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Potential of natural groundwater recharge in the Chennai Basin with a special emphasis on the urban area

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Declaration of Originality

I hereby certify that, as the author of this thesis and one of the main authors of the publications involved, the work presented in this thesis was composed and invented by me, except as acknowledged in the text and related reference list. The work was not submitted previously to any other institutions.

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Summary

Groundwater is the primary source of drinking water in India, and the Chennai River Basin (CRB) is no exception. However, available resources of both groundwater and surface water, are constantly decreasing because of overexploitation and contamination. Well fields in the northern part of the CRB control the water supply for the region, including the Chennai Metropolitan Area (CMA), the capital of the state of Tamil Nadu. Thus, any changes in groundwater storage and availability in the basin directly affect the 11-million people who live in the CMA. So, even though the focus of this study is on the CMA, the entire basin must be considered in order to understand the hydrogeological condition and groundwater situation. This research aims to provide a holistic study of the topographic condition of the basin, the amount of water stress, the identification and mapping of the groundwater potential zones, a review of the groundwater recharge estimation techniques on national scale, and most importantly, the creation of an estimate of the natural groundwater recharge in the CRB and how climate and landuse patterns affect the recharge process.

A critical review has been made of popular groundwater recharge estimation practices. The suitability of each method is found to be dependent on time-space, hydrogeological condition, and data availability. Considering the hydrogeological and climatic conditions, the Water Table Fluctuation (WTF) method is the most appropriate method of recharge estimation. Groundwater recharge is largely controlled by topographical factors such as morphometric and hypsometric analysis and understanding these factors is necessary in water resource development planning. Shuttle Radar Topographic Mission (SRTM) and Digital Elevation Model (DEM) data were used in the Geographical Information System (GIS) platform to derive the morphometry and hypsometry. The CRB is an elongated basin of the 7th order and has been classified into 11 sub-basins. Major linear, areal and relief aspects were calculated and discussed based on their hydrologic significance. Steep slopes in the basin may affect the infiltration rate and, subsequently, recharge. Hypsometric curves show the concave type for most of the sub-basins, indicating an old stage. These results provide vital information about the hydrological conditions of the basin.

Protecting the resource from depletion and identifying potential zones is essential for sustainable development. Remote Sensing (RS) and GIS technologies with field data were used to map groundwater potential zones in the CRB. For the most accurate results, a total of 11 controlling factors were brought into the GIS platform and a multi-criteria decision making (MCDM) tool, Analytical Hierarchal Process (AHP), was also used. Based on this analysis, groundwater potential zones were classified into five categories- very poor, poor, moderate, good, and very good.

The final groundwater potential map showed that 35% of the total area has good to very good groundwater potential, 27% has moderate potential, and 38% has poor to very poor potential. Comparison of the specific capacity obtained from borehole data with these results showed that the predicted groundwater potential identified in this study matches 80% of the area.

Groundwater potential depends on climatic conditions such as droughts, atmospheric temperatures, and monsoonal patterns. Using long-term temperature and rainfall data, meteorological drought has been calculated and agricultural drought has been determined using NDVI, NDWI and VCI indices. Agricultural drought indices showed that the vegetation is healthy in the northern and southern regions. However, more than 40% of the area was found to be water stressed. The calculation was made on a decadal scale and the highest water stress was observed in the year 2010. Agricultural drought is more prominent than meteorological drought in the CRB.

Chennai faces a severe water shortage in the summer season and flooding in the rainy seasons. The groundwater recharge rate for the Chennai River Basin has been estimated using the empirical method, the rainfall infiltration (RIF) technique, a GIS based distributed model, and the Water Table Fluctuation (WTF) method. The average groundwater recharge rates for different methods vary, with results of 196mm/ year (Empirical formula), 127mm/year (WTF method) and 122mm/year (RIF method). The ratio of effective recharge to rainfall is found as 10% for RIF and WTF methods and 16% using the empirical formula. Considering the conditions in India, as recommended by the Groundwater Estimation Committee (GEC), the WTF method was found to be the most reliable. Still, using multiple methods is suggested for a more fully accurate estimate.

This is one of the first extensive studies that covers aspects such as terrain characteristics, proposing the most suitable groundwater recharge estimating methods, groundwater potential zone identification, water stress analysis and natural groundwater recharge estimations in the Chennai River Basin. During this study, large amount of field data on water level, atmospheric temperature, rainfall, and aquifer parameters was collected from different institutions and brought into a single scale. All this data has been brought into the GIS platform and created maps. Thus, a baseline has been created for future groundwater studies. After considering variable recharge estimates and the effective recharge ratio (approx. 10%), it is suggested that groundwater recharge be improved either by repairing existing structures or implementing artificial recharge structures based on the groundwater potential identified. This thesis contains both basic and advanced levels of scientific information, all that is necessary for policymakers to begin improvements, and even provides a number of recommendations for the most effective approach to groundwater management.

Zusammenfassung

Das Grundwasser stellt in Indien die wichtigste Quelle zur Gewinnung des Trinkwassers dar. Das Flusseinzugsgebiet Chennai (CRB) bildet dabei keine Ausnahme. Durch Übernutzung und Verunreinigung schwinden jedoch verfügbare Wasserressourcen, sowohl Grundwasser als auch Oberflächenwasser, stetig. Die sich im nördlichen Teil des Flussbeckens befindenden Brunnenfelder kontrollieren die Wasserversorgung der Region, einschließlich der Metropolregion Chennai (CMA) und somit der Hauptstadt des Bundesstaats Tamil Nadu. Aus diesem Grund haben jegliche Änderungen des Grundwasserspeichers und -verfügbarkeit im Flussbecken direkte Auswirkungen auf die 11 Millionen Einwohner der Metropolregion. Obwohl der Fokus dieser Arbeit auf der Metropolregion Chennai liegt, muss zum Verständnis der hydrogeologischen Verhältnisse und der Grundwassersituation das ganze Flussbeckens berücksichtigt werden. In dieser Arbeit wird eine ganzheitliche Betrachtung der topografischen Verhältnisse des Flussbeckens, der Stärke des Wasserstresses, der Bestimmung und Abbildung der möglichen Grundwasserzone, einer Überprüfung der Ermittlungsverfahren zur Grundwasserneubildung auf nationaler Ebene und, am wichtigsten, der Ermittlung der natürlichen Grundwassererneuerung im Flussbecken Chennai sowie der Weise, wie Klima- und Bodennutzungsmuster diesen Erneuerungsprozess beeinflussen, durchgeführt.

Die gängigsten Praktiken zur Ermittlung der Grundwassererneuerung wurden kritisch untersucht. Es wurde festgestellt, dass die Eignung der einzelnen Methoden von den Raum-Zeit-Bedingungen, hydrogeologischen Umständen und der Datenverfügbarkeit abhängt. Bei Berücksichtigung der hydrogeologischen und klimatischen Bedingungen stellt die WTF-Methode (Water Table Fluctuation) die passendste Methode zur Ermittlung der Grundwassererneuerung dar. Die Grundwassererneuerung wird größtenteils von den topografischen Faktoren, wie der morphometrischen und hypsometrischen Analyse, bestimmt. Das Verstehen dieser Faktoren ist für die Planung der Wasserressourcenentwicklung unerlässlich. Für die Durchführung der Merphometrie und der Hypsometrie wurden SRTM- und DHM-Daten in geografische Informationssysteme (GIS) eingesetzt. Das Flusseinzugsgebiet Chennai ist ein längliches Becken der 7. Ordnung und wird in 11 Unterbecken unterteilt. Die wichtigsten Linear-, Areal- und Reliefaspekte wurden anhand ihrer hydrologischen Bedeutung berechnet und überprüft. Steilhänge in Becken können die Infiltrationsrate und somit die Grundwassererneuerung beeinflussen. Die hypsografischen Kurven der meisten Unterbecken weisen eine konkave Form vor und geben somit ihre Altersstufe an. Diese Ergebnisse bieten entscheidende Informationen über die hydrologischen Verhältnisse des Beckens.

Der Schutz vor der Erschöpfung der Ressource und die Bestimmung der möglichen Zonen ist für eine nachhaltige Entwicklung unumgänglich. Die Felddaten der Fernerkundung und GIS-Technologien wurden zur Abbildung der möglichen Grundwasserzonen im FlusseinzugsgebietChennai eingesetzt. Um ein genaues Ergebnis erzielen zu können, wurden in die GIS-Plattform insgesamt 11 Kontrollfaktoren eingebracht und ein Hilfsmittel für mehrkriterielle Entscheidungen, ein analytischer Hierarchieprozess (AHP), genutzt. Aufgrund dieser Analyse wurden die möglichen Grundwasserzonen in fünf Kategorien eingeteilt: sehr schwach, schwach, mittel, gut und sehr gut. Die endgültige Karte der möglichen Grundwasserzonen zeigt, dass 35 % des Gesamtbereichs über ein gutes bis sehr gutes Grundwasserpotential, 27 % über ein mittleres Potential und 38 % über ein schwaches bis sehr schwaches Grundwasserpotential verfügen. Vergleiche der spezifischen Kapazität, die aus dem Bohrlochdaten gewonnen wurden, mit diesen Ergebnissen zeigen, dass das in dieser Arbeit vorhergesagte Grundwasserpotential zu 80% des Gebiets passt.

Das Grundwasserpotential hängt von den Klimabedingungen wie Dürren, Atmosphärentemperaturen und Monsunmustern ab. Durch den Einsatz der Langzeitdaten über Temperatur und Regenfällen wurde die meteorologische Dürre berechnet, die landwirtschaftliche Dürre wurde mittels der Indexe NDVI, NDWI und VCI bestimmt. Die Indexe für die landwirtschaftliche Dürre zeigen, dass sich die Vegetation in den nördlichen und südlichen Gebieten im guten Zustand befindet. Eine Fläche von 40% des Gebiets erlebt jedoch Wasserstress. Die Berechnung erfolgte auf der dekadischen Skala, wobei der höchste Wasserstress im Jahr 2010 zu beobachten war. Im Flusseinzugsgebiet Chennai ist die landwirtschaftliche Dürre starker als die meteorologische Dürre zu spüren.

In Chennai herrscht im Sommer gravierender Wassermangel, während der Regenzeit sind jedoch starke Überflutungen vorhanden. Die Grundwasserneubildungsrate für das Flussbecken Chennai wurde anhand der empirischen Methode, des Modells der Regeninfiltration (RIF), eines auf dem GIS-basierten verteilten Modells und der WTF-Methode ermittelt. Die durchschnittliche Grundwasserneubildungsrate variiert je nach Methode/Modell und zeigt die Ergebnisse von 196mm/Jahr (empirische Formel), 127mm/Jahr (WTF-Methode)und122mm/Jahr(RIF-Methode) vor. Der auf den Regen zurückgehender Anteil der effektiven Erneuerung liegt bei den Methoden RIF und WTF bei 10%, bei dem Einsatz der empirischen Formel erreicht dieser Anteil 16%. In Anbetracht der in Indien herrschenden Verhältnisse wurde die WTF-Methode, wie vom indischen Komitee für Grundwasserermittlung (GEC) empfohlen, als die zuverlässigste Methode bestimmt. Für eine möglichst genaue Ermittlung wird jedoch empfohlen, mehrere Methoden zu nutzen.

Diese Arbeit gehört zu den ersten ausführlichen Studien, die sich mit Aspekten wie den Geländeeigenschaften, einer Empfehlung der geeignetsten Methoden zur Ermittlung der Grundwasserneubildung, der Bestimmung der möglichen Grundwasserzonen, der Wasserstressanalyse und der Ermittlung der natürlichen Grundwasserneubildung im Flussbecken Chennai beschäftigen. In dieser Arbeit wurde von diversen Einrichtungen eine hohe Zahl an Felddaten über den Wasserstand, Atmosphärentemperatur, Regenfälle und aquiferspezifische Parameter erworben und in einer Skala zusammengeführt. Alle diese gesammelten Daten wurden in die GIS-Plattform eingetragen und es wurden Karten erstellt. Somit wurde eine Ausgangsbasis für zukünftige Grundwasserstudien geschaffen. In Anbetracht der variablen Ermittlungswerte und des effektiven Erneuerungsanteils (etwa 10%) wird empfohlen, die Grundwasserneubildung entweder durch die Sanierung vorhandener Strukturen oder durch den Einsatz künstlicher Anreicherungsstrukturen auf der Grundlage des bestimmten Grundwasserpotentials zu verstärken. Es werden wissenschaftliche Basisinformationen vorgelegt, welche den Entscheidungsträgern zur Optimierung einer angepassten und nachhaltigen Wasserbewirtschaftung dienen können.

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Abbreviations

CRB	Chennai River Basin
CMA	Chennai Metropolitan Area
DEM	Digital Elevation Model
WTF	Water Table Fluctuation
WLF	Water Level Fluctuation
SRTM	Shuttle Radar Topographic Mission
GIS	Geographical Information System
RS	Remote sensing
MCDM	Multi criteria decision making
AHP	Analytical Hierarchal Process
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
VCI	Vegetation Condition Index
IMD	India Meteorological Department
GEC	Groundwater Estimation Committee
RIF	Rainfall Infiltration
AK	Araniyar and Korataliyar
PWD	Public Works Department
IWS	Institute of Water Studies
CGWB	Central Ground Water Board
TWAD	Tamil Nadu Water Supply and Drainage Boar
UNEP	United Nations Environment Programme
GMST	Global Mean Surface Temperature
IPCC	Intergovernmental panel on climate change
SPI	Standard precipitation index

CHAPTER 1

General Introduction

1.1 Background of the Research

India uses an enormous amount of groundwater for agricultural, industrial, drinking and domestic uses. According to the World Bank Report (2012), it is calculated that 230 km^3 of water is used each year for the aforementioned purposes. Uncontrolled extraction of the groundwater for these purposes due to various reasons such as population growth and industrialization have resulted in the depletion of this resource.

In terms of groundwater utility, the Chennai Metropolitan area (CMA) is no exception. The CMA has an area of 1189 km^2, constituting the metropolitan city of Chennai (Madras) and its suburban areas in the Kanchipuram and Thiruvallur districts and forms an integral part of the Chennai River Basin(CRB). The majority of the basin is in Tamil Nadu (5542km^2) and there stin the nearby state AndharaPradesh (7282 km^2). The water demand of the city is mainly met by the Adyar, Kooum, Aranaliyar, and Korataliyar river basins and the well fields in the A-Kbasin.

Chennai has emerged as the fourth largest metropolitan area in India, after Mumbai, Calcutta and Delhi. However, Chennai was the centre of Southern peninsula from the British ruling period in India. The most important reason for this being that the city has port, so connections to other parts of the world was easier compared to most southern Indian cities. A sudden increase in population is observed after India's independence from the British (ref. Figure. 1.1). People from different regions came to Chennai for education, work, business and many other

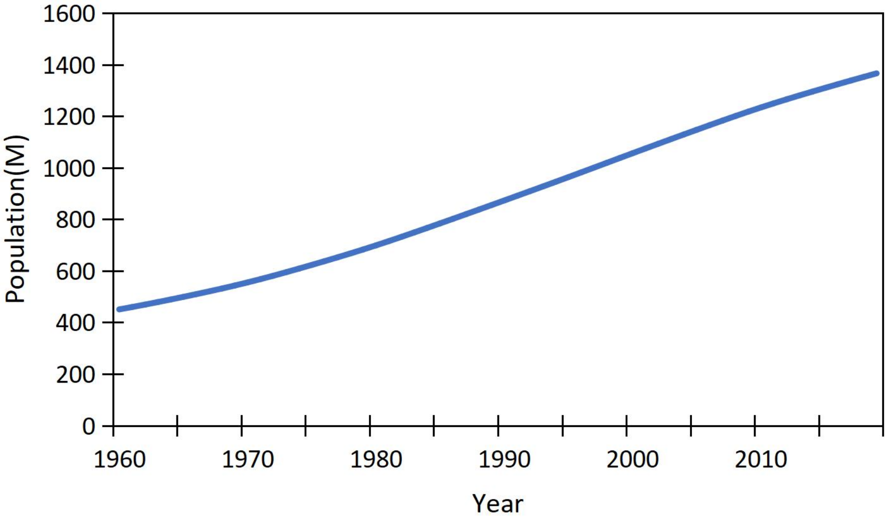

Figure 1.1: A sudden increase in population is observed after India's independence from the British (UN World population prospects 2019)

purposes. As per the census of 2011, the population of the Chennai Metropolitan Area was 7.08 million. An abnormal concentration of the population in urban areas is giving rise to serious problems in the socio-economic, political and environmental sectors. The most common impact on the environmental sector is insufficient water supply and dispersal of water- borne diseases (Meinzen-Dick and Appasamy 2002). Existing water resources becomes insufficient for the growing population and the groundwater table has started to decline. Additionally, as a coastal city, saline water has started to encroach to freshwater resources of the CMA.

