work entitled WATER FOOTPRINT IN THE CONTEXT OF URBAN WATER MANAGEMENT: CHALLENGES AND OPPORTUNITIES has been carried out by ALIK BANERJEE for the degree of Doctor of Philosophy at *Dhirubhai Ambani Institute of Information and Communication Technology* under our supervision.

Prof. Alka Parikh
Thesis Supervisor

Prof. Mukesh Tiwari
Thesis Co-Supervisor

Acknowledgments

I want to express my profound appreciation to Professor Alka Parikh, my Thesis Supervisor, for her inestimable feedback and unwavering support throughout my thesis process. Her guidance has been necessary in shaping my exploration.

I am immensely thankful to Professor Mukesh Tiwari, my Co-Supervisor, for his active involvement in helping me shape my ideas throughout my thesis process.

Moreover, I thank Professor Ranendu Ghosh for his constant support and cooperation. His moxie and perceptivity played an essential part in shaping my ideas and defining the compass of my Thesis.

Furthermore, I would like to thank the Director of my institution and other faculty members who played a necessary part in spreading mindfulness about my thesis. Their backing has been invaluable.

I would also like to thank all the staff members of my institution. Their support has been greatly appreciated. Numerous thanks to my musketeers Viral, Swati, Sourav, Pranav, Apratim, Biswajit, Kalgi, Madhvi, Dhiraj, Bhargav, Sayan, and others who participated in their precious perspectives during my entire exploration Phase. I am genuinely thankful for their support.

Incipiently, I would like to thank my brothers Sandeep, Nishant, Mayank, and my other family members for their constant support in promoting my usability testing in completing this thesis.

Contents

Abstract

Water, a crucial resource in preserving the ecology in good shape, has become scarce. Water footprint (WF) measure has been proposed in the literature to understand this prevailing water crisis. The WF, which consists of green, blue, and grey, can be defined as the green water footprint (WF_{green}) that shows how much water is used by forests and non-irrigated agriculture; the blue water footprint (WF_{blue}), shows the amount of water used by irrigated agriculture, industry, and residences, and grey water footprint (WF_{grey}) shows how much water would be required to neutralize the pollution in the water and bring it back to the acceptable discharge water quality. This study conducted a comprehensive WF calculation in Purulia, Dhanbad, and Ranchi municipalities of West Bengal and Jharkhand, India. The primary reasons for choosing these municipalities were that they are water-scarce and have an inadequate municipal water supply system.

The researcher used published data to estimate WF. The results show WF_{green} values depict that Purulia reports the highest mean values (182.6 to 296.3 (M^3*10^3) per square kilometer (sq km)), followed by Dhanbad (170.3 to 241.2 (M^3*10^3) per sq km), and then Ranchi (131 to 219.2 (M^3*10^3) per sq km) for four consecutive years (2016-19). These figures imply that Purulia overuses its water resources in agriculture, and hence its high WF green needs to be corrected by increasing water productivity. Dhanbad's high WF is because of the water consumption by its forests. The high WF is not of concern given that the forests help hold up the soil and water. Ranchi's WF is low because it has less land under forests and agriculture.

Moreover, WF_{blue} values of 2019 illustrate that Ranchi reports the highest (108 M^3 per capita), followed by Purulia (81.5 M^3 per capita), and Dhanbad reports the

least (68.8 M^3 per capita). The primary factor for getting such results is high runoff followed by evaporation, and then the municipality supplies water. Therefore, Steps should be taken to retain the rainwater in some form in the soil and man-made channels.

In addition, this study examines the per capita per-day water availability among 272 sample households of different income classes to understand the ground-level situation. The result reports that slum dwellers are the worst sufferers since they do not get even the bare minimum amount of water – 70 lpcd, while affluent people living in apartments or bunglows suffer no shortage. The study finds that this inequality prevails because the primary water source is groundwater, accessibility to which depends on wealth ownership. As the residences change from poor to non-poor, people depend less on centralized water supply and more on tube wells/bore wells. This is because the water supplied through the municipality is not enough. Also, the correlation between sources of water and seasonal dearth shows significantly less value, which signifies that seasonal dearth does not relate to which water sources households are fetching the water from. Water quality is terrible for all income classes, but the rich can purify it through R-O.

Furthermore, the study also found that in the case of municipality water balance, all three municipalities are going through a deficit water balance. For Purulia, it is 14 (M^3*10^3) per day; for Dhanbad, it is 490.4 (M^3*10^3) per day; and for Ranchi, it is 439.6 (M^3*10^3) per day, respectively. This means that water withdrawal is far more than the recharge rate. Water availability is expected to be even more compromised as we move forward.

In such a situation, check dams, ponds, wells, reservoirs, etc., seem to be helping in water conservation. In addition, water recycling, as tried out by Surat Municipal Corporation, can also reduce WF. Based on these practical solutions, in the end, some policy recommendations are proposed for water conservation.

List of Principal Symbols and Acronyms

AMC Antecedent moisture Condition

BCM Billion cubic meters

$cumt$ Cubic meter

ET Evapotranspiration

$lpcd$ Liter per capita per day

$LULC$ Land use and land cover

mt Meter

RWH Rainwater harvesting

$sqkm$ Square kilometer

WF WF

WF_{blue} Blue WF

WF_{green} Green WF

WF_{grey} Grey WF

mm Millimeter

List of Tables

List of Figures

CHAPTER 1

Introduction

Water, a crucial resource for preserving the ecology in good shape [55], has become scarce and insecure [100]. Since the last decade, the water demand has increased more than twice the population growth, increasing the global water demand by 1% per year [99]. The environmentally stretched resources cannot satisfy the demand [14]. In this crisis period, the issue emerged as a significant attribute in the literature of hydrology and economics [26, 46]. Water Footprint (WF) measure has been proposed in the literature to understand this prevailing water crisis [30, 94]. It measures the amount of water used. The WF, which consists of green, blue and grey, can be defined as the total volume of water in M^3 per square kilometer the green water footprint shows how much water is used by forests and non-irrigated agriculture (WF_{green}) , the water used by irrigated agriculture, industry, and residences (WF_{blue}) and how much water would be required to neutralize the pollution in the water and bring it back to the acceptable discharge water quality (WF_{grey}) [33].

WF was introduced to analyze and support better water management, though the experience of calculating it at an urban level is limited. Earlier, agriculture and food production received the most attention on the WF [18]. However, the notion of WF might be useful for water utility planners during this growing concern about water scarcity and the policies associated with water management in urban areas [24]. Rapid urbanization stresses urban water resources, and cities with inadequate surface water resources import water to meet the needs of a rapidly growing population [96]. Local administrative bodies worldwide frequently hold water supply in urban areas accountable. Several Urban Local Bodies (ULBs) import water from long distances in India. The study of [11] considered 30 million-plus Indian cities with low surface water availability. Moreover, the study found a significant positive correlation between per capita water supply and service level benchmarks such as continuity of supply, metering efficiency, revenue collection efficiency, and cost recovery ratio. On the other hand, there is a significant negative correlation between per capita water supply and service level benchmarks such as non-revenue water percentage and unaccounted-for water percentage [11]. Overall, the challenges faced by Indian cities with low surface water availability in meeting their growing population's needs for clean drinking water. It also provides valuable insights into how local administrative bodies can improve their management of urban water resources by focusing on key service level benchmarks such as continuity of supply, metering efficiency, revenue collection efficiency, and cost recovery ratio while reducing non-revenue and unaccounted-for water percentages.

Thus, adopting relevant measures and providing solutions for urban bodies are critical challenges for WF analysts [47]. With these perspectives, this study mainly focuses on the following objectives:

- Calculation of WF

  (WF_{green}) and (WF_{blue}) calculation shall be attempted to determine the link between water availability and consumption.

- Understanding the level of water security

  To understand the level of water security experienced by different economic classes in these three municipalities.

- Calculation of Water Balance (as proxy parameters)

  To estimate the water use or overuse, a water balance corresponding to natural water availability and per capita consumption would be done based on primary data sources of three municipalities.

- Examine the best practices for Sustainable water use and develop a Policy Outline

Individuals or organizations have attempted to develop methods to sustain the deteriorating resource. Thus, Exploring ways to use relevant policy measures to tackle the issue of depleting the water level. This study looks into such efforts that have made an impact to show the way forward.

A policy outline will be developed based on these best practices and the study's findings.

1.1 Problem–Statement

To calculate the green and blue WF of municipalities in terms of environmental and consumption parameters and the sustainability of the water utilization system; also to develop a policy outline for sustainable water use.

1.2 Research Question

- Which are the appropriate models for calculating WF and how to apply them to three sample municipalities?
- What is the prevailing water situation in three sample municipalities based on the primary data?

1.3 Study Area and Data Set

The study considers different geographical conditions such as land use land covers (LULCs), topography, hydrology, meteorology, population, and water supply-demand dynamics as represented by administrative units (Municipalities) to define the concept of WF. The study area includes Purulia in West Bengal, and Ranchi and Dhanbad in Jharkhand, India. The primary reasons for choosing these municipalities were that they are water-scarce and have an inadequate municipal water supply system. Moreover, the similarity in socio-economic conditions, such as standard of living, occupational structures, etc., are the other aspects for choosing these municipalities.

For the primary data, 272 sample households from these municipalities were interviewed. 100 sample households from Ranchi, 90 from Purulia, and 82 from Dhanbad have been covered. The ongoing COVID-19, pandemic during this period, restricted our data collection ability. We therefore adopted the purposive but convenient sampling method to record the water consumption patterns for various income classes. These include residences of huts and chawls, tenements, bunglows, and apartments. 272 households cannot represent the entire population of the three municipalities but given the constraints of budget and time, it wasn't possible to take a sample of even .5% of the population. However, we have ensured maximum geographical coverage by reaching out to all the wards under each municipality for data collection. We have also tried to estimate the water consumption patterns of the different income classes. Amongst the 272 households, 106 were hutment dwellers, 93 were tenement residents, 29 were bunglow dwellers, and 44 living in apartments. This study has allowed us to gain insight into the problems faced by these different economic classes.

1.4 Background of the Study

The late Mr. Argen Hoekstra set the background of the concept of WF. He founded the concept, 'The WF of humanity.' This study comprehensively analyzes the global WF, including consumption, production, and pollution levels.

It shows that about one-fifth of the global WF in 1996-2005 was not meant for domestic consumption but for export. This highlights the issue of water scarcity in a global context and emphasizes the need for governments in water-scarce countries to recognize their dependency on external water resources. The study quantifies and maps the WF of humanity at a high spatial resolution, reporting on the consumptive use of rainwater and ground and surface water and volumes of polluted water. This data will help national governments formulate policies to increase water use efficiency. It implies that water-intensive commodities are replaced by commodities that require less water. This is crucial for governments striving towards more sustainable water use. The study also highlights the impact of agricultural and industrial production on the global WF. Agriculture accounts for 92 % of global WF_{green}, while industrial production accounts for 4 %. The remaining 4 % is attributed to domestic use [1]. This emphasizes the need for sustainable agricultural practices and efficient increment of groundwater recharge to reduce the overall global WF, as, nowadays, groundwater contributes significantly to human food security through irrigated agriculture [1]. There is enough groundwater on the planet for 7 billion people, but due to uneven distribution, it is unsustainably managed, and, Growth and development, changing crop patterns, and other socio-economic parameters are the reasons for increasing water use [99].

India, being the largest subcontinent, is no exception. Instead of shrinkage in the abovementioned issues, they are expected to escalate soon as more groundwater consumption than recharge has drastically reduced groundwater levels over the past 60 years [17]. It is estimated that India's groundwater abstraction was 245 billion cubic meters (BCM) in 2011, and 90 % of it was consumed by irrigation [57]. Moreover, after the green revolution, farmers have shifted from low water-consuming crops such as maize, millet, and oilseeds to high water water-hungry crops such as paddy [21]. This swing, followed by digging many bore wells/tube wells (from 0.1 million in 1960 to 1.27 million in 2008) in India, raised concerns about groundwater [54]. Too much dependence on irrigated agriculture throughout the country's prerequisite for groundwater abstraction led to severe exploitation of the groundwater system and threatened the sustainability of aquifer and agricultural productivity [27].

Even the alluvial aquifers of the Indo-Gangetic basin are heavily exploited for groundwater and are used for 62 % of regional irrigation, 50 % of urban water supply, and 85 % of rural water supply [57]. During the last decade, there has been strong evidence of massive groundwater depletion in northern India. Data for states like Punjab, Haryana, and Rajasthan has been estimated from the Gravity Recovery and Climate Experiment (GRACE) satellite [76]. GRACE studies marked India as a region of high groundwater depletion [45]. Moreover, numerous studies have investigated the Spatio-temporal variability of groundwater storage across India using in-situ measurements [15]. [9, 10] used a data set of 5800 wells across India to examine the relationship between rainfall and groundwater recharge. They concluded that low-intensity monsoon rainfall dominates aquifer recharge in India.

However, despite significant development in hydrological research, managing groundwater resources is still difficult because of groundwater level variability. This is a critical shortcoming because such information is needed to support sustainable WF management [52]. If overlooked, it may disturb the hydrological cycle accompanied by related socioeconomic effects, making it difficult to allocate the resources and manage the city's water supply [12].

1.5 Literature Review

Thanks to the painstaking efforts of several academicians, wes, and industrialists today, we have a sizeable amount of literature dealing both with the empirical and theoretical properties of this local and global issue. As discussed, Arjen Hoekstra was the maiden proposer of the concept of WF at the global level. In his first book, the WF manual, he described valuable information on how to measure and reduce your WF. He describes the direct and indirect water use of consumers and producers and proposes ways to minimize your impact on the environment. There are three questions he raised: How to calculate individual WF? What are some strategies for reducing the WF of businesses? How does virtual water impact global water resources? To calculate individual WF, you need to determine the total volume of freshwater used to produce the goods and services you consume. This includes both direct and indirect water use. Moreover, you may estimate individual WF based on factors such as your diet, energy consumption, and transportation habits. Businesses can reduce their WF by implementing strategies to save water in their operations and supply chain. Some ways to reduce operational water use include: installing water-efficient fixtures and equipment, conducting regular maintenance and leak detection, recycling and reusing wastewater, and implementing water management plans and policies to reduce the supply chain WF; businesses can: work with suppliers to improve their water efficiency, source materials from regions with abundant water resources, use alternative production methods that require less water, encourage consumers to use products more sustainably by taking these steps; businesses can reduce their impact on freshwater resources while also improving their bottom line through cost savings and increased efficiency. Virtual water refers to the water used to produce goods and services that are traded between regions or countries. When a country imports water-intensive products, it is essentially importing virtual water, which can have significant impacts on global water resources. For example, countries that rely heavily on food imports may be indirectly consuming large amounts of water from other regions. This can put pressure on the water resources of exporting regions, particularly if those regions are already experiencing water scarcity or other environmental challenges. Virtual water trade can also have economic and political implications, as countries seek to secure access to critical resources and protect their domestic industries. By understanding the virtual water balance of different regions and products, policymakers and businesses can make more informed decisions about resource management and trade policies. Moreover, he also explains how the WF of a nation relates to its consumption and trade, the relationship between water management, consumption, and globalization of trade from various perspectives. It aims to develop an understanding of the relationship between water, production chains, and trade. The WF of a product is defined as the volume of water used to produce the goods and services consumed by individuals/organizations. He explains how to calculate the WF of a product and highlights its importance in identifying opportunities for reducing water use in production processes. The WF of a nation is defined as the volume of water used to produce goods and services consumed by its citizens. It has two components: internal and external. Internal refers to freshwater resources within the country's borders while external refers to resources used outside the country's borders. He also discusses how businesses can reduce their WF through various measures such as improving efficiency in production processes, using alternative sources of water, and implementing sustainable practices. It emphasizes that reducing a business's WF not only benefits the environment but also improves its bottom line by reducing costs associated with excessive use of freshwater resources. Primarily, he provides valuable information on how we can better manage our freshwater resources by understanding our individual and collective impact on them. By calculating our WF at different levels (product, nation, business), we can identify opportunities for reducing our consumption and improving efficiency in production processes. This will help us ensure that we have enough freshwater resources for future generations while also protecting our planet's ecosystems.

Additionally, Hoekstra along with Mekonnen measured the WF of humanity, which is spatially mapped. They have conceptualized the WFs of consumption, as well as the WFs of the commodities eaten; determine a nation's WF of consumption. With a total footprint of 1,368 Gm^3/y, China has the biggest WF of consumption in the world, followed by India and the United States with 1,145 and 821 Gm^3/y, respectively. However, the average American consumer spends 2,842 m^3 per year, compared to 1,071 m^3 and 1,089 m^3 per year for ordinary people in China and India, respectively. Nevertheless, this study contains several limitations that are inherent to its comprehensive character. The prior research of Hoekstra contained estimates of WF for countries as a whole, without taking into account the heterogeneity within countries, whereas their combined study employs a spatial resolution of 5X5′ in assessing the WF in crop output, industrial production, and domestic water supply. Secondly, distinguishing between the green and blue WF in the case of agricultural production has not been done in the prior global WF research. Moreover, Hoekstra and Mekonnen looked at a 10-year period; however, we have provided yearly variations in hydrological or meteorological trends. The data availability supports that, which is why. We used these concepts in estimating green WF, which has been shown in chapter three of this thesis.

Konar and Marston (2020), in their article, provide a few helpful perceptions on reducing water scarcity in the United States. It provides some valuable insights on how to improve water use efficiency and save freshwater resources. The article reveals that of all the US industries, agriculture has the biggest overall water footprint. They suggested that studies on the water footprint of agriculture distinguish between blue and green water sources, even though these two sources of water are connected. For instance, the need for crop irrigation throughout the growing season can be significantly reduced by preseason soil moisture, which is mostly from precipitation. Producers frequently increase irrigation (blue water) during soil moisture shortage situations to make up for a green water deficiency. However, it is also critical to acknowledge the importance of green water in production, since we use green water to produce food, fiber, animal feed, lumber, and bioenergy crops, the environment and society compete for a limited supply of green water resources. We have used this conceptual difference of green and blue water in mapping evapotranspiration (ET) through the CROPWAT model that is estimated in chapter three. The study concluded by questioning how have water footprints changed over time in the United States. To respond to this inquiry, the authors suggested needing more accurate temporal estimates of WFs across lengthy periods.

Nevertheless, estimating accurate temporal trends across lengthy periods of WFs (ET) is a big challenge in data-scarce and heterogeneous landscapes. Kiptala et al. (2013) on 'Mapping Evapotranspiration Trends in Eastern Africa' showed us the similar challenges of accurately estimating evapotranspiration in data-scarce and heterogeneous landscapes. This article provides information in tabular form that shows annual estimates for each of the water balance components, aggregated from monthly totals, for each year of analysis on the big geographically heterogeneous and data-limited Upper Pangani River Basin, which is located in East Africa. For the years 2008 to 2010, 138 pictures at 250 m, 8-day scales were examined using the multitemporal Moderate-resolution Imaging Spectroradiometer (MODIS) and Surface Energy Balance Algorithm of Land (SEBAL) model to estimate actual ET for 16 different land use categories. The results showed that estimated ET for open water evaporation showed good agreement with pan evaporation using an optimized coefficient of 0.81 (R = 0.95; R^2 = 0.91; Mean Absolute Error (MAE) and Root Means Square Error (RMSE) of less than 5%). Based on the Penman-Monteith equation, the projected ET for diverse agricultural land uses revealed a consistent pattern with the seasonal variations of the crop coefficient (Kc). The findings could be applied to hydrological analysis and water accounting. The article also discusses how remote sensing can be used to estimate actual ET values in areas where ground-based measurements are not available or are unreliable.

We have done a logical mapping to find out green and blue WF using the methodology of this article, as our study is a maiden WF calculation in the Indian context particularly important in data-scarce and heterogeneous landscapes of municipality areas where accurate estimates of evaporation and evapotranspiration are essential under remote sensing technology for effective water resource management. Furthermore, Zhu et al. assessed the green water based on the Soil moisture and Water Assessment Tool (SWAT) model in the Hai River Basin, China in the year 2018. Their study aimed to make an inclusive evaluation of green water using new indicators, maximum possible storage of green water (MSGW), consumed green water (CGW), and utilizable green water (UGW). The hydrological cycle processes for the period of 1995-2004 were simulated using the SWAT model. The SWAT model is a widely used tool for simulating hydrological processes and assessing the impact of land use changes on watershed hydrology. The results provide practical and efficient references for water-short agricultural water management. This thesis highlights the importance of managing green water resources effectively to address water scarcity issues in agricultural regions, and we have also used this concept in finding green water utilization efficiency.

In addition to Kiptala et al. (2013) and Zhu et al. (2018), Long et al. (2020) illustrated the spatiotemporal variations of crop WF in Xinjiang, China. In his article, someone will learn about the influencing factors of crop water consumption and how it has changed over the past three decades from 1988 to 2017. The authors used STIRPAT models to analyze the indirect factors that influence crop water footprint (CWF) and found that irrigated area was the key factor affecting CWF. The study revealed that human activity has a greater contribution to CWF than natural factors such as climate. The research also showed that there were significant effects of population, urbanization, agricultural added value, water intensity, grain crops yield per unit area, and effective irrigated area on the CWF quantitatively. The findings suggest that urbanization percentage, irrigated water intensity, and grain crop production per unit area were found to have a negative correlation with the CWF using elasticity coefficient analysis. In particular, the results show that the correlation coefficient of urbanization percentage was 0.21 ($p > 0.05$), demonstrating that the CWF was not responsive to regional urbanization even if increasing urbanization level had a suppressive effect on it. The development and acceptance of efficient water-saving technology, both of which helped to lower agricultural water use, led to a rise in irrigated water intensity and grain crop output per unit area. In contrast, there were positive relationships between the CWF and the population, the value added to agriculture, and the effective irrigated area. This kind of research can help policymakers in estimating the CROPWAT model and comparing it with the MODIS and SEBAL models in similar regions around the world.

A similar experiment was done by Rao et al. (2019) in the Banjar River Watershed (BRW), India on the WF Assessment of Agriculture. This study provides a valuable understanding of the amount of water required for crop production. The study assessed the WF of agriculture in the BRW over the period 2000-2013. The study also quantified the crop WFs grown in the BRW to make a comparison with other WF studies executed at the global and basin or catchment level. These WF readings for several crops cultivated in India are significantly greater than the country's average WF. The main causes of such high values of WF of crops in BRW include lower crop yields brought on by faulty irrigation practices, low fertilizer application rates, and improper on-farm water management practices. The result reports that agriculture in BRW has a total WF of 690.37 million m3/y. Out of which 59.74% is WFgreen, 39.69% is WFblue, and 0.56% is WFgrey. With 87.38% of the overall WF in BRW, rice had the highest proportion in agriculture. The study found that there is a need for better water management practices to improve water use efficiency in agriculture in the region. However, no specific recommendations were made based on the findings. Overall, this study highlights the importance of WF in agriculture, in terms of sustainable water resources to ensure food security and livelihoods for communities dependent on agriculture. We have highlighted these importances in chapter five through different success stories of water conservation techniques made by NGOs, such as Tarun Bharat Sangh, Manavlok, etc.

Now, when we are looking for an overview of WF under municipality areas (preciously, blue WF), we should consider those articles that primarily focus on the urban domain. The article of Fialkiewicz et al. (2018) discusses a simplified WF model by modifying the strategy suggested by Hoekstra et al. (2016). The model that is created for accounting for blue WF makes the urban planner managing water resources in urban areas simpler and more efficient. A few relevant equations have been created to calculate components of urban WF are presented in the Methodology section. The model is tested through the application in three different cities in Europe (with different characteristics i.e., Wroclaw (Poland), Innsbruck (Austria), and Vicenza (Italy)) with different characteristics, and the results are presented using different metrics. From 291 dm3/(day/capita) in Wroclaw to 551 dm3/(day/capita) in Vicenza to 714 dm3/(day/capita) in Innsbruck, different WFs were attained.

The outcomes demonstrated the model's robustness in producing acceptable findings with less data. The Simplified Direct WF Model can be applied to urban water management by providing a simplified way to measure direct water use in cities. This could help identify areas where improvements can be made to reduce water consumption or increase efficiency. Therefore, we have used these methodological thoughts in estimating blue WF in this thesis, which has been shown in chapter four. Besides Fialkiewicz et al. (2018), Paterson et al. (2015) entailed a few important features of the WF of cities in their article. This article provides some key findings and recommendations for future research on WF and some potential solutions or strategies for reducing the WF of cities, and how effective have they been in practice. The article primarily identifies and discusses key themes related to urban WF analysis, including virtual water trade, urban metabolism, life cycle assessment (LCA), environmentally extended input-output (EEIO) analysis, embedded resource accounting (ERA), and water scarcity. Based on the reviews, he suggested that WFA and EEIO are useful for urban WF analysis. The application of LCA is limited by its emphasis on individual products. Moreover, the article also provides a summary of the potential strategies for reducing the WF of cities. These include improvement in the maintenance of data; ensuring water security; promoting sustainable urban design practices; implementing demand-side management measures; enhancing public awareness and education; and fostering international cooperation on water-related issues.

Overall, this review provides a comprehensive overview of the current state-of-the-art in urban WF analysis while also identifying key areas for future research. We have seen that many articles tried to provide a few policy recommendations. This is a crucial part of reducing WF. However, proper implementation of those policies is also a major challenge for the government. Expert consultation is required on water policy reform, as, it can relate to a lot of questions: What are some of the key policy issues discussed in the consultation? How has the focus of water resource development shifted in recent years? What are some of the challenges facing demand-management policies for water resources? The above-mentioned questions raised by Paterson et al. (2015) can only be answered by creating a comprehensive policy reform guideline on WF. We have made an effort to make such recommendations at the end of this thesis.

However, the jointly published article of Frohlich with the European Institute of the Mediterranean on ensuring 'Water Security' in the Middle East in the year 2020 is also an example of that. The primary questions he raised were: What are the main water security challenges faced by countries in the Middle East? How can policymakers ensure equitable access to water resources in the region? The article titled "Ensuring Water Security in the Middle East: Policy Implications" provides valuable insights and policy implications for addressing water security challenges in the region. The article entails that the entire region of the Middle East is affected politically and socioeconomically by this growing water scarcity. Without appropriate countermeasures, the food supply, public health, and economic growth of states with limited water resources are increasingly threatened. Thus, access to water is crucial for ensuring political stability, economic development, and the health of the general public in locations with limited water resources. The overall analysis concludes that despite the Middle East's highly securitized water management system and the fact that resource access is seen as a national security concern, multilateral cooperation, and water security are not only threatened but also not guaranteed by current securitization trends. According to that, securitization encourages a national and centralized approach to water management at the expense of civil society involvement, unbiased monitoring and data gathering, and the provision of safe, transparent, and long-lasting access to water for local populations.