The CMA is under serious water stress for the last few decades in terms of water availability hours per day, Chennai and Delhi are the worst ranked metropolis in India (Background Paper- International Conference on New Perspectives on Water for Urban & Rural India - 18-19 September, 2001, New Delhi). The total water supply of the city is dependent mainly on surface water resources such as Poondi Reservoir, Cholavaram Reservoir, Chembarapakkam Lake, and Red Hills Lake. The contribution from these water resources to the water supply is approximately 200 MLD. The biggest contribution of groundwater is coming from the Araniyar-Kottalaiyar (A-K) basin, 300 MLD, thrice the sustainable yield of 100 MLD. The other source comes from the agricultural fields located in the northern region of Chennai, primarily from the Manali Industrial Area (Janakarajan et al., 2007). This additional groundwater supply provides 125 MLD of water, and making the total available water supply 425 MLD. Considering the per capita need of 100 lpcd, the current population of Chennai Urban region needs 760 MLD, showing extensive shortage in supply. The projected demand of water for the year 2021 is 1370 MLD, without including the industrial uses and losses during the conveyance. (Janakrajan et al., 2007). The South Chennai coastal aquifer was formerly one of the major contributors of the water supply in Chennai; however, overexploitation in this area caused saline intrusion and many of the region's wells are now useless.

Major issues affecting the urban environment are increased sewage problems, industrial pollution, and trash disposal etc., The Chennai Urban Area has 6 main waterways, namely Adyar River, Cooum Buckingham Canal, Captain Cotton Canal, Otteri Nallah and Mambalam drain. These drains together carry more than 532 MLD of sewage, which is much higher than the total sewage collection by the metro water treatment plants. The quality of water is good only in the rainy seasons.

The Chennai Urban Area was originally built on floodplains, as is evident from lithological and geomorphological analysis. The urban area keep on expanding and a four fold increase was reported in the year 2011. Drastic changes were reported in the last decade, as Southern Chennai become the hotspot for Industries and IT sectors because of globalisation. It is reported that the population increase of 2 million was observed in the period between 2001 and 2011. Increased built up areas posed serious threats to agricultural villages, hamlets, wetlands and lakes. The

Indian Institute of Science (IISC) reported that the increase in built up areas reached 64.4% in 2014 against 29.53% in 1991. The city administration failed to provide necessary drainage and sanitation measures to support this abnormal development. As a result, natural water courses and recharge structures either gave way to human encroachment or were not properly taken care of. This is one of the major reasons for flooding in urban areas of this region. Urban flooding is one of the indicators of an inadequate drainage network according to rainfall events. It also shows the lack of sufficient groundwater recharge within the area.

Groundwater recharge is one of the key components of the hydrologic cycle. It can be defined as the downward movement of water from the surface, through the soil until it finally reaches the groundwater table (Alley 2009). The process of groundwater recharge generally happens in two different ways–diffuse recharge and localized recharge. Diffuse recharge is the widespread movement of groundwater through the unsaturated zone, principally as a result of precipitation. On the other hand, localized recharge is a non-uniform movement from the surface water to groundwater (Alley 2009). Localized recharge has more significance than diffusive recharge in arid to semi-arid regions.

Chennai receives approximately 1290 mm of rainfall each year, more than the national average (Janakarajan et al., 2007). This suggests that the region receives sufficient precipitation mainly from the North-East monsoon (September -November). It is reported that of the total rain received, only 5% reaches the groundwater and the rest ends up in the sewage drains or the Bay of Bengal. This decrease in recharges and constant increase in the groundwater extraction resulted in overexploitation of the 80% of the groundwater reserves (Janakarajan et al., 2006). However, rainfall patterns changed recently, and frequent floods and droughts have been observed in the past decade. Flooding in certain regions of Chennai is a usual annual phenomenon due to the North-East Monsoon (Sept- Nov). Unusual rainfall of 1,024 mm occurred in November 2015 and continued in December of that year, with a record rainfall of 290 mm rainfall occurring within a 24 hour period on December 1, 2015, the highest in the last 100 years (Sreeenijan et al., 2017). This resulted a devastating flood in Chennai, affected 4 million people, in which 470 lives were lost and millions of rupees were lost in reconstruction.

In the case of the Chennai Basin, the total available precipitation occurs in a short span of 3-4 months period. The city is not yet completely equipped to store and redistribute the extensive volume of water for future use. Recently, after the flood and drought events, awareness about water conservation and recharge among the authorities increased drastically and several projects were proposed, such as the expansion of existing reservoirs, and the construction of new reservoirs and desalination plants. Rainwater Harvesting Structures were made mandatory for new constructions (Brunner et al., 2014). Managed Aquifer Recharge (MAR) has been in practice in the northern part of Chennai since the beginning of this decade and the most implemented ones are check dams and infiltration ponds. The Arani- Koratalai (A-K) river basin, located north of Chennai, has several check dams already built and many more are planned (Periyanayaki and Elango 2015). Positive impacts such as groundwater quality improvements, rising groundwater level and receding saline intrusion etc., were already reported from the CMA (Parimala and Elango 2013; Indu et al., 2013; Parimalarenganayaki and Elango 2014).

Though these efforts are producing positive impacts and good results, considering the huge water demand of the Chennai Urban Area, a more extensive planning and implementation strategy for groundwater recharge structures is necessary. Groundwater recharge is the key factor governing the availability of water. A top to bottom analysis has become necessary to solve the water crisis of this area. Based on this information formulated the objectives of this study were formulated.

1.2 Objectives

1. Study the topography of the entire Chennai River Basin
2. Assess water stress in the Chennai River Basin
3. Estimate and quantify natural groundwater recharge in the Chennai River Basin
4. Compare available groundwater recharge measurement techniques and identify those suitable for the Chennai River Basin
5. Identify groundwater potential zones in the Basin
6. Assess the impact of climate change and land use patterns on groundwater recharge in the Chennai River Basin
7. Compile databases available from public/private departments into the same scale
8. Compile satellite and RS data and compare it with groundwater recharge data in order to create a natural recharge information map of the Chennai River Basin.

1.3 Synopsys of the Remaining Chapters

Chapter 2 – Characterization of the Study Area

This chapter gives an overall idea about the study area which explains the geology, geomorphology, hydrogeology, land use, soil characteristics and other important aspects of the study area.

Chapter 3 – The state-of-the art estimation groundwater recharge and water balance with reference to India: a critical review

This chapter is about state of the art groundwater recharge estimation techniques practiced all over the world and India. Then it is reviewed and compared with the specific application sites. Case studies from India are assessed separately and compared each other based on their usability in different aquifer systems and climatic regions.

Chapter 4–Hydro-morphometric and Hypsometric Analysis of Chennai River Basin Using GIS and Remote Sensing Methods

This chapter looks at morphometry and hypsometry of the Chennai River Basin, which play important roles in the groundwater management. The importance of topographic analysis of the CRB critically assessed using GIS analysis.

Chapter 5 – Geographical information system (GIS) and analytical hierarchy process (AHP) based groundwater potential zones delineation in Chennai river basin, India.

This chapter aim to identify the groundwater Potential zones in CRB. Locating the potential locations will be necessary while planning the groundwater resources projects. Additionally, it helps to identify the locations where recharging is necessary to keep the balance between the extraction and recharge.

Chapter 6 – Climate change induced water stress evaluation in Chennai basin using water stress indicators

This chapter examines the water stress which has been noticed in the Chennai River Basin using existing rainfall and climatic data, as well as NDVI methods.

Chapter 7 – Integrated approaches for the estimation of natural groundwater recharge in Chennai river basin

This pivotal chapter evaluates natural groundwater recharge in the Chennai River Basin using various methods. Recharge is the key factor that controls the existence of hydrologic cycles in groundwater dependent river basins. Estimation of recharge is not always 100% accurate, thus different methods have been used in this study depending on the data availability and suitability of each methods in the study area.

Chapter 8 – Combined conclusions and recommendations for future studies

This chapter provides the combined conclusions of all the other chapters based on the results, gives recommendations for future management plans.

1.4 Publications related to this thesis

Sajil Kumar PJ, Schneider M, Elango L (2022) The state-of-the art estimation of groundwater recharge and water balance with a special emphasis on India: A critical review. Sustainability, 14(1), 340 https://doi.org/10.3390/su14010340

This chapter is prepared in the form of a Journal paper and published in Sustainability Journal. As the first author, I was the main contributing author for this review paper. The structure of the paper was formulated after discussing with Prof. Schneider and Prof. Elango. This comprehensive review was prepared by me and further changes were incorporated by the suggestion from co-authors.

Sajil Kumar PJ, Elango L, Schneider M, (2022) Hydro-morphometric and Hypsometric Analysis of Chennai River Basin Using GIS and Remote Sensing Methods. In preparation.

I have written this paper completely, and the quality of the paper is improved a lot with the comments and suggestions from Prof. Schneider and Prof. Elango. This paper is ready to submit to a peer-reviewed Journal.

Sajil Kumar PJ, Elango L, Schneider M, (2022) Geographical Information System (GIS) and Analytical Hierarchy Process (AHP) based groundwater Potential Zones delineation in Chennai River Basin, India. Sustainability, 14(3),1830; https://doi.org/10.3390/su14031830

This Chapter is published in Sustainability Journal. I was involved in data collection, acquiring various maps and formulating the paper. Prof. Schneider and Prof. Elango were involved in the discussions to improve the scientific merit of the paper and reviewing the final version before submission.

Sajil Kumar PJ, Elango L, Schneider M (2022) Climate change induced water stress evaluation in the Chennai Basin using water stress indicators. In preparation

It was entirely written by me and the article is benefited by suggestions from Prof. Schneider and Prof. Elango.

This paper is ready to submit to a peer-reviewed Journal.

Sajil Kumar PJ, Schneider M, Elango L (2022) Estimation of Natural Groundwater Recharge in Chennai River Basin (CRB). Hydrological Sciences Journal DOI: 10.1080/02626667.2022.2064223

This is the main chapter of the thesis and it is published in Hydrological Sciences Journal. The recharge estimation methods were selected after discussing with Prof. Schneider and Prof. Elango. I have collected the data, maps, and literature for the paper. Co-authors helped in improving all the sections of the paper and discussed through the preparation of the paper and finally proofread the paper before submission.

CHAPTER 2

Characterization of the Study Area

2.1 General

Chennai basin covers an extensive surface area of 7282 km^2, located in the North-East region of Tamil Nadu State with latitudes 12° 40' N and 13° 40' N and longitudes 79° 10' E and 80° 25' E. Out of the total area, 1740 Km^2 area is lies in the nearby Andhra Pradesh State (Figure 2.1). The Major portion on the basin is falling in the Chennai and Thiruvallur districts and partially in Kanjeepuram and Vellore districts. Physiographical classification of the basin can be classified as (i) Western mountainous terrain with valley complex (ii) Central elevated terrain and (iii) Eastern coastal plain.

Chennai river basin is a group of four subbasins, namely Araniyar, Kosathalayar, cooum and Adyar, and all of them are flowing western hilly regions to Bay of Bengal in the east. Among the four, Kosathalayar sub basin has the largest surface area 3,240Km^2 and the remaining as follows, Adyar (857Km^2), Araniar 763 (Km^2) and Cooum (682 Km^2). Araniyar, and Kosathalayar originates from Andhra Pradesh. Adyar and Coovum river are mainly originating from the surplus water from Cooum and Chembarambakkam tanks. Both these rivers have no flow except in the rainy season. In addition to these four rivers, a manmade Buckingham canal, is running from Visakapattanam to Kaluveli tank in Tamil Nadu, along the eastern coast.

High level of urbanization and industrialization have depleted the groundwater resources and imparted pollution to the water resources of the area. Uncontrolled pumping of the groundwater caused lowering of water table and subsequent saline water ingression from the Bay of Bengal, which marks the eastern boundary of the study area.

2.2 Climate

The major climatic factors that affecting the water resources and its effective development and management are temperature, rainfall, humidity, wind speed and sunshine. Informations and record about these parameters is available from the climatic stations located in the basin. The major changes in the climatic parameters are observed based on the factors such as hilly to plain areas, and also on season such as rainy, Winter and Summer. Tamil Nadu and the Chennai basin as a whole has arid to semi-arid tropical climatic zone. The mean annual temperature of 24.3 to 32.9°C, in extreme situation it may range also from 13.9 to 45°C (CGWB 2008).

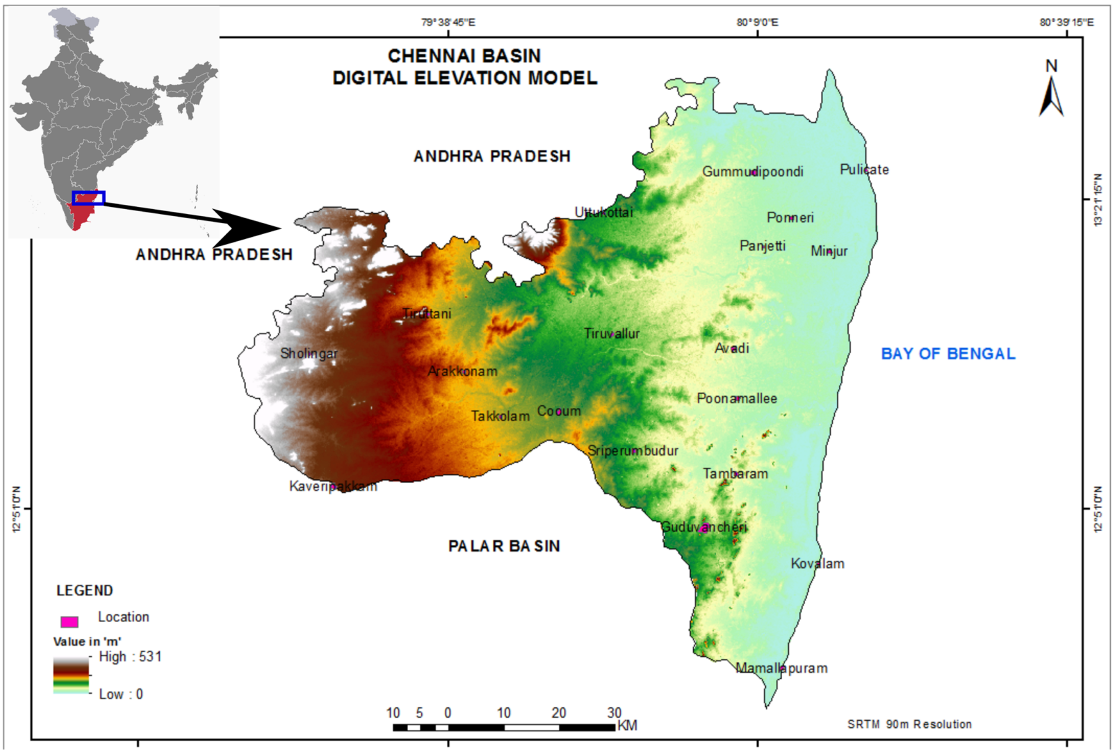

Figure 2.1: Location of Chennai River Basin in India and Digital Elevation Model (DEM) (source http:// earthexplorer.usgs.gov)

The highest temperature is recorded in Chennai in Summer season and the lowest in Tiruthani in Winter season. Considerable seasonal variation in sunshine is observed in the study area..