The Proceedings of the expert consultation on policy reform in water provide an overview of major macroeconomic and sectoral policy issues, followed by a discussion of the major issues at the farm and household levels. Ahmad and Abdou (2020) a similar article, where the authors draw conclusions and lessons learned based on FAO experience in providing economic policy advice to the countries of the region. Their paper highlights that water resource development has shifted from a focus on supply management to demand management policies. They suggested that this shift is due to increasing water scarcity, population growth, and climate change impacts. Moreover, the authors argue that demand management policies are more effective in addressing water scarcity than supply management policies. One of the key challenges facing demand-management policies for water resources is that they require significant behavioral changes from users. This can be difficult to achieve without proper incentives or penalties for non-compliance. Additionally, they elucidated that there is often a lack of political will to implement these policies due to concerns about their potential impact on economic growth. The paper also discusses the importance of stakeholder participation in developing and implementing water policy reforms. Stakeholder participation can help ensure that policies are tailored to local needs and priorities, and can increase buy-in from affected communities. However, effective stakeholder participation requires adequate resources, capacity building, and institutional support. Overall, the Proceedings provide valuable insights into water policy reform. The authors highlight key challenges facing policymakers and offer recommendations for addressing these challenges through demand-management policies, stakeholder participation, and other measures.

1.6 Organization of the Thesis Chapters

The thesis is organized into six chapters, including the introduction and the conclusion. In the introductory part, the motivation of the study, along with the objectives and the study areas, are discussed.

Chapter 2 talks about the environmental perspective of WF (WF_{green}), primarily focusing on evapotranspiration (ET). Initially, the study estimates ET using the SEBAL model and then checks the consistency of the result through standard CROPWAT 8.0 to obtain WF_{green}. While Purulia reports the highest temporal mean value of WF_{green} (231.3 M^3 (*10^3) per sq km), Ranchi illustrates the lowest (185.3 M^3 (*10^3) per sq. km). Moreover, the author has also analyzed the implications of WF_{green} on sustainable utilization, conservation, and skewed water distribution.

The next chapter depicts the calculation of municipal WF (WF_{blue}) for better water supply management in the urban domain. Estimation of WF_{blue} is the amalgamation of evaporation, runoff, municipality supply water, and transportation loss. The study shows that Ranchi reports the highest WF_{blue} value (108 M3 per capita), and Dhanbad produces the minimum (68.8 M3 per capita). In addition, a sub-section analyzes water scarcity vs. water availability in these municipality areas. The result indicates that while Ranchi supplies a fair amount of water to people, the situation of Purulia and Dhanbad municipalities is alarming. These two municipalities cannot supply even the basic standard of water to the needy individual.

Subsequently, analyzing the water situation of these municipalities using primary data is the study of Chapter 4. This chapter records the consumption patterns of water use according to different income classes (people residing in huts and chawls, own houses, apartments, and bunglows). Moreover, mapping of water availability with its sources and per capita consumption has been done quantitatively. Other related elements like the quality of the water, its taste, color, and presence of minerals available to different classes of households have also been surveyed using the structure of a decision tree.

After that, chapter 5, 'Water Management: Sustainable Best Practices,' comes. This chapter showcases different success stories of water conservation techniques by an individual, municipality/government organization, private bodies, NGOs, etc. Stories, such as how perennials of rivers were enabled by making tiny earthen dams along the river belt, were done by Mr. Rajendra Singh (Waterman of India) have been produced. Moreover, the chapter also demonstrates how Manavlok, a non-profit organization, helped the people of Beed district to find jobs and stopped the seasonal migration and how Puri municipality supplies 24*7 quality drinking water to the entire hutment dwellers of the city.

This thesis concluded by recommending a relevant policy outline for sustainable water use that would help to address the prevailing water scarcity.

CHAPTER 2

Mapping Evapotranspiration Using CROPWAT and SEBAL Model and Assessment of Green Water Footprint for Diverse Topographic Units

2.1 Introduction

Evapotranspiration (ET) , that union of evaporation and transpiration, accounts for significant water loss in arid and semiarid regions. And, it is especially challenging to estimate ET in dry and semiarid locations because of its spatial heterogeneity and temporal variability [44, 59]. Topographies such as Purulia, Dhanbad, and Ranchi, in Eastern India are also semiarid regions, and because of the variety in land use and land covers (LULCs) ET estimation becomes difficult here. Moreover, Spatio-temporal changes in geographic and socioeconomic conditions in these topographies impacted the water resources, and, thus, the ecosystem services. Therefore, a systematic understanding of ET helps to assess the water loss in the system and exhibit a few strategies and solutions to water management study [101]. One such idea was introduced in academics by evaluating water footprint (WF) [30]. It analyzes human and non-human activities about water scarcity and, additionally, how to make that a sustainable one [90].

However, water is a complex system, and the calculation of WF is a big challenge because of the difficulty in the estimation of ET [74, 105]. A minor modification in the estimation process can significantly impact the result. An explicit understanding of LULCs and associated spatiotemporal variability is required by the school of thought to estimate ET [44]. Moreover, conventional models of ET estimation need large-scale spatiotemporal meteorological data, and the in-situ measurements are time-consuming and difficult in terms of cost-benefit analysis.

Therefore, scholars have tried to create new tools and techniques for suitable results over the years. New models have been developed through hydrology [20, 46], spatiotemporal study [68, 79], and LULCs [70, 103, 7]. SEBAL model is another example, where scholars using, limited data, produced significant results [43, 18]. The recent advancements in the SEBAL model have further enhanced its application potential [8, 61]. Moreover, research using SEBAL has previously produced significant results in estimating ET for a temporal study on several LULCs [83, 88].

In this study, the estimation of ET was done using precipitation and coefficients. Initially, the SEBAL algorithm was utilized to map the coefficients using published experimental data over six LULCs of the topographies [35, 36]. Ranchi municipality has been chosen for the temporal estimation of ET during 2016-19. The reasons for preferring Ranchi over the other topographies were because of its spatial uniqueness, and it holds the highest area in agriculture. Moreover, Ranchi accounts for the availability of meteorological data such as daily rainfall, minimum, and maximum temperature, relative humidity, and wind velocity to help estimate ET significantly. However, the coefficients calculated using SEBAL ET values at one location may or may not be consistent for a different location. Therefore, it is crucial to check the consistency of the estimated ET values [98].

For checking the consistency of the estimated ET values, the SEBAL model was compared with the standard CROPWAT model, using several proxy variables such as crop water requirement (CWR), reference evapotranspiration (ET_0), crop coefficients (K_c), and effective precipitation (P_{eff}). The United Nations Food and Agriculture Organization (FAO) identified the CROPWAT model to determine evapotranspiration in agriculture using the Penman-Monteith equation [4]. [6] used the Penman-Monteith method to estimate the ET_0 of eastern North Carolina. The strong correlation between Penman-Monteith with other standard methods helped him to conclude that CROPWAT could be used as a standard method to estimate evapotranspiration in agriculture. Similarly, [29] used the CROPWAT model to calculate ET_0, and further developed a new model of ET_0. The newly developed model performed well while checking its effectiveness. Later, [56] studied CWR for Jatropha cultivation in Botswana from 2014 to 2016, using weather data and crop characteristics data. To estimate actual crop evapotranspiration (ET_c) and CWR, CROPWAT 8.0 model was chosen. The findings revealed a consistent outcome.

Based on the above facts and literature, we believe that if the estimated ET values are consistent with the standard CROPWAT model thoroughly, the SEBAL application could be implemented in estimating WF_{green} also. Moreover, the evaluation of WF_{green} could be extended over diverse topographic units. Thus, in the context of the estimation of ET, WF, and water conservation, this article seeks to understand the following objectives:

- Estimate the ET of a region using the SEBAL model
- Consistency checking of the SEBAL ET values using the standard CROPWAT model
- Extend the ET estimation to calculate WF_{green} for diverse topographic units
- Sustainability assessment of WF_{green} on different topography

2.2 Methodology

2.2.1 Study Area

The study considers different geographical conditions such as Land Use Land Covers (LULCs), topography, hydrology, and meteorology to demonstrate the concept of green WFs. Furthermore, the reasons for selecting these study areas are indicated water scarcity and an inappropriate water management system.

The initial idea was to study, calculate, and compare the WFs within the Purulia and Dhanbad municipalities of West Bengal and Jharkhand. However, during data collection, the study found that both municipalities were placed at the same altitude (200 meters (mt) and 222 mt). Thus, the study area was extended to the capital city of Ranchi, Jharkhand having an altitude of 651 mt without compromising other aspects.

2.2.2 Data

Municipality maps

Purulia is a small municipality consisting of 23 administrative wards, covering only 36.6 square kilometers (sq km) and having a population of 1,21,067 as per the 2011 census; Dhanbad and Ranchi each have 55 administrative wards and a population of 11,62,472 and 10,73,427 as per the 2011 census, illustrates 231.8 and 201.5 sq km respectively.

Rainfall data

The study used the rainfall data (in mm) of three Municipalities. Rainfall data for Purulia and Dhanbad have been collected from their respective agriculture offices, whereas, for Ranchi, it has been collected from Birsa Agriculture University (BAU). The following table, Table 2.1 confirms that 2018 reports the least rainfall for all three municipalities.

Table 2.1: Annual rainfall (mm) data of Municipality areas

Municipalities	Year			
	2016	2017	2018	2019
Purulia	1346	1764	1087	1310
Dhanbad	1368	1161	966	1226
Ranchi	1456	1579	944	1362

Satellite data

Satellite data were used to classify different land covers. High-resolution multispectral Sentinel-2 data having four bands, Blue, Green, Red, and Near-Infrared, were used for classification. Three seasons (Jan, May, Oct- 2020); multi-temporal data were also used for classification.

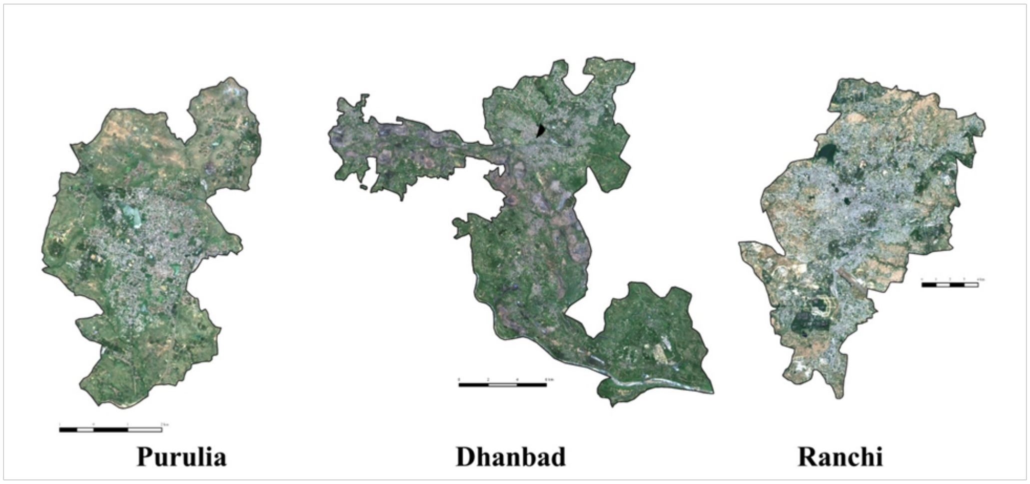

Figure 2.1: The satellite images of Three municipalities

2.2.3 Methods

Classification of satellite data

The study areas were classified into six categories of LULCs: water, forest, urban, barren, grass/shrub, and agricultural (Ai in square km.) using multi-season satellite data. A random forest algorithm was used for classifying land cover. Training sites required for this algorithm were obtained using visual interpretation from Google Earth. The classification algorithm provides six land-cover classes with an overall accuracy of 92% and a kappa coefficient of 0.89; that means that in 92 out of 100 cases, the six LULC classes were correctly classified from satellite data. Following are the classification of the LULC classes from satellite data:

Estimation of ET Using SEBAL Model

A common method in hydrology to calculate ET is through precipitation [38]. In particular, it is expressed as

$$ET = CR \tag{2.1}$$

where C represents the coefficients of the corresponding LULC class and R represents the rainfall of the respective municipality. To estimate the value of the coefficients we used the SEBAL model. For our case, we also performed a logical [35, 36] from the experimental data of sixteen LULC classes to the six relevant

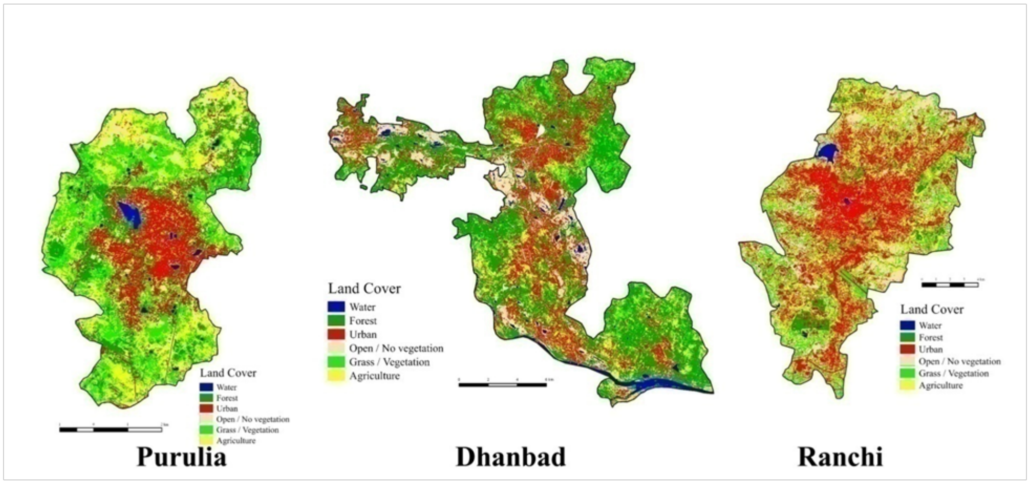

Figure 2.2: LULC classes from satellite data of three municipalities

LULC classes mentioned previously. Typically, the value of C would depend on the types of vegetation or the terrain under study [24]. Since the areas that we have selected for our studies are in close proximity ($\sim$ 100 aerial kilometer) we have assumed the same value of the coefficients for the three municipalities. For rainfall, the absolute rainfall data during the cultivation period has been considered here.

Estimation of ET Using CROPWAT Model

Evapotranspiration using climate and soil data during crop growth can be estimated using CWR and P_{eff}. P_{eff} is the fraction of precipitation retained by the soil available for the water requirement of the crop. CWR is the water required for the measurement of evapotranspiration from planting to harvest. Multiplication of ET_o and K_c will give us CWR. For a rain-fed agricultural crop (e.g., wheat, paddy, and maize), ET_c will be equal to CWR based on the assumption that the water requirements for the particular crop are fully met [4].

Estimated ET through CROPWAT is divided into two parts, evapotranspiration of rainfall (ET_g) and Field evapotranspiration of irrigation (ET_b). ET_g can be equated with the minimum of ET_c, and P_{eff}, and ET_b is equal to the ET_c minus P_{eff}. However, it will be zero when effective rainfall exceeds crop evapotranspiration:

$$ET_g = Min(ET_c, P_{eff}) \quad (2.2)$$

$$ET_b = Max(0, ET_c - P_{eff}) \quad (2.3)$$

[All water flows are expressed in mm/day (e.g., a decade over ten days)]

This study considers the paddy crop of Ranchi municipality as the input for the CROPWAT model. Paddy is one of the primary crops produced in Ranchi during the Kharif season using rain-fed irrigation.

Estimation of WF$_{green}$

WF$_{green}$ can be estimated once the consistency of the estimated SEBAL ET values is established. Thereafter, it can be evaluated by multiplying the area of each LULC with the estimated ET [32, 24].

Therefore,

$$WF_{green} = \sum(A_i * ET) \quad (2.4)$$

Or,

$$WF_{green} = \sum[A_i(C_i * R_i)] \quad (2.5)$$

where i represents different LULC classes and A$_i$ is the area of the LULC classes. Figure 2.3 shown below, is the Schematic representation for the estimation of WF$_{green}$.

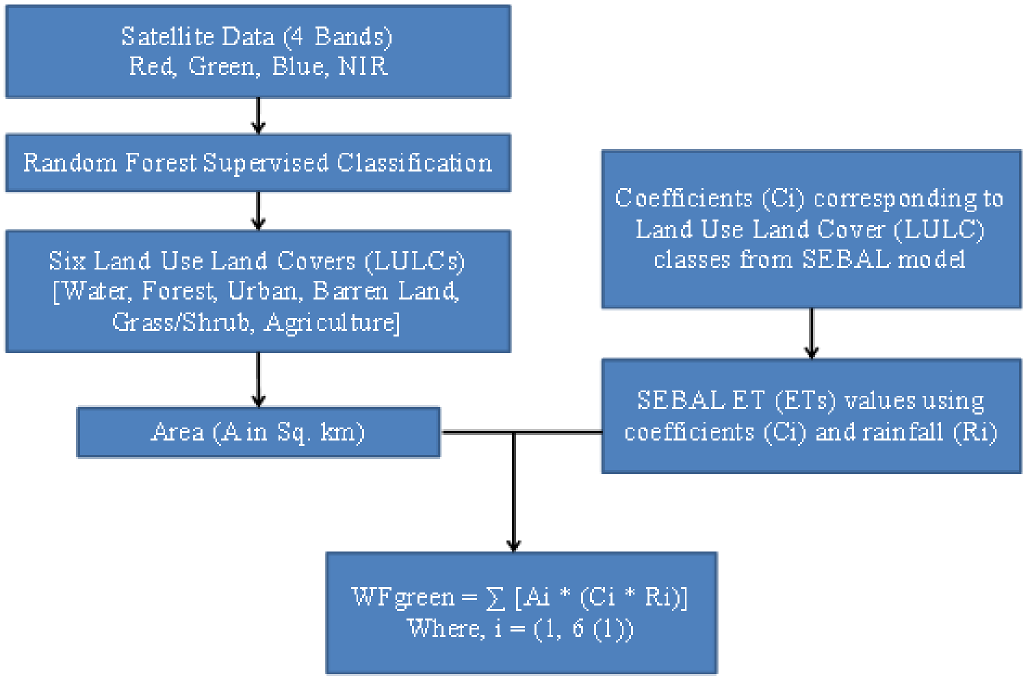

Figure 2.3: Schematic representation for the estimation of WF_{green}

2.3 Results and Discussions

2.3.1 LULC classifications

Table 2.2: LULC details of Municipalities areas in sq km

LULCs	Purulia	Dhanbad	Ranchi
Water Bodies	0.5	7.3	1.7
Forest	5.7	86.1	12.3
Urban	7.4	54.7	73.2
Barren Land	2.2	27.2	38.8
Grass/Shrub	10.2	22.9	29.1
Agriculture	10.6	33.5	46.3
Total	36.6	231.7	201.4

Classification manifests a large heterogeneity during the illustration of the highest LULCs by the topographies. However, the minimum areas in all three topographies are water bodies. Table 2.2 entails that Purulia manifests 29% of the total area under agriculture as the highest LULC, followed by 28% grass-land. Dhanbad illustrates the highest area as 37% under forest followed by 23% in urban. To simplify the estimation process, this study considered mining and minerals areas of Dhanbad municipality under the domain of urban area. Quite expected, Ranchi holds 36% of the urban area because of rapid urbanization, followed by 23% of agricultural land. A close look at the classification images confirms that agriculture plays a crucial role in these regions. However, Ranchi manifests the highest agricultural land among the topographies. It captures 46.3 sq km of total agricultural area compared to 33.5 sq km in Dhanbad and 10.6 in Purulia. As mentioned, it is a primary reason for choosing Ranchi under the CROPWAT model over other topographies. Moreover, whereas Dhanbad reveals a mere three percent, Ranchi reflects 0.8 percent; Purulia holds even fewer water bodies (o.6%) within the municipality area.

2.3.2 Assessment of ET and consistency checking of the SEBAL model

Table 2.3 reports the temporal ET values of Ranchi Municipality under the SEBAL model (ET_s), that coming from equation 1, derived from the study of Kiptala et al. (2013) [35, 36]. Over the years, ET replicates a common tendency with rainfall, i.e., ET is directly proportional to the annual rainfall [40, 95]. This model also finds an identical result. ET_s was highest during 2017 because of the highest rainfall, followed by 2016. Rainfall in the year 2018 reflects the least produce over the lowest ET value.

Table 2.3: The result of the temporal ET values (mm) under SEBAL model and comparison with CROPWAT model in Ranchi

Year	Rainfall	ET Coefficient	ET_s	ET_c	Gap
2016	1325	0.3	397.5	715.5	318
2017	1567		470	595.9	126
2018	877		263.1	716.3	453.2
2019	1231		369.3	708.5	339.2

Table 2.4 showcases the ET values of the CROPWAT model (ET_c) for four consecutive years that coming from equations 2 and 3, derived from the study of

Allen et al. (1998) [4]. ET values are the amalgamated results of meteorological data, crop data, and soil data. The result reports the water loss from the system for paddy cultivation over six months due to evaporation and transpiration. Four stages of the cultivation scenario have been reflected, and accordingly, the K_c values are changing. K_c values are highest during the crop growth period and decline afterward. ET_c amounts to the sum of ET_g and ET_b.

To check the consistency of the SEBAL model, the study primarily focuses on the CROPWAT based on several studies [19, 4, 89, 32, 56, 58, 60]. The ET values calculated using the CROPWAT model are consistently higher than the SEBAL model in all four years. the underlined explanations could be that the CROPWAT model considers the contributions of the soil, whereas the SEBAL model does not consider the contribution of the soil exclusively [19].

This gap has occurred primarily due to the presence of soil data, and it is being neutralized through evaporation from the soil, especially exposed soil [4, 60]. When the soil surface is dry, but transpiration occurs at a potential rate, the transpiration component mainly represents ET_c. However, it also includes an evaporation component supplied by soil water that describes the evaporation component of ET_c. Compared to when the soil surface is dry, the amount of water that lingers near the soil surface for evaporation is maximal when the topsoil is moist after rain or irrigation. [58].

However, it is also observed that the amount of rainfall in a particular year affects the calculation of ET in both models. In case when the rainfall is higher, the gap between the two models is less. the possible reason could be in the CROPWAT model the loss of water from the soil through the evaporation process is higher because the soil column is saturated. And, the calculation of the ET in the SEBAL model is process-independent. which means it always considers 30 % of the rainfall. therefore the difference between these two models is less. Conversely, when the rainfall is less, the contribution of the soil through evaporation is reduced considerably. However, the ET calculation of the SEBAL model remains 30% of the rainfall. so the difference between the two models is high.

Table 2.4: Result of the ET (mm) of Ranchi Municipality under CROPWAT 8.0 model

Year				**2016**				**2017**				**2018**				**2019**			
Mon.	Dec.	Stage	K_c	ET_c	Eff rain	ET_g	ET_b	ET_c	Eff rain	ET_g	ET_b	ET_c	Eff rain	ET_g	ET_b	ET_c	Eff rain	ET_g	ET_b
May	2	Init	1.05	4.9	3.7	3.7	1.2	5.5	0.9	0.9	4.6	4.8	1.6	1.6	3.2	5.3	1	1	4.3
May	3	Init	1.05	53.9	40.3	40.3	13.6	57.5	21.2	21.2	36.3	52.3	23	23	29.3	58.3	15.1	15.1	43.2
Jun	1	Init	1.05	49.5	43	43	6.5	49.8	35.9	35.9	13.9	47.8	32.5	32.5	15.3	53.2	19.9	19.9	33.3
Jun	2	Deve	1.05	49.7	47.6	47.6	2.1	47.7	47.8	47.7	0	47.8	40.2	40.2	7.6	53.2	24.3	24.3	28.9
Jun	3	Deve	1.08	45.5	50.5	45.5	0	41.2	55.2	41.2	0	44.7	41.2	41.2	3.5	49.3	32.9	32.9	16.4
Jul	1	Deve	1.12	39.5	54.5	39.5	0	32.8	65.9	32.8	0	40.8	41.3	40.8	0	45.1	44.1	44.1	1
Jul	2	Deve	1.16	34.5	58.3	34.5	0	25.2	75.7	25.2	0	37.6	43	37.6	0	41.3	53.3	41.3	0
Jul	3	Mid	1.2	40.9	56.7	40.9	0	28.4	68.1	28.4	0	42.7	45.9	42.7	0	43.7	53.1	43.7	0
Aug	1	Mid	1.21	39.8	54.6	39.8	0	26.6	60.1	26.6	0	39.4	50.4	39.4	0	36.4	52.2	36.4	0
Aug	2	Mid	1.21	40.6	53.7	40.6	0	25.6	55.2	25.6	0	39	54	39	0	33.2	53.3	33.2	0
Aug	3	Mid	1.21	43.6	52.4	43.6	0	27.8	42.8	27.8	0	44.2	51.1	44.2	0	37.9	52.6	37.9	0
Sep	1	Mid	1.21	38.7	54.8	38.7	0	24.1	25.8	24.1	0	41.4	51.2	41.4	0	36.1	51.8	36.1	0
Sep	2	Mid	1.21	37.8	55.5	37.8	0	23.3	12.3	12.3	11	42.6	50.8	42.6	0	37	51.4	37	0
Sep	3	Mid	1.21	38.6	39.1	38.6	0	28.5	16.2	16.2	12.3	40.8	34.1	34.1	6.7	36.5	51	36.5	0
Oct	1	Mid	1.21	40.1	17.2	17.2	22.9	35.7	24.7	24.7	11	39	2.1	2.1	36.9	35.9	55.4	35.9	0
Oct	2	Late	1.2	40.9	0.9	0.9	40	41	28	28	13	36.9	0	0	36.9	35	57.4	35	0
Oct	3	Late	1.1	37.8	0.6	0.6	37.2	37.5	18.9	18.9	18.6	35.4	0	0	35.4	33.6	38.2	33.6	0
Nov	1	Late	1	27.6	0.1	0.1	27.5	26.7	2.1	2.1	24.6	27.3	0	0	27.3	26.1	0.1	0.1	26
Nov	2	Late	0.92	11.5	0	0	11.5	11.1	0	0	11.1	11.9	0	0	11.9	11.3	0	0	11.3
TOTAL						**715.5**				**595.9**				**716.3**				**708.5**	

2.3.3 Assessment of WF_{green}

Since the trend of ET values estimated using the SEBAL and CROPWAT models is similar, we can use the inputs of either the SEBAL or CROPWAT model for extrapolating the WF_{green} values for other municipalities. Table 2.5 indicates the results of WF_{green} for Purulia, Dhanbad, and Ranchi in M^3 (*10^3) per sq. km for the year 2019 that coming from equation 4, derived from the study of Hoekstra et al. (2016) and Fialkiewicz et al. (2018) [35, 24]. The result shows that the WF_{green} values are varying either across municipalities or across land covers for four consecutive years (From 2016 to 2019).