In the rainy season the sunshine hours are varied from 5.5 to 7 hours, whereas 8.5 to 9.1 hours/ day in the summer season. The longest sunshine hours/day are reported from Chennai region during the winter season. Relative humidity in the basin varies from 53 to 84% and the wind velocity varies from 5.69 to 14.15 km/hr.

Rainfall being an important source of water for the replenishment of the groundwater, analysis of rainfall can give vital information about the hydrological condition of the study area. The total annual rainfall of the basin is calculated from 50 years' rainfall observation data as 1156 mm/year. The important contributors are Southwest Monsson (431mm), Northeast Monsoon (616 mm), Winter (46mm) and Summer (75mm). The trends in rainfall also showed variation in according to the physiography of the regions, i.e., the average rainfall varies for hilly, plain and coastal regions as 965mm, 1140 mm and1272 mm, respectively.

2.3 Geomorphology and Geology

Geomorphology of an area represents the origin, structure, development of landforms and alteration by human beings. Geomorphology can also hint to the underlying futures and also the processes that controls the evolution of the land forms. A wide range of geomorphological features are available in the study area. The major formations are beaches, Beach Ridges, Beach terraces, Buried Pediments, Wash Plains, Salt Pans, Swamps, Swale, Deltaic Plains, Deep Pediment, Pediment and Shallow Pediment, Buried Course & Channels, Tertiary Uplands, Flood Plains, Piedmont, Inter Fluveo. The geomorphology map of the study area is shown in Figure 2.2.

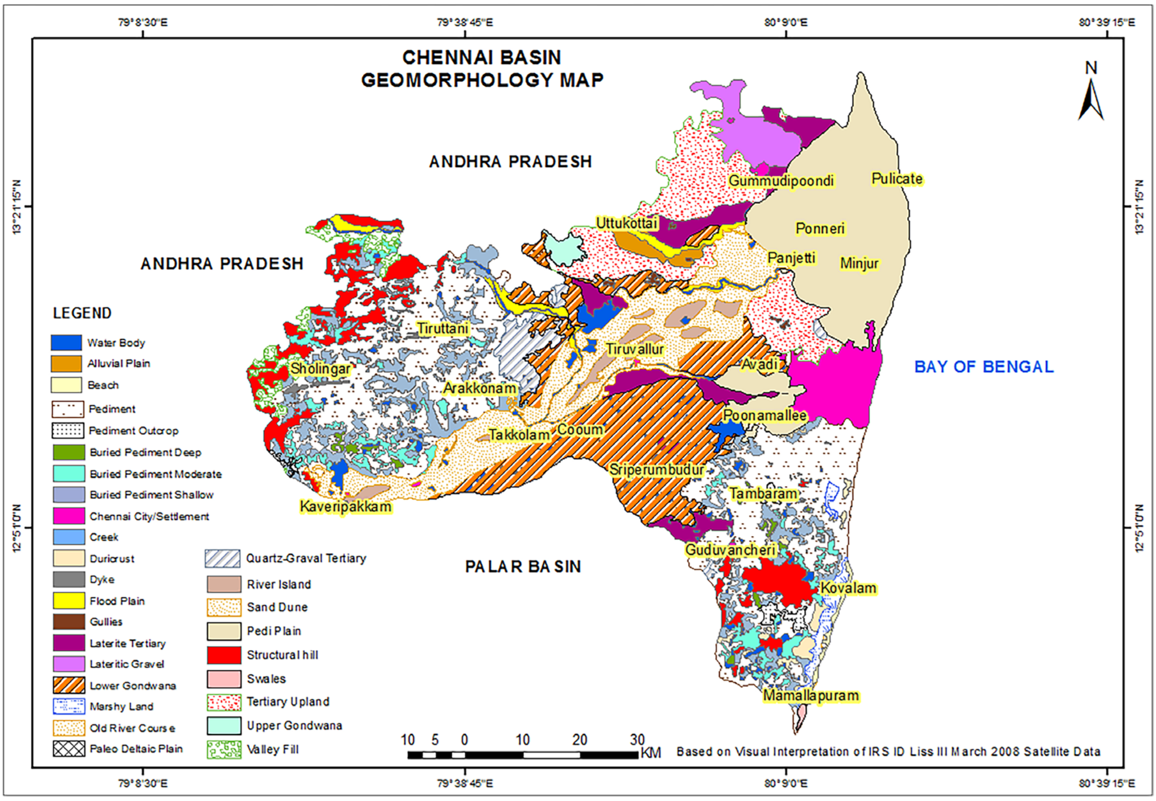

Figure 2.2: Geomorphological map of Chennai River Basin (modified from Survey of India Toposheets)

Beaches of the basin are long and formed by unconsolidated sandy materials with great amount of porosity and acting as an important medium for groundwater recharge. Beach ridges are the elevated sandy regions with an elevation of 27 meters and fresh water coming upto surface in the post monsoon season, and can also found in upto 6 meters' depth in the pre-monsoon season. Buried Pediments are surfaces within soil cover bordering streams or rivers (Achyuthan and Thirunavukarasu 2009). water courses and water channels are found in the buried pediments adjoining Araniar. Salt pans are usually found near the Ennore creek in the study area, formed by channelizing the salt water from the see and also by pumping the brackish water from underground. Deltaic plains formed at the river mouth and they are huge spread of unconsolidated formations of variable grain size. They are heterogeneous, having high water holding capacities and also highly suitable for agricultural activities. Panjetty, Minjur and Ponneri regions in the basin are deltaic plains (CGWB 2008).

These are wide landforms occurring along the river combs and hydrological structures passing from the origin of the rivers to the mouth of the ocean. These plains covered by sediments deposited by the rivers have high water holding capacities. The sediments deposited by the rivers are forming unconsolidated deposits on the river banks, which are of heterogeneous nature and have great water holding capacity. Panjetty to Minjur and Ponneri regions are the major deltaic plains of the basin. Flood plains consisting of sand clay are found along the boundaries of Araniar and Kosathalayar rivers. The thickness of the alluvial sand varies from 1 to 7 m and also the flood plain itself is found spread over width varying from 0.25 to 5.0km from the riverbanks (CGWB 2017).

The basin's geology shows gneisses and Precambrian charnockite as the basement, overlaid by marine, estuarine and fluvial alluvium. Crystalline rocks are mainly granite, gneissic complex, schist's and chamockites, which are related to basic and ultra-basic intrusive (CGWB 2017). The charnockites form the major rock types and constitute the residual hills around Pallavaram, Tambaram and Vandalur. Among the sedimentary formations conglomerates, shale, and sandstone, and are covered by a thick cover of laterite. Tertiary Sandstone is seen in small patches in the area around Perambur, and around northwest of Chennai city and upto Satyavedu, and is capped by lateritic soil. The geological map of the study area is shown in Figure 2.3.

Alluvial formations are found in the shallow valleys of Araniyar, Kosathayar, Cooum and Adyar, rivers. Alluvial sediments showing variable thickens with inter-layered clays, silts, sand and gravel and pebble beds. Coastal strips are available in narrow strip with Aeolian dune and beach sands. The marine alluvium dominate the coastal region, stretching in the north from Ennore to Mahabalipuram in the South. The fluvial alluviums are predominant in the Araniar and Kosathalayar basins (A-K Basin). In Kosathalayar, the alluviums are intermixed with clay and sandy loam, observed in red color (Achyuthan and Thirunavukarasu 2009), and those of Araniyar is mostly pure sand.

At, Orangadam, CGWB has drilled an exploratory bore well till 288mbgl, and there was no aquifer zone up to 174mbgl. Randomly, granular zones were found between 175 and 280mbgl, but the yield was very low(60 lps). Alluviums of this area comprise mainly sandy and clay; in these major aquifer zones are sandy alluvium. In the other parts of the basin, alluviums can be found between 9-15mbgl and 20- 47mbgl. The hydrogeological framework of the Chennai basin largely depended on the amount and distribution of rainfall, geology and the groundwater movement through the primary and secondary pores. A conceptual geological cross-section of an area is shown in Figure 2.4

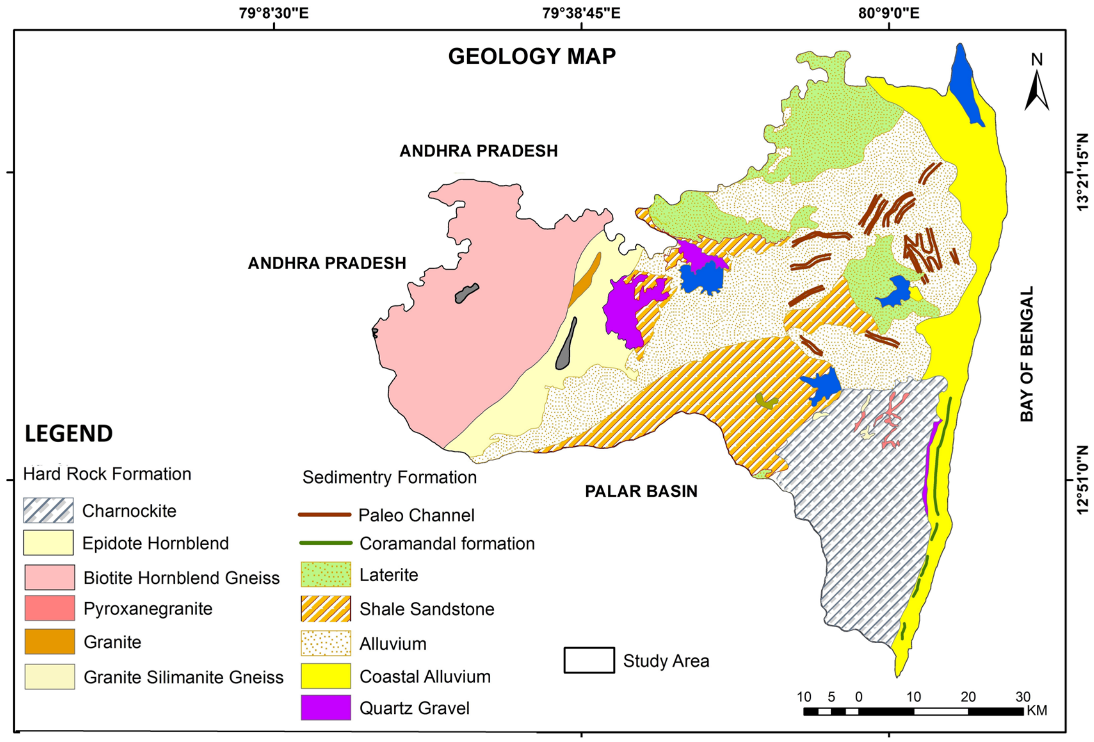

Figure 2.3: Geological map of Chennai River Basin (modified from Survey of India Toposheets)

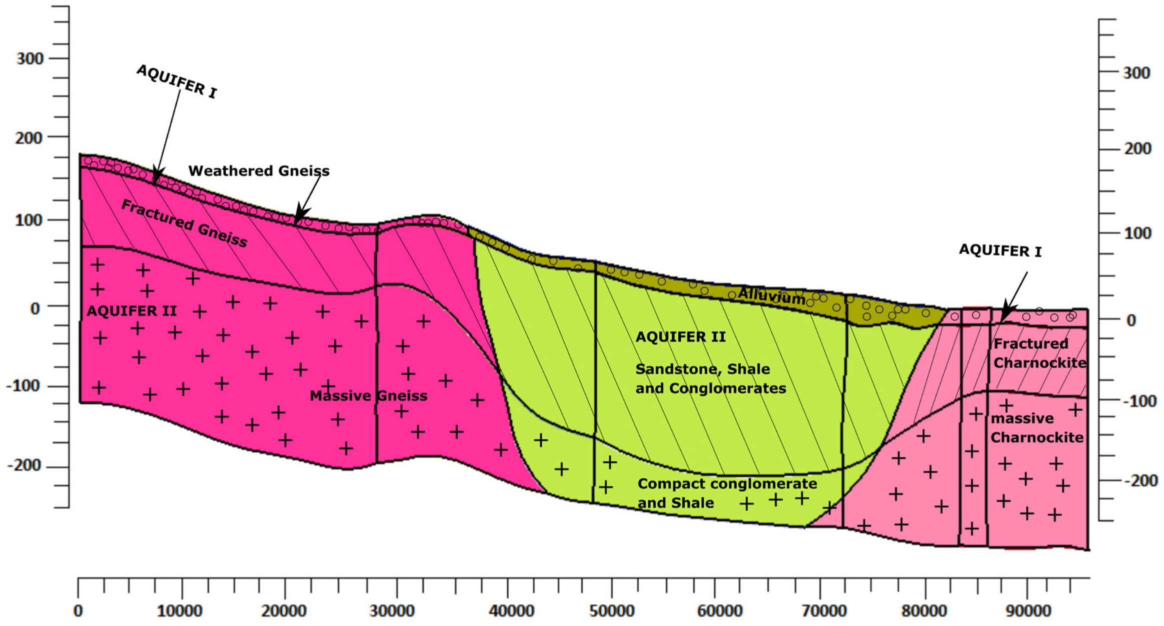

Figure 2.4: The geological cross section of Chennai (Modified from CGWB 2017)

2.4 Soils

Soils plays an important role in the hydrology of a region. The classification of soils in an area is done mainly by considering their colour, texture, fertilities and Chemical-mineralogicala spects. In the Chennai basin four different types of Soils were observed (i) Entisols, (ii) Inceptisols, (iii) Vertisols and (iv) Alfisols (CGWB 2017). A detailed soil map of the study area is shown in Figure 2.5.

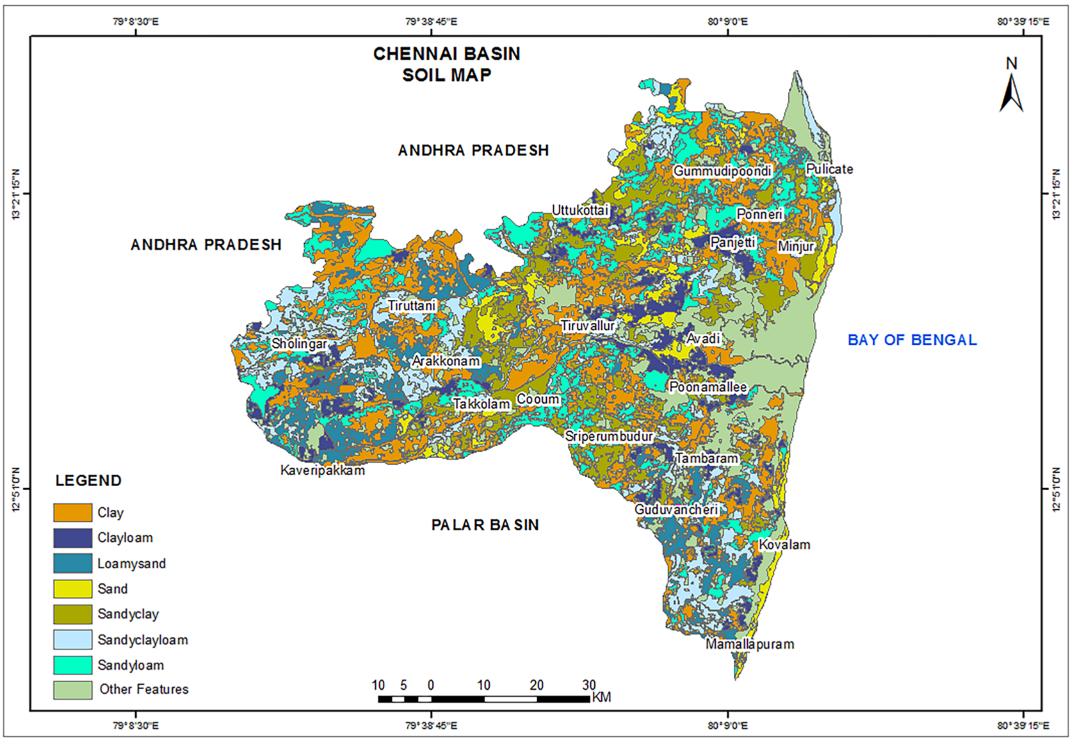

Figure 2.5: Soil Map of the Chennai River Basin (modified from Survey of India Toposheets)

Entisols are alluvial soils comprising sand and sandy materials occurring on the beaches and at the confluence of rivers and by the side of the rivers & channels (Raghunath et al., 2015).Because of their permeability, the sesoils are good storage spaces of groundwater, but groundwater not fit for cultivation.These are found along coastal belt in small strips, eastern part of Ponneri Taluk, south of Pulicat Lake to Ennore Creek, south of Coovum confluence to Adyar Estuary and Thiruvanmiyur-Covelong stretch, throughout the length of beach of the Eastern Coast.

Inceptisols consist of red sandy to brownish clayey soil fragments derived from parent rock and are spread all along the westward side of the east coast road. The inceptisols are suitable for agriculture and hold moderate groundwater reserves (Raghunath et. al., 2015. Systematic water-bearing rocks border this type and percolate more water into these soil formations for agricultural development. Intensive agriculture is practiced in these soil.

The Vertisols comprise mainly clay and thus have high specific water retention capacity but not suitable for agriculture (Dudal 1965). These are found as ground-mass in the extreme northern parts such as Gummidipoondi, Ponneri, Minjur, Madhavaram, and Manali and Thiruporur in the west. Hydrogeologically Vertisols are grouped under Aquitard and tertiary age. The water-bearing capacity is null, and the yielding nature is void. The rate of infiltration varies from 1 to 3cm/hr for fine red sandy, clay, clayey and, sandy clay, sand fine to medium, and medium to coarse and very coarse and gravel and weather drock, fractured and jointed rocks, it varies from 0.2 to 0.5cm/hr.

Alfisols may be a special type of soil, which contains a peculiar colour shade differing from one area to other (Palaniappan et al., 2009). These red sandy and red loamy soils, deep to very deep, coarse loamy to fine loamy are found along the seashore. Due to indiscriminate withdrawal of groundwater seawater incursion occurred. Because of this the soil has been affected in about 10,000ha in Gummidipoondi and Ponneri Taluks. Alfisols, though not suitable for intensive cultivation, can support moderate cultivation, particularly the raising of dry crops. The groundwater reserve potential of these soils is moderate.

2.5 Hydrogeology

Existence and dynamics of the groundwater is largely controlled by geological formations and the structures. In Chennai Basin the major aquifer zones are marked by river alluvium and Tertiary formations of AK basin. The top layer is often comprising of sand with clay loams with a varying thickness(60-70m) below ground level, followed by thick sands, clays and friable medium to coarse grained Tertiary sandstone encountered between 70 and 172m. A thick Gondwana Siltstone/claystone/ yellowish or black clay or grit as a contact zone is observed below 185m. Groundwater recharge in the basin is mainly by the rainwater and Rivers. Three different and interdependent aquifers such as phereotic/leaky, non-leaky and semi confined of three-tier aquifer system. The thickness of these three aquifer zones varies from ground level to 60-80m (Top Aquifer-Minjur Aquifer), 60 to 140/170m (Middle level Aquifer- Panjetty Aquifer) and 120 to 180/200m (Bottom Aquifer–Tamaraipakkam/Kannigaipair/Poondi)(Meijer 2012). In many places the differentiation of these three-aquifer systems is not possible, as the fall in groundwater level below 70-90m, resulting in a single unconfined aquifer system. Minjur aquifer is almost dry and over extraction resulted in saline water intrusion upto 13km inland (CGWB 2017).

The top part of the Minjur aquifer is dry, with no base flow, while the other parts are semi-productive. Continuous extraction of groundwater resulted in an uneven lowering of water levels in dug wells and bore wells and subsequent seawater intrusion up to 13 km from the coast. These shallow aquifer zones were encountered between 10 to 20m in the north, northeastern, eastern and south-eastern regions, especially near the riverbed and its environment.

The alluviums have more recharge capacity when compared with sandstone or crystalline rocks. So, alluviums form very good groundwater-bearing zones. The Groundwater potential of different good fields is as follows; 7.5 mgd(Minjur), 9.0 mgd (Panjetty) and 13.3 mgd (Tamaraipakkam). The total calculated potential was 29.8 mgd. However, the UNDP has recommended extracting only 27.5 mgd from these three aquifer zones (CGWB 2017).

The water extraction structures in the study area are mainly bore wells and dug wells. A total of 68 Bore wells by the Metro water agency, and there is a daily extraction of 20 to 22 mgd. These are deep bore wells with depths between 30 and 120 mbgl, yielding 100 to 2,000 litres per minute. Several private wells also operate for drinking and irrigation (Venkatachalam 2015). As the water level deepened, several wells were not in operation. The number of bore wells drilled by different agencies is as follows; UNDP(96wells), Groundwater Cell Division, PWD Chennai (28 wells), TWAD Board (35wells), CMWSSB(76wells), groundwater division Chennai (484 wells), ETO, CGWB, BTAO and other agencies altogether 11 wells. In total, 0.32 million wells are available in the study area and which 0.15million wells are abandoned. Due to the constructed buildings, roads and concrete pavements, rainfall infiltration is practically absent in the urban areas. This is one of the fundamental reasons for the water level lowering even after getting enough rainfall. Most regions never retain their original position. A decline in groundwater levels, from 0.6 to 2.5m, is reported yearly and much worse in the Gondwana region. Groundwater extraction in the city region is mainly for drinking, whereas in AK Basin, it is meant for irrigation. The earlier hydrogeological investigation reported there is no aquifer zone below 300m. Thus, deepening wells for excess withdrawal is not successful in most cases.

CHAPTER 3

The state-of-the art estimation of groundwater recharge and water balance with a special emphasis on India: A critical review

3.1 Abstract

The calculation of groundwater recharge is essential for sustainable water management and water supply schemes. In this review, we analyzed groundwater recharge estimation techniques available in literature with reference to India. Major components of recharge, factors affecting groundwater recharge, aquifer systems of India and historical groundwater recharge estimation practices are reviewed. Currently used recharge estimation methods are assessed based on case studies. The most popular estimation methods are studied and compared with each other based on their application in various regions. We observed that the accuracy of the recharge estimates is largely influenced by false assumptions, the possibility of erroneous measurements, potential lack of reliable data and a variety of problems associated with parameter estimation. The suitability of different methods for a region is found to depend on time and space considerations, objective of the study, hydrogeological condition and availability of data. In Indian conditions, it is suggested to use water table fluctuation and water balance method for the recharge estimation, provided accurate water level measurements are assured.

3.2 Introduction

Increasing urbanization, industrialization and population growth is continuously increasing the demand for water on a global scale. Surface water was the easiest source for domestic and agricultural purposes for many generations. Preference has been given to groundwater in recent years mainly because of the pollution and scarcity of surface water due to failure in precipitation. Groundwater is readily available in nature and its occurrence within the premises of stakeholders has made it preferable over surface waters. In India, on a national level, groundwater serves 50–80% of domestic and 45–50% of all irrigation needs. India has faced high water shortages for the past few decades due to increased population, industrialization, climate change and unsustainable management of water resources. A considerable reduction in freshwater availability was reported from 5,177 m^3 in 1951 to 1,820 m^3 in 2001, with a further reduction to 1,545 m^3 in 2011 (Ministry of Water Resources). A central groundwater authority was founded in 1986 to suggest preparatory measures for regulating uncontrolled exploitation of groundwater (CGWB 2009).

Important factors in controlling the sustainability and stability of any system is an equilibrium between inflow and outflow. In the case of groundwater, this generally comprises of three factors, inflow, outflow and change in the storage of groundwater. Water balance is an important factor that determines the efficiency and recurrence of groundwater systems. The replenishment of groundwater in nature is maintained by the process of recharging. The downward movement of water from various sources to the subsurface and ultimately reaching the water table is called groundwater recharge.

Groundwater recharge is variable because of natural factors such as climate, land cover, geology, morphology, rainfall timing and intensity, soil type and vegetation (De Vries and Simmers 2002; Ruiz et al., 2010). Additionally, manmade modification of topography, land use and land cover, etc., also affect recharge. The major sources of recharge are infiltration of rainfall, recharge along watercourses, by lakes, irrigation return flow and seepage through subsurface flow by natural hydraulic gradient (Israil et al., 2006). The timely availability and distribution of source water plays a vital role in the total groundwater recharge. In India, precipitation is the leading source of water for recharge. Thus, analyzing rainfall patterns, frequency, number of rainy days, and maximum rainfall in a day and its variation in space and time are the important factors influencing the recharge. Surface water bodies such as rivers, lakes, canal seepage, surface, groundwater irrigation (Allison et al., 1994) and snow melting in the Himalayas also contribute to groundwater recharge. Different lithology has different recharge characteristics. Sedimentary formations such as sand, gravels and fractures in hard rocks, fault zones, karst topography and absence of barriers such as impervious formations etc., are of great importance. Recharge under different land use areas i.e., forest, grassland, cropland, urban land with concrete pavements etc., also varies considerably (Yun et al., 2011). Climatic factors such as change in precipitation, evapotranspiration, and decrease in soil moisture with increasing temperature are also affecting the recharge rates. In India, the spatial variation in rainfall distribution is extremely high and varies from 11,000 mm/yr. at Cheerapunji near Shillong to 200 mm/yr in parts of Rajasthan (Rangarajan and Athavale 2000).

India is the largest user of groundwater in the world at 230 km^3 (World Bank 2012). The contribution of groundwater to drinking and irrigation purposes is 85% and 60%, respectively. In India, 85-90% of the rural and 48% of the urban populations depend on groundwater for their drinking water supply (World Bank 2010; Narain 2012; Mihir Sha 2016). According to the Ministry of Agriculture (2013) nearly 70% of irrigation is dependent on groundwater. The water supply and sanitation program of the Government of India covers only 74% of households and those remaining have no access to these facilities (Plan International; Undmale et al., 2016). Considering this situation in India, there must be adequate management of water resources and it is essential to implement measures to increase groundwater recharge. Such efforts have been made by many researchers and by governmental agencies. The most important step was made in 1972 by the Government of India's Ministry of Agriculture by recommending guidelines for groundwater evaluation. A definite scientific norm was proposed by the "Groundwater Estimation Committee" (GEC) only in 1984. They recommended two methods such as groundwater level fluctuation (WLF) & specific yield method and rainfall infiltration factor (RIF) method for the groundwater resource assessment. The WLF method is suggested for the monsoon season and in case of lack of data on the water level, rainfall infiltration factor norms can be used. The major advances of these methods are that they are simple, with easy access of the data from the corresponding departments, as the WLF method is based on a widely-accepted principle of groundwater balance. Additionally, rainfall infiltration method is suggested in case of the absence of reliable data. Several limitations also reported, as it is recommended to use a block as unit of measurement and other than this no specific unit is suggested. This unit is unable to represent the spatial variability within the groups, other than a block level is suggested, which is unable to reasoning the. Seasonal variability in the recharges and baseflow is not accounted for in the norms. A few refinements can be made by considering these limitations, and improvements were suggested as when watershed is considered as an assessment unit with due consideration of the geomorphological and hydrogeological conditions. Also, seasonal assessment of the recharge and a different specific yield estimation is suggested for hard rock and alluvial areas.

In this chapter, we critically review current recharge measurement practices in India and suggest the appropriate method for recharge estimation in different topographic and climatic regions of the country.

3.3 Review of commonly used groundwater recharge estimation techniques

Groundwater recharge estimation techniques can be generally classified into physical methods, chemical methods and numerical methods. All these models are theoretically significant but failed or proved to be incorrect because of problems with accuracy or difficulties in implementation.

3.3.1 Physical methods

Physical methods are the most straight forward and most common measure of recharge by precipitation. These methods are popular because they give direct results, easy to measure and they can be performed without much expense (Scanlon 2002). The influence of topography, soil characteristics and climatic conditions are higher in these methods. Aquifer media of the region play an important role in determining the actual and potential recharge (Scanlon 2002). The most important physical methods used in the field are presented in the following sections.

3.3.1.1 Zero flux plane (ZFP) method

A zero-flux plane (ZFP) is the plane that distinguish the upward movement of water for evaporation and the downward movement to the water table and subsequent drainage to completely wetted deep soil (Khalil et al., 2003; Krishnaswamy et al., 2013). This condition exists when evaporation surpasses rainfall. A simultaneous downward drainage and upward movement then occurs. Tensiometers can be used to fix the region of Zero hydraulic gradient. The volume for water passing through a unit area per unit time is the flux (q), which can be obtained by Darcys Law,

$$q = -K(\theta)\delta H/\delta z \tag{3.1}$$

Where, K(θ)= Unsaturated hydraulic conductivity, H= Total water potential h(θ)-z, h= matric potential (negative), z = depth below the surface, θ= water content.

Common problems face the determination of K, which may vary from place to place. ZFP method is limited to regions where FP exists and the water table is deeper than the ZFP (USGS).

3.3.1.2 Soil water balance method

The basic concept of the soil water balance method is the calculation of the balance between inflow and outflow and the water required for soil to become saturated and is expressed as depth of water. This method was initially developed by Thornthwaite (1948) and modified by many researchers. This can be expressed as,

$$Ri = P - E_a + \Delta W - R_o \tag{3.2}$$

Where, R_i = Recharge, P = Precipitation, E_a = Actual Evapotranspiration, ΔW= Change in soil water storage, R_o = Runoff.

The practical significance of this method is largely influenced by the change in soil water storage, which is never a direct measurement. In the case of large areas, different values must be given to all input parameters as per the ground conditions. As these parameters are measured in the field, a great amount of uncertainty and inaccuracy is often encountered. Additionally, a big set of data is needed to perform these calculations.

3.3.1.3 Groundwater level fluctuation method

Groundwater level fluctuation method is an indirect recharge measurement technique, which is widely used for the recharge measurement of unconfined aquifers where groundwater fluctuation occurs seasonally. It is based on the concept that a rise in the water table is directly proportional to the amount of water that recharges to the groundwater table (Scanlon 2002). The general expression for recharge can be written as,

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \qquad (3.3)$$

Where, S_y= specific yield, h= hydraulic head, and t = time.

This method assumes subsurface inflow and outflow that is uniformly distributed over the area. The best suitable application sites for this method are shallow water table regions with sharp rise and decline in water levels, especially within short time periods (hours or a few days; Scanlon 2002; Healy and Cook 2002).

3.3.1.4 Groundwater balance method

Groundwater balance estimation remains one of the straightest forward methods used in understanding groundwater recharge. Water budget is one of the essential parts of any conceptual model (Nimmo et al., 2005). The three basic components that must be accounted for in this method are inflow, outflow and change in storage. A good recharge estimate must also consider all the water that could not recharge the aquifer (Lerner et al., 1990; Nimmo et al., 2005)

A general expression for the groundwater balance equation is as follows,

$$\Delta S = (P+G_{in}) - (Q+ET+G_{out}) \qquad (3.4)$$

Where P = precipitation, G_{in} = groundwater inflow, Q = discharge, ET = evapotranspiration, G_{out} = groundwater outflow and ΔS = change is storage.

In case of a normal unconfined aquifer, the major factors that contribute to the inflow and outflow components are recharges from rain, canals, irrigation, tanks, influent recharges from rivers inflow from other basins, draft from groundwater, effluent recharge to rivers and outflow to other basins etc.