Table 2.5: Results of WF_{green} of the Municipalities (M^3 (*10^3) per sq km)

Municipalities	Year	Land Use Land Covers (Coefficient)						
		Water (0.2)	Forest (0.25)	Urban (0.05)	Barren (0.12)	Grass (0.08)	Agri (0.3)	Total
Purulia	2016	3.8	52.2	13.7	9.9	30	116.6	226.1
	2017	4.9	68.4	17.9	12.9	39.3	152.8	296.3
	2018	3	42.2	11	8	24.2	94.2	182.6
	2019	3.7	50.8	13.3	9.6	29.2	113.5	220.1
Dhanbad	2016	8.6	127.1	16.1	19.3	10.9	59.3	241.2
	2017	7.3	107.9	13.7	16.3	9.2	50.3	204.7
	2018	6	89.7	11.4	13.6	7.7	41.9	170.3
	2019	7.7	113.9	14.5	17.3	9.7	53.2	216.2
Ranchi	2016	2.5	22.3	26.4	33.7	16.8	100.4	202.1
	2017	2.7	24.1	28.8	36.5	18.2	108.9	219.2
	2018	1.6	14.4	17.1	21.8	10.9	65.1	131.1
	2019	2.4	20.8	24.7	31.5	15.8	93.9	189.1

The primary contributing factors for higher WF_{green} are rainfall, types of vegetation, and the proportional area of a particular LULC to the total LULCs. Numerous studies have demonstrated the correlation between rainfall and green water at spatial and temporal resolutions [102, 78, 95]. This study reports the same associational validity for both cross-sectional and time-series results of WF_{green} values. The more the rainfall values in a particular assessment year, the more WF_{green} values. As a result, rainfall may be utilized to estimate the amount of green water quickly. The flow and storage of green water can also be influenced by other meteorological phenomena, such as temperature. In addition, changes in land use might affect WF_{green} [103]. According to the land use types, green water has a clear geographical pattern with the proportional area of a particular LULC to the total LULCs.

A viewpoint across municipalities manifests that Purulia, which produces the highest mean WF_{green} compared to the other two Municipalities (231.3 M^3 (*10^3) per sq. km), produces maximum WF_{green} under agriculture (with a mean value of 119.3 M^3 (*10^3) per sq. km) and minimum underwater body (with a mean value of 3.9 M^3 (*10^3) per sq. km). Dhanbad, which illustrates the highest area under the forest domain, loses maximum green water from that LULC itself throughout four consecutive years (with a mean value of 109.7 M^3 (*10^3) per sq. km). Moreover, though Ranchi reveals its central area as urban, its WF_{green} values are highest in agriculture (a mean value of 92.1 M^3 (*10^3) per sq. km) within the Municipality. This hilly city reflects the least area in the water body, and the WF_{green} values are mapping likewise. Both Purulia and Ranchi Municipalities produced the highest WF_{green} in the year 2017 (In Purulia, 296.3*(10^3) M^3 per sq km, and in Ranchi, it is 219.2*(10^3) M^3 per sq km), while in Dhanbad, it is highest in 2016 (241.2*(10^3) M^3 per sq. km).

However, when we look at the results of WF_{green} of the municipalities across land covers, the major contributing factor for getting different values of WF_{green} is the proportional area of a particular LULC to the total LULCs. Therefore, different land covers will have different WF_{green}, depending on the land use.

Urban, water bodies and barren lands contribute insignificant to WF_{green} values. Urban areas have a WF_{green} because they generally have little vegetation and do not require large amounts of water for production. However, Water bodies such as lakes, rivers, and oceans have a negligible WF_{green}, as they do not consume water for production, and barren areas such as deserts and rocky terrain have a very low WF_{green}, as there is little or no vegetation to consume water. this study follows a similar trend with these three land covers. Moreover, Table 2.5 indicates that the mean WF_{green} values across municipalities vary based on the proportionality of a particular LULC to the total LULCs, in terms of their areas. As the proportional area of Dhanbad is highest in water bodies compared to Purulia and Ranchi, Dhanbad produces the highest WF_{green} under the terrain of water bodies. However, the mean WF_{green} values of urban areas and barren land in Table 2.5 of the three municipalities illustrate pretty different results. Under both these LULCs, Ranchi manifests the highest mean proportional WF_{green} values, followed by Purulia and Dhanbad.

However, forests have a relatively low WF_{green} because trees are generally able to obtain moisture from deep in the soil and through their roots and, the WF_{green} may increase if forests are logged or cleared for agricultural use. And, agriculture typically has a high WF_{green} because crops require large amounts of water for growth. The water required varies depending on the crop, soil conditions, and climate. Moreover, grasslands have a moderate WF_{green} because grasses require water for growth but are generally less water-intensive than crops grown for food or fiber. The mean proportional WF_{green} values under forest are maximum in Dhanbad, followed by Purulia and Ranchi. However, under agriculture, Purulia showcases the highest mean proportional WF_{green} values, followed by Ranchi and then Dhanbad. For grass or shrubs, the trend is similar for the municipalities.

2.4 Sustainability Assessment of Green WF on Diverse Topographic Units

Demand for sustainability may be achieved by optimizing the environmental, social, and economic parameters. However, each has its criteria to fulfill, and here, we are more interested in ecological changes, which is a part of environmental sustainability. These changes could be measured by the availability of green water along with the examination of the time-series effects of different LULCs on WF_{green}.

To explore the effectiveness of the measurement, this paper divides the six LULCs into two components: utilizable and non-utilizable WF_{green} based on the water available in the root zone, used by the plants, and evapotranspirates from the system [105]. Agriculture, forest, and grass/shrubs fall under utilizable WF_{green}, while water bodies, urban areas, and barren land are the non-utilizable components of WF_{green}.

Table 2.6 presents the results of mean Utilizable and Non-Utilizable WF_{green} values across all the Municipalities over four consecutive years. The trend says that under the utilized WF_{green}, the maximum mean value of the WF_{green} is coming from agriculture (262523 M^3 per sq km) followed by forest (183455 M^3 per sq km), and the least is from grass/shrub (55440 M^3 per sq km). However, the non-utilized part depicts the mean value of the maximum precipitation under barren land (57561 M^3 per sq km) followed by the urban area (52145 M^3 per sq km). The water body reflects the least WF_{green} (13533 M^3 per sq km) under the non-utilized category only after considering both categories.

Table 2.6: Results of Utilizable and Non-Utilizable WF_{green} (M^3 (*10^3) per sq km)

	Utilizable WF_{green}			Non-Utilizable WF_{green}		
Year	Agriculture	Forest	Grass/Shrub	Water	Urban	Barren Land
2016	276.3	201.6	57.6	14.8	56.2	62.8
2017	312	200.4	66.7	14.9	60.3	65.8
2018	201.2	146.3	42.8	10.7	39.6	43.4
2019	260.6	185.5	54.6	13.7	52.5	58.3
Mean	262.5	183.5	55.4	13.5	52.1	57.6

Moreover, it is assumed that the reduction of WF_{green} is unnecessary because rainfall is a prominent part of the hydrological cycle. It is also considered that WF_{green} is a location-specific phenomenon. Both of these are serious misconceptions for society as well as for the environment, and thus Reduction of water footprint is likely to be necessary even in high water-abundant areas. Therefore, in Table 2.7, we try to find the effective utilization rate of WF_{green} per unit amount of rainfall. The WF_{green} value of a particular LULC divided by the rainfall gives us the effective utilization rate of that particular year. It will help us not only solve the problem of WF reduction in these topographies but also contribute to efficient and reasonable water use. The results report that:

- Agriculture reflects the maximum utilization rate with a mean value of 6.7, synchronizing with our conclusion about the importance of this LULC in these regions.

Table 2.7: Results of the effective utilization rate of WF_{green} (M^3 (*10^3) per sq. km) per mm rainfall

Year	Rainfall	Agriculture	Proportion	Forest	Proportion	Grass	Proportion
2016	4170	276.3	6.6	201.6	4.8	57.6	1.3
2017	4504	312	6.9	200.4	4.4	66.7	1.4
2018	2997	201.2	6.7	146.3	4.8	42.8	1.4
2019	3898	260.6	6.6	185.5	4.7	54.6	1.4
Mean	3892	262.5	6.7	183.5	4.7	55.4	1.4

- The mean value of the effective utilization rate under forest is 4.7. The plausible explanation for forests having a low value compared to agriculture might be the nature of the plants found in these Municipalities. These areas have deciduous forest, which faces the incident of leaf shedding during spring, and due to that, the forest experiences less transpiration.

- Grass/shrub under these Municipalities is replicating a meager effective utilization rate with a mean value of 1.4. Having such a low value reflects lower evapotranspiration rates.

- Agriculture reflects the maximum utilization rate with a mean value of 6.7, synchronizing with our conclusion about the importance of this LULC in these regions.

- The mean value of the effective utilization rate under forest is 4.7. The plausible explanation for forests having a low value compared to agriculture might be the nature of the plants found in these Municipalities. These areas have deciduous forest, which faces the incident of leaf shedding during spring, and due to that, the forest experiences less transpiration.

- Grass/shrub under these Municipalities is replicating a meager effective utilization rate with a mean value of 1.4. Having such a low value reflects lower evapotranspiration rates.

Quantification of green water is crucial for scrutinizing sustainability in the topographies. However, identifying those places where WF is unsustainable should be the next objective, thus reducing the WF. The study reports that these municipalities suffer terribly from water scarcity during summer. Moreover, agriculture is the primary source of livelihood here. These areas are mostly single-cropped, mainly rice or maize, highly dependent on monsoons. Due to changes in the rainfall cycle/nature, many changes are observed, such as groundwater falling in the wells, the decline in crop production and crop failure, and migration to nearby cities for employment [72]. Therefore, the water loss could be minimized by converting unutilized barren land to utilizable agricultural or forested land to make better use of the resource [53]. Some currently developed scientific watershed techniques, such as dam desilting methodology, interventions for the ridge-to-valley approach as per the proposed region's topography, and climate-resilient agriculture practices for the farmers could be thought of as a tool to help for the conversion [73]. Furthermore, Micro-irrigation techniques, efficient water use for more crop production (more crops per drop), change in cropping pattern (climate resilience farming), and demonstration of different organic farming techniques, horticulture, and sustainable livelihood could also be considered as welfare measures for the farmers [87].

Moreover, WF_{green} can be reduced by increasing water productivity. Agriculture is primarily focused on maximizing land productivity, and it is sensible when land is scarce and water is abundant. However, optimizing water productivity is more important when it is the other way around. This contributes to the reduction of WF through innovative irrigation procedures, resulting in higher yield and less water evaporation per cubic meter. As seen earlier, municipalities such as Purulia and Ranchi produce the highest WF_{green} under agriculture (and Dhanbad produces the second-highest WF_{green} under agriculture), which brings us to a situation of reducing WF_{green} by increasing water productivity through both rain-fed and irrigated agriculture using more scientific and efficient techniques as discussed above [104, 48].

2.5 Summary and Conclusions

The Important findings of this study are as follows:

- Using satellite images and historically experimented data, we can map and estimate the LULCs and the coefficients, respectively, which are the ingredients to find the value of WF_{green}. The range of areas is significantly high, which reports the highest WF_{green} in agriculture for Purulia (10.5), forest for Dhanbad (86.1), and urban for Ranchi (73.1) in M^3 per sq km respectively. As far as coefficients are concerned, the urban area with the least evaporation rate revealed the most negligible value of 0.05, and agriculture depicts the highest value of 0.3.

- The WF_{green} values since (2016 – 19) depict that Purulia reports the highest WF_{green} ($182.6*10^3$ to $296.3*10^3$ M^3 per sq km), followed by Dhanbad ($170.3*10^3$ to $241.2*10^3$ M^3 per sq km), and Ranchi reports the least ($131*10^3$ to $219.2*10^3$ M^3 per sq km).

- Purulia overuses its water resources in agriculture and hence its high WF green needs to be corrected by increasing water productivity. Dhanbad's high WF is because of the water consumption by its forests. Given that the forests help hold up the soil and water, the high WF is not of concern. Ranchi's WF is low, it does not utilize its water resources properly. Steps should be taken to retain the rainwater in some form in the soil and man-made channels.

- Moreover, the evidence mentioned above articulates the current predicament of water scarcity in these municipalities. In this era of global warming, we have to realize the actual value of water and the apparent effects of its scarcity. To mitigate the problem, we believe that municipalities must act wherever it is likely to be necessary. The task should be to achieve the goal of water conservation and sustainable use of resources.

- Furthermore, the evidence mentioned above articulates the current predicament of water scarcity in these municipalities. In this era of global warming, we have to realize the actual value of water and the apparent effects of its scarcity. To mitigate the problem, we believe that municipalities must act wherever it is likely to be necessary. The task should be to achieve the goal of water conservation and sustainable use of resources.

CHAPTER 3

Blue Water Footprint (WF$_{blue}$): An Instrument to support Urban Water Management

3.1 Introduction

India is the highest populous country in the world [75], and 35.4% of the Indian population lives in urban areas [62]. The continuous urban-centric migration corresponding to urban growth has made water resource conservation a significant challenge for urban water management [25]. There is always a strong linkage between groundwater and urbanization as it can change the quality and quantity of the groundwater in several ways, mainly: water shortage, flooding, change in the river stream, and the overall aquifer system [97].

Wakode's paper [97] examines how urbanization affects groundwater recharge and the urban water balance in Hyderabad, India. His research demonstrates how the process of urbanization has changed the natural hydrological cycle and how an important part of urban balance is played by urban recharge. In the case of urban groundwater recharge, several factors, such as leakages from water supply networks and sewage networks, must be taken into account in addition to the natural recharge from precipitation. Actual evapotranspiration and surface runoff were calculated using remote sensing and GIS methods to calculate the natural recharge from precipitation. Results indicated that for increasing groundwater use, adequate analysis of the existing aquifers must be conducted, and no withdrawal above the mean annual total recharge rate should be allowed. Moreover, an appropriate study of the current aquifers is required to increase the usage of groundwater.

It is also estimated by India's Ministry of Water Resources, River Development, and Ganga Rejuvenation that the per capita accessibility of water in both rural and urban India is decreasing continuously. By 2025 and 2050, it will decrease by 36 and 60%, respectively, compared to what it was in 2001 [16]. Study shows that the per capita accessibility of water in India during 1951 was about6 (* 10-6) BCM, which decreased to 2 (* 10-6) BCM in 1991, and by the year 2011, it had further declined to 1(* 10-6) BCM [16, 81]. Approximately 600 million urban people in India are under "extremely high" to "high" water stress conditions [82].

During the last decade, strong evidence for massive groundwater depletion has been found around the urban part of the Gangetic basin, where the aquifers are heavily exploited as it has been used for 50% of the urban water supply [80]. Additionally, because of the changing land use land cover (LULCs) area, urban development puts pressure on urban infrastructure and the water bodies [37]. The development sectors are now more vulnerable because of significant urban water depletion brought on by the lack of communication between water users and decision-makers. Due to the varying ambient circumstances between cities, standard methods for analyzing and measuring water availability are no longer adequate to evaluate usage, conservation, and sustainable water management [24].

Academia uses the concept of blue WF to deal with the issue of water scarcity and per capita water accessibility in the urban domain [31, 39, 48], and suggested policy outlines [64, 94]. WF_{blue} was introduced to analyze and support better water management; however, the experience at an urban level is limited [5]. As a result, one of the key problems for WF_{blue} is adopting appropriate measures and offering solutions for urban entities [64]. The management of water needs to be done from both a qualitative and quantitative standpoint [47]. With this perspective, this chapter mainly focuses on WF_{blue} instead of the WF_{green} or WF_{grey}.

Hoekstra et al. (2009) [30] define WF_{blue} as "The blue water footprint is an indicator of consumptive use of so-called blue water, i.e., fresh surface or groundwater. The term 'consumptive water use' refers to one of the following four cases:

- Water evaporates

- water is incorporated into the product
- water does not return to the same catchment area, e.g. it is returned to another catchment area or the sea
- water does not return in the same period, e.g. it is withdrawn in a scarce period and returned in a wet period

Looking from these perspectives, this chapter considers different geographical and socio-economic conditions such as the land use land covers (LULCs), topography, hydrology, meteorology, population, and water supply-demand dynamics as represented by municipalities to signify the concept of WF_{blue}, as it helps to find a link between the consumptive use of water resources and human security in terms of adequate water supply in the municipal area [93, 24]. However, it is not possible to measure the groundwater used by individual households or business entities because no data is available. We attempt to measure only the parts of WF blue for which data is available. The only data available for water supply is the data from the municipalities. This study aims to develop a model by integrating hydrologic and economic models [34, 35, 77, 86] of WF for domestic and other water users within the urban domain. Therefore, this chapter aims to achieve the following objectives:

- Methodology to calculate the WF_{blue}
- Calculations of WF_{blue}

3.2 Methodology

3.2.1 Data

General Characteristics of the Municipalities

We have collected the population data for 2011 from the census data. The water department of each municipality has confirmed their actual water supply, which helped us to derive the WF_{blue} values. Data for poor and non-poor households have been supplied by the economic and planning departments of the respective municipalities.

Table 3.1 describes the socio-economic and geographical characteristics of all three municipalities .

Table 3.1: Characteristics of the municipalities

Characteristics	Purulia	Dhanbad	Ranchi
Altitude (mt)*	200	222	651
Rainfall in the year 2019 (mm)	1310	1226	1362
Administrative wards**	23	55	55
Total area (sq km)	36.6	231.8	201.5
Slum households	27%	6.5%	8.3%
Non-poor households	73%	93.5%	91.7%
Slum population	27.8%	6.4%	8.3%
Non-poor population	72.2%	93.6%	91.7%

Source: * The data on altitude and rainfall is taken from the Agriculture departments of the municipalities.

**The rest of the data are taken from the economic and planning departments of the municipalities.

Satellite data

Satellite data were used to classify different land covers. High-resolution multispectral Sentinel-2 data having four bands, Blue, Green, Red, and Near-Infrared, were used for classification. Three seasons (Jan, May, Oct- 2020); multi-temporal data were also used for classification.

3.2.2 LULC classification of satellite data

The study areas were classified into three categories of LULCs: water, urban, and open (A_i in square kilometers (sq km)) using the LULC classification technique of the previous chapter. The other three LULCs used in calculating WF*green*, such as forest, grass, and agriculture, have been masked here to calculate evaporation and avoid transpiration. Due to the masking, errors may be introduced in our results. However, we do not expect this to have a significant effect on our analysis

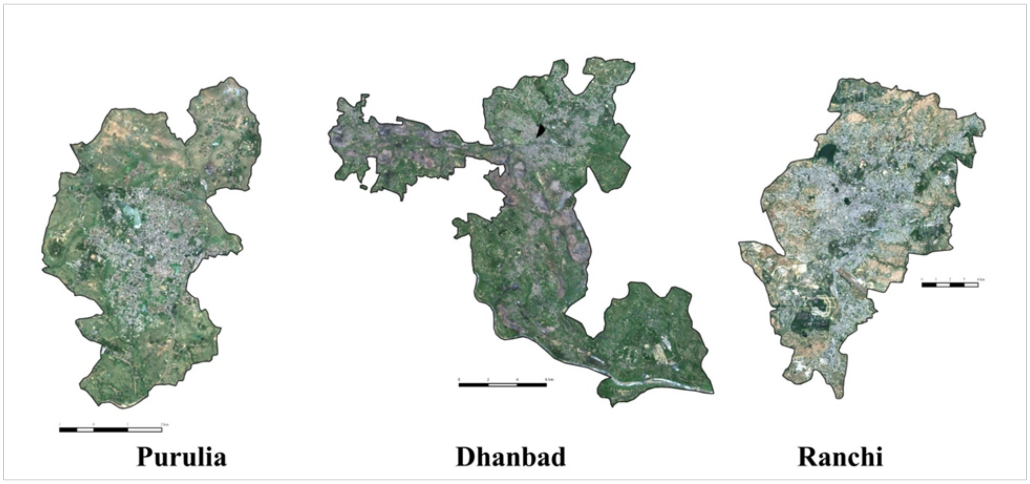

Figure 3.1: The satellite images of Three municipalities

as the contribution of these land covers in terms of transpiration is consequential, and evaporation is dormant. The classification algorithm provides an accuracy of 92% with a kappa coefficient of 0.89.

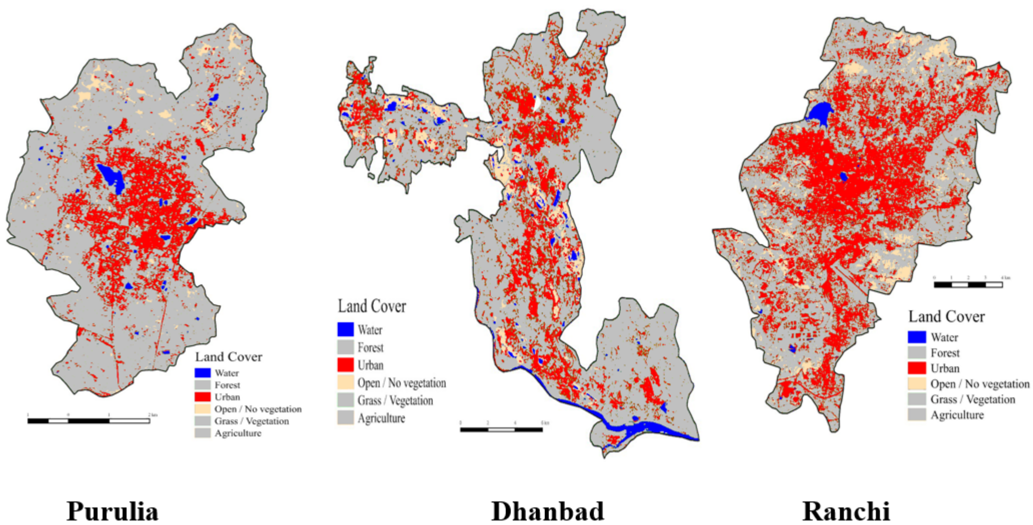

Figure 3.2: LULC classes from satellite data of three Municipalities

3.2.3 Estimation Model of WF_{blue}

WF_{blue} is calculated as follows:

$$WF_{blue} = [A + B + C + D] \tag{3.1}$$

where A is the total evaporation, B is the runoff, C is the total water supplied by the respective municipalities, and D is the water loss due to transportation [32].

As the calculation of evaporation is a big challenge, particularly in spatially large and heterogeneous, we used observed evaporation values from published data. A logical mapping was done from the experimental data of sixteen to the three LULC classes in the present case [35, 36]. Similar to the coefficients of the ET values, the evaporation coefficients also vary depending on the type of vegetation and geographical region. We, however, assume it to be a constant for all three municipalities due to their proximity.

Thus, Total evaporation = [(area of the LULC classes) * {(evaporation coefficients corresponding to LULC classes) * (annual rainfall)}]

Moreover, runoff (Q) is calculated using the SCS curve number method after adjusting the Antecedent Moisture Condition (AMC).

$$Q = (P - 0.2S)^2/(P + 0.8S) \tag{3.2}$$

where P is the annual rainfall, and S is the potential maximum retention after runoff begins [91].

3.3 Calculation of the Different Components of WF_{blue}

3.3.1 LULC classifications

Table 3.2 represents the LULC area covered by each municipality, respectively.

Table 3.2: LULC details of Municipalities areas in sq km

LULCs	Purulia	Dhanbad	Ranchi
Urban Area	7.4	54.7	73.2
Open Space	2.2	27.2	38.8
Water Bodies	0.5	7.3	1.7
Total	10.1	89.2	113.7

In general, it is beneficial for a municipality with a comparatively low permeable area, as it reflects a lower value of WF_{blue} due to less runoff and high water retention capacity [24]. However, the LULC classification demonstrates that all the municipalities reflect the highest LULC area under the urban domain that does not allow any water infiltration, and that area is increasing continuously. Purulia manifests the highest percentage of urban area with 74%, followed by Ranchi 64%, and then Dhanbad 61%. Municipalities do not seem to make any effort to lower the water loss from the system. Moreover, Table 3.2 illustrates that in the case of open area (barren land), Ranchi holds 34%, Dhanbad 31%, and Purulia 22%. However, water does seep in from the barren land and enriches the groundwater/aquifers. Therefore, the authorities should utilize the open space by transforming them into grasslands, parks, etc., such that the water loss could be mitigated.

Furthermore, Table 3.2 reports that the water bodies occupy the least area in the area classification, though Dhanbad shows a few canals and reservoirs. Therefore, the aim should be to increase the number of water bodies by constructing reservoirs/check dams, etc., to increase the groundwater percentage and minimize the water loss [13]. A close look at the LULCs confirms that though we are not considering vegetation area in our assessment, it plays a crucial role in these regions. The activities under vegetation, such as agriculture, afforestation, and such, are considered an effective utilization of water resources.

3.3.2 Evaporation Loss

Table 3.3: Result of the Total Evaporation of Municipalities (M^3 per capita)

Municipalities	Land Use Land Covers (Coefficient)			
	Water (0.59)	Urban (0.23)	Open (0.18)	Total (1)
Purulia	3.4	19.2	4.5	27.1
Dhanbad	4.8	14.2	5.5	24.5
Ranchi	1.3	21.4	8.9	31.6

Table 3.3 reports evaporation, a significant variable of WF_{blue} as it relates to the estimation of WF frequently [32]. Every consumption and production-related evaporation incorporated during WF_{blue} calculations, including different categories of the LULC, processing of food and other production, municipality supply,

transportation, etc. Consumptive use does not mean the disappearance of water, as it's a renewable source and remains within the system through the hydrological cycle. However, it does not have unlimited availability.