3.3.2 Tracer Techniques

Tracer techniques can estimate groundwater recharge without measuring water fluctuations. This method is now widely used in groundwater recharge estimation studies. Several researchers have made useful contributions to the development of this method (Zimmermann et al., 1966, 1967; Dincer et al., 1974; Athavale et al., 1980; Wood and Sanford, 1995; all; Rangarajan and Athavale, 2000; Chand et al., 2004). This method has been preference over the other methods because the entire process is short term and collecting the data is very easy. Tracers can be classified as historical tracers, environmental tracers and applied tracers (Edson 1998; Wang et al., 2008).

A historical tracer can be defined as a tracer that has a very high concentration in the environment resulting from mostly anthropogenic inputs like nuclear testing, industrial or agricultural contaminant spills. Tracking the movement of this tracer will give significant information on recharge. Some of the common tracers- bromide, nitrate, atrazine, and arsenic- are commonly derived from anthropogenic inputs (Wang et al., 2008).

Environmental traces are already available in nature by atmospheric deposition. Chloride is one important tracer in this category. Estimation is based on mass balance studies based on its accumulation and spatial pattern. Application of this method can be found in both unconfined and confined aquifers.

Applied or artificial tracers are those tracers used in recharge estimation, by enhancing their background concentration in nature. Important tracers in this category are chromium EDTA sodium iodide ammonium bromide, uranine sodium chloride, ammonium chloride, sodium iodide etc. All the tracers assume that its movement will be directly proportional to the movement of water.

Among these, the most used tracer techniques are the chloride method, the tritium method and the stable isotope method.

3.3.2.1 Chloride Method

Chloride is one of the best environmental tracers that satisfy most of the requirements of an ideal tracer i.e., low cost, and the conservative nature that allows for the preservation of atmospheric inputs. There is no such process in the subsurface that can alter the concentration by interacting either with aquifer media or with vegetation (Edmundus and Gaye 1994). For a region, recharge can be estimated by the following method,

$$R = P(C_p + C_d)/C_{si} \tag{3.5}$$

In this equation, P= mean annual precipitation, C_p= weighted mean concentration of chloride in rainfall, C_d= the amount of chloride in the dry deposition and C_{si}= average concentration of chloride over interval chloride over interval "i" in interstitial water in the unsaturated zone (as described in Allison and Hughes, 1978; Edmunds et al., 1988; Edmundus and Gaye 1994).

Though this method has lots of merits, there is a drawback in the ambiguity in determining the chloride concentration in quantifying the wet and dry deposition. Extreme rainfall events also may affect the concentration when calculating based on the mean annual rainfall.

3.3.2.2 Tritium method

Tritium is used for the estimation of groundwater age and so as the recharge rates. Atomic bomb tests in the 1960s are largely responsible for t concentrations of tritium in the atmosphere elevated above the normal level (UNEP report). Production of tritium by the action of cosmic rays on the nitrogen atoms o the air helps in maintaining its current level (Vogel et al., 1974). Tritium is chosen as a tracer because of its shorter half-life period, compared to the other radioactive tracers. However, there are disadvantages such as the neoconservative nature of tritium, which results in loss by evapotranspiration, thus a mass balance study is not possible, contamination during the sample collection and processing is a problem, and the whole process is costly and needs especially skilled people to conduct the studies.

3.3.2.3 Stable isotopes

Oxygen-18 (^{18}O) and deuterium (^{2}H) are conservative isotopes that can be used for groundwater recharge estimation and can give. valuable inference to processes such as evaporation, transpiration, infiltration etc. This method uses the differences in the isotopic concentrations in groundwater and precipitation by a mass balance approach (Yeh et al., 2009, Shahul Hameed et al., 2015). Isotopic concentration in precipitation varies considerably from hilly regions to coastal and temperate regions to cold regions.

3.3.3 Numerical model-based estimation methods

Numerical model approaches establish a numerical relationship between the basic components in the water budget method and give the recharge estimate as a residual term (Scanlon 2002). In any modeling approach for groundwater, hydraulic conductivity is the decisive factor. Recharge rates for an equal amount of precipitation vary considerably under different hydraulic conductivities. A combination of an unsaturated zone model with groundwater models can be effectively used to evaluate groundwater recharge (Chen et al., 2012; Hsieh et al., 2000; Lowry 2008). Integrated models can predict the recharges with a comparatively higher accuracy than simple groundwater models (Sophocleus 2002). Sanford (2002) reported that knowledge of the process that controls the recharge rate is essential for a successful recharge model. The climate, geological framework and topography are the three main factors that control the flow of water (Winter 2001; Sanford 2002). Based on aquifer characteristics, modeling methods are mainly classified as models based on (i) unsaturated zone and (ii) saturated Zone. Unsaturated zone modeling is very well described in many studies (Simunek et al., 1998, Scanlon et al., 2002; Chen et al., 2008). In saturated zone modeling, it is often recommended to use inverse modeling added by the numerical groundwater models (Knowling and Werner 2016). The basic concept behind this technique is the correlation between groundwater recharge and hydraulic conductivity, and the reliability of the latter is the decisive factor of an accurate estimation (Scanlon et al., 2002; Chen et al., 2012).

3.3.3.1 One-dimensional soil water flow method

One-dimensional soil water flow method can be used in the recharges estimation, if there is suitable models for the boundary conditions are provided (Simmers 1987). The general one-dimensional equation can be written as,

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left[k\left(\frac{\partial S}{\partial z}\right) + 1\right] - s \tag{3.6}$$

Where θ= volumetric water content (cm^3/cm^3); t= time (min); k= the unsaturated conductivity (cm/ min); S= soil moisture tension; z= depth (cm), s= sink term (1/min). The moisture retention (S) can be calculated from the following equation,

$$S = (\theta - \theta_r)/(\theta s - \theta_r) \tag{3.7}$$

Where θs= saturated water content and θr= residual water content.

The major advantage of this method is that there are possibilities for the study of areal variability of recharge in addition to the recharge processes and dynamics.

3.3.3.2 Inverse modeling

In the inverse model, the recharge rate is predicted from the hydraulic head, hydraulic conductivity etc., based on a two-dimensional finite element (or finite difference) groundwater model (Sacanlon et al., 2002; Sanford et al., 2002). In this method, the ratio of recharge with the hydraulic conductivity is estimated, thus the accuracy of the estimate depends on the hydraulic conductivity data. A nonlinear regression between a simulation and the measured values was evaluated, either by a trial and error method or by a direct approach which treats the parameter as dependent variables.

3.4 Groundwater scenario and aquifer systems in India

As mentioned in the introduction, India is one of the biggest users of groundwater, mainly for drinking, domestic and irrigational purposes. A drastic increase in groundwater extraction has been observed in the past five decades in India. Shah et al., (2007) reported that in this period groundwater use increased from 100 million m^3 (1950) to 1000m^3 (2000) due to development in the agricultural, infrastructure and industrial sectors. Developments in technology provided easy access of dug and bore wells to more people. It is evident from the increase in the number of wells from 3.86 to 4.75 million during a span of 40 years from 1950 to 1990 (Muralidharan and Athavale 1998; Sakthivadivel 2007). Introduction of deep borewells is becoming a serious threat to deep groundwater resources.

Hydrogeological settings in India can be generally classified as porous formation and fissured formations. Few karstified formations are observed in Cuddapah System, Vindhyan and Kurnool System, Raipur Indravati Series and in Kashmir valley (Singh et al., 2021). The hard-fissured formations include crystalline, trappean basalt and consolidated sedimentary rocks (CGWB 2014). In the central part of the country, alluvial formations are observed. Basically, the aquifers in India can be classified as alluvial aquifers, laterite aquifers, sandstone-shale aquifers, limestone aquifers, basalt aquifers and crystalline aquifers.

Alluvial aquifers are mainly comprised of recent alluvium, older alluvium and aeolian and coastal deposits. The composition of these sediments is principally sand, silt, clay, pebbles etc. These are the most important groundwater reserve and the most important example is Indo-Gangetic plain. Another important aquifer system is formed by the laterite, formed by the chemical weathering of parent rocks in the tropical regions. These aquifers are extensively developed aquifers, especially in the peninsular states of India (CGWB 2014). They are largely found along valleys and topographically low lying areas. Sandstone-Shale aquifers are developed in the Gondwana System and tertiary deposits along the east and west coast of peninsular India. Limestone aquifers are consolidated sedimentary rocks such as limestones, dolomite and marble. These aquifers have fracture zone and cavities by solution activities, that are acting as the water-bearing zones. Cuddapah and Vindhyan subgroups and their equivalents are one of the largest limestone and dolomite aquifers. Basaltic formations are usually observed in the decan trap area. These formations have alternate layers of compact and vesicular beds of lava flows. The water-bearing zones are the weathered and fractured zones. The permeability of these formations is medium and thus the groundwater occurrence is controlled by the nature and extent of their weathering, the presence of vesicles and lava tubes, the thickness, the number of flows and the nature of inter-trappean layers. Crystalline aquifers are mainly comprised of granite, gneisses and high grade metamorphic rocks. Groundwater occurrence and its distribution is controlled by the presence of weathered rocks and fractures, joints and bedding planes. In this formation groundwater is mostly in a semi-confined or confined state.

As mentioned in the introduction, in general, the aquifers of India can be classified based on extension and groundwater potential as unconsolidated, semi-consolidated and consolidated formations and hilly formations. Unconsolidated alluvial formations cover the Indo-Gangetic and Brahmaputra plains, coastal aquifers and desert regions of Rajasthan and Gujarat on the eastern and west coast of India with very high groundwater reserves. This region is mainly composed of the Indus-Ganges- Brahmaputra (IGB), considered as the most productive aquifer systems in India (Mukherjee et al., 2015). Semi- consolidated and consolidated formations with consolidated sedimentary formations, basalts and crystalline rocks found in the peninsular India. Groundwater is available at shallow depths. The volcanic aquifers (basalt) form mainly occurring in Deccan traps, with a large geographic extend of 500,000km^2. Mountainous aquifer systems are present in hilly states, which is always connected to springs and streams. Pore systems have lengthy interconnections and water travels longer distances (Kulkarni et.al., 2015). A map of aquifer systems in India is provided in Figure 3.1.

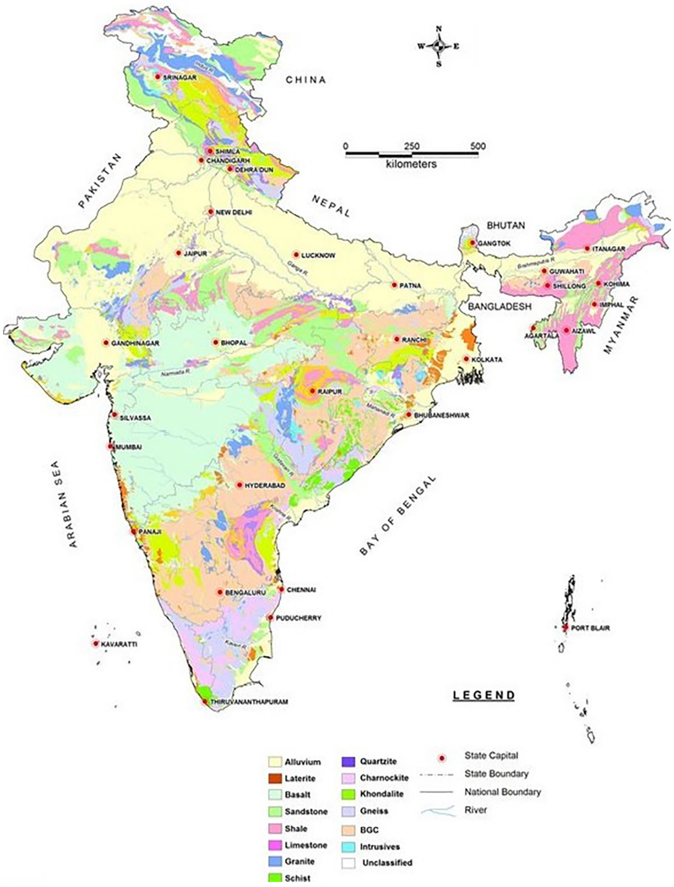

Figure 3.1: Map showing aquifer systems in India (adopted from CGWB 2012)

3.5 Historical background for groundwater recharge estimation in India

Surface water resource estimation using empirical methods started in India during the beginning of the 19th century. Though groundwater is a widely-used resource, it took a few more decades to start the scientific estimation of the groundwater resources. There is evidence for an empirical approach by Chaturvedi formula in 1936 is reported in Kumar and Seethapathi (2007), who estimated the recharge in Ganga-Yamuna doab using water level fluctuations and precipitation data. There was a modification suggested by the UP Irrigation Research Institute, Roorkee.

The original Chaturvedi method can be calculated using the following equation,

$$R = 2.0(P - 15)^{0.4} \tag{3.8}$$

The modified equation can be written as,

$$R = 1.35(P - 14)^{0.5} \tag{3.9}$$

Where R= net recharge due to precipitation during the year (in inches) and P= annual precipitation.

Later in 1949, Khoshla developed a method (a modified Vermeule's formula) for the estimation of surface water resources suitable for Indian conditions (Kumar and Seethpathi 1976).

$$L_m = (T_m - 32)/9.5 \tag{3.10}$$

This method is based on monthly evaporation loss in inches (L_m) and mean monthly temperature (T_m).

A guideline circulated in 1972 among the respective organizations with norms for groundwater estimation. Apart from these approaches, different departments started to estimate countries' groundwater resources; however, unavailability of scientific data and poor understanding of the recharge and discharge process has resulted in erroneous approximation (CGWB 2009). The first scientific approach was the one made by Groundwater Over Exploitation Committee in 1979. Later, in 1982, the Groundwater Estimation Committee (GEC) was formed with members from various governmental and educational institutions. Since its formation, this committee stands as a regulating authority for groundwater estimation in India. The formal guidelines for recharge estimation came into existence in 1984 (Kumar and Seethpathi 1976). Since then, this committee remains the authority making decisions on groundwater estimation in India.

Two methods were recommended by the GEC for recharge estimation, namely (i) groundwater level fluctuation and specific yield for those areas where routine groundwater level monitoring is done and for other regions (ii) rainfall infiltration method, which is recommended for those areas where water level monitoring is not/poorly done and there is a subsequent lack in accurate data. Of these, groundwater fluctuation and specific yield method have been explained in the earlier section.

In general, the monsoon fed India shows drastic changes in groundwater recharge due to precipitation. The Indian meteorological department suggested a formula to represent groundwater recharge during monsoon season,

$$\text{Monsoon recharge} = \left(S + DW - R_s - R_{igw} - R_{is}\right) \times \frac{Normal\ monsoon\ Rf}{Annual\ monsoon\ Rf} \times R_s + R_{is}$$

Where S= change in groundwater storage volume during pre- and post-monsoon period, DW= gross groundwater draft during monsoon (mcm), Rs= recharge as canal seepage in monsoon (mcm). R_{igw}= recharge from groundwater irrigation in monsoon, whereas Ris = recharge from recycled water from surface water irrigation and Rf = rainfall (meter).

3.6 Critical review of groundwater recharge estimation practices in India

As a versatile country with a wide range of environmental and hydro-geological settings, it is always a matter using multiple methods for the groundwater recharge estimation. In the large basins, local estimation and later extrapolating the results to the entire region is generally practiced, with more efficiency. As per the guidelines of the groundwater estimation committee (GEC), the official recharge estimation method of the country is water level fluctuation (WLF) and rainfall infiltration method. As per the reports, groundwater resources of the country are classified based on the exploitation rate into white, grey and black. Among the 7928 units in total, 425 are more than 85% were exploited, termed as the dark category, 673 units were termed as over exploited with an exploitation level of 65% to 85% coming under the grey category. Remaining units are classified as white. In this study, we would like to review most common recharge estimation methods and its efficiency extensively. A short review of the literature for the groundwater recharge estimation is given in Table 3.1.

Table 3.1: Review of the recharge estimation methods practiced in India

Reference Title (alphabetical)	Location	Area of Estimate	Methodology used	Inferences
Athavale et al., 1980	Lower Maner Basin, Andhra Pradesh	1575 km^2	Tritium injection	- Recharge varies with depth and soil types - Total annual input to groundwater was 152×10^6 -+ 15×10^6 m^3, i.e., 8% of total annual rainfall (125 cm) - Recharge value were comparable with those physical methods
Sukhija et al., 1988	Cuddalore Aquifers, Pondichery	6 50 km^2	Env. Chloride & Tritium Injection	- Recharge rates; for Cuddalore, as 26cm/yr and 22cm/yr; for alluvium 10cm/yr and 14cm/yr, estimated for tritium and chloride methods respectively. - Validity of the chloride method for semiarid tropical coastal successfully demonstrated
Srinivas et al., 1999	Kanchanapally watershed, Andhara Pradesh	11 km^2	Water Balance/ Groundwater flow model	- Average groundwater recharge was 86.7 mm/year for an avg. annual rainfall 759.6 mm. - Monthly recharge estimates found as useful for accounting dynamic temporal variations
Rao and Chakraborti 2000	3 blocks in Karim Nagar Dt. Andhra Pradesh	68 km^2	Semi Empirical water balance model/RS	- Net recharge estimated as 2.54 MMC, still water level falls 0.79 m. - Water logging contribute an increase in WL of 0.35m - Rotational operation of canal and aquifers are suggested
Ahmed and Umar 2008	Krishni–Yamuna Micro-watershed, Uttar Pradesh	434 km^2	Water balance & Tritium method	Total recharge in the basin is estimated as 185.25 MCM
Prasad and Rastogi 2001	Mahi Right Bank Canal project area	2997 km^2	Numerical/Inverse Model	- Net annual recharge estimates as 741.97 MCM - Supremacy of Genetic algorithm on Numerical modelling method, when using noisy data is proved.
Chand et al., 2004	Bairasagara watershed, Karnataka	111 km^2	Injected tritium tracer and Geo-electric methods	- Recharge is found to be proportional to depth to basement, degree of weathering, water level -Fluctuations and sand content. Natural Recharge found to be 0 to 200 mm
Chand et al., 2005	Hayat Nagar Micro-watershed	0.045 km^2	Neutron Moisture probe	- Simple, practical and less expensive method - Recharge due to water level rise is estimated as 0.22 to 0.37, with an average 0.30m, which is equivalent to 0.0135 MCM

Reference Title (alphabetical)	Location	Area of Estimate	Methodology used	Inferences
Sharda et al., 2006	Kheda, Gujarat	2.62 km^2	Water table fluctuation(WTF)/ chloride mass balance (CMB)	- Estimated groundwater recharge from rainfall by WTF is 7.3% (2003) and 9.7% (2004) whereas by CMB method was 7.5% (2 years' average value) - Showing the need of at least 104.3mm cumulative rainfall for making 1mm recharge by storage structures.
Saha and Agarwal 2006	Torla Odha watershed, Maharashtra	22.05 km^2	Water Balance/ Groundwater Budgeting	- Specific yield- an integral part of water balance- is calculated for the different geological formation - Values raged from 0.0019(May) to 0.0173(November) with an average of 0.0093.
Thomas et al., 2009	Sagar Block, Madhya Pradesh	847.47 km^2	Water Balance	- Rainfall recharge in monsoon season in the range of 122.45 and 183.71 MCM - Declining trends were found in the groundwater storage
Rangarajan et al., 2009	SIIL watershed, Tuticorin, Tamil Nadu	112 km^2	Tracer/Pumping test Methods	- Rainfall recharge is estimated on an average 61.7mm, i.e., 10.6% of the rainfall in the study period - Specific yields for different formations were measured, water level fluctuations were correlated with the recharges estimates
Singhal et al., 2010	Pathri Rao watershed, Uttarakhand	52 km^2	Geo-electrical /Isotope	- Groundwater recharge vs development were in the order of 19% vs 164% - Critical over-exploitation of groundwater is reported.
Ajay Singh 2011	Haryana India	44,212 km^2	Hydrological Budget model	- Irrigation is the major factor for groundwater recharge with 49% - Average annual increase in the water level is 0.14m, creating water logging - Suggested solutions were 10% reduction in rice area along with 2% increase in pumping volume and 20% canal lining.
Rawat et al., 2012	Shankergarh block of Allahabad	km^2	Water Balance/ Empherical formula/RS-GIS	- Groundwater recharge is 393mm/year, mostly in rainy season - Runoff (880.35) is two time or more than the actual recharge value

3.7 Selection of suitable recharge estimation methods

Estimation of recharge with any method is subject to a high amount of uncertainty and error. Choosing a suitable method is often dependent on the objective of the study, whether to monitor paleo-recharge, long term average recharge values, annual or monthly recharge estimates, area of estimation (aquifer/ watershed/basin level) or spatial variation of recharge (Healy 2010). The chosen method of recharge must address the complexity of geological formations, flow process, erratic nature of precipitation, conversion rate of total input water to effective recharge, improvement of estimation practices and the accuracy of data. The major classification of suitable methods can be made based on climate, recharge rate and area of estimation, aquifer parameters and hydrogeological settings.

Climate is important to choose the proper methodology for a given area. The methods used in semi- arid/arid regions would not be effective in humid regions. For example, in arid regions the observation wells monitoring the water table will typically be of less frequency. Lack of data will force to do the interpolation and this often causes errors (Mc Millan et al., 2018). In India, monsoon plays a significant role in groundwater recharge. The variation of the water table in pre- and post-monsoon seasons gives the opportunity to use the water table fluctuation method for the estimation (CGWB 2009). In the unsaturated aquifers, other than the water table fluctuation method, lysimeters, zero-flux plane was suggested. Tracers, age dating and numerical modeling will be suitable for both saturated and unsaturated zones (Gvirtzman et al., 1986; Delin et al., 2000; Scanlon et al., 2002).

Space and time considerations are important and have a major impact on choosing appropriate recharge estimates (Healy 2010). Spatially the estimates can be point/local estimates or regional estimates. Point estimates are more accurate but often unable to represent the characteristics of the whole basin. On the other hand, regional estimates can represent a large geographical area, but may give a generalized estimation (Delin et al., 2007). Chand et al., (2005) successfully used a neutron moisture probe in a micro-watershed to estimate groundwater recharge. Numerical model-based estimates are effective in representing large geographical areas. However, it is suggested that the consistency of the model parameters must be examined (Scanlon et al., 2002). Watershed modeling was also suggested as a suitable method for large areas. In case of a time constraint, it is always advisable for a short-term estimation to go with tracer techniques because for this method a single sampling is enough and can provide an average recharge estimate over several years (Healy 2010).

The limited access of climatic data is usually a problem in the estimation of recharge. Either the data will not be available throughout the application site because of a lack of a monitoring station or because of other errors associated with monitoring. The other issue is that the scientific monitoring of the climatic variable is stated in the beginning of the 19th century, so no prior date is available for the monitoring of historical recharge. Spatial variation of the recharge is important in case of groundwater vulnerability studies (Delin et al., 2000; Scanlon et al., 2002). Physical methods such as water table fluctuation need a high data density. Fore long-term variation analysis, it is suggested to use isotopic techniques.

Availability of resources is a major concern in choosing the methods. Financial constraints will be another issue that prevent researchers from using sophisticated methods. For example, isotopic tracers are useful in many cases, but the analytical procedure involved in this method needs modern laboratory facilities and a big budget. On the other hand, the cost of an estimation is not an indication of the accuracy of the method. Unavailability of the data is another problem often encountered in hydrologic analysis. Unavailability may lead to the use of data of different spatial and temporal scales (Delin et al., 2007).

For India, it is recommended to estimate the recharge seasonally in pre- and post-monsoon seasons. The water balance approach is found to be a very effective method in establishing the rainfall recharge coefficient and for evaluating the methods adopted for the quantification of discharge and recharge from other sources (Kumar and Seethapathi 2007). In semi-arid regions with certain conditions and assumptions, chloride mass balance has been found to supplement sensible estimates of groundwater recharge which are potentially comparable to other classical physical measurement techniques (Wood and Sanford 1995; Sharda 2006). The water table fluctuation method is the most widely used and recommended method for Indian conditions, because of the straightforward estimation and comparatively lower parameter and data needed. An important delimiting factor is the difficulty in determining a representative value of storability (S) for the entire study area. However, the major drawback is that there is no consideration of lateral flow, which is assumed as zero.

As all methods have their own limitations, the best possible solution is to choose multiple methods (Scanlon et al., 2002; Nimmo et al., 2005). Use of multiple methods helps to understand the measurement errors and problems which arise in the assumptions and thus permit the revision of the conceptual model. The best part is that many methods use similar data sets to derive the recharge estimate, thus, the use of different methods can occur without additional data collection. There are several examples available in the literature that benefited from using multiple methods. Delin et al., (2007) used four different techniques (1) unsaturated-zone water balance (UZWB), which utilizes soil-moisture data, (2) water-table fluctuations (WTF), (3) age dating of water in the saturated zone and (4) RORA, a basin-scale analysis of streamflow records using a recession-curve-displacement technique to quantify the regional scale estimation of the recharge in Minnesota, USA. Multiple method approaches are also reported in India as well. Ebrahimi et al., (2015) used inverse modeling coupled with remote sensing to study the groundwater recharge in Mosian aquifer in the west of Iran. In India, multiple method estimation was reported by several researches; surface resistivity method and isotope technique (Israel et al., 2006) were used to estimate recharge in the Himalayas. In another study water table fluctuation, chloride mass balance and storage balance were used by Sarda et al., (2006) and many more studies of this kind is reported. Based on the literature and the hydrological-climatic conditions, suitable methods for different regions of India are presented in Table 3.2.

Table 3.2: Suitable estimation method for groundwater recharge in India

Hydrologic zone	**Appropriate Techniques for different climates**		
	Arid/Semi-arid	Tropical/sub-tropical	Humid/Mountainous
Unsaturated zone	Zero-flux plane, Historical and environmental tracers, Numerical modelling	Water Table Fluctuation (WTF), Zero-flux plane, Soil water Balance model	Isotropic tracers, Darcy law, Lysimeters
Saturated zone	Historical and environmental tracers, Numerical modelling	Isotopic tracers, Numerical modeling	Water Table Fluctuation (WTF), Numerical modeling, Darcy law

3.8 Conclusions

Groundwater recharge estimation is important in regions like India, where the water supply is largely dependent on it. Groundwater resources in India are highly exploited and vulnerable to pollution. This review, evaluated aquifer systems in India and the key factors that affect groundwater recharge. Aquifer systems in India are mostly comprised of alluvial systems and crystalline rocks. Generally, choosing the most suitable method for the estimation is based on many factors such as the objective of the study, whether to monitor long term or short term, space constraints, climatic conditions, availability of reliable data etc. If the study needs to address large areas, numerical modeling or watershed modeling is suggested. In unconfined aquifers, water table fluctuation methods and water balance methods are found to be effective. Tracer techniques have application in both saturated and unsaturated formations. Climate based databases have been recorded only for the last 100 years. Thus, for a longer period of estimation, data will not be available. In this case, physical methods will not be effective. Recharge estimate in India started at the beginning of the 19th century and has a long tradition in this field. The Groundwater Estimation Committee (GEC) of the Indian government suggested water table fluctuation as the most suitable method.

Because of the monsoons, this method gives a cost effective and reliable result, under the condition that rainwater is the only source. Application of both point estimation methods and regional estimation methods were found in literature for India. We suggested suitable recharge estimate techniques for India based on hydrologic and climatic conditions. Use of multiple methods for the same area is suggested to evaluate the accuracy of the methods as well as to provide an opportunity to compare and the results and reach a conclusion.

CHAPTER 4

Hydro-morphometric and Hypsometric Analysis of Chennai River Basin Using GIS and Remote Sensing Methods

4.1 Abstract

Topographic analysis of a river basin provides vital information regarding the dynamics of water resources for the formulation of an effective water management plan. The Chennai River Basin is one of most important basins in southern India because it provides most of the water supply for the Chennai Metropolitan Area (CMA). In this study the morphometric and hypsometric properties of Chennai river basin were quantified using Geographical Information Systems (GIS). The Morphometric parameters were derived from Shuttle Radar Topographic Mission (SRTM) and Digital Elevation Model (DEM) data. The whole basin has an area of 6119 km^2, which is then classified into 11 sub-basins and the major linear, areal and relief aspects were calculated and discussed based on their hydrologic significance. Furthermore, hypsometric analysis was also performed and the hypsometric curve integral for the sub-basins were calculated. Hypsometric curves show the concave type for most of the sub-basins, indicating an old stage. However, basins 1, 6 & 7 showed nearly S - shaped curves, indicating the mature state of the basin. Hypsometric integral (HI) was then calculated and were found to be in agreement with the curves, with sub-basins 1, 6 & 7 having HI values greater than 0.30 (mature stage), whereas the rest of them were below this value confirming old (monadnock) stages.

4.2 Introduction

As the surface water – groundwater continuously interacting with each other, a thorough knowledge of hydrology and hydrogeology is necessary to study the dynamics. Groundwater resources are always influenced by the geographical, geomorphological and hydrological aspects of drainage basins (Magesh et al., 2011). Thus topographic and morphometric analysis of the river basin forms the backbone of investigations pertaining to the groundwater potential and recharge estimations.

The conflict between the demand and the supply is always a crucial issue in these regions. Thus, sustainable water management plays a key role. In India, watershed is considered the basic development unit of water resources projects (Aher et al., 2014), because most of the hydrologic and geomorphic phenomena occurs within the watershed (Singh 1992; Reddy et al., 2009). Understanding the topography of the drainage basins or the watershed then becomes an integral part of water resources studies. Many researchers reported the correlation between physiographic characteristics of drainage basins including liner, areal and relief aspects to various hydrological processes. A clear understanding of the morphometric parameters at the basin level is necessary to study the groundwater recharge mechanisms and water balance estimations (Sreedevi et al., 2013). At this point, we can see the importance of watershed mappings, which is getting recognition in the national level in India (Gopinath et al., 2014).

In recent decades, the topography of drainage basins can be studied by morphometric analysis using advanced techniques such as remote sensing and GIS technologies. Morphometry can generally be explained as the measurement and analysis of the mathematical configuration of earth's surface, the shape and dimensions of its landforms (Agarwal 1998; Reddy et al., 2002; Altaf et al., 2013), which can provide significant information about the formation and development of a drainage system. Another important parameter of the terrain is hypsometry, which can be defined as the distribution of the elevation data of an area of land surface, which is affected by lithological irregularities or tectonics (Singh 2008). Early application of hypsometric analysis was used to differentiate between erosional land forms during different stage of evolution (Strahler 1952; Schumm 1956).

Many researchers used GIS and remote sensing technologies for analyzing the morphometry of watershed and drainage basins (Mesa 2006; Cenetemore et al., 1996; Rekha et al., 2011; Yanina and Angillieri 2008; Kaliraj et al., 2014; Biswas et al., 1999; Mesa et al., 2006 and many more). Due to the large variation in the drainage properties of the Indian subcontinent, many studies have been aimed in this direction (Chopara et al., 2005; Vijith and Sathesh 2006; Thomas et al., 2012; Javed et al., 2009; Subyani et al., 2012). In the same way, lots of studies can be found on hypsometric analysis as well (Dowling et al., 1998; Singh et al., 2008; Sivakumar et al., 2011; Rebai et al., 2013). The aim of this paper is to to understand the drainage characteristics of the Chennai River Basin, using morphometric and hypsometric analysis within the GIS environment, it is an important basic information for the water resources development and management.