Table 3.3 gives the results of evaporation loss in three municipalities in M^3 per capita for the year 2019, that coming from equation 1, derived from the study of Kiptala et al. (2013) [35, 36]. All three municipalities reveal the central area as urban/built-up and minimum under water bodies because of the land cover area. The evaporation is mapping likewise and reports an identical pattern. The water loss is highest in urban areas, followed by open spaces and water bodies.

Furthermore, table 3.3 shows that the water loss through evaporation ranges from 14 to 21 M^3 per capita for urban land use, whereas it is only 4.5 to 8.9 M^3 per capita for open lands. It is even lower for the water bodies, 1.3 to 4.8 M^3 per capita. This means that to reduce the water loss from evaporation, an urban establishment should have enough water bodies and lands covered with vegetation.

Table 3.3 reports that the water loss through evaporation is at par for the municipalities. It is 33% for Purulia, 35% for Dhanbad, and 29% for Ranchi. However, some omissions and commissions are present due to the production of final commodities for domestic and small industries within these municipalities. Moreover, LULC areas under each category differ, another reason for getting different evaporation percentages among municipalities.

3.3.3 Estimation of Runoff

Earlier, the estimation of WF_{blue} was primarily based on the measuring of water withdrawal, known as utilization level of water [23] or withdrawal-to-availability ratio [2]. However, water withdrawal is not a suitable indicator as it considers run-off that partly returns to the same catchment [65]. Therefore, it's better to express WF_{blue} in terms of consumptive water use that does not return to the same catchment area, i.e., after considering the natural runoff, not total runoff [32].

This is because total runoff is not the primary factor in measuring water loss/availability in the system, as it ignores the fact that part of the runoff needs environmental requirements, such as the maintenance of soil moisture. Therefore, subtraction of the environmental requirements from total runoff should be considered [84, 66]. Moreover, it makes sense to consider natural runoff instead of actual runoff as it would not return to the same catchment area. And the calculation of WF_{blue} within municipalities is augmented intensively.

Table 3.4: Result of the Total Natural Runoff of Municipalities (M^3 per capita)

Municipality	Rainfall	LULCs	CN Values	Actual Runoff	Actual Runoff (AMC)	Natural Runoff (LULCs)	Total Natural Runoff
Purulia	1310	Water	0	0	0	0	54.3
		Urban	92	1283.9	743	45.6	
		Open	84	1253.7	471	8.7	
Dhanbad	1226	Water	0	0	0	0	44.3
		Urban	90	1189.8	717	33.8	
		Open	79	1145.6	448	10.5	
Ranchi	1362	Water	0	0	0	0	76.1
		Urban	92	1335.9	817	55.7	
		Open	84	1305.6	564	20.4	

Table 3.4 reports the result of the total natural runoff of the municipalities in M^3 per capita, which comes from equation 2, derived from the study of Tiwari et al. (2014) [91]. Ranchi reports the highest runoff value (76.1 M^3 per capita), followed by Purulia (54.3 M^3 per capita) and then Dhanbad (44.2 M^3 per capita). Such a high runoff volume resulted in these municipalities because of high CN values, added on with the LULC areas. The runoff is highest in urban areas, followed by open spaces and water bodies; because of high to low water infiltration rates. The runoff volume of three municipalities is mapping likewise.

In the SCS method, the change in CN values is based on AMC (AMC I, II, and III) determined by the total rainfall in the five-day period proceeding a rainfall. Accordingly, the result of natural runoff also changes. Hence, we have considered actual runoff based on CN values, based on the change in AMC conditions [91].

Now, if we want to reduce water loss created due to runoff, the main purpose should be to make soil and water conservation structures. The frequency number of the structures per unit km of stream length should be higher in Ranchi compared to the other two municipalities as it reflects the maximum runoff and WF_{blue}. This will facilitate to recharge of the groundwater aquifer. In addition to water, soil loss would also be minimal. Another example of the watershed approach for Ranchi municipality would be Deep Continuous Contour Trenches (DCCT). It is created in hilly areas, particularly on the upper hilly tract, which helps conserve soil and water, and thus the water would percolate down [67]. Excavating more such water bodies would strengthen the water supply sources and conserve water by recharging the groundwater. Furthermore, educating farmers on adopting sustainable best practices, such as more micro-irrigation techniques, drip irrigation, etc., could be highly beneficial.

3.3.4 Municipality Water Supply and Transportation Loss

Table 3.5: Water Distribution System of the Municipalities (M^3 per capita)

Municipalities	Purulia	Dhanbad	Ranchi
Water Released from the Treatment Plant	0.1	0.08	0.27
Amount of Water Reached to the Destination	0.08	0.05	0.23
Transportation Loss	0.02	0.03	0.04

Table 3.5 and Figure 3.3, 3.4, and 3.5 report three municipalities' water supply distribution networks (the number in the parentheses reflects the total amount of water (mld) distributed). The study finds that while Dhanbad and Ranchi have three main water reservoirs to supply water for the entire city, Purulia has an additional source of spot boring though the amount of water withdrawn from that is minimal. Dhanbad transports water from water bodies such as dams/reservoirs from 30-35 km away and then distributes that through elevated surface reservoirs (ESR). Ranchi follows the same process of water management for centralized water supply. However, the water transportation distance is less in the latter than in the former. Purulia is the only municipality to use groundwater. Mapping the water distribution with per capita population reports that Ranchi supplies more water than Dhanbad and Purulia.

In addition, the per capita water supply by Ranchi Municipality is the highest among the three, and it is 0.23 M^3. Compared to Ranchi, the water supplied by the municipality in Purulia and Dhanbad is less. It is 0.08 and 0.05 M^3 per capita, respectively. These numbers reflect the water scarcity and poor accessibility of water in these municipalities, a concern for the authorities. Moreover, the water loss through transportation is also at par among municipalities. However, Dhanbad and Ranchi make transportation loss a major factor as this municipality lost significantly by bringing water from far away.

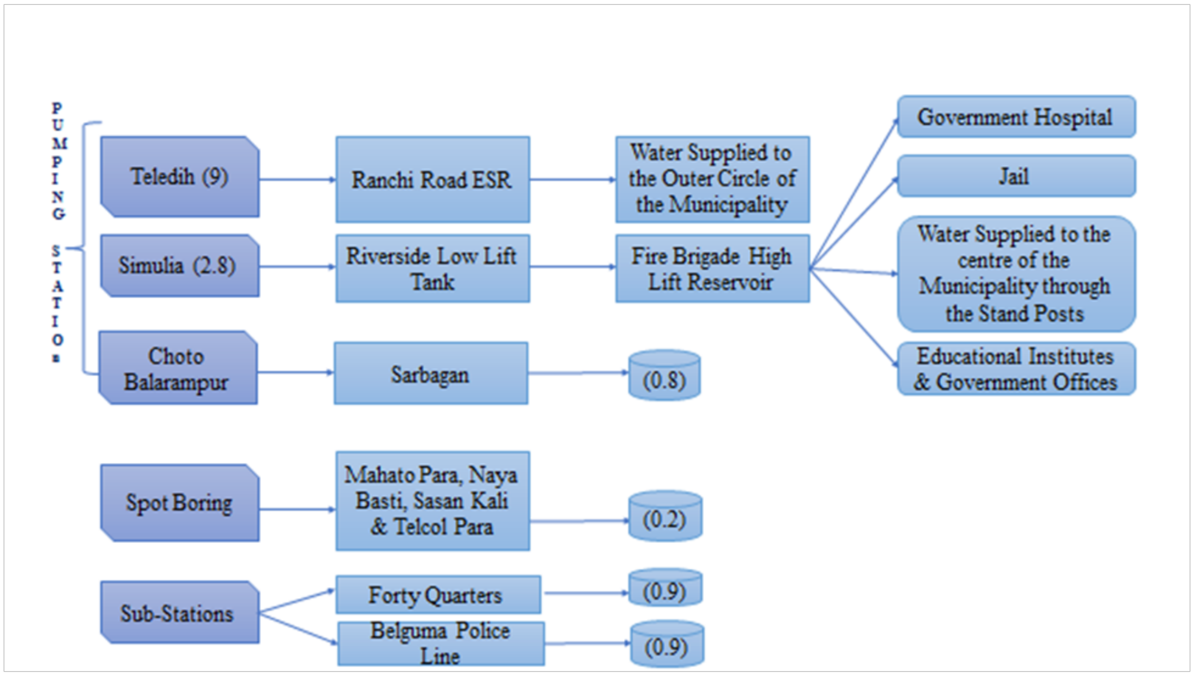

Figure 3.3: The Water Supply Distribution Network of Purulia Municipality

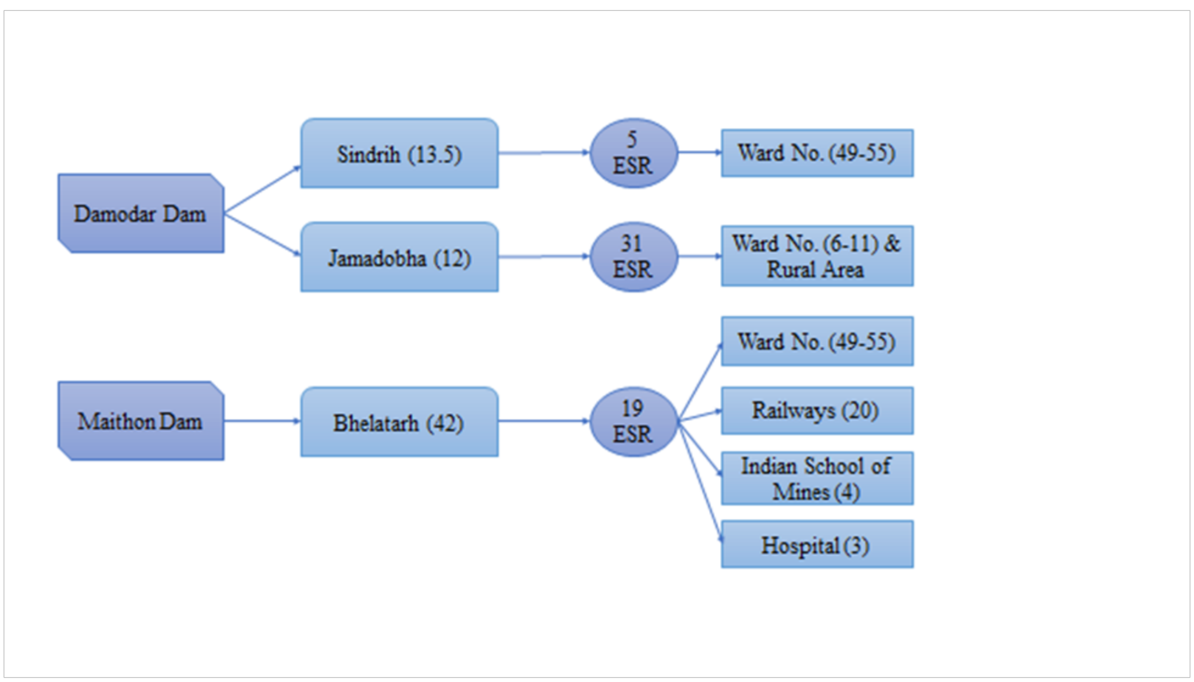

Figure 3.4: The Water Supply Distribution Network of Dhanbad Municipality

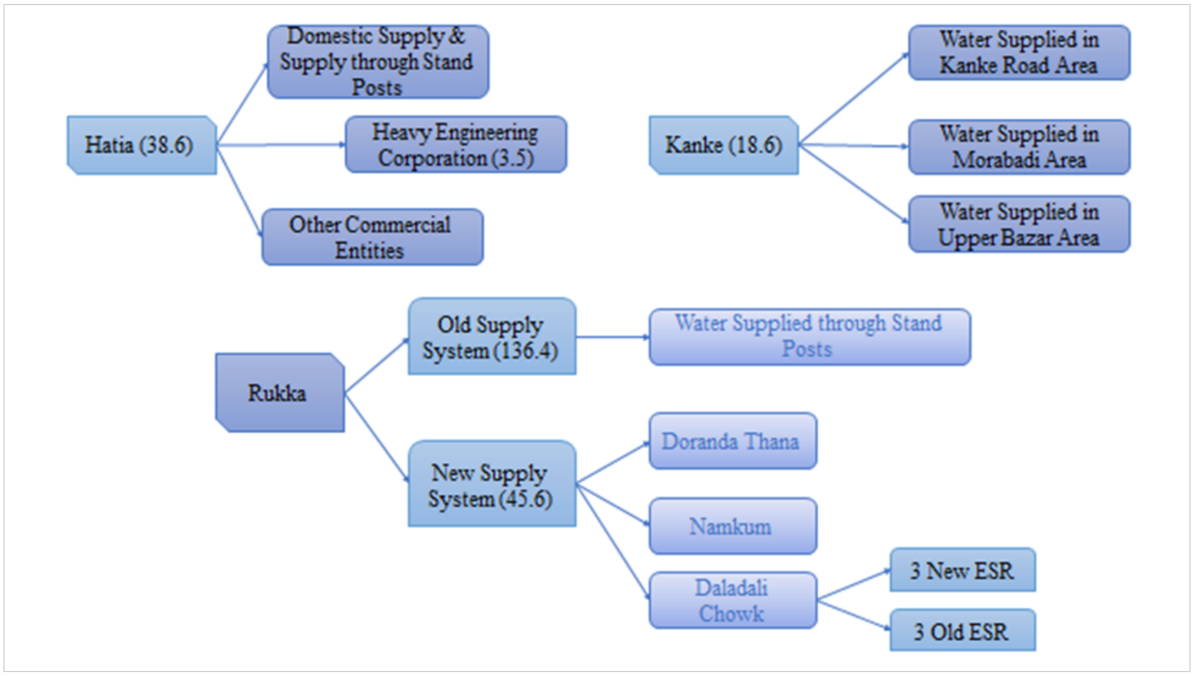

Figure 3.5: The Water Supply Distribution Network of Ranchi Municipality

3.3.5 Overall Estimation of WF_{blue}

Table 3.6: Result of the WF_{blue} of Municipalities (M^3 per capita)

Characteristics	Purulia	Dhanbad	Ranchi
Total evaporation	27.1	24.5	31.6
Runoff	54.3	44.2	76.1
Water supplied by the municipalities	.08	.05	.23
Transportation loss	.02	.03	.04
Total	81.5	68.8	108

The comparative analysis of WF_{blue} among municipalities expressed over per capita is relevant as it reflects on the volume of water used, groundwater withdrawal, and water supplied by the municipalities along with the transportation loss [24].

Table 3.6 combines all 4 components of WF_{blue} and shows the overall WF generated by three municipalities. It reports that Dhanbad leaves behind the least WF_{blue}, followed by Purulia and Ranchi. Our analysis shows that the least footprint generated by Dhanbad is primarily due to the soil types in the municipalities. Dhanbad's soil retains water in open lands, however, in the other two municipalities, soil retention capacity is lesser.

We understand the soil type cannot be changed. Still, the water retention capacity of the soil can be increased by using suitable types of vegetation and appropriate land use patterns [71].

3.4 Conclusions

The Important findings of this study are three folds; those are as follows:

- Using satellite images and historically experimented data, we can map and calculate the LULCs and the evaporation coefficients, respectively, which are the ingredients to find the value of WF_{blue}. The range of areas is significantly high, which reports a maximum in the urban area for Purulia (7.4), Dhanbad (54.7), and Ranchi (73.2) in Sq Km, respectively. As far as coefficients are concerned, the open space with the least evaporation rate revealed the most negligible value of 0.18, and the water body depicts the highest value of 0.59.
- The WF_{blue} values depict that Ranchi reports the highest (108 M^3 per capita), followed by Purulia (81.5 M^3 per capita), and Dhanbad reports the least (68.8 M^3 per capita). The primary factor for getting such results is high runoff followed by evaporation, and then the municipality supplies water. However, in most cities and towns in India, water supplied by the centralized water system is insufficient.
- However, it is not possible to measure the groundwater used by individual households or business entities because no data is available. We attempt to measure only the parts of blue WF for which data is available. The only data available for water supply is the data from the municipalities.

Chapter 4

The Haves and Have-nots for water: Analysis of the Primary Data

4.1 Introduction

Water scarcity and insecurity have become inextricable in almost every world region [100]. Many countries are experiencing severe water problems and conflicts [22]. The constant increase in the population growth rate followed by rapid industrialization compels the global water demand to be augmented by one percent per year [92]. Water scarcity develops when artificial or environmentally extended resources cannot satisfy the overall demand at a particular point in time [14]. Currently, water scarcity is aggravated by the continuous deterioration of surface water availability [81]. The results of [51] confirm that nearly four billion global people are facing water insufficiency, and half belong to India and China. It is, to an extent, expected that a developing country like India, with a population of more than 1.3 billion, suffers from this global paucity of water [63], but what is alarming is that the national average annual per capita water availability is reducing continuously; from 1,816 cubic meters in 2001 to 1,544 cubic meters in 2011, and further down to 1486 cubic meters in 2021 [63]. A country is labeled as water stressed if its water demand is 40% more than its supply, which is what India faces [42]. Nearly 54% of Indian people live in the water threat region - southern India is the worst affected [82]. To make matters worse, factories release untreated waste, pesticides, and fertilizers into water bodies leading to about 163 million Indians receiving poor-quality water [17].

Institutional impediments and political factors are the main reasons for this water mismanagement [49]. [17] pointed out that the possible way out of this upcoming scarcity situation could be implementing green and grey water management. The study of [11] finds the influential determinants of per capita water supply for 30 Indian cities with deficient surface water availability. The multiple regression model presented in this study indicates that non-revenue water, continuity of water supply, coverage, and metering are the significant variables for per capita water supply. Ensuring the bare minimum water availability per capita is the central topic of debate that academia is dealing with now [3]. Not only academicians but numerous international organizations such as the American Water Works Association, the Asian Development Bank for the People's Republic of China, the International Benchmarking Network for developing countries, the International Water Association, The Bureau of Meteorology in Australia, and Water Services Regulation Authority of the United Kingdom also have addressed the issue of per capita water availability. They set up their benchmark for the world [11]. All these parameters are used in this study. This chapter tries to contribute to the literature on water availability by studying the accessibility to water of different income households and the amount of water they get to satisfy their various needs.

4.2 Study Area and Data Set

This chapter studies the water availability within Purulia, Dhanbad, and Ranchi municipalities. As discussed in chapter one, a total of 272 sample households from these municipalities were interviewed. 100 sample households from Ranchi, 90 from Purulia, and 82 from Dhanbad have been covered. The consumption patterns of water use according to different income classes are recorded. Other related elements like the quality of the water, its taste, color, and presence of minerals available to different classes of households have also been surveyed. Mapping of water availability with its sources and per capita consumption has been done quantitatively. Parameters such as total members of the households, the amount of water stored per day, how many times the storage has to be refilled, and whether they are doing any gardening have also been looked at. Since the houses do not always use the entire water tank, their water consumption per day is lesser than their storage capacity, but it is impossible to find how much water remains in the tank for houses. So we assume that the households use the entire water tank daily. In that sense, the study may err somewhat on overestimating the water demand.

4.3 Findings

4.3.1 sources of Water

Table 4.1 reveals that 59.4 percent of people living in huts and chawls (63 out of 106 households) use well Water and community bore wells/tube wells, whereas 38.7 percent of households (41 out of 106) are solely dependent on municipal water supply. However, a different pattern is observed for the non-poor. While 70 percent of households use bore well/ tube well water and 16 percent use dug wells, only 11 percent are solely dependent on municipal water sources. The non-poor households do not depend much on the centralized water supply. Government supply is only a supplementary supply for them. The primary source of water is groundwater for these people. Although this is true for the poor also, more proportion of them (38.7%) solely depend on municipal water supply compared to the non-poor (11%).

Table 4.1: Sources of Water for Different Residences

	Tube Well/ Bore Well	Municipality	Well	Others	Total
Huts & Chawls	50	41	13	2	106
Houses	46	16	27	4	93
Bunglows	28	1	0	0	29
Apartments	43	1	0	0	44

4.3.2 Per capita Consumption of Water

The per capita consumption of water in different residences is as follows:

Per capita consumption of Water = (Total consumption of water by the household)/(The total number of family members)

Total water consumption for a household has been calculated based on the storage capacity and how many times the households refill the storage per day. Figure 4.1 - 4.4 demonstrates the per capita water consumption in different residences.

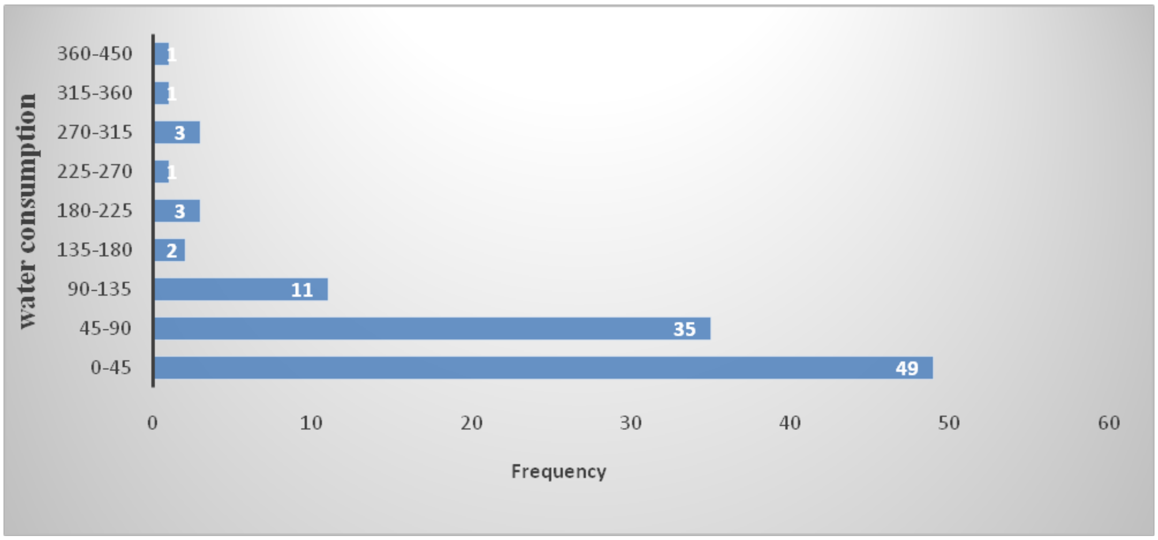

Figure 4.1: Per capita water consumption of huts and chawls

We have used the mode to measure central tendency rather than the mean. The arithmetic mean would include extreme values and give an erroneous picture. However, if the mode is used, it can tell us about the maximum number of households that use a certain quantity of water. The modal value of water use increases as we move from poor to non-poor households. The modal value of per capita consumption of huts & chawls is 50 (with a range of 12 to 400 lpcd), far less than the bare minimum of 70 lpcd [85], and 70 out of 106 reports not getting even that amount (with a probability value of .7). In addition, the data also reports 36 out of 106 respondents(with a probability value of .3) are not getting that critical minimum water level of 40 lpcd [85]. A lady from Bauri Para Bhatbandh, Purulia, reveals getting only 12 lpcd water, and A man from Shiv colony, Deshbandhu Road, Purulia, reported getting a mere 16 lpcd water. They depend entirely on the municipality water supply through stand post. Water is supplied only once in two days, for two hours, and about 100 people fetch water. These people asserted before the surveyor that people were fighting for a bucket of water. Inefficient supply management, along with infrequent water service, made their life miserable. In Dhanbad, the surveyor found that the situation is similar in the Guljar bag, Wasseypur area. A lady who has nine people in her house reported getting only 27 lpcd from the community tube well situated more than a half km away. Sometimes during scarcity, she also had to ask for help from her neighbors. A railway employee, who resides behind the S.P. Kothi, Dhanbad, reports receiving only 33 lpcd. 12 members are there in his house, and if the accessibility of water follows such less number, anyone can assume how they carry out their daily chores. All these people suffering from water scarcity, including others, who do not even receive a bare minimum of 50 lpcd water, urged the surveyor to rectify the situation because they thought the surveyor was a government representative.