4.3 Methodology

4.3.1 Data Used

The Survey of India topographical maps with 1:50000 scale were used as the preliminary source of information for the watershed delineation including the preparation of a base map and drainage network. The digital elevation model is downloaded from the Shuttle Radar Topographic Mission (SRTM) In the current study, the latest 30m resolution DEM was downloaded from the official website http:// earthexplorer.usgs.gov/ and brought into the GIS environment. The entire basin is covered by four different quadrangles, these images mosaicked into a single image.

Basin morphometry can be divided into linear, areal and relief based classifications. Some of these parameters can be derived from Geo-database and some from empirical mathematical equations (Vincy et al., 2012) as expressed in Table 4.1. The basic concepts of the parameters and standard calculating methods were followed from the classical works in literature (Horton 1945, Miller 1953; Schumm 1956; Strahler 1964)

4.3.2 Hypsometric Analysis

The basic statistical components of hypsometric analysis are hypsometric integral (I), hypsometric curve, hypsometric skewness, etc., (Luo and Harlin 2003; Sivakumar et al., 2011;). The term hypsometric integral (HI) can be defined as the area under the curve which relates the percentage of total relief to cumulative percentage of area. This can be calculated as,

$$HI=(H_{mean}-H_{min})/(H_{max}-H_{min})$$

where H_{mean} is the average height and H_{max} and H_{min} are the maximum and minimum heights of the catchments.

Hypsometric Integral values are generally represented from 0 to 1. Values near to 0 show highly eroded regions, whereas values near to 1 show weakly eroded areas.

The hypsometric curve of a catchment represents the relative area below or above a given altitude; these curves can be used to identify stages of development of drainage networks.

4.4 Results and Discussion

4.4.1 Morphometric Analysis

The Chennai River Basin is a large basin and we identified 11 sub-basins based on our morphometric analysis (see Figure 4.1). Morphometric analysis has been classified into linear aspects, areal aspects, and relief aspects. Results are presented below in separate tables.

Table 4.1: Methodology for the Morphometric Analysis

Aspect	Morphometric Parameters	Method of Calculation	References
1	Stream Order (*Nu*)	Hierarchical order	Strahler (1964)
2	Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$ where Nu = total no. of stream segments of order 'u', Nu+1 = number of segments of the next higher order	Schumm (1956)
3	Length of the main channel (L_m)	Length along longest water course from the outflow point of to the upper limit of catchment boundary	
4	Length of main Stream of order u (L_u)	Length of the stream	Horton (1945)
5	Mean Stream Length (L_m)	$L_m = L_u/N_u$	Strahler (1964)
6	Stream length ratio (R_L)	$R_L = L_u/L_{u-1}$ where Lu = total stream length of order 'u', L_u-1 = the total stream length of its next lower order	
7	Length of Overland Flow (*Lg*)	Lg = 1/D × 2 where Lg = length of overland flow, D = drainage density	Horton (1945)
8	Basin length (*Lb*)	Distance between outlet and farthest point on the basin boundary	Horton(1932)
9	Basin Perimeter (*P*)	Length of watershed divide which surrounds the basin	
10	Basin Area (*A*)	Area enclosed within the boundary of watershed divide	
11	Drainage density (*D*)	$D = L_u/A$	Horton (1932)
12	Constant of Channel Maintenance (*C*)	$C = 1/D$	Schumm (1956)
13	Texture Ratio (*Tt*)	$T = N_1 (\frac{1}{P})$	
14	Stream Frequency (*Fs*)	$F_s = N_u/A$	Horton (1932)
15	Circulators ratio(*Rc*)	$R_C = 4 \times Pi \times A/P$	Miller (1953)
16	Elongation ratio (Re)	$Re = \sqrt{4 \times \frac{A}{Pi}}/L$	Schumm (1956)
17	Form factor (*Rf*)	$R_f = A/Lb^2$	Horton (1932)
18	Compactness constant (*Cc*)	$C_c = 0.2821P/A^{0.5}$	Horton (1945)
19	Drainage Texture (*Rt*)	$R_t = N_u/P$	Horton (1945)
20	Total relief (*H*)	Maximum vertical distance between the lowest and highest points on the valley floor of a watershed	Hadley and Schumm (1961)
21	Relief Ratio(*Rh*)	$R_h = H/L_b$	Schumm (1956)
22	Ruggedness no.(*Rn*)	$R_n = H \times D$	Melton (1957)

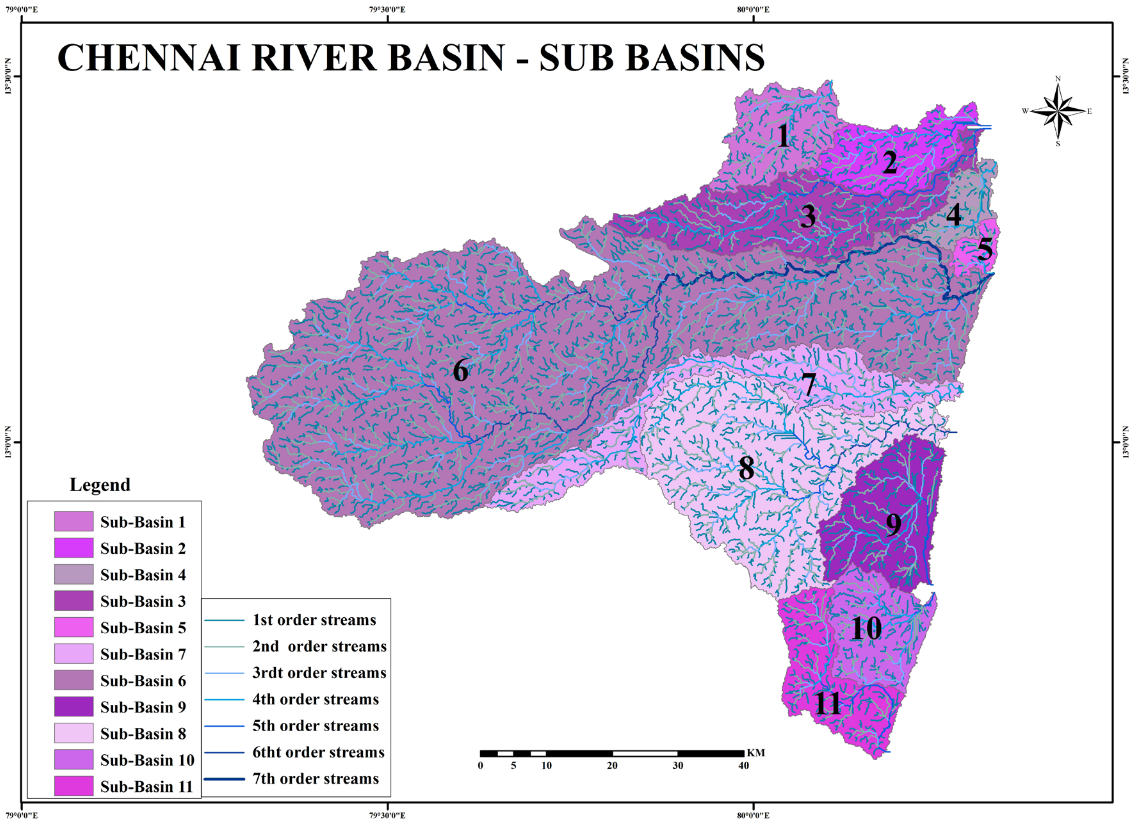

Figure 4.1: Chennai River Basin with 11 sub-basins

4.4.1.1 Linear Aspects of the Basin

4.4.1.1.1 Basin Length

Basin length (L_b) is an important parameter in characterizing the size of the drainage basin. It can be defined as the straight-line distance from a basin mouth to the point on the water divide (Horten 1932). The major practical difficulty found in this method is that it is also possible to have tributaries that are longer than the main channel (Ongley 1968). Basin length is a determining factor of the shape of the basin, i.e., the longer the L_b, the more elongated the basin. The L_b value of the Chennai Basin is 112.21km. The basin length of each sub-basin is shown in Table 4.2.

Table 4.2: Results of Basin Length, Stream order, Stream length and Bifurcation ratio of CRB

Sub - Basin (SB)	**Basin Length (L_b)**	**Stream Order (u)**								**Stream Length (Lu)**								**Bifurcation Ratio (Rb)**						
		I	II	III	IV	V	VI	VII	Total	I	II	III	IV	V	VI	VII	Total	Rb1	Rb2	Rb3	Rb4	Rb5	Rb6	Mean Rb
SB 1	24.38	130	22	4	1				157	135.36	68.29	31.79	14.05				249.49	5.91	5.50	4.00				5.14
SB 2	27.53	114	16	5	1	1			137	115.08	57.00	33.52	20.85	8.62			235.07	7.13	3.20	5.00	1.00			4608
SB 3	58.48	262	52	6	2	1			323	234.78	137.12	48.68	52.12	42.20			514.90	5.04	8.67	3.00	2.00			4.68
SB 4	17.11	59	9	2	1				71	60.21	27.41	5.93	16.63				110.18	6.56	4.50	2.00				4.35
SB5	7.84	33	4	2	1				40	25.67	13.74	5.33	5.48				50.22	8.25	2.00	2.00				4.08
SB 6	111.29	1616	270	52	13	3	2	1	1957	1572.09	791.07	372.07	208.4	38.99	78.49	73.5	31,34.60	5.99	5.19	4.00	4.33	3.00	2	4.50
SB 7	112.21	241	44	8	1				294	218.24	105.25	53.40	77.50				454.38	5.48	5.50	8.00				6.33
SB 8	46.61	525	88	17	3	1	1		635	475.34	251.02	91.44	70.92	24.17	24.66		937.54	5.97	5.18	5.67	3.00	1.00		4.16
SB 9	22.81	179	28	7	1	1			216	177.99	87.99	48.93	17.89	14.50			347.29	6.39	4.00	7.00	1.00			4.60
SB 10	19.65	131	25	6	2	1			165	127.66	67.72	29.10	27.90	5.42			257.80	5.24	4.17	3.00	2.00			3.60
SB 11	27.64	149	24	7	1	1			182	152.91	67.57	26.06	8.31	26.41			281.25	6.21	3.43	7.00	1.00			4.41

4.4.1.1.2 Stream Order (U) and Number (Nu)

Stream ordering and numbering is one of the basic preliminary steps in the drainage morphometric analysis of any basin. In this study, we adopted the classic method of Strahler (1952) for the ordering of streams, which is based on the location, slope, inflow, and volume of water. The smallest number is given to those streams that do not have any tributaries, and flow only in the rainy/wet seasons (Chow et al., 1988; Mahesh et al., 2013). Second order streams have first order stream as tributaries, whereas third order streams will have first and second order streams as tributaries. As the order goes up, the volume of water increases and the flow reduces. Sreedevi et al., (2013) reported that the size and order of the basin is influenced by the physiographic and structural condition of the study area. Based on this analysis, it is found that the CRB is a seventh order basin. The 7th order is found in 6th Sub-basin, whereas sub- basin 8 has 6th order. Sub-basin 9, 10 and 11 have 5th order. The complete information about the stream order and number is presented in Table 4.2. Higher orders are found near the coastal regions whereas the first order streams are found in the western hilly regions. A total of 4177 streams were found in the Chennai Basin in which 3439 were in the first order and the remaining numbers were 582,116,27, 9,3 and 1 for the 2nd, 3rd, 4th, 5th, 6th and 7th order respectively (see Table 4.2).

4.4.1.1.3 Stream Length (Lu)

Stream length (Lu) of a basin refers to the total length of the stream channels in the drainage basin. This parameter has important control over discharge and subsurface flow (Babu et al., 2014). Stream length is an indicator of the topography of the basin i.e., longer streams often resulting from the flat surface and short streams represent steep slopes with fine texture (Strahler 1964). Stream length is calculating based on Hortons Law (1932) which states that among the total stream length, lower order streams contribute more to the total stream length and higher order stream has very less contributions. The stream length found in the Chennai Basin is 3295.31 km, 1674.18 km, 746.24 km, 529.04 km, 160.30km, 103.142 km and 3.426 km for 1st to 7th order streams respectively (see Table 4.2). Horton´s observation has proved to be true in this study and a similar observation is made by other researchers for different basins (Thomas et al., 2012; Sreedevi et al., 2013; Al Saady et al., 2016).

4.4.1.1.4 Bifurcation ratio (Rb)

Bifurcation ratio (R_b) can be expressed as the ratio of the number of stream branches of a certain order to the number of stream branches of the next higher order (Horten 1932). It is a dimensionless linear property of the basin, in which high R_b values indicate high discharge with steep slopes. On the other hand, low values show high residence time and infiltration rate (Rawat et al., 2013). Strahler (1957) reported that this ratio will have only small variation for different terrains. In the Chennai Basin, R_b values range between 1 and 8.6, with a whole basin average of 4.5. Comparable results were reported by several researchers where the geology of the region does not have much control over the drainage network (Strahler 1964; Chow 1964; Sreedevi et al., 2013). A detailed result for the R_b values of the sub- basins is presented in Table 4.2.

4.4.1.1.5 Mean Stream Length (Lsm)

Mean stream length (L_{sm}) is a property of the basin that measures the extent of a drainage network and its contributing basin surfaces (Strahler 1964). This linear property of the basin can be calculated by dividing the total stream length of order 'u' by the number of stream segments in the corresponding order (see Table 4.1). In general, the mean stream length increases with increasing stream order. However, this relation may not exist in some cases because of topographical and structural irregularity. The mean stream length of each order stream is shown in corresponding sub-basin and is presented in Table 4.

4.4.1.1.6 Stream Length ratio (RL)

The ratio of mean stream length of current order (u) to the next lower order termed as Stream Length ratio (RL). This parameter has a significant connection with surface flow and the erosional stage of the basin (Vincy et al., 2012). In this study, RL values range between 0.50 and 1.52 and more detailed results within the sub basins are presented in Table 4.3. The variations in the RL values observed are due to the differences in slope and topographic conditions (Sreedevi et al., 2005; Magesh et al., 2011).

4.4.1.1.7 Length of Overland Flow (Lg)

Overland flow is the water flowing over the ground surface before being channelized into the streams and this length is called as Length of overland flow (Lg) (Aher et al., 2014). This is an independent variable, which can be explained as the half of the reciprocal of drainage density (Dd) (Hortaon 1932). The Lg value obtained in this study was 0.52. Smaller values of Lg represent well developed drainage networks with higher slope, on the other hand higher Lg values show that water has to travel comparatively greater distances to reach a stream (Chitra et al., 2011; Magesh et al., 2013).

4.4.1.1.8 Rho Coefficient (P)

Horton (1945) defined the rho coefficient as a measure relating drainage density to the physiographic development of a watershed and enables evaluation of the storage capacity of a drainage network. This is one of the important parameters to determine drainage development precisely. Changes in this parameter are largely influenced by climate, geology, geomorphology and anthropogenic factors (Rawat et al., 2013). The ϱ value for the Chennai River Basin is 0.15 (Table 4.4). Higher values of indicate higher hydrologic storage during elevated discharge.