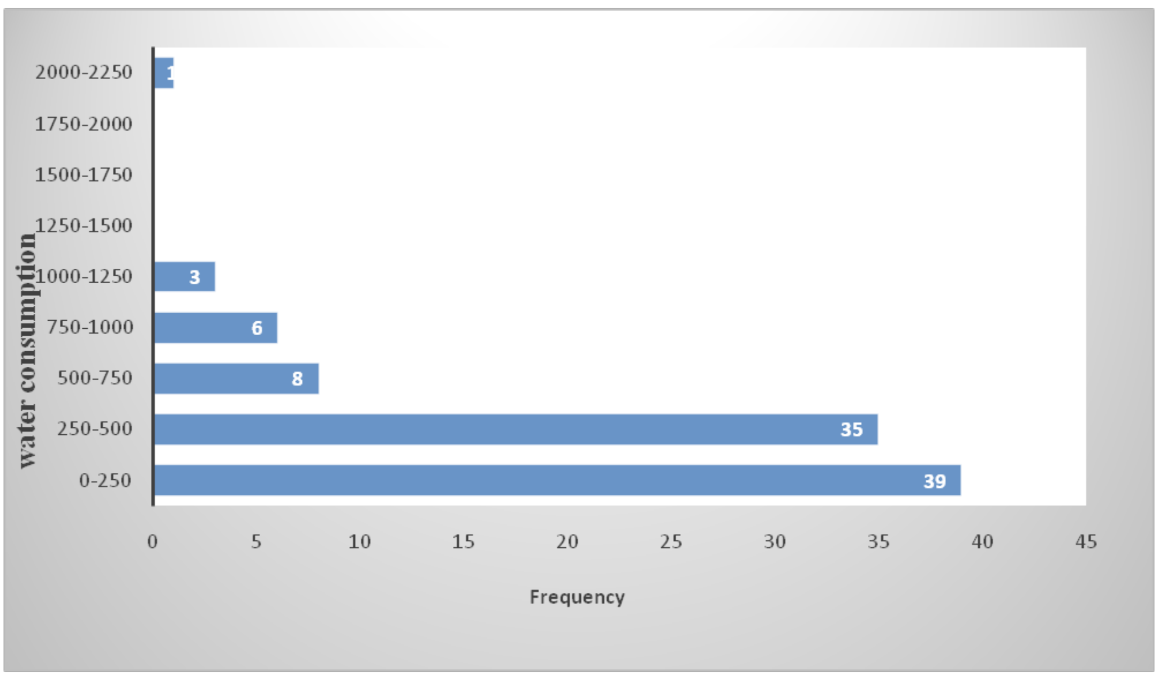

Figure 4.2: Per capita water consumption of houses

For houses, the modal value of per capita availability of water is 250 lpcd (with a range of 75 and 3326 lpcd); for bunglows, it is 400 (with a range of 216.6 to 4462.5 lpcd) but, in the case of apartments, it is 666.6 (with a range of 166 to 3999.9 lpcd). The figures reflect a wide range of water availability. We want to clarify that this study errs on making a higher estimate of water consumption by the non-poor, such as, in the case of apartments, we considered three people (app.) for each flat

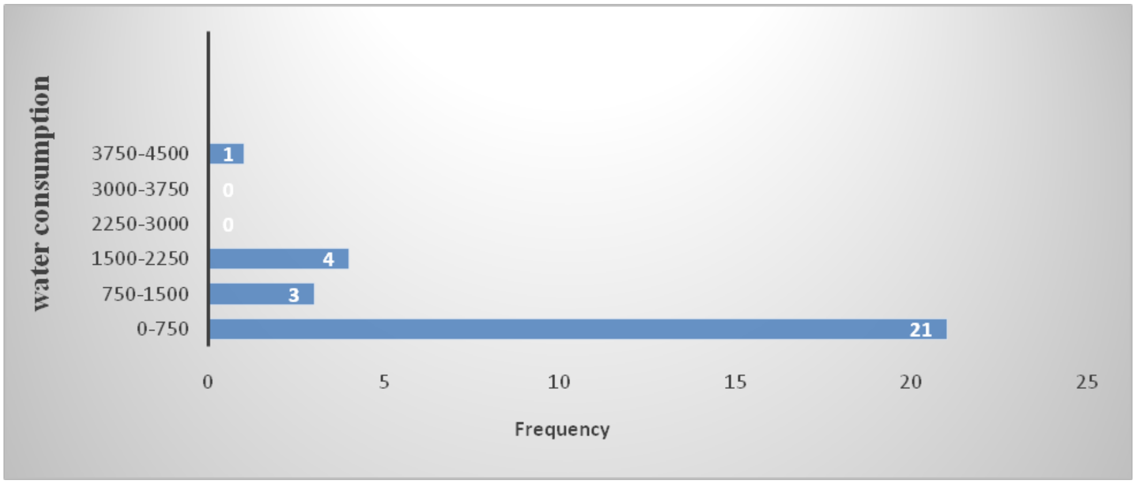

Figure 4.3: Per capita water consumption of bunglows

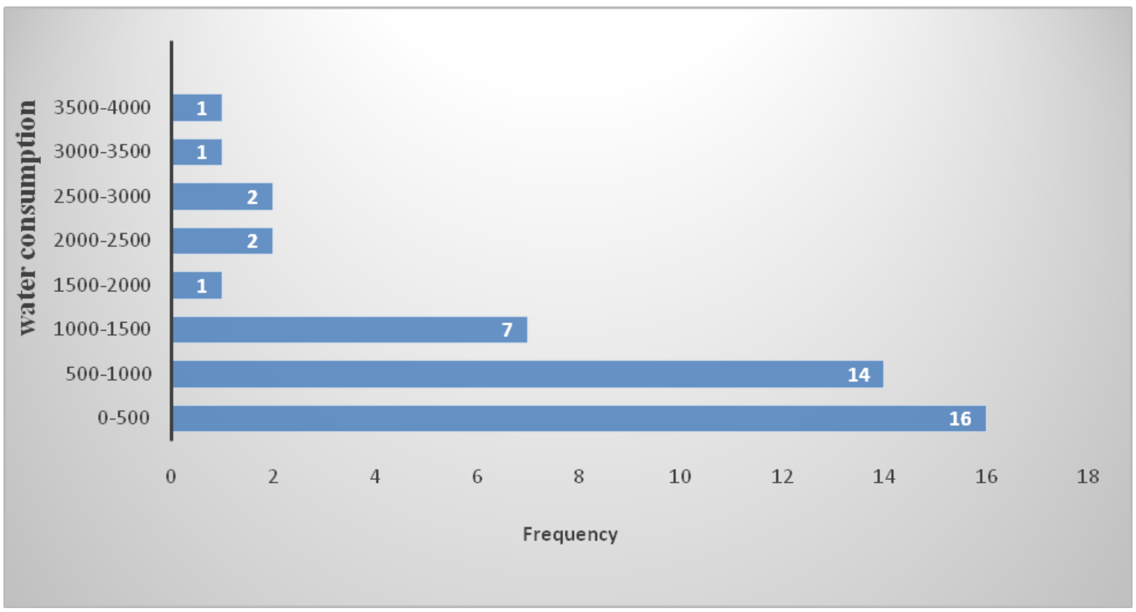

Figure 4.4: Per capita water consumption of apartments

for the calculation of per capita consumption as it was tough to know the exact number of members per flat in an apartment complex. Considering the non-poor in the data set, we found that 19 people (with a probability value of .2) are getting less than 150 lpcd, the standards set up by the [85]. A possible explanation could be the method of storing water at different residences. It has been seen that nine out of these 19 are getting less per capita water as they do not have the water tank to store water. Either they store water in a bucket or barrel.

4.3.3 Mapping of water availability, its sources, and per capita consumption

The primary data seek to identify factors that determine per capita consumption/availability of water, which has been done by estimating a dummy variable regression model. Sources of Water and Types of Residences are the essential variables to determine the households' per capita water consumption. The intercept was insignificant because of the dummy variable trap, so the regression excluded the intercept term.

Table 4.2: Regression results for dummy variable model

	Coefficient (β)	t-Statistics	P-value	R Square
Intercept	-	-	-	0.5
Sources of Water	19.77	0.59	0.55	
Types of Residences	346.17	15.75	4.07 * E-40	

The above result reports that the value of the R-square that shows the goodness of fit of the estimated model is 0.5. This means the chosen explanatory variables explain almost 50% of the variation in water availability. The equation shows that the relation between water availability and water sources is statistically insignificant. This is not surprising. We observed that affluent households find their water from many sources and get enough water. The poor (hutment dwellers) do not have economic access to most water sources, so irrespective of the water source, the water they can acquire is far less than their wealthy counterparts. It has been found that the per capita water consumption is adequate if people have access to more than one water source or their water source. Nevertheless, if the water sources are restricted to community tube wells or bore wells, or if they have to travel far to fetch water, per capita consumption becomes less.

The relationship between per capita water consumption and types of residences is positive and statistically significant. This signifies inequality in water accessibility for different income classes across municipalities. There is a considerable gap in the average per capita consumption of sample Dhanbad households when we move from huts and chawls to bunglows (from a mean value of 67.3 to a mean value of 1203.7). However, the sample households of Purulia and Ranchi reflect somewhat lesser inequality (from a mean value of 45.6 to a mean value of 768.8 for Purulia and a mean value of 97 to 715.2 for Ranchi). While Ranchi enables the highest average water consumption in the huts and chawls studied (97 lpcd), Dhanbad prefers the rich (with a mean value of 1081 and 1203.7 lpcd in the apartments and bunglows).

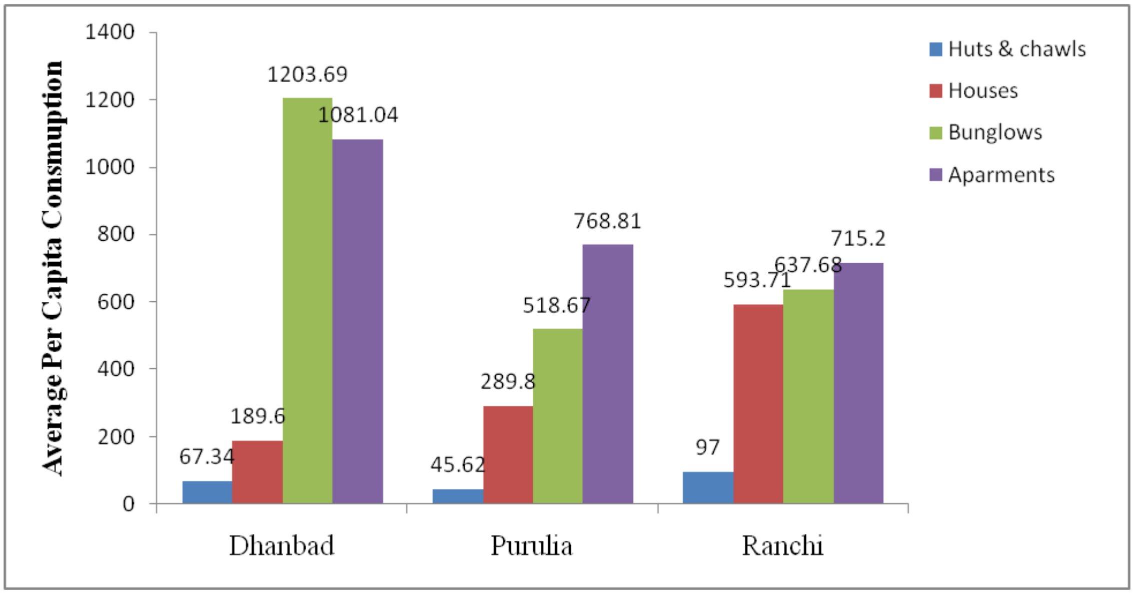

Figure 4.5: Per capita water consumption of apartments

Therefore, it seems from the sample that Dhanbad favors the 'Haves' in water distribution while Ranchi emphasizes the 'Have-nots.'

4.3.4 Correlation matrix among parameters

The degree of association between variables is measured by correlation. Here in the below table, we have found a correlation among essential attributes of our model, which affect the concept of WF.

The above table shows that water sources and quality (Taste, Appearance, and Presence of Minerals) are negatively related. This means that as we move from the municipality supply water to the well water and the water supplied through tube well/bore well, water quality will deteriorate. Also, the correlation between sources of water and seasonal dearth shows significantly less value, which signifies that seasonal dearth does not relate to which water sources households are

Table 4.3: Correlation matrix showing the degree of association among parameters

	Per capita consumption	Sources of Water	Types of Residences	Taste	Appearance	Presence of Minerals	Hard - ness	Seasonal Dearth	Region
Per capita Consumption	1								
Sources of Water	-0.21	1							
Types of Residences	0.53	-0.32	1						
Taste	0.11	-0.58	0.04	1					
Appear - ance	0.16	-0.59	0.06	0.98	1				
Presence of Minerals	0.21	-0.52	0.14	0.78	0.79	1			
Hard - ness	0.23	-0.36	0.13	0.52	0.53	0.64	1		
Seasonal Dearth	-0.07	0.11	-0.06	0.05	0.04	0	-0.02	1	
Regions	0.013	-0.1	0.08	0.19	0.21	0.16	0.03	0.24	1

fetching the water from. Seasonal dearth in the water-scarce region is experienced irrespective of the water source.

4.3.5 Quality of Water

As mentioned earlier, we have taken three parameters to showcase the quality of water: Taste of Water, its transparency, and whether the water carries any minerals such as iron or fluorides. Table 4.4 explains the water quality for different residences in 3 municipalities.

As far as the municipalities are concerned, Purulia municipality seems to be providing better water quality than the other two municipalities. 67.5% sample residences in Purulia (27 out of 40) under huts & chawls report that they get sweet and transparent water, compared to 40% in Dhanbad and a mere 20% in Ranchi.

Table 4.4: Quality of Water for Different Residences along with Municipalities (The figures in parentheses show the percentage values of respondents suffering from the problem)

		Sweet	Transparent	Iron
Huts & Chawls	Dhanbad	12 (40)	12 (40)	18 (60)
	Purulia	27 (67.5)	27 (67.5)	13 (32.5)
	Ranchi	7 (19.4)	7 (19.4)	30 (83.3)
Houses	Dhanbad	18 (60)	18 (60)	20 (66.7)
	Purulia	28 (82.4)	27 (79.4)	10 (29.4)
	Ranchi	11(37.9)	11(37.9)	26 (89.7)
Bunglows	Dhanbad	4 (36.4)	4 (36.4)	10 (91)
	Purulia	8 (100)	8 (100)	2 (25)
	Ranchi	2 (20)	2 (20)	10 (100)
Apartments	Dhanbad	4 (36.4)	4 (36.4)	10 (91)
	Purulia	6 (66.7)	6 (66.7)	2 (22.2)
	Ranchi	6 (25)	4 (16.7)	20 (83.3)

Similarly, only 32.5% of respondents report the presence of iron in the water they get in Purulia compared to a higher presence of iron in Dhanbad (60%) and Ranchi (83%). For houses, the quality parameter numbers are far better for all municipalities, although the trend continues that water quality is worrisome for sample households in Ranchi(37.9% are getting sweet and transparent water, and 89.4% are getting water with the presence of iron).

4.3.6 The Hardness of Water

The hardness of water was established by asking the respondents whether their soaps lather or not and whether it get washed off easily.

The results of Table 4.5 confirm that for sample households of Dhanbad and Ranchi, water is quite hard, and we found that this phenomenon exists common for bore wells or tube wells. Whereas in Dhanbad, 50% (30 out of 60) of the sample households in huts & chawls, and houses report getting soft water, the number in Ranchi is significantly less, and it is only 15% (10 out of 65). However, the figure illustrates that Purulia municipality produces a far better outcome under this parameter. More than 67% (50 out of 74) of the sample receive water of soft nature. In the case of apartments and bunglows, these municipalities reflect a similar pattern of enjoying soft and hard water.

Table 4.5: Hardness of Water of Different Residences along with Municipalities (The figures in parentheses show the percentage values)

		Soft	Hard
Huts & Chawls	Dhanbad	12 (40)	18 (60)
	Purulia	27 (67.5)	13 (32.5)
	Ranchi	7 (19.4)	29 (80.6)
Houses	Dhanbad	10 (33.3)	20 (66.7)
	Purulia	23 (67.6)	11 (32.4)
	Ranchi	3 (10.3)	26 (89.7)
Bunglows	Dhanbad	1(9)	10 (91)
	Purulia	6 (75)	2 (25)
	Ranchi	0	10 (100)
Apartments	Dhanbad	1(9)	10 (91)
	Purulia	6 (66.7)	3(33.3)
	Ranchi	4 (16.7)	20 (83.3)

4.3.7 Seasonal Fluctuations

As far as the seasonal fluctuations are concerned, Table 4.6 confirms that residences like huts & chawls, and houses are suffering the most, and it is well expected. 31.1% (33 out of 106) of the sample from huts & chawls and 25.8% (24 out of 93) from houses report seasonal dearth. However, for bungalows and apartments, it is almost nil. Primary data reveals that people residing adjacent to the Pahari Mandir area in Ranchi suffer dreadfully because they are on the hill. Hence, the water level goes down in their bore wells, making them dysfunctional. These people also said that they have to depend on the infrequent water supplied by the municipality through the water tank from March to August. While conducting his survey, the surveyor found that collecting water during summer when water becomes scarce is quite troublesome. 8 people reported getting help from their well-off neighbors, 12 reported collecting water from nearby alternative resources, and 5 respondents reported having to travel far to fetch one or two buckets of Water (more than 1 or 1.5 km).

4.3.8 Filtration of Water of Different Residences

Table 4.7 reveals that the awareness of water purification is significantly less among poor people than non-poor ones.

Table 4.6: Seasonal Fluctuations of Different Residences along with Municipalities (The figures in parentheses show the percentage values)

		Yes
Huts & Chawls	Dhanbad	(43.3)
	Purulia	(10)
	Ranchi	(44.4)
Houses	Dhanbad	(6.7)
	Purulia	(29.4)
	Ranchi	(41.3)
Bunglows	Dhanbad	0
	Purulia	0
	Ranchi	(60)
Apartments	Dhanbad	0
	Purulia	(22.2)
	Ranchi	(37.5)

Table 4.7: Filtration of Water for Different Residences (The figures in parentheses show the percentage values)

	R-O Water	Filtered Water	Boiled Water	Water Bubble	No Purification
Huts & Chawls	3 (2.8)	4 (3.7)	19 (18)	9 (8.4)	71 (67)
Houses	37 (39.7)	14 (15)	5 (5.4)	10 (10.8)	24 (25.8)
Bunglows	27 (93)	2 (7)	0	0	0
Apartments	37 (84)	0	0	5 (11.3)	2 (4.5)

While 67% of the sample poor households are drinking water without purification, only 25% non-poor are present in that list. However, as shown in Table 4.7 68% of the non-poor sample use R-O water. The report also reveals that 32% of the sample (88 out of 272) do not purify the municipality-supplied water, i.e., because they use it only for drinking, and they assume that municipalities provide water after purification.

We would like to emphasize that water purification can be harmful to the environment as using R-O and releasing far saltier water into the ecosystem makes the groundwater more and more polluted and reduces the sustainability of the natural system.

Table 4.8: Extent of Water Scarcity for Poor Households

		Not Sufficient (%)
Huts & Chawls	Drinking	15
	Bathing	22
	Cooking	21
	Washing Clothes	22
	Cleaning Vessels	20
	Overall Sufficiency	27

4.3.9 The extent of Water Scarcity of Poor Households

Table 4.8 reflects the extent of water scarcity for poor households. 16 out of 106 (15%) sample households say that they do not have access to even drinking water. They remain thirsty or scout around for water, even for cooking. The percentage is high for a decent civilized society; no one should remain without access to drinking water. 24 out of 106 (22%) surveyed say that they do not have water for bathing every day. For cooking, washing clothes, and cleaning vessels, the percentage rate is almost similar (21%) as far as the non-accessibility of water is concerned. Moreover, in terms of overall sufficiency, the percentage rate of non-accessibility is slightly higher, i.e., 27%. If we look at the percentage rate, it is clear that some people are not reporting their experience of water scarcity accurately. 33% of the surveyed hut dwellers get access to only 40 lpcd or less. However, only 27% of them report an overall deficiency of water. We feel that the reason could be that people's expectations about water availability are low. They may not have ever seen how it feels to get enough water (100 lpcd). So they have to be satisfied with what they receive. Dhanbad Municipality illustrates a severe water crisis in the Wasseypur area. Three interviewed persons residing here reveal that neither they get sufficient water for drinking nor for daily activities. The only source from which they can fetch water is a community tube well, which provides colored water that is bitter. They get a bare minimum of 30 lpcd. The primary survey also finds a few more cases in Saraidhela and Dhansar of Dhanbad Municipality, where people live in dire conditions. The same grave water scarcity situation has been found in the Dhurwa area of Ranchi, where people only depend on a community bore well. People who live here, disclose that more than 25 families rely on a single bore well provided by the municipal authority. The water tap from that source is also far from their homes, which is yellow (too much iron). Life is really tough for these women.

4.3.10 Measures of Skewness and Kurtosis

Table 4.9: Measures of Skewness and Kurtosis of Different Residences along with Municipalities

		Skewness	Kurtosis
Huts & Chawls	Dhanbad	1.8	4.2
	Purulia	0.9	0.1
	Ranchi	1.3	0.8
Houses	Dhanbad	1.2	1.3
	Purulia	1.6	2.3
	Ranchi	3	10.5
Bunglows	Dhanbad	2	4.8
	Purulia	-.4	-1
	Ranchi	1.9	4.1
Apartments	Dhanbad	1.1	0
	Purulia	1.6	1.5
	Ranchi	2.4	6.4

Table 4.9 illustrates that in the sample huts & chawls, though all the municipalities reflect positively skewed distribution, Dhanbad faces the highest asymmetry (value of 1.8) in the average per capita water consumption. This municipality's kurtosis value also suggests unequal water consumption. For the sample non-poor, Ranchi replicates the highest asymmetry (3 and 10.5). Therefore, the trend of symmetry advocates that except few incidences, the possibility of the average per capita water consumption hovering around its mean values is minimal. So, there is a lack on the part of the municipalities to provide an equal distribution of water, and it is their sole responsibility to make the distribution system more sustainable.

4.3.11 Probability Calculations among parameters

Here, we have used the concept of flowcharts to showcase the conditional probability of several attributes affecting water availability among different residences.

It is calculated using the decision tree structure. Consider the quality of water (S for sweet Water, T for tasteless, and B for bitter taste water) under the tube well/bore well in sample huts and chawls. As the events depend on each other, the probability of getting sweet water through the Tube well/bore well in sample huts and chawls would be P(S)/P(H & T) =1/50 = 0.02. Moreover, the probability of getting tasteless and bitter taste water under the tube well/bore well in sample huts and chawls is = 2/50 = 0.04 and 47/50 = 0.94.

Under municipality supply water in sample huts and chawls, the conditional probability of getting sweet water is 30/41= 0.73, for tasteless, it is 10/41= 0.24, and for bitter taste, 1/41 = 0.02. This shows the superior quality of municipal water emphatically. Moreover, for wells, it is 1, 0, and 0, respectively. Thus well water gives the best water quality.

Thus, the conditional probability of getting sweet water in sample huts and chawls is (1+30+13/50+41+13) = 44/104 = 0.4, and the conditional probability of getting tasteless water in sample huts and chawls is (2+10/50+41+13) = 12/104 = 0.1and the conditional probability of getting bitter water in sample huts and chawls is (47+1/50+41+13) = 48/104 = 0.5. In short, it is more probable to get bitter water in sample huts and chawls compared to sweet water; the water quality, in general, is inferior in sample huts and chawls.

Likewise, we have prepared Table 4.7, which reports the total probability of different parameters in different residences.

Table 4.10: Results of the total probability of different parameters in different residences

	Quality of Water						
	Taste			Appearance		Presence of Minerals	
	Sweet	Tasteless	Bitter	Colored	Transparent	Yes	No
Huts & Chawls	.4	.1	.5	.6	.4	.6	.4
Houses	.6	.2	.2	.4	.6	.6	.4
Bunglows	.5	.3	.2	.5	.5	.8	.2
Apartments	.4	.3	.3	.7	.3	.8	.2

Table 4.10 reports that a high chance of receiving sweet and transparent water lies in the case of sample houses (with a probability value of 0.6) compared to others. In the case of minerals, all four types of sample residences are getting poor water (huts and chawls, houses receive water with a probability of 0.6 each, and 0.8 each for bunglows and apartments, respectively). Moreover, we found that the water fetched from bore well/tube well in these municipalities contains a significant amount of iron, which makes the color of the water yellow. People living in apartments fetch water from a bore well and thus receive colored water with a probability value of 0.7. Therefore, we can say that the bunglows and apartments surveyed also suffer from bad quality water; the only difference is that they convert this into better quality using R-O machines. Nevertheless, the probability of getting low-quality water seems high for almost all types of residences in these cities.

Figure 4.6 - 4.9 is the flowchart representing the attributes of water in different types of households.

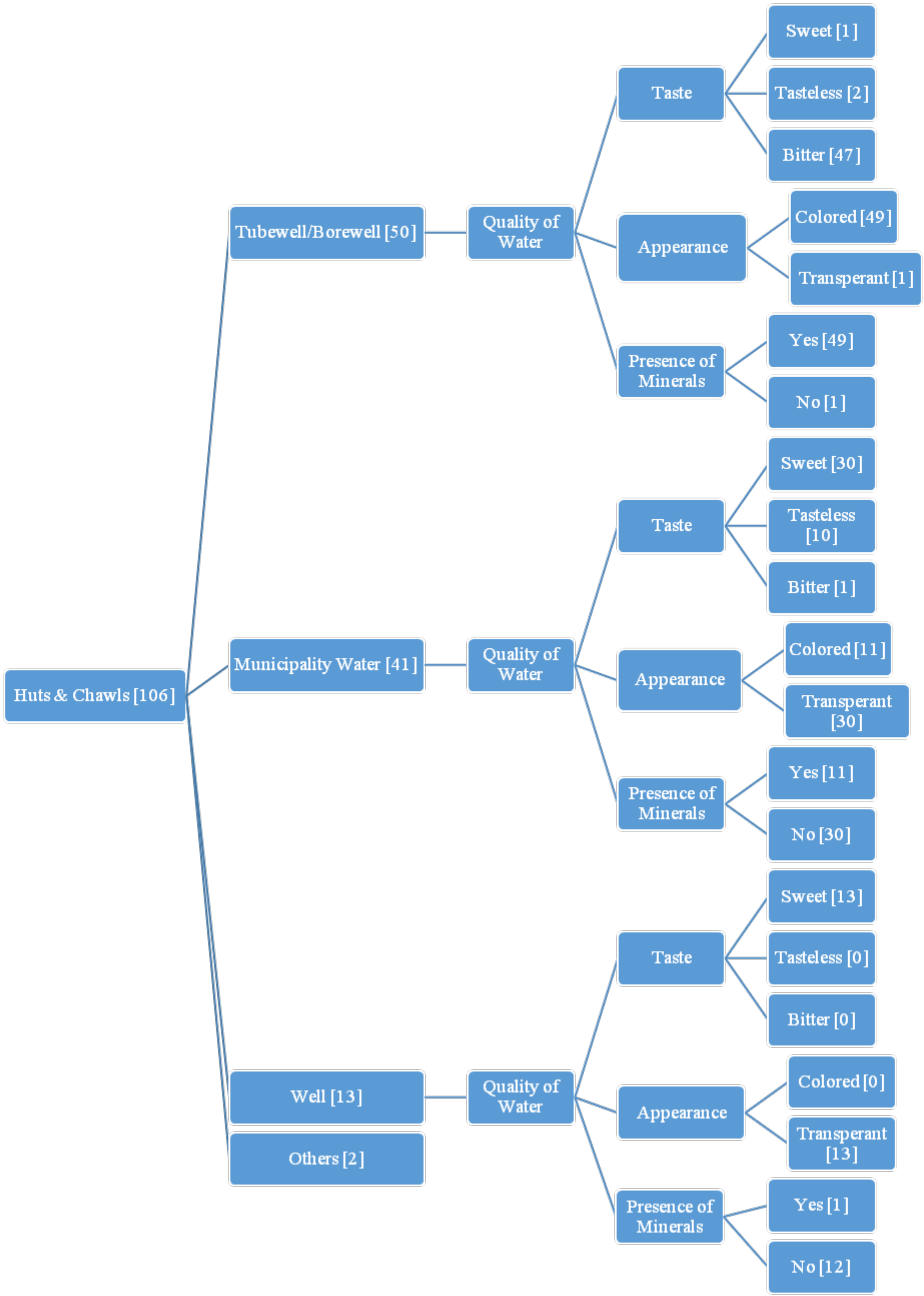

Figure 4.6: Decision tree showcasing attributes of water in huts and chawls

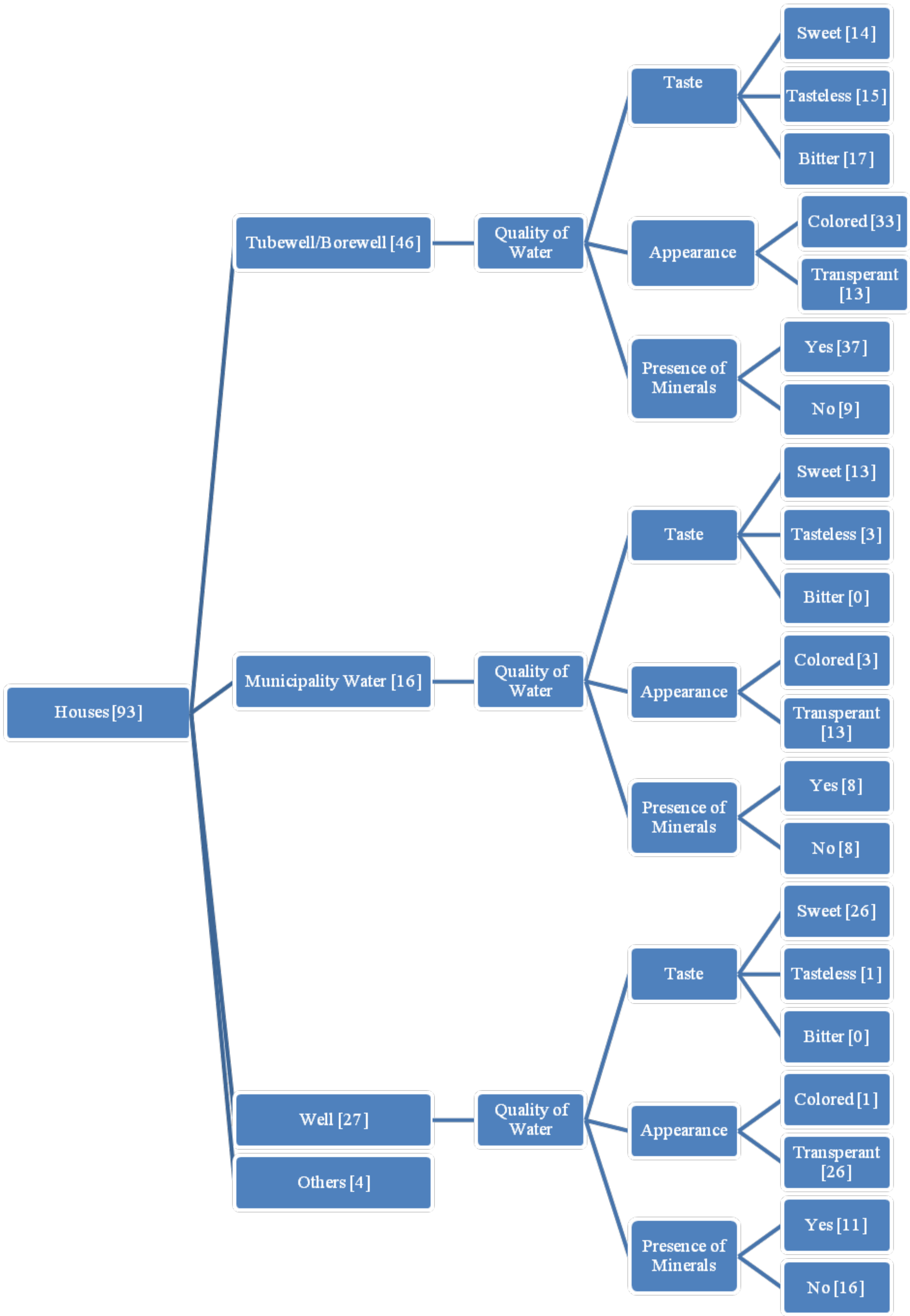

Figure 4.7: Decision tree showcasing attributes of water in houses

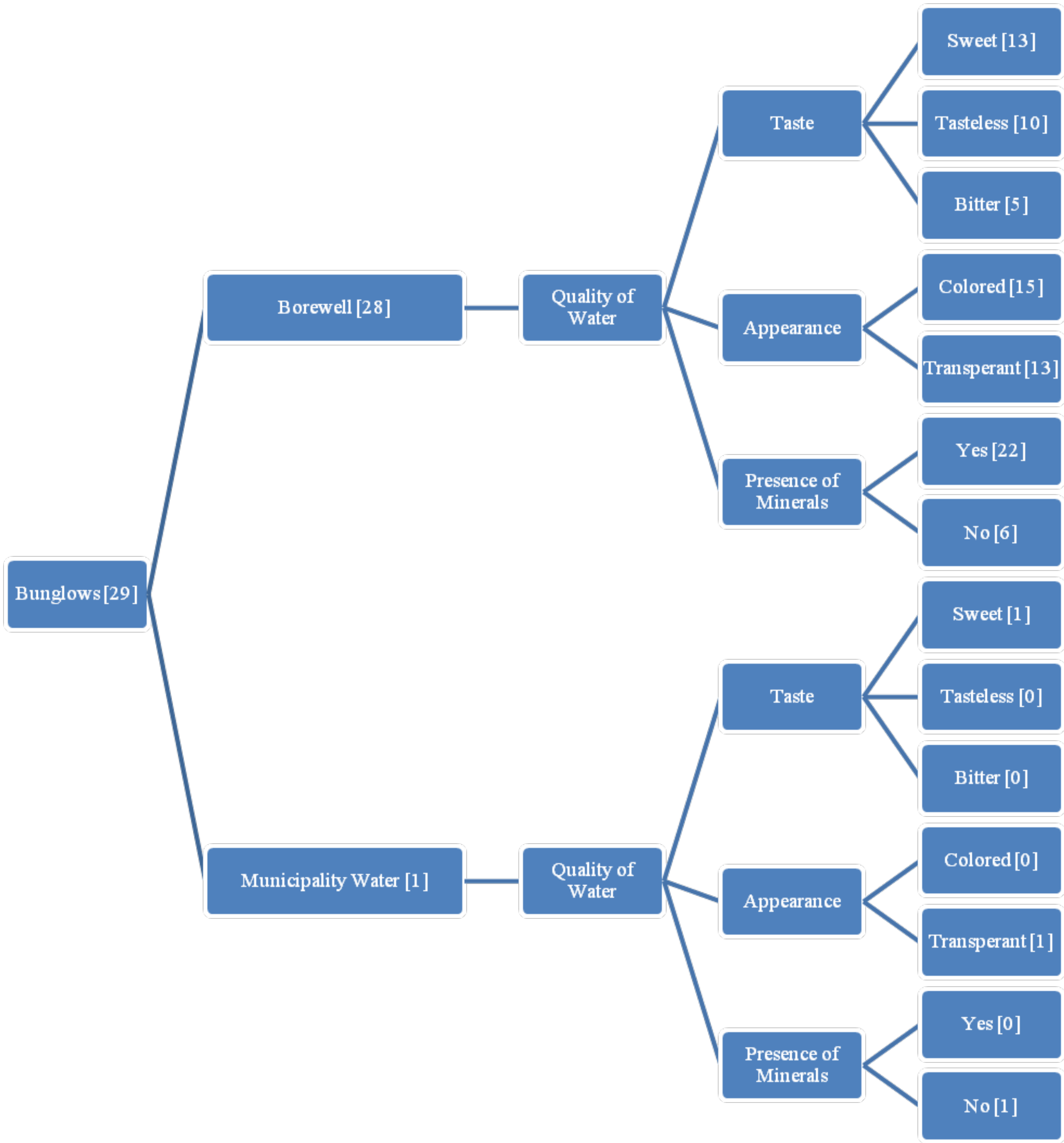

Figure 4.8: Decision tree showcasing attributes of water in bunglows

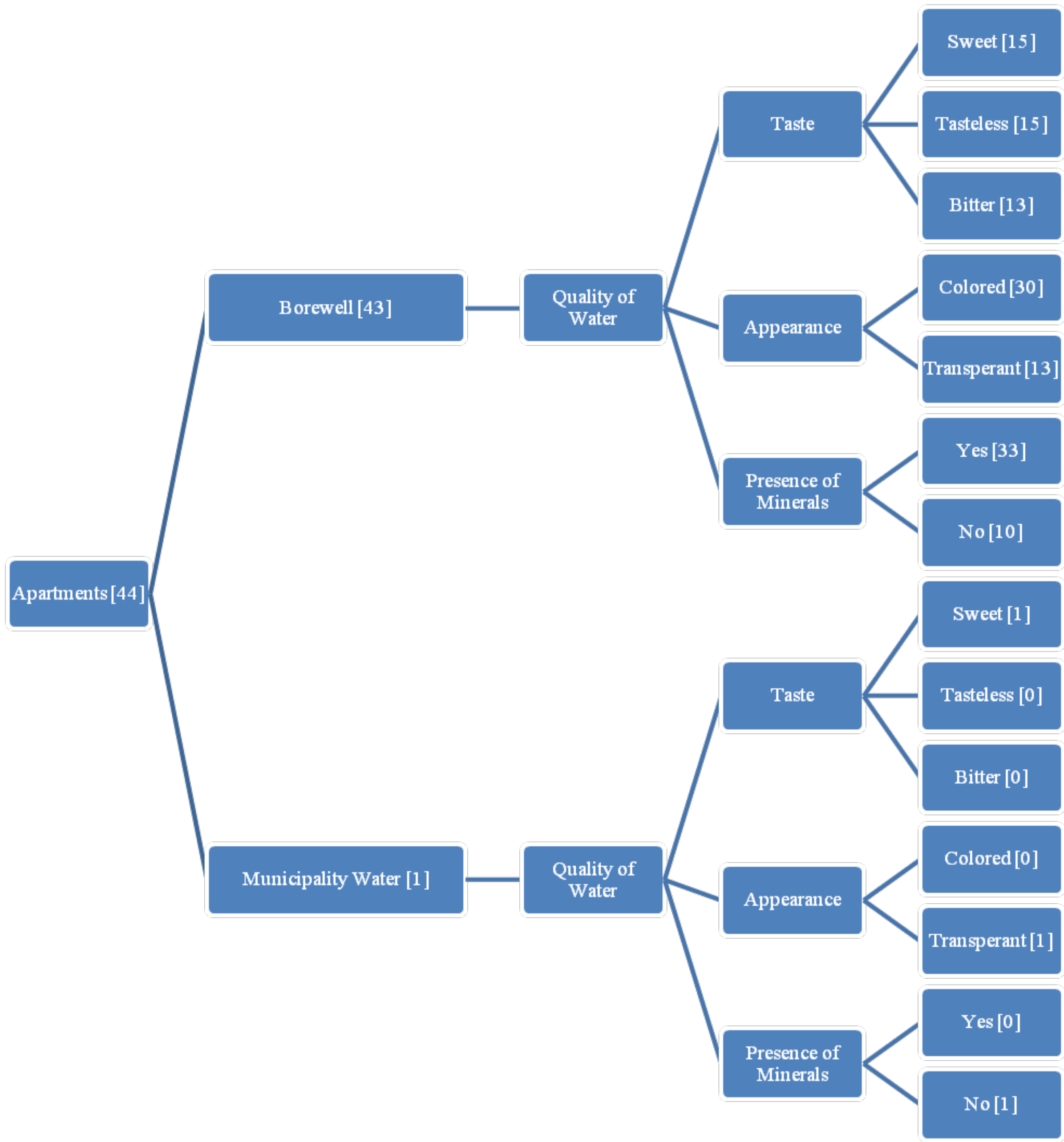

Figure 4.9: Decision tree showcasing attributes of water in apartments

4.3.12 Calculation of Water Balance and Implications for Sustainability

The tables below (Tables 4.11, 4.12, 4.13) indicate the water balance calculation. The result reveals the demand-supply gap between three municipalities during the year 2019. The units of each parameter are given in parentheses (cu mt) .

Table 4.11: Total Water Demand per Day (M^3)

Municipalities	Population (2011)	Population (2019)	Per Capita Water Demand (M^3)	Total Water Demand per Day
Purulia	121067	140437.7	0.25	35039.2
Dhanbad	1162472	1348467.5	0.46	615036
Ranchi	1073427	1245175.3	0.45	559955.3

Table 4.11 reflects the total water demand of each municipality. It is calculated by multiplying the estimated population in 2019 (based on the actual population of 2011) [28] with the weighted average of the per capita water consumption of different income classes (see appendix). Dhanbad municipality, which illustrates the highest population among the three, generates maximum per capita water demand, followed by Ranchi and then Purulia [28].

Table 4.12: Total Water Supply per Day (M^3)

Cities	Area (sq km)	Rainfall (mm) (2019)	Rainfall in the City (liters)	Groundwater Recharge (liters)	Groundwater Recharge per Day
Purulia	36.6	1310	47946000000	7671360000	21017.4
Dhanbad	231.8	1226	284186800000	45469888000	124575
Ranchi	201.5	1362	274443000000	43910880000	120303.8

Table 4.12 reports the groundwater recharge per day. Initially, the multiplication of the area of the municipalities and per square meter of rainfall gives the result of total rainfall in the city. However, to get the per day groundwater recharge, we consider only 16% of that total rainfall as suggested by the Chaturvedi formula because the rest will flow away (runoff) even after considering the Antecedent Moisture Condition (AMC) [38].

Table 4.13: Calculation of Water Balance ($M^3 * (10^3)$ per day)

Cities	Total Water Demand per Day	Groundwater Recharge per Day	Water Balance
Purulia	35039.2	21017.4	(-) 14
Dhanbad	615036	124575	(-) 490.4
Ranchi	559955.3	120303.8	(-) 439.6

Table 4.13 reflects the three Municipalities' water balance. It is the gap between the total water demand per day and the total groundwater recharge per day. The negative sign highlights the deficit. The red mark exhibits that the current water situation for all three municipalities is very alarming.

4.4 Summary and Conclusions

This study gives adequate knowledge regarding water availability in Purulia, Dhanbad, and Ranchi municipalities regarding various econometric parameters. The following are a few significant results that this chapter has found:

- Slum dwellers are the worst sufferers since they do not get even the bare minimum amount of water – 70 lpcd, while affluent people living in apartments or bunglows suffer no shortage.

- The study finds that inequality prevails because the main water source is groundwater, accessibility to which depends on wealth ownership. As the residences change from poor to non-poor, people depend less on centralized water supply and more on tube wells/bore wells. This is because the water supplied through the municipality is not enough.

- There is inequality in water accessibility and distribution for sample households in different municipalities. While Dhanbad favors the 'Haves'(with a mean value of 1081, and 1203.7 lpcd in the apartments and bunglows), Ranchi emphasizes the 'Have-nots' (with a mean value of 97 lpcd).

- Another important finding is that the water quality is reported to be poor by sample households across all income classes. Water sources share a negative correlation with water quality (the value of r is -.5). Water from tube well/bore well is inferior in quality to water from the municipality and dug well.

- Per capita water consumption shares a significant relation with types of residences and an insignificant one with water sources. The goodness of fit of the estimated model comes out as 0.5. This implies that the non-poor gets enough water, no matter what the source chosen. However, as the poor (hutment dwellers) do not have economic access to most water sources, the water they can acquire is far less than their wealthy counterparts.

- Awareness of water purification is significantly less among the surveyed poor people than the non-poor. While 67% of the poor are drinking water without purification, only 25% non-poor are present in that list.

- The study reports that houses interviewed receive good quality water with a high chance (with a probability value of .6) compared to others. All four types of surveyed residences are getting poor water due to minerals (huts and chawls, houses receive water with a probability of .6 each, and .8 each for bunglows and apartments, respectively). The only difference is that the affluent can convert this into better quality.

- Moreover, we believe that as water is a public good, it should be the primary responsibility of the governments to ensure safe access to water for both domestic (poor and non-poor) and other economic users (industry) [11, 88]. Therefore, we believe that initially, the municipalities must distribute a minimum standard of 70 liters per head per day (lphd) to the poor and 135 lphd to the non-poor. And then allocate the rest to the others having multiple bore wells to fetch water. Such as, to reach economies of scale in urban water supply governance, the municipality should create a balance between primary and secondary sectors to ensure a fair and efficient water supply.

CHAPTER 5

Water Management: Saving the Future with Lessons Learnt

The earlier discussion shows that the water situation is very serious for India's poor and lower middle-class populations. Water availability is expected to be even more compromised as we move forward. In such a situation, finding ways to address future water issues is important. In this chapter, we give the solutions tried out successfully by some individuals, NGOs, and government agencies. These can show some options ahead for the future.

5.1 Sustainable Water Use: Story of Simon Oraon Minz, Bero Block, Jharkhand

Sustainable living requires health and dignity. And health and dignity need both water and development. Working on a topic about water asks what sustainable water use is. By sustainable use of water, we mean the ideas and the efforts taken over by water management throughout the years to protect our current and future generations by saving water and its resources. We have done enough destruction of forests and lands; now time to save water, as it is under severe threat.

Simon Oraon Minz, also known as the "Waterman of Jharkhand," is an environmentalist who has enormously impacted Jharkhand. His actions to combat drought through sustainable water development have been seminal. Not only that, but his endeavors toward afforestation also had a massive impact on his state. Simon Oraon Minz, known as Simon Baba, was born in Khaki Toli village of Bero block.

With the help of his fellow villagers, he has built five irrigation reservoirs and several ponds and helped his area become a hub of agricultural activity. In 1964, his village honored him by bestowing upon him the title of Parha Raja, which is equivalent to being the chief of the tribe, and in 2016 he was awarded the Padma Shri. The initial efforts were to make five reservoirs based on five geographically significant places. In the first two years, he did not get the result according to people's expectations. However, the outcome started coming in from the third year. Afterward, several ponds and wells were made.

5.1.1 A Continuous Suffering

He had seen people suffer for drinking water. Mothers and their children in that location used to walk considerable distances, even for a bucket of water, so their families could have enough food to survive. Water was available only during the monsoon, and whatever would be available, everyone ran to collect it. Moreover, in mountainous areas, individuals need at least two days of proper watering to do farming. During that time, people would collect water from streams and drains. And till the rains came, they could not plow the land. There would be no water for six months, and the only water they could use was from underground. Nevertheless, they would have enough water to take to the fields once the rains came. It would be a tiresome task, but that had to do with it. When the rains would come, there could be floods that would sweep away the crops. People would walk around two kilometers searching for water, making small indentations to direct the water.

5.1.2 Early Success

All these forced this man to develop the efforts that made him the 'Waterman of Jharkhand.' He started making dams by himself only. His inspiration and the idea of building reservoirs in 1961, benefitting currently, will do that for future generations. The first dam he built was 45 feet wide and 7 feet deep. It was started in 1961 and lasted till the year 1970.

After that, the numbers started increasing. He organized all the people of his village and made them understand the importance of water in human life. He held meetings weekly to discuss the usefulness of water in our lives and how to use this water which has come from rain and is going towards the sea. On Sundays, they discussed how to make a dam so that rainwater could be stopped, gathered in one place, and supplied to the field wherever needed. Initially, the villagers wanted to avoid making this possible because they were not ready to work free of cost. Therefore, Simon Oraon Minz started giving sums so that they could help him make a dam. The first dam was built being built-in 1961. It is still useful for people in the area. Water is being supplied to every area of the field through that dam. Next, they dug wells to gather rainwater so that we could use it in need of water in summer. These wells are linked with a dam so that dam water goes to the wells and gathers. People from different areas of the dam use this well's water. According to their need from January to December, whatever crops they grow in the field. The water supply increased because of the dam itself. Water irrigated in the field indirectly comes to the dam through underground water due to its depth. He made the second dam of 5,000 feet and, on the other side, another of 3,500 feet. The outcome started to come in. The fields became prospered. Two crops now grow where one used to, and three grow where there was none.

5.1.3 Methodological Evaluation of Water Sustainability

According to Simon Oraon Minz, something is only possible for a farmer with water. Water is life for a farmer. Water is needed for all because cattle and crops are interdependent. Because they work like a food chain to teach others. So wells are very important because it provides water for life as God provides air to live on. When the government built dams, so many houses got flooded. Simon Oraon Minz has built multiple dams, however, floods haven't taken place. This is because the dams are small. They do not stop water to the extent that it would form a reservoir and flood the neighboring areas. Good-quality canals have been made from both sides of the dams. It helps the water to come out from the dam as it overflows in the rainy season. Water itself comes out from the dam as soon as it overflows to the dam. Moreover, the excess water went to the fields through small canals attached to the big ones. In this way, many villages save themselves from this kind of misfortune. According to Simon Minz, dams should be small and have provided water to farms on top of mountains. There is a proper way in which farming is done.

Furthermore, he suggested that the government should see people who have done this work before and follow their examples. You need to know the best way to supply water to a particular place in the best possible manner. Inspecting the area and having good knowledge about the land is very important. Without proper study about the area, it is impossible to supply water. Simon Oraon Minz visited areas many times from morning to evening to study the land where the water could be supplied.

5.1.4 Sustainable Thinking Against the Construction of Tube Wells

Earlier, the wells would be 40-50 feet deep having full of water. However, the recent construction of unlimited tube wells/bore wells creates many issues that evolved with well water. A maximum of them became dry, and their water level decreased significantly for those who survived. He thought the construction of excess tube wells/bore wells was why. He had warned them about this. Simon Oraon Minz protested against the construction of tube/bore wells as the water levels of the land went down. Tube/bore wells are dug deeper than ordinary wells, hand pumps, and ponds. So the water in the area of tube/bore wells dries faster. Therefore, he was against the tube wells/bore wells. He elucidates that the government also does not think about future generations and sustainability. Thinking only about the present can hamper the future generation. Water should be used sustainably in the present and future.

Simon Oraon Minz is undoubtedly a man of great passion, even at 85, who loves his community with all his heart. His message of having love within our hearts is of great importance in this day and age. He also highlights the importance of sustainable and grassroots development. While he is disillusioned with the government, he sees excellent potential within people when they come together for the good of the community. Simon Minz's story inspires the creation of sustainable and environmentally friendly projects and showcases the importance of community, camaraderie, and love for our fellow human beings.

Figure 5.1: Simon Oraon Minz: An Eco-friendly Man

5.2 Sustainable Water Use: Story of Tarun Bharat Sangh (TBS), Rajasthan

Tarun Bharat Sangh (TBS) is a non-profit organization, primarily working in Rajasthan, that strives to bring dignity and prosperity to the life of the deprived community through sustainable development. The unique modus operandi that they follow for overall development is to promote the community-driven-decentralized management of natural resources. The primary objective of balancing human and natural resources like water shapes the story of TBS's work for water conservation and its impact on climate change through adaptation and mitigation.

5.2.1 The process of making water bodies

Over the last 35 years (1985-2020), 11800 water bodies have been created by TBS, which get filled up with rainwater every year. These water bodies have led to the growth of vegetation. The process of the working of water bodies is as follows:

- Due to the increase in green vegetation and cloud formation, there has been a marked increase in rainfall here since 1985.
- Groundwater recharge rejuvenated 250000 wells, and soil moisture helped increase green cover; the region's temperature has been reduced by 3 degrees.

Reduced evaporation due to temperature reduction and increased rainfall has also started reviving the surface water bodies. The water level increased, leading to more fruitful agriculture. Those who had been displaced or migrated from the village began to return. According to TBS, reverse migration by 17 lakh people has happened.

5.2.2 Mr. Rajendra Singh – Waterman of India

Mr. Rajendra Singh is the man behind TBS. He made the first pond in Gopalpura by digging out its earth. It was time-consuming as he was the only one working there then. Once the earth was dug out, that place became plentiful in the water. People saw the impact themselves. Subsequently, people began replicating it in other places and made other ponds. Later, the work was expanded from making ponds; he extended his work to the rivers. With his efforts, for the first time in 1996, the Arvari River became perennial after remaining dry for over 60 years. He and TBS worked in a vast area of 10600 acres, once waterless but able to bring water to it.

Figure 5.2: Mr. Rajendra Singh – Waterman of India

5.2.3 The Perennials of Arvari River

Arvari basin is a compact, hydrological unit with complex geology-rock types and structures. Mr. Singh did a detailed calculation about this basin structure to make the river perennial. He started working with the people of Bhanota-Kolyala village (situated 20 km away from Gopalpura). Villagers there had seen how water tables rose in Gopalpura due to the work of TBS. They agreed to donate their labor (shram-daan). The villagers and the TBS volunteers constructed a pond at the source of a dried Arvari River. Adjacent to the riverbed, Mr. Singh built tiny earthen dams, the largest being 244 meters long. A 7-meter-high concrete dam was made in the Aravalli hills. 375 small earthen dams were built. Soon after the building of these dams, the river started flowing again in 1995.

5.2.4 Challenges Faced During the Perennial of Rivers & Solutions

However, the battle was far from over, even after constructing ponds. The water level in the ponds on and around Arvari and Sariska did not go up as expected. Mr. Singh discovered that missing water evaporated from mining pits left unfilled by the miners in the riverbed after their operations in the area. A legal battle ensued. He filed public interest litigation (PIL) on 7 May 1991 in the Supreme Court, and the court ruled in his favor to stop the illegal mining on 26 October 1991in the Aravalli. However, just because mining stopped does not mean the greenery returned immediately. After five or six years, the greenery returned. He brought back rain by digging ponds and lakes and allowing vegetation to grow. The efforts soon paid off; by 1996, Arvari became a completely perennial.

In May 1992, the Ministry of Environment and Forests notification banned mining in the Aravalli hill system altogether. 470 mines were operating within the Sariska sanctuary buffer area and the periphery. They all were closed. Gradually TBS built 115 earthen and concrete structures within the sanctuary and 600 other structures in the buffer and peripheral zones. Now Sarsa, Bagari, and Jajwali rivers have also become perennial. It was like a miracle being created and recreated. Today, Mr. Rajendra Singh has rejuvenated twelve rivers. Once these rivers became perennial, he realized that this work could be extended throughout the country and the world. He is trying to popularize the technique elsewhere. He was awarded the Water Nobel Prize in 2015 in Stockholm.

5.3 Watershed Development: A Sustainable Water Use by Manavlok in Marathwada Region

Marathwada is infamous for drought, and Beed is one of the districts of the Marathwada region that comes under semi-arid climate zones. Agriculture is the main source of income for many in the Beed district. Agriculture is highly dependent on the monsoon in Marathwada. The region (specifically, Ambajogai, Parli, Kaij, and Dharur blocks) suffers from problems like groundwater levels falling in the wells, decline in crop production and crop failures, and migration to nearby cities for employment. Major water bodies supplying drinking water in these blocks are getting dried up even during January- February causing distress among the villages and cities for drinking water. Almost 100% villages in the Beed district fall under the red zone every year and have reported more than one meter drop in groundwater level.

5.3.1 Challenges due to Drought and Emergence of Manavlok

Around five lakh people would migrate seasonally for 5-6 months to cut sugarcane or for similar employment. Here comes an NGO named Manavlok, which wanted to reduce this seasonal migration and help these migrating people by employing their place of residence. What Manavlok has been doing for the past 20-25 years is working on watershed development. This wasn't a planned initiative. The people that Manavlok works with are generally small farmers. They started to figure out how to provide a steady water source to farmers who solely depend on agriculture for their livelihood. While doing this job, they realize that the best way to tackle this scarcity is by watershed development, and this is how the work of Manavlok began nearly 25 years ago.

5.3.2 Watershed Development Program of Manavlok

Manavlok implemented several watershed development activities in 661 villages to combat water shortages and improve the livelihood of farmers. A watershed is

Figure 5.3: Watershed development program of Manavlok

a hydrogeological unit draining to a common point by a system of natural drains. All lands on earth are part of one watershed or another. The watershed is thus the land and water area, which brings the runoff to a common point.

5.3.3 Strategies taken for Proper Implementation

Manavlok used the following strategies for increasing agricultural productivity and reducing seasonal migration:

1. Planning the watershed interventions for a ridge to the valley or as per the geography of the proposed region

2. Disseminating knowledge about climate-resilient agriculture practices to farmers

3. Advocating efficient water use for more crop production (more crop per drop)

4. Suitable cropping pattern

5. Demonstration on different organic farming techniques, horticulture, and sustainable livelihood

6. Formation of watershed development committee (WDC) and water user groups to ensure water budgeting
7. Planning the interventions with people's participation to create the feeling of ownership for the watershed among the farmers/villagers
8. Convergence with agriculture, forest, and other local NGOs

5.3.4 Watershed Management Practices

Rainwater harvesting through structures like check dams, contour bunding, etc., is the main component of watershed management. However, other watershed measures that Manavlok uses are New Community Dug wells, Desilting of old wells, Earthen Nala Bund, River Rejuvenation, etc. The following table describes the Quantum of Watershed Management Activities done by Manavlok.

Table 5.1: Quantum of Watershed Management Activities by Manavlok

Activities	Unit	Quantity of Work Done	Capacity of Structures	No of Villages	Number of Beneficiary Families	Quality of Water Saved
New Community Dug wells	No	314	554602	107	3942	Irrigation / Drinking
Bore well Recharge	No	53	662.5	15	53	Groundwater Recharge
Composite Gabion	No	4	1000	1	85	Irrigation / Drinking
Stone Bunds	mt	10019	3334.49	3	39	Soil Conservation
Recharge Shaft	No	165	479	10	600	Water Conservation
Dam Desilting	cu mt	4054788	4054788	60	10033	Irrigation / Drinking
—-	—-	—-	—-	—-	—-	—-
—-	—-	—-	—-	—-	—-	—-
Total			9506212 (cu mt)	661 (App.)	40000 (App.)	

5.4 Drink from Tap Mission: Case Study of Puri Municipality

Jagannath Puri is one of the most important pilgrimage centers in India. The Public Health Division, Puri, managed the town's water supply system since 1982. The Municipality took over the water supply management system a few years back, aimed to supply 150 liters per capita for three lakh people resulting in 46 million liters per day (mld) of water required from the natural system. 42 mld supplied from one source, i.e., the water treatment plant (the plant takes raw water from the Bhargavi river), and two to four mld from the sweet water zone (the ponds inside the city).

5.4.1 Objectives

The objective of the Municipality was to ensure 24X7 quality and safe water to both the poor (including a total of 62 slum areas) and the non-poor, including the commercial sectors, with a combined intent of smart monitoring and minimum loss of revenue. Initially, two rivers in Puri were identified as the significant drinking water sources (Bhargavi is the essential one) for the water supply system. Within three months, a reservoir for raw water was made on 437 acres of land. Another 270 acres of land were provided for storage purposes. Then the number of households and the number of families were collected. Afterward, the respective zones for water supply were defined, the net flow height was determined (depending on the houses to be served), and water was supplied to all zones for four hours each. Next, an attempt was to provide water for 24 hours in two zones. One of the zones would be in the slum area, and the other is in the slum and apartment area.

The cost was also a constraint for the Municipality. Puri received some funding through JNNURM, which was used to create 19 elevated reservoirs in the respective zones at twenty feet. It was estimated that the construction cost would be 26.4 cr., and accordingly, the tender was announced. Balaji Agency took the tender for

22.88 cr. and completed the entire project within a year and the cost.

5.4.2 The process of Water Treatment

The idea to process the water was imported from Israel. Initially, chemical alum and limes are added to the raw water. Next, aeration is allowed to release the volatile compounds from the water. The water is then agitated using the mixer to condition sludges and slurries. Water goes through the canal, and clean water is sent into circulation. After that, the scrapper settles the sludge. Sludge that is recovered is automatically put back into the raw water. This process is called sludge handling of water. Then there is a Dual media filter with GSI yield technology through which water percolates. Water in dual media filters passes through moderately smaller pores. Anthracite exudes out the largest molecules. Next, the layer removes the particles with the help of sand & charcoal with nozzles. Filters do not block as fast as in a single filtration process. It is due to multiple depths or filters in the dual media filter process. Clean water comes through the pipe gallery and is subsequently ready to supply. The water supply goes by gravity. The water treatment is fully automatic here; only one person is required for the chemical insertion.

Moreover, a Membrane technology of 14,500 for UF will soon be installed to distill the infection.

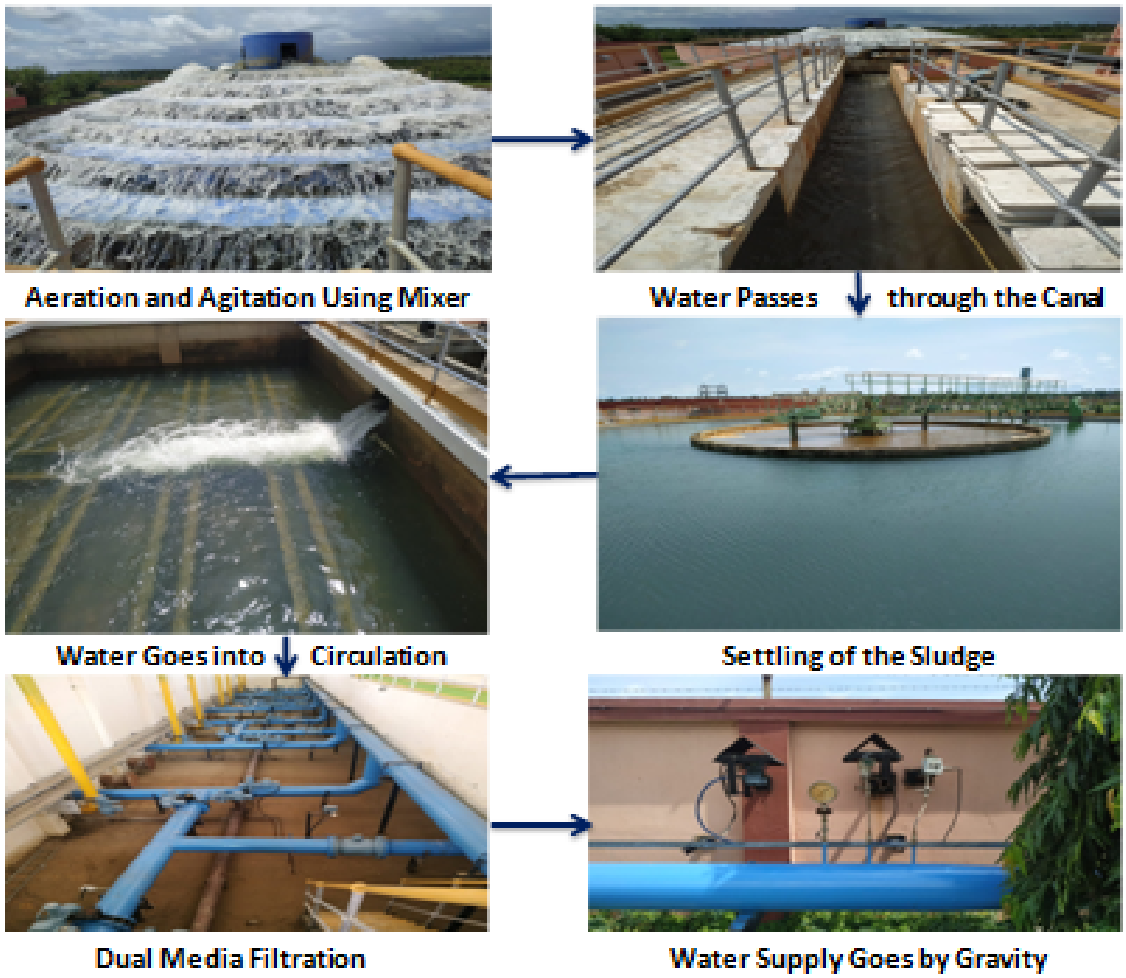

Figure 5.4: The process of water treatment

5.4.3 Water Quality

Earlier, water was supplied from the river for a long time without any treatment. However, the current water supply system holds water treatment as essential. People get access to good quality water with a TDS of less than two PPM, which is unheard of in the Indian water supply systems. Moreover, this is all because of the project 'Drink from Tap Mission.' The zero-waste treatment plant has also received an ISO 9000 certification.

Several stand posts have been provided at various locations in the city, such as beaches and near the temple. Since Puri is a tourist town, the idea is to provide safe drinking water in the stand post so that all the tourists have easy access to safe water. The Municipality also has two LED screens that advertise its mission to the masses.

5.4.4 Leakages and Other Constraints

Leakages are the primary constraint in water supply through the PLC treatment process. However, this project provides a few better solutions related to this issue. In case of any leakages in the mainline, repairs are done within 1-2 hours. The 'JalSakhi,' apart from collecting household revenue, also checks for leakages and ensures water supply is at par with the demand. In case of any leakage, the JalSakhi passes the information to the third-party mobile van hired by the Municipality to monitor the water supply constantly; if they find any leakage, they stop it. Another critical constraint is water theft which the Municipality is considering with utmost concern. If there is water theft, Watco is generally alerted through two parameters. First, they will be notified about the place that has been dug. Second, the water meter will be inconsistent on that date. The amount of water released from the tank is measured along with the pressure. So, any discrepancy in the water meters can be noticed quickly, and in case of theft, the ward committee leader collects the fines. By doing so, water theft has been reduced by 50

5.4.5 Achievements

According to Mr. S. K Swain (the Municipality officer of Puri Municipality), every Indian should have access to safe and adequate drinking water. In Puri, it is being provided at the doorstep. Of the 4700 households in Puri, 3200 have taken the water connection from the Municipality. In Puri, 100 Water is provided to everyone with a metered connection round the clock, 24 hours a day. It is the first city in the country to have achieved this feat. The source of Puri's water supply is the river water, provided free of charge through the Water Project, which is fully state-funded.

5.5 Rainwater Harvesting (RWH)

The concept of rainwater harvesting (RWH) is not new. It is considered the purest form of water source, both scientifically and traditionally.RWH is a process of collection and reuse of runoff water in the most effective manner. It can be further processed for other purposes, such as using iron, chlorine, etc.

In recent times, due to environmental distress such as climate change, and aquifer depletion, RWH has emerged as an alternative water resource to mitigate the problem of water scarcity. Although RWH requires collection, storage, and distribution of rainwater, it can also be used for potable purposes such as drinking and cooking only after undergoing several filtrations through chemical treatments. When filtrations or treatment cannot be done, RWH can be used for non-potable purposes such as washing, gardening, and toilet flushing. RWH is considered a sustainable resource as it reduces freshwater production costs, decreases ground and surface water contamination, works as a backup for emergencies, and most importantly, if included as a community development project, it can create job opportunities [69]. Consequently, RWH has become integral to water management techniques in societies [5].

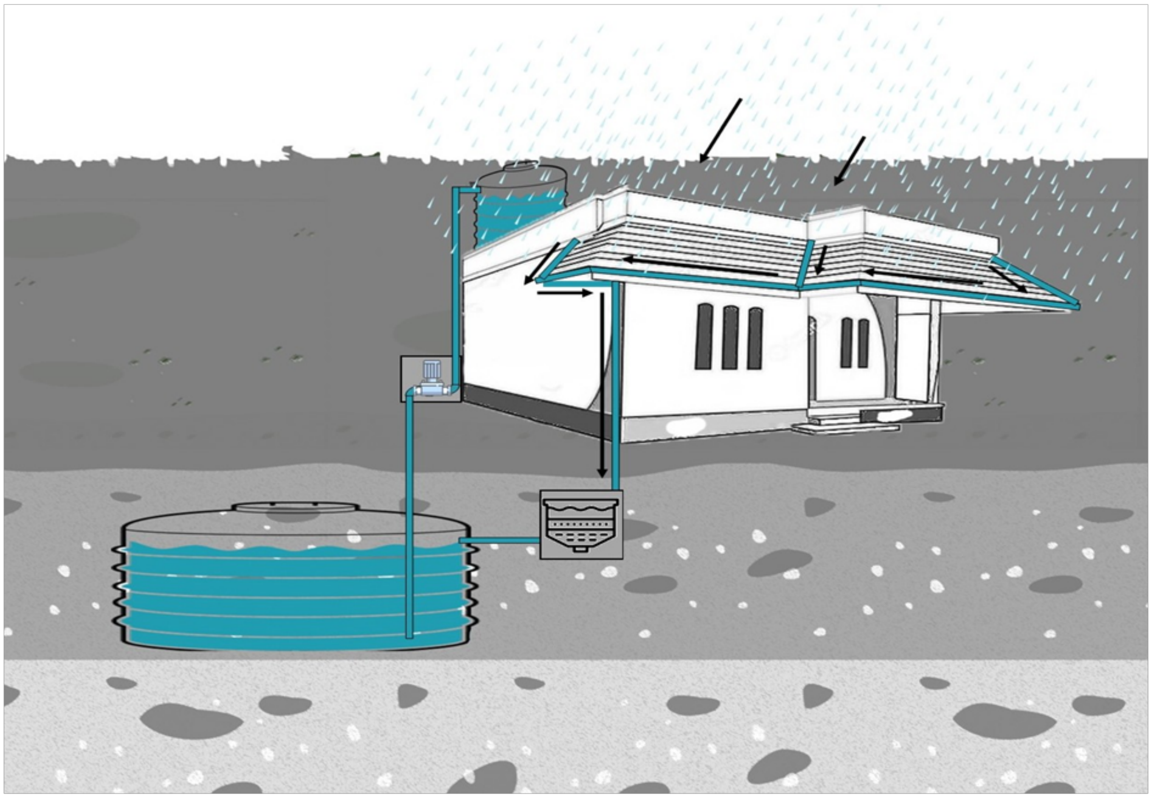

Figure 5.5: Rainwater Harvesting

5.6 Zero Water Output and Sewage Revenue Model

To conserve the resource, we have to reduce the dependency on groundwater and promote using recycled water for non-drinking purposes as an initial measure. Using grey water for flushing, gardening, etc., can also help reduce the demand for clean water in a housing colony by almost 40%. Keeping this in mind, Surat, a city in Gujarat, India, has set up an example of a sewage revenue model for water management, which could be a learning exercise for every city and nation. Setting up state-of-the-art Sewage Treatment Plants (STP) ensures that every drop of wastewater is treated and reused for purposes other than drinking. To meet the fundamental industrial requirement of water through treated or recycled water, Surat Municipal Corporation (SMC), from March 2019, has started supplying 115 million liters per day (mld) of treated water to industries within the city. The water has been treated from domestic sewerage in tertiary treatment plants in the 20 Bamroli and Dindoli areas. Then it will be supplied to the textile factories in the

Pandesara and Sachin industrial areas. The city treats around 1400 mld of sewage water, of which 320 (33%) mld is reused [50]. This is the first city in the country to start selling recycled water to industries since 2014. To create tertiary water treatment facilities in Surat, SMC has invested Rs 2.8 billion, charging industrial units Rs 23 per 1,000 liters of water [41].

5.7 Summary and Conclusions

We believe that merely finding water consumption patterns to be unsustainable is not very satisfactory research, although theoretically, it is considered complete. Therefore, some best practices from different parts of India using a few practical solutions were studied to find some solutions. In this chapter, we discuss some water management techniques that have been tried out successfully by some individuals, NGOs, and government agencies. These can show some options ahead for the future. A few significant strategies merging from the study are as follows:

- Padma Shri Mr. Simon Oraon Minz, also known as the "Waterman of Jharkhand," of Bero block, Ranchi, has built irrigation reservoirs, ponds, and wells to help his area become a hub of agricultural activity.

- Tarun Bharat Sangh (TBS), Rajasthan, has rejuvenated wells and rivers by constructing water bodies. they have built 11,800 water bodies and rejuvenated 25,000 wells and 12 rivers.

- Manavlok in Maharastra has been constructing watershed structures like earthen dams and check dams to rejuvenate water bodies in more than 660 villages.

- Puri municipality has provided pure water (TDS less than 2 PPM), 24X7 to three lakh people and 1000 pilgrims by having an automated water supply and water quality monitoring system. They have managed to stop water theft and leakages in pipes, making the country's most efficient water supply system.

- Surat Municipal Corporation (SMC) has managed to recycle its wastewater for industrial purposes. The city treats around 1400 mld of sewage water, of which 320 (33%) mld is reused. This is the first city in the country to start selling recycled water to industries since 2014.

CHAPTER 6

Conclusions, Future Work and Policy Recommendations

6.1 Conclusions:

The Important findings are as follows:

- Using satellite images and historically experimented data, we calculated the LULCs and the evaporation coefficients, respectively, which are the ingredients to find the values of WF_{green} and WF_{blue}.
- While the WF_{green} values depict that Purulia reports the highest WF_{green} values ($182.6 * 10^3$ to $296.3 * 10^3$ M^3 per sq km), followed by Dhanbad ($170.3 * 10^3$ to $241.2 * 10^3$ M^3 per sq km), and Ranchi reports the least ($131 * 10^3$ to $219.2 * 10^3$ M^3 per sq km) for four consecutive years (2016-19), the WF_{blue} values of 2019 depict that Ranchi reports the highest (108 M^3 per capita), followed by Purulia (81.5 M^3 per capita). Dhanbad reports the least (68.8 M^3 per capita). These figures imply that Purulia overuses its water resources in agriculture, and hence its high WF green needs to be corrected by increasing water productivity. Dhanbad's high WF is because of the water consumption by its forests. The high WF is not of concern given that the forests help hold up the soil and water. Ranchi's WF is low and does not utilize its water resources properly. Moreover, WF_{blue} values of 2019 illustrate that Ranchi reports the highest (108 M^3 per capita), followed by Purulia (81.5 M^3 per capita), and Dhanbad reports the least (68.8 M^3 per capita). The primary fac-

tor for getting such results is high runoff followed by evaporation, and the municipality supplies water. However, in most cities and towns in India, water supplied by the centralized water system is insufficient. Therefore, Steps should be taken to retain the rainwater in some form in the soil and man-made channels.

- Moreover, the study also found that in the case of municipality water balance, all three municipalities are going through a deficit water balance, which is a significant concern for them. The demand-supply gap for Purulia is 14,000 M^3 per day, for Dhanbad, it's 4,90,400 M^3 per day, and for Ranchi, it's 4,39,600 M^3 per day. This shows that the higher the population, the more deficit in the water balance. In other words, cities like Dhanbad and Ranchi will not be able to sustain themselves on water for long. There would be severe water shortages soon.

- This study gives an insight into water availability/accessibility for the people of Purulia, Dhanbad, and Ranchi municipalities by surveying 272 households. The consumption patterns of water used by different income classes, the quality of the water, its taste, and color, and the presence of minerals available to different classes of households have also been surveyed. Mapping of water availability with its sources and per capita consumption has been done quantitatively. The findings are as follows:

    1. The surveyed slum dwellers are the worst sufferers since they do not get even the bare minimum amount of water – 70 lpcd, while the affluent people interviewed (living in apartments or bunglows) reported no shortage.

    2. The study finds that inequality prevails because the main water source is groundwater, accessibility to which depends on wealth ownership. As the sample residences change from poor to non-poor, people depend less on centralized water supply and more on tube wells/bore wells. This is because the water supplied through the municipality is not enough.

3. Another important finding is that the water quality is reported to be poor by sample households across all income classes. Water sources correlate negatively with water quality (the value of r is -.5). The deeper the water source, the inferior the quality. Water from tube wells/bore wells is inferior in quality to water from the municipality and dug wells.

4. Per capita water consumption shares a significant relation with types of residences and an insignificant one with water sources. The goodness of fit of the estimated model comes out as 0.5. This implies that the non-poor gets enough water, regardless of the chosen source. However, the type of residence (huts Vs. tenements Vs. bunglows and apartments) is a significant parameter to determine the per capita availability of water. As the poor do not have economic access to most water sources, the water they can acquire is far less than their wealthy counterparts.

5. All four types of surveyed residences are getting poor quality water due to minerals (huts and chawls, and houses receive poor quality water with a probability of .6 each, and .8 each for bunglows and apartments, respectively). The only difference is that the affluent can convert this into better quality using the R-O plant.

6. Moreover, we believe that as water is a public good, it should be the primary responsibility of the municipalities to ensure safe access to water for both domestic (poor and non-poor) and other economic users (industry) [11, 88]. Therefore, initially, the municipalities must distribute a minimum standard of 70 liters per head per day (lphd) to the poor and 135 lphd to the non-poor. And then allocate the rest to the others having multiple bore wells to fetch water. Such as, to reach economies of scale in urban water supply governance, the municipality should balance primary and secondary sectors to ensure a fair and efficient water supply.

6.2 Future Work

The most important contribution of this thesis is in analyzing the water availability through water footprint calculations in the Indian context. We believe that this should provide an important direction in estimating existing water availability. It should also open up new pathways for future studies and in designing long-term policy recommendations. Given the geographical diversity of India, systematic, comprehensive, and extensive studies need to be undertaken for the entire country. The analysis presented in this thesis was also limited by the challenges due to the COVID-19 epidemic and the data provided by the three municipality authorities. In this section we present a list of some of the future studies that we envisage should be carried out to further gain clarity on the challenges of water management in our country.

1. Access to larger data with proper sampling could have added significantly to the conclusions in this thesis. Future studies should aim at developing a mechanism that allows for the collection of extensive data. This would enable us to conclude an area rather than sample households.

2. Water footprint computations should be extended to other municipalities in the country. In many regions of the country, such as in capital cities and metros geo-spatial data is well maintained but either not shared or is very expensive. This needs to be corrected by the data providers to enable good research. The future researchers should be able to work with more accurate and longitudinal data.

3. In smaller places such as those studied in this thesis, the primary data sources are the municipalities and the universities. Future studies should have access to data from other sources, like, airport authorities or state departments of water resources.

4. Recycling and reuse are two important methods of water conservation. We have not analyzed the grey water footprint in this thesis. The reason was the limitations in the data that was made available to us. Future work should

develop methods to get an estimate of grey water footprint. This would also enable in development of a more robust framework for water sustainability.

5. In this thesis our calculations of the coefficients are based on the SEBAL model. While, we have ensured that the values obtained are reasonable estimates, more elaborate model studies are also required. This would involve both developing new models as well as extending the existing ones in the Indian context.

6.3 Policy recommendations

This study indicates that none of the cities examined can sustain their water supply for long. Even our conservative estimates indicate that these cities are consuming more water than what they receive from nature. Serious steps need to be taken to address this threat. Municipalities must take a comprehensive and integrated approach to water management, which includes a range of policies and strategies to conserve, protect, and sustainably use water resources. Based on the work carried out in this thesis, we list below a few recommendations, that would both help in developing policies as well as aid future research.

6.3.1 Incorporation of Remote sensing technology

Water loss through WF can be a significant problem, and addressing it requires specific technological policies to target these areas' unique challenges. municipalities can invest in water monitoring systems such as smart water meters and remote sensing technologies to track proper water usage in water distribution systems. This can help to identify areas where water is being lost and take corrective action.

6.3.2 Introducing Startups in Water Industry

Startups can help prevent water loss through technologies by developing and implementing innovative solutions that address specific water loss challenges. Some examples include:

1. Providing funding and support for start-ups working on water management practices better suited to the unique challenges of different regions, such as drought-tolerant crops and better irrigation systems.

2. Offering tax incentives and grants for start-ups working on water conservation and water recycling technologies that can reduce water demand and improve water availability.

3. Connect start-ups with government agencies, research institutions, and private sector organizations to help them access the resources and expertise needed to develop and implement their solutions.

4. Providing mentorship and training programs for start-ups to help them navigate the regulatory and business landscape of the water sector.

5. Start-ups can help prevent water loss through technologies by developing and implementing innovative solutions that address specific water loss challenges.

6.3.3 Implementing few Specific Technological Parameters

Water loss through WF can be a significant problem, and addressing it requires specific technological policies, as many developed countries have already adopted. Therefore, to target the unique challenges that these areas face, the following are some standard technological policy recommendations for the government to prevent water loss through WF:

1. Implementing advanced metering infrastructure (AMI) to measure and track water usage accurately can help identify and address leaks and other sources of water loss.

2. Develop a real-time water management system to monitor water levels, flow rates, and other key parameters and provide early warning of potential water shortages.

3. Encouraging collaboration between researchers, government agencies, and private sector organizations to develop innovative solutions for water loss prevention in these areas.

4. Investing in research on water treatment technologies to improve the quality of water resources, such as removing pollutants and reducing water hardness.

5. Encouraging research on the water-energy nexus and the development of new technologies that can help to reduce water loss and energy consumption.

6.3.4 Reducing WF in Primary Sector

The second chapter demonstrated that agriculture is a major water consumer for Purulia municipality. Once the major consumer of water is identified, efforts should be tailored to that specific sector. For example, in the Purulia municipality studied in this thesis, water-efficient irrigation systems and drought-resistant crops should be promoted. Further, water use in livestock farming should be reduced.

6.3.5 Promoting Water Recycling and Reuse

Ranchi and Dhanbad municipalities should lay more emphasis on implementing water recycling and water reuse regulations to reduce water consumption in the mining and engineering industries. Adapting the best practices of other municipalities facing similar problems (such as Surat Municipal Corporation) would be useful.

6.3.6 Households Can Play a Pivotal Role in Addressing Water Scarcity

Reducing the WFs in households can also be important in addressing water scarcity. municipalities can implement policies to promote water-efficient appliances and practices, such as low-flow showerheads, faucet aerators, and grey water reuse. Using grey water for toilet flush can save a considerable amount of water. Mumbai has imposed such regulations for its multi-storeyed housing colonies. Nevertheless, many households in the studied municipalities can also use grey water for watering the garden areas. Such water recycling can reduce the demand for freshwater by 40% for housing colonies.

6.3.7 Building Watershed to Reduce Runoff

Chapter three illustrates that all three municipalities are characterized by rapid runoff, which can lead to soil erosion and allow little water retention. Hence, watershed and water harvesting structures such as afforestation, terracing, as well as soil and water conservation structures, should be built out of concrete, such as contour bunding, check dams, gabion walls, and other structures, to reduce runoff, and ensure proper water seepage into the soil, regulate water flow and decrease water storage. Ranchi which is a hilly terrain would require more structures than Dhanbad and Purulia. The density of such structures should be increased in Ranchi municipality to mitigate the large runoff.

6.3.8 Promoting Rainwater Harvesting Mechanism

The municipality areas used in this study often receive high amounts of precipitation, however, the result shows that much of it is lost as runoff. Therefore, all three municipalities should increase their focus on building rainwater harvesting systems to capture and store rainwater for later use. This can help increase water availability during times of scarcity and reduce the demand for surface water resources.

6.3.9 Water Pricing

Water should be priced to encourage conservation and ensure effective use. After extensive consultation with all stakeholders, each State should establish an independent statutory water regulatory authority to determine egalitarian access to water for all and its fair pricing for drinking, sanitation, and agriculture.

The water charges should ideally/generally be calculated on a volumetric basis to adhere to equality, efficiency, and economic principles. Such fees ought to be examined regularly.

Legislative authority should be granted to municipalities under the municipal areas to manage the volumetric amount of water allotted to them, collect and keep a share of water rates, and maintain the distribution network under their control. Each municipality should be permitted to set different rates for water depending on what they adhere to.

6.3.10 Maintenance of Database and Information

One genuine problem that we faced while doing the surveys was that each studied municipality was reluctant to maintain and distribute its data set. Therefore, all hydrological data should be available to the public except for information classified due to national security concerns. However, a recurring evaluation for future data declassification may be done. A National Water Informatics Centre should be established to collect, combine, and process hydrologic data from around the country. A GIS platform could be established to handle the initial processing and maintain those data openly and transparently.

All the data about water management, including rainfall, snowfall, geomorphological, climatic, geological, surface water, groundwater, water quality, ecological, water extraction and use, irrigated area, etc., should be made a part of a public repository to the extent possible. This has already been done in other data-intensive fields such as physiology and has allowed us to examine them and present meaningful insights and conclusions.

Publications

Journal Articles

- **A. Banerjee**, V. Dave, R. Ghosh, and A. Parikh. Blue WF: An Instrument to Support Urban Water Management with Best Practices. *Eco. Env. & Cons.* 28, pp. (S439-S446), 2022.

- **A. Banerjee** and A. Parikh. The Haves and Have-nots for water: Case Study of Three Municipalities, *Journal of Rural Development*, 2021.

  The paper is under review.

- **A. Banerjee**, V. Dave, and R. Ghosh. Mapping Evapotranspiration Using CROPWAT and SEBAL Model and Assessment of Green WF for Diverse Topographic Units, *Paddy and Water Environment*, 2022.

  The paper is under review.

Conference Articles

- A. Parikh and **A. Banerjee**. Water Management: Saving the Future with Lessons Learnt.
  International Center Goa (ICG) Annual Conference "India @75 and Beyond: New Ideas for the Present and Future," 2022.

- **A. Banerjee** and A. Parikh. A Comprehensive Study of WF and Analysis of its sustainability, *Recent Advances in the Field of Economics, Commerce, and Finance (ICRAECF)*, 2021.

References

[1] W. Aeschbach-Hertig and T. Gleeson. Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience*, 5(12):853–861, 2012.

[2] J. Alcamo and T. Henrichs. Critical regions: A model-based estimation of world water resources sensitive to global changes. *Aquatic Sciences*, 64(4):352–362, 2002.

[3] H. Alegre. Performance indicators for water supply services - second edition. *wio*, 12, may 2013.

[4] R. G. Allen, L. S. Pereira, D. Raes, M. Smith, et al. Crop evapotranspiration-guidelines for computing crop water requirements-fao irrigation and drainage paper 56. *Fao, Rome*, 300(9):D05109, 1998.

[5] A. P. Almeida, T. Liberalesso, C. M. Silva, and V. Sousa. Dynamic modelling of rainwater harvesting with green roofs in university buildings. *Journal of Cleaner Production*, 312:127655, 2021.

[6] D. Amatya, R. Skaggs, and J. Gregory. Comparison of methods for estimating ref-et. *Journal of irrigation and drainage engineering*, 121(6):427–435, 1995.

[7] J. A. Anache, E. Wendland, L. M. Rosalem, C. Youlton, and P. T. Oliveira. Hydrological trade-offs due to different land covers and land uses in the brazilian cerrado. *Hydrology and Earth System Sciences*, 23(3):1263–1279, 2019.

[8] B. Aryalekshmi, R. C. Biradar, K. Chandrasekar, and J. M. Ahamed. Analysis of various surface energy balance models for evapotranspiration esti-

mation using satellite data. *The Egyptian Journal of Remote Sensing and Space Science*, 24(3):1119–1126, 2021.

[9] A. Asoka, T. Gleeson, Y. Wada, and V. Mishra. Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in india. *Nature Geoscience*, 10(2):109–117, 2017.

[10] A. Asoka, Y. Wada, R. Fishman, and V. Mishra. Strong linkage between precipitation intensity and monsoon season groundwater recharge in india. *Geophysical Research Letters*, 45(11):5536–5544, 2018.

[11] A. Bandari and S. Sadhukhan. Determinants of per capita water supply in indian cities with low surface water availability. *Cleaner Environmental Systems*, 3:100062, 2021.

[12] B. Barik, S. Ghosh, A. S. Sahana, A. Pathak, and M. Sekhar. Water–food–energy nexus with changing agricultural scenarios in india during recent decades. *Hydrology and Earth System Sciences*, 21(6):3041–3060, 2017.

[13] C. Batchelor, M. Rama Mohan Rao, and S. Manohar Rao. Watershed development: A solution to water shortages in semi-arid india or part of the problem? *Land Use and Water Resources Research*, 3(1732-2016-140278), 2003.

[14] J. J. Batten III. Realizing a more sustainable water future from a "one water" view. *Journal: American Water Works Association*, 110(6), 2018.

[15] S. N. Bhanja, M. Rodell, B. Li, D. Saha, and A. Mukherjee. Spatio-temporal variability of groundwater storage in india. *Journal of hydrology*, 544:428–437, 2017.

[16] T. A. Bhat et al. An analysis of demand and supply of water in india. *Journal of Environment and Earth Science*, 4(11):67–72, 2014.

[17] R. K. Chakraborti, J. Kaur, and H. Kaur. Water shortage challenges and a way forward in india. *J Am Water Works Assoc*, 111(5):42–49, may 2019.

[18] V. d. P. R. da Silva, S. D. de Oliveira, C. C. Braga, J. I. B. Brito, F. d. A. S. de Sousa, R. M. de Holanda, J. H. B. Campos, E. P. de Souza, A. C. R. Braga, R. A. RS, et al. Virtual water and water self-sufficiency in agricultural and livestock products in brazil. *Journal of environmental management*, 184(Pt 2):465–472, 2016.

[19] N. Dastane. Effective rainfall in irrigated agriculture. *Bulletins FAO d'Irrigation et de Drainage (FAO)-Estudios FAO. Riego y Avenamiento (FAO)*, 1978.

[20] T. Davie. *Fundamentals of hydrology*. Routledge, 2019.

[21] K. F. Davis, D. D. Chiarelli, M. C. Rulli, A. Chhatre, B. Richter, D. Singh, and R. DeFries. Alternative cereals can improve water use and nutrient supply in india. *Science advances*, 4(7):eaao1108, 2018.

[22] U. ESCAP et al. *Water security & the global water agenda: A UN-water analytical brief*. United Nations University (UNU), 2013.

[23] M. Falkenmark. The massive water scarcity now threatening africa: why isn't it being addressed? *Ambio*, pages 112–118, 1989.

[24] W. Fialkiewicz, E. Burszta-Adamiak, A. Kolonko-Wiercik, A. Manzardo, A. Loss, C. Mikovits, and A. Scipioni. Simplified direct water footprint model to support urban water management. *Water*, 10(5):630, 2018.

[25] W. Fialkiewicz, E. Burszta-Adamiak, A. Kolonko-Wiercik, A. Manzardo, A. Loss, C. Mikovits, and A. Scipioni. Simplified direct water footprint model to support urban water management. *Water*, 10(5):630, may 2018.

[26] C. Fröhlich. Desecuritisation of water as a key for water diplomacy. *IEMed.*, page 12, 2020.

[27] T. Gleeson, M. Cuthbert, G. Ferguson, and D. Perrone. Global groundwater sustainability, resources, and systems in the anthropocene. *Annual review of earth and planetary sciences*, 48:431–463, 2020.

[28] Govt. of India. The census data. Technical report. https://censusindia.gov.in/census.website/.

[29] A. Hashem. Performance evaluation and development of daily reference evapotranspiration model. *Irrigation Drainage Systems Engineering*, 05, 01 2015.

[30] A. Y. Hoekstra. A comprehensive introduction to water footprints. *On line at: www. waterfootprint. org*, 2009.

[31] A. Y. Hoekstra. Water footprint assessment: Evolvement of a new research field. *Water Resour Manage*, 31(10):3061–3081, mar 2017.

[32] A. Y. Hoekstra, A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen. *The water footprint assessment manual: Setting the global standard*. Routledge, 2016.

[33] R. J. Hogeboom. The water footprint concept and water's grand environmental challenges. *One Earth*, 2(3):218–222, 2020.

[34] V. Kanakoudis, S. Tsitsifli, and A. Papadopoulou. Integrating the carbon and water footprints' costs in the water framework directive 2000/60/EC full water cost recovery concept: Basic principles towards their reliable calculation and socially just allocation. *Water*, 4(1):45–62, jan 2012.

[35] J. Kiptala, Y. Mohamed, M. L. Mul, M. J. Cheema, and P. Van der Zaag. Land use and land cover classification using phenological variability from modis vegetation in the upper pangani river basin, eastern africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 66:112–122, 2013.

[36] J. Kiptala, Y. Mohamed, M. L. Mul, and P. Van der Zaag. Mapping evapotranspiration trends using modis and sebal model in a data scarce and heterogeneous landscape in eastern africa. *Water Resources Research*, 49(12):8495–8510, 2013.

[37] M. Kleidorfer, C. Mikovits, A. Jasper-Tönnies, M. Huttenlau, T. Einfalt, and W. Rauch. Impact of a changing environment on drainage system performance. *Procedia Engineering*, 70:943–950, 2014.

[38] A. Kommadath. Estimation of Natural Ground Water Recharge. *Lake*, 2000.

[39] M. Konar and L. Marston. The water footprint of the united states. *Water*, 12(11):3286, 2020.

[40] K. Kristensen and S. Jensen. A model for estimating actual evapotranspiration from potential evapotranspiration. *Hydrology Research*, 6(3):170–188, 1975.

[41] A. Kumar and K. Goyal. Water reuse in india: Current perspective and future potential. In *Advances in chemical pollution, environmental management and protection*, volume 6, pages 33–63. Elsevier, 2020.

[42] M. Kummu, J. H. A. Guillaume, H. de Moel, S. Eisner, M. Flörke, M. Porkka, S. Siebert, T. I. E. Veldkamp, and P. J. Ward. The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Sci Rep*, 6(1), dec 2016.

[43] Y. Lee and S. Kim. The modified sebal for mapping daily spatial evapotranspiration of south korea using three flux towers and terra modis data. *Remote Sensing*, 8(12):983, 2016.

[44] A. Long, P. Zhang, Y. Hai, X. Deng, J. Li, and J. Wang. Spatio-temporal variations of crop water footprint and its influencing factors in xinjiang, china during 1988–2017. *Sustainability*, 12(22):9678, 2020.

[45] A. MacDonald, H. Bonsor, K. Ahmed, W. Burgess, M. Basharat, R. Calow, A. Dixit, S. Foster, K. Gopal, D. Lapworth, et al. Groundwater quality and depletion in the indo-gangetic basin mapped from in situ observations. *Nature Geoscience*, 9(10):762–766, 2016.

[46] S. S. Mali, P. B. Shirsath, and A. Islam. A high-resolution assessment of climate change impact on water footprints of cereal production in india. *Scientific reports*, 11(1):1–13, 2021.

[47] A. Manzardo, A. Mazzi, A. Loss, M. Butler, A. Williamson, and A. Scipioni. Lessons learned from the application of different water footprint approaches to compare different food packaging alternatives. *Journal of Cleaner Production*, 112:4657–4666, 2016.

[48] L. T. Marston, G. Lamsal, Z. H. Ancona, P. Caldwell, B. D. Richter, B. L. Ruddell, R. R. Rushforth, and K. F. Davis. Reducing water scarcity by improving water productivity in the united states. *Environmental Research Letters*, 15(9):094033, 2020.

[49] S. Mathur. Public-private partnership for municipal water supply in developing countries: Lessons from karnataka, india, urban water supply improvement project. *Cities*, 68:56–62, aug 2017.

[50] Y. B. Mehta. Surat sewage reuse model goes global. https://timesofindia.indiatimes.com/city/surat/surat-water-reuse-model-goes-global/articleshow/85668103.cms.

[51] M. M. Mekonnen and A. Y. Hoekstra. Four billion people facing severe water scarcity. *Sci. Adv.*, 2(2), feb 2016.

[52] A. Milman and A. MacDonald. Focus on interactions between science-policy in groundwater systems. *Environmental Research Letters*, 15(9):090201, 2020.

[53] P. K. Mishra, A. Rai, K. Abdelrahman, S. C. Rai, and A. Tiwari. Land degradation, overland flow, soil erosion, and nutrient loss in the eastern himalayas, india. *Land*, 11(2):179, 2022.

[54] V. Mishra, A. Asoka, K. Vatta, and U. Lall. Groundwater depletion and associated co2 emissions in india. *Earth's Future*, 6(12):1672–1681, 2018.

[55] H. Mooney, A. Cropper, and W. Reid. Confronting the human dilemma. *Nature*, 434(7033):561–562, 2005.

[56] O. Moseki, M. Murray-Hudson, and K. Kashe. Crop water and irrigation requirements of jatropha curcas l. in semi-arid conditions of botswana: applying the cropwat model. *Agricultural Water Management*, 225:105754, 2019.

[57] A. Mukherjee. Hydrodynamics of groundwater flow in the arsenic-affected areas of the gangetic west bengal, india. *clean and sustainable groundwater in India*, pages 301–320, 2018.

[58] A. Narmilan and M. Sugirtharan. Application of fao-cropwat modelling on estimation of irrigation scheduling for paddy cultivation in batticaloa district, sri lanka. *Agricultural Reviews*, 42(1), 2021.

[59] A. Nassar, A. Torres-Rua, L. Hipps, W. Kustas, M. McKee, D. Stevens, H. Nieto, D. Keller, I. Gowing, and C. Coopmans. Using remote sensing to estimate scales of spatial heterogeneity to analyze evapotranspiration modeling in a natural ecosystem. *Remote Sensing*, 14(2):372, 2022.

[60] S. Nath, N. Devakumar, S. S. Patra, and A. Nanda. Estimation of crop water requirement and irrigation scheduling of rice in shivamogga district of karnatakausing fao cropwat. *Journal of Cereal Research 14 (Spl-2): 18-26. http://doi. org/10.25174/2582-2675/2022*, 125782, 2022.

[61] J. Nsiah, C. Gyamfi, G. Anornu, and S. Odai. Estimating the spatial distribution of evapotranspiration within the pra river basin of ghana. *Heliyon*, 7(4):e06828, 2021.

[62] A. O'Neill. Urbanization in India 2021. https://www.statista.com/statistics/271312/urbanization-in-india/.

[63] C. Pandit and A. K. Biswas. India's national water policy:'feel good'document, nothing more. *International Journal of Water Resources Development*, 2019.

[64] W. Paterson, R. Rushforth, B. L. Ruddell, M. Konar, I. C. Ahams, J. Gironás, A. Mijic, and A. Mejia. Water footprint of cities: A review and suggestions for future research. *Sustainability*, 7(7):8461–8490, 2015.

[65] C. Perry. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage: The Journal of the International Commission on Irrigation and Drainage*, 56(4):367–378, 2007.

[66] N. L. Poff, B. D. Richter, A. H. Arthington, S. E. Bunn, R. J. Naiman, E. Kendy, M. Acreman, C. Apse, B. P. Bledsoe, M. C. Freeman, et al. The ecological limits of hydrologic alteration (eloha): a new framework for developing regional environmental flow standards. *Freshwater biology*, 55(1):147–170, 2010.

[67] R. Poyatos, J. Latron, and P. Llorens. Land use and land cover change after agricultural abandonment. *Mountain research and development*, 23(4):362–368, 2003.

[68] E. Psomiadis, K. X. Soulis, and N. Efthimiou. Using scs-cn and earth observation for the comparative assessment of the hydrological effect of gradual and abrupt spatiotemporal land cover changes. *Water*, 12(5):1386, 2020.

[69] R. Quinn, C. Rougé, and V. Stovin. Quantifying the performance of dual-use rainwater harvesting systems. *Water research X*, 10:100081, 2021.

[70] P. Quinteiro, A. C. Dias, M. Silva, B. G. Ridoutt, and L. Arroja. A contribution to the environmental impact assessment of green water flows. *Journal of Cleaner Production*, 93:318–329, 2015.

[71] M. Rajeshwar, S. Mani, et al. Water retention characteristics of red lateritic soils, red soils and black soils of tamil nadu in relation to soil texture. *International Journal of Agricultural Sciences*, 11(2):307–315, 2015.

[72] H. RamezaniEtedali, K. Ahmadaali, F. Gorgin, and B. Ababaei. Optimization of the cropping pattern of main cereals and improving water productivity: application of the water footprint concept. *Irrigation and Drainage*, 68(4):765–777, 2019.

[73] J. H. Rao, M. K. Hardaha, and H. Vora. The water footprint assessment of agriculture in banjar river watershed. *Current World Environment*, 14(3):476, 2019.

[74] C. Ray, D. McInnes, and M. Sanderson. Virtual water: Its implications on agriculture and trade. *water international*, 43(6):717–730, 2018.

[75] W. P. Review. Total population by country, 2023. https://worldpopulationreview.com/countries.

[76] M. Rodell, J. S. Famiglietti, D. N. Wiese, J. Reager, H. K. Beaudoing, F. W. Landerer, and M.-H. Lo. Emerging trends in global freshwater availability. *Nature*, 557(7707):651–659, 2018.

[77] M. Rosegrant. Integrated economic–hydrologic water modeling at the basin scale: the maipo river basin. *Agricultural Economics*, 24(1):33–46, dec 2000.

[78] E. Rouholahnejad, K. C. Abbaspour, R. Srinivasan, V. Bacu, and A. Lehmann. Water resources of the black sea basin at high spatial and temporal resolution. *Water Resources Research*, 50(7):5866–5885, 2014.

[79] E. Rouholahnejad Freund, M. Zappa, and J. W. Kirchner. Averaging over spatiotemporal heterogeneity substantially biases evapotranspiration rates in a mechanistic large-scale land evaporation model. *Hydrology and Earth System Sciences*, 24(10):5015–5025, 2020.

[80] D. Saha, S. Marwaha, and A. Mukherjee. Groundwater resources and sustainable management issues in india. In *Springer Hydrogeology*, pages 1–11. Springer Singapore, nov 2017.

[81] D. Sharma and A. Bharat. Conceptualizing risk assessment framework for impacts of climate change on water resources. *Current Science*, pages 1044–1052, 2009.

[82] T. Shiao, A. Maddocks, C. Carson, and E. Loizeaux. 3 maps explain india's growing water risks. 3.

[83] R. K. Singh, A. Irmak, S. Irmak, and D. L. Martin. Application of sebal model for mapping evapotranspiration and estimating surface energy fluxes in south-central nebraska. *Journal of irrigation and drainage engineering*, 134(3):273–285, 2008.

[84] V. Smakhtin, C. Revenga, and P. Döll. A pilot global assessment of environmental water requirements and scarcity. *Water international*, 29(3):307–317, 2004.

[85] I. Standard. Code of basic requirement for water supply, drainage and sanitation. *Public Health Engineering. IS_1172 (1993)*, 1993.

[86] C. Sullivan. Calculating a water poverty index. *World Development*, 30(7):1195–1210, jul 2002.

[87] S. Sun, P. Wu, Y. Wang, and X. Zhao. Impact of changing cropping pattern on the regional agricultural water productivity. *The Journal of Agricultural Science*, 153(5):767–778, 2015.

[88] Z. Sun, B. Wei, W. Su, W. Shen, C. Wang, D. You, and Z. Liu. Evapotranspiration estimation based on the sebal model in the nansi lake wetland of china. *Mathematical and Computer Modelling*, 54(3-4):1086–1092, 2011.

[89] U. Surendran, C. Sushanth, G. Mammen, and E. Joseph. Modelling the crop water requirement using fao-cropwat and assessment of water resources for sustainable water resource management: A case study in palakkad district of humid tropical kerala, india. *Aquatic Procedia*, 4:1211–1219, 2015.

[90] L. Tang, S. Zhang, J. Zhang, Y. Liu, and Y. Bai. Estimating evapotranspiration based on the satellite-retrieved near-infrared reflectance of vegetation (nirv) over croplands. *GIScience & Remote Sensing*, 58(6):889–913, 2021.

[91] M. K. Tiwari, M. Gaur, P. R. Siyag, and A. Kumar. Impact assessment of land use change on runoff generation using remote sensing & geographical information systems (gis). 2014.

[92] UNESCO et al. *The United Nations World Water Development Report 2021: Valuing Water*. United Nations, 2021.

[93] D. Vanham. Does the water footprint concept provide relevant information to address the water–food–energy–ecosystem nexus? *Ecosystem services*, 17:298–307, 2016.

[94] D. Vanham. Open access: The water footprint of the eu: quantification, sustainability and relevance. In *Virtual Water: Implications for Agriculture and Trade*, pages 15–29. Routledge, 2018.

[95] P. Wagle, N. Bhattarai, P. H. Gowda, and V. G. Kakani. Performance of five surface energy balance models for estimating daily evapotranspiration in high biomass sorghum. *ISPRS Journal of Photogrammetry and Remote Sensing*, 128:192–203, 2017.

[96] H. B. Wakode, K. Baier, R. Jha, and R. Azzam. Impact of urbanization on groundwater recharge and urban water balance for the city of hyderabad, india. *International Soil and Water Conservation Research*, 6(1):51–62, 2018.

[97] H. B. Wakode, K. Baier, R. Jha, and R. Azzam. Impact of urbanization on groundwater recharge and urban water balance for the city of hyderabad, india. *International Soil and Water Conservation Research*, 6(1):51–62, mar 2018.

[98] S. Wanniarachchi and R. Sarukkalige. A review on evapotranspiration estimation in agricultural water management: Past, present, and future. *Hydrology*, 9(7):123, 2022.

[99] U. Water. Un world water development report, nature-based solutions for water. https://unesdoc.unesco.org/ark:/48223/pf0000261424.

[100] F. World Economic. The global risks report, 2017. https://www.weforum.org/reports/the-global-risks-report-2017/.

[101] Y. W. Youssef and A. Khodzinskaya. A review of evaporation reduction methods from water surfaces. In *E3S web of conferences*, volume 97, page 05044. EDP Sciences, 2019.

[102] C. Zang and J. Liu. Trend analysis for the flows of green and blue water in the heihe river basin, northwestern china. *Journal of Hydrology*, 502:27–36, 2013.

[103] A. Zhao, X. Zhu, X. Liu, Y. Pan, and D. Zuo. Impacts of land use change and climate variability on green and blue water resources in the weihe river basin of northwest china. *Catena*, 137:318–327, 2016.

[104] H. Zheng, Q. Bian, Y. Yin, H. Ying, Q. Yang, and Z. Cui. Closing water productivity gaps to achieve food and water security for a global maize supply. *Scientific reports*, 8(1):1–10, 2018.

[105] K. Zhu, Z. Xie, Y. Zhao, F. Lu, X. Song, L. Li, and X. Song. The assessment of green water based on the swat model: a case study in the hai river basin, china. *Water*, 10(6):798, 2018.

CHAPTER A

Appendix

This chapter reports on the primary data collected regarding water availability within the three municipalities.

The questionnaire was based on the consumption patterns of water use according to different income class people. Other related elements like the quality of the water, its taste, color, and the presence of minerals available to different classes of households were also present there. Moreover, parameters such as the total members of the households, the amount of water stored per day, how many times the storage has to be refilled, and whether they are doing any gardening have also been looked at. Since the houses only sometimes use the entire water tank, their daily water consumption is lesser than their storage capacity. However, it is impossible to find how much water is precisely used by these houses. So the researcher assumes that the households use the entire water tank daily.

Below is the link to see the PDF copy of the primary data:

https://drive.google.com/file/d/1rKO26A2LWSYJkAst61vTuSEAueXJR3l9/view?usp=sharing