Table 4.3: Results of Length of overland flow, Mean Stream Length and Stream length ratio in CRB

	Length of over land flow (Lg)	**Mean Stream Length (Lsm)**								**Stream Length Ratio (RL)**						
		I	II	III	IV	V	VI	VII	**Total**	II/I	III/II	IV/III	V/IV	VI/V	VII/ VI	**Total**
Sub-basin 1	0.59	1.04	3.10	7.95	14.05				**26.14**	0.50	0.47	0.44				**1.41**
Sub-basin 2	0.60	1.01	3.56	6.70	20.85	8.62			**40.75**	0.50	0.59	0.62	0.41			**2.12**
Sub-basin 3	0.61	0.90	2.64	8.11	26.06	42.20			**79.91**	0.58	0.36	1.07	0.81			**2.82**
Sub-basin 4	0.61	1.02	3.05	2.96	16.63				**23.66**	0.46	0.22	2.81				**3.48**
Sub-basin 5	0.63	0.78	3.43	2.67	5.48				**12.36**	0.54	0.39	1.03				**1.95**
Sub-basin 6	0.01	0.97	2.93	7.16	16.03	13.00	39.25	73.50	**152.83**	0.50	0.47	0.56	0.19	2.01	0.94	**4.67**
Sub-basin 7	0.37	0.91	2.39	6.67	77.50				**87.48**	0.48	0.51	1.45				**2.44**
Sub-basin 8	0.57	0.91	2.85	5.38	23.64	24.17	24.66		**81.60**	0.53	0.36	0.78	0.34	1.02		**3.03**
Sub-basin 9	0.60	0.99	3.14	6.99	17.89	14.50			**43.51**	0.49	0.56	0.37	0.81			**2.23**
Sub-basin 10	0.61	0.97	2.71	4.85	13.95	5.42			**27.90**	0.53	0.43	0.96	0.19			**2.11**
Sub-basin 11	0.62	1.03	2.82	3.72	8.31	26.41			**42.28**	0.44	0.39	0.32	3.18			**4.33**
Chennai Basin		**10.52**	**32.62**	**63.17**	**240.39**	**134.31**	**63.91**	**73.50**	**618.42**	**0.50**	**0.43**	**0.95**	**0.85**	**1.52**	**0.94**	**30.59**

4.4.1.1.9 Basin Perimeter (P)

The length of the outer boundary of the watershed or basin is known as basin perimeter (P). This linear parameter is measured along the divides between the two watersheds. P values can represent the size and shape of the basin. The perimeter of the Chennai Basin is 534 km (Table 4.4).

4.4.1.2. Aerial Aspects

Table 4.4: Areal aspects of the Sub-basins in the CRB

	Areal Parameters							
Sub-basin Name	**Perimeter (P)**	**Basin Area (A)**	**Stream Frequency (Fs)**	**Drainage Density (Dd)**	**Drainage texture (T)**	**Cirulcarity Ratio (Rc)**	**Elongation Ratio (Re)**	**Form Factor (Rf)**
Sub-basin 1	93.96	210.76	0.74	1.18	0.88	0.30	0.60	0.35
Sub-basin 2	100.09	194.92	0.70	1.21	0.84	0.24	0.57	0.26
Sub-basin 3	196.69	421.62	0.77	1.22	0.94	0.14	0.40	0.12
Sub-basin 4	67.23	90.02	0.79	1.22	0.97	0.14	0.63	0.31
Sub-basin 5	42.66	39.85	1.00	1.26	1.26	0.32	0.91	0.65
Sub-basin 6	431.66	2659.86	0.74	1.15	.001	0.18	0.52	0.21
Sub-basin 7	534.00	611.90	0.05	0.07	0.35	0.27	0.79	0.49
Sub-basin 8	206.45	821.38	0.77	1.14	0.88	0.24	0.69	0.38
Sub-basin 9	102.73	291.48	0.74	1.19	0.88	0.34	0.84	0.56
Sub-basin 10	80.81	210.19	0.79	1.23	0.96	0.40	0.83	0.54
Sub-basin 11	105.36	228.15	0.80	1.23	0.98	0.26	0.62	0.30

4.4.1.2.1 Basin Area (A)

Basin area denotes the total area covered by the basin and it is an indicator of the size of the drainage basin. Discharge and flow are largely dependent on basin size. Basin area can be defined as the total area projected on a horizontal plane contributing overland flow to the channel segment under consideration and including all tributaries of the lower order (Oyegoke and Ifeadi 2007). The Chennai Basin is a comparably large river basin with an area of 6119 km^2. Rawat et al., (2013) observed that large basins generally have well developed drainage networks and thus a greater water storage capacity. Contrarily, small basins will have a packed hydrograph and can only generate an irregular water supply. The basin area of the sub-basins is shown in Table 4.

4.4.1.2.2 Drainage density (Dd)

Drainage density is the measure of the total line length of the stream network to the total basin area and is important in identifying the nature of the drainage basin. Highly dense streams usually indicate the texture of a mature, well-developed channel system with limited infiltration and high runoff (Babu et al., 2014). In the present study, the drainage density of the Chennai Basin is observed as 1.15 km/km^2; the measurements for the sub-basins are presented in Table 4. Dd is an indicator of the nature of subsurface materials, land use patterns, basin response, infiltration rate, etc. Permeable rocks with high infiltration rate decrease drainage density. It is observed that the drainage density is proportional to the relief variations. In the Chennai Basin, the drainage density is comparatively low because of the permeable formations in most of the area as well as the built urban nature of the area. The drainage network map of Chennai is shown in Figure 4.2.

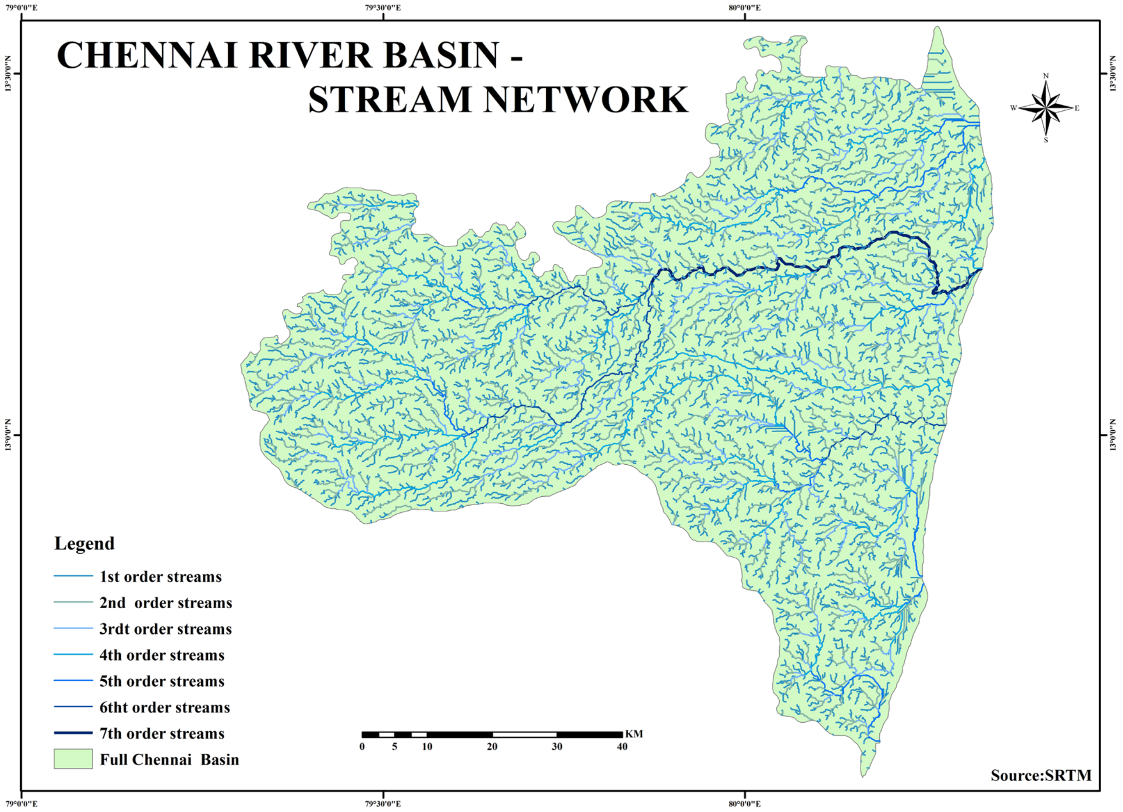

Figure 4.2: Stream network of Chennai River Basin

4.4.1.2.3 Stream Frequency (Fs)

Stream frequency is a measure to quantify the density of natural drainage in a catchment. This can be defined as the number of stream junctions within a unit area and is usually measured in square kilometers. The Fs of the whole Chennai Basin is 0.74km/km^2. High values of Fs show impermeable subsurface, high relief, low infiltration capacity and scarce vegetation. The Fs values 0.74km/km^2 is representing the high permeable surface with high vegetation cover. Similar observations were made by Magesh et al., (2013) in Bharathapuzha Basin.

4.4.1.2.4 Drainage Texture (Rt)

Drainage texture (Rt) can be defined as the ratio of the total number of streams (of all orders) to the basin perimeter (Horton 1945). Many factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development influence this texture. Smith (1950) proposed a classification for Rt values like very coarse (< 2), coarse (2–4), moderate (4–6), fine (6–8), and very fine (>8). The Rt value in the Chennai Basin was calculated as 0.85, falling under the coarse category. Table 4.4 gives an overview of the drainage texture of the sub-basins.

4.4.1.2.5 Constant of Channel Maintenance (C)

The reciprocal of the drainage density is often mentioned as the Constant of Channel Maintenance (C) (Schumm 1956). The major geo-environmental influences on this parameter are lithology, permeability, vegetation cover, relief and finally climatic conditions (Sreedevi et al., 2013). The ratio of the drainage basin area to the total lengths of all the channels can be expressed as square meter per meter (Aher et al., 2014). The C value for the Chennai Basin is determined as 0.87. The C value shows direct implication on surface runoff, i.e., a basin with a high C value will have more infiltration and percolation, whereas a lower value indicates more surface runoff.

4.4.1.2.6 Circulatory ratio (Rc)

Strahler (1964) defined circulatory ration (Rc) as the ratio of an area to the area of a circle of the same perimeter as the basin under study. Rc values near one indicate a near circular shape of the basin, which will have longer residence time for the surface flow to reach the outlet and results in more uniform infiltration (Sreedevi et al., 2013). Factors such as geology, slope, land use and land-cover, stream length and frequency etc., also affect Rc values. The circularity ratio of the Chennai Basin is 0.085, showing a more elongated nature and thus tending towards maturity. High Rc values indicating the increased chances for flood hazard.

4.4.1.2.7 Elongation ratio (Re)

Elongation ratio (Re) was originally proposed by Schumm (1956) and can be defined as the ratio of the diameter of a circle with same area of the basin under study to the maximum basin length. Theoretically this ratio will range from 0 for highly irregular to 1 for circular basins. However, on field observations show that this value can be expected to range from 0.6 to 1.0 in various geological and climatic conditions, with those values close to one representing low relief. A higher elongation ratio is an indication of higher discharge in short duration. This index is highly useful in understanding the hydrological characteristics of a basin. Strahler (1964) reported that Re values ranging from 0.6 to 0.9 have strong relief and steep slopes. In the Chennai Basin the Re value obtained is 0.98, indicating strong relief. Re values of the sub- basins are presented in Table 4.4.

4.4.1.2.8 Form factor (Rf)

Form factor (Rf) is an index developed by Horton (1945) to represent the shape of a basin. It can be expressed as the ratio of the basin area to the square of the basin length (see Table 1). The expected range of the form factor is in the range of 0.1 to 0.8. Small values of Rf show elongated basins whereas higher values show more spherical shaped basins. A basin with a long form factor has high peak flows with shorter duration. In the other, low peak flows and longer duration will be exhibited. The Rf value in the Chennai River Basin is 0.49, meaning a moderate sphericity.

4.4.1.3 Relief aspects

Table 4.5: Relief aspects of the Chennai River Basin

Name	Basin relief	Relief Ratio	Relative Relief	Ruggedness Number
Sub-basin 1	130	2.79	0.72	80.5
Sub-basin 2	114	1.23	0.34	41
Sub-basin 3	262	4.36	1.3	311
Sub-basin 4	59	1.4	0.36	29
Sub-basin 5	33	4.46	0.82	44
Sub-basin 6	1616	2.29	0.59	7
Sub-basin 7	241	2.27	0.48	189
Sub-basin 8	525	3.5	0.79	186
Sub-basin 9	179	6.84	1.52	185
Sub-basin 10	131	8.24	2	199
Sub-basin 11	149	6.22	1.63	212

4.4.1.3.1 Aspect

Aspect is a measure of the direction of slope in a basin. It has impacts on precipitation patterns, snowmelt, vegetation and wind (Gordon et al., 2013). The most important influence of this parameter is on the vegetation, as vegetation patterns in sun facing and shaded terrains will vary significantly (Warren et al., 2010; Al Saady et al., 2016). A detailed aspect map of the Chennai Basin is shown in Figure 4.3.

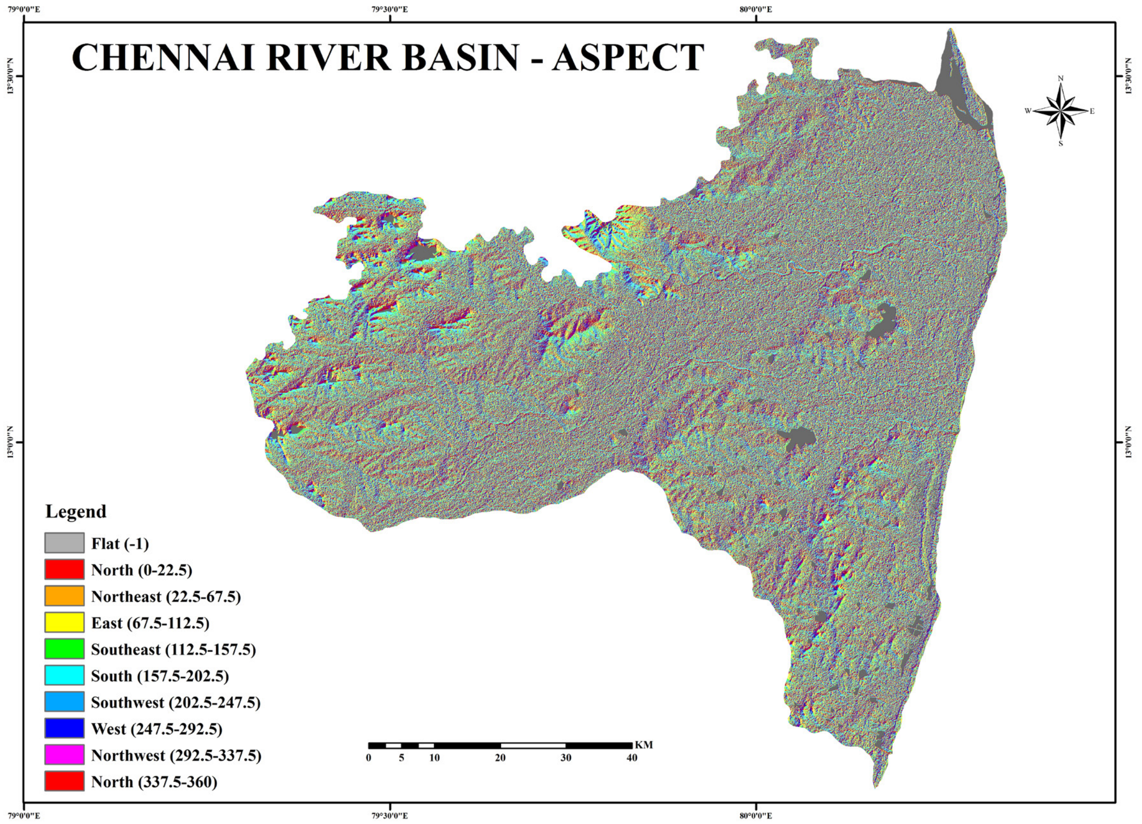

Figure 4.3: Aspect map of Chennai Basin

4.4.1.3.2 Total relief or Basin relief (H)

Total relief of the basin is the vertical distance between the highest point and the lowest point in the basin. Basin relief aspects play a vital role in the water flow (surface and sub-surface) drainage and landform development and also on the erosional property of the basin (Sreedevi et al., 2013). The total relief of the Chennai Basin is 255m. High relief of any basin indicates low infiltration and high run off due to gravitational effects. A detailed elevation map of the basin is presented in Figure 4.4.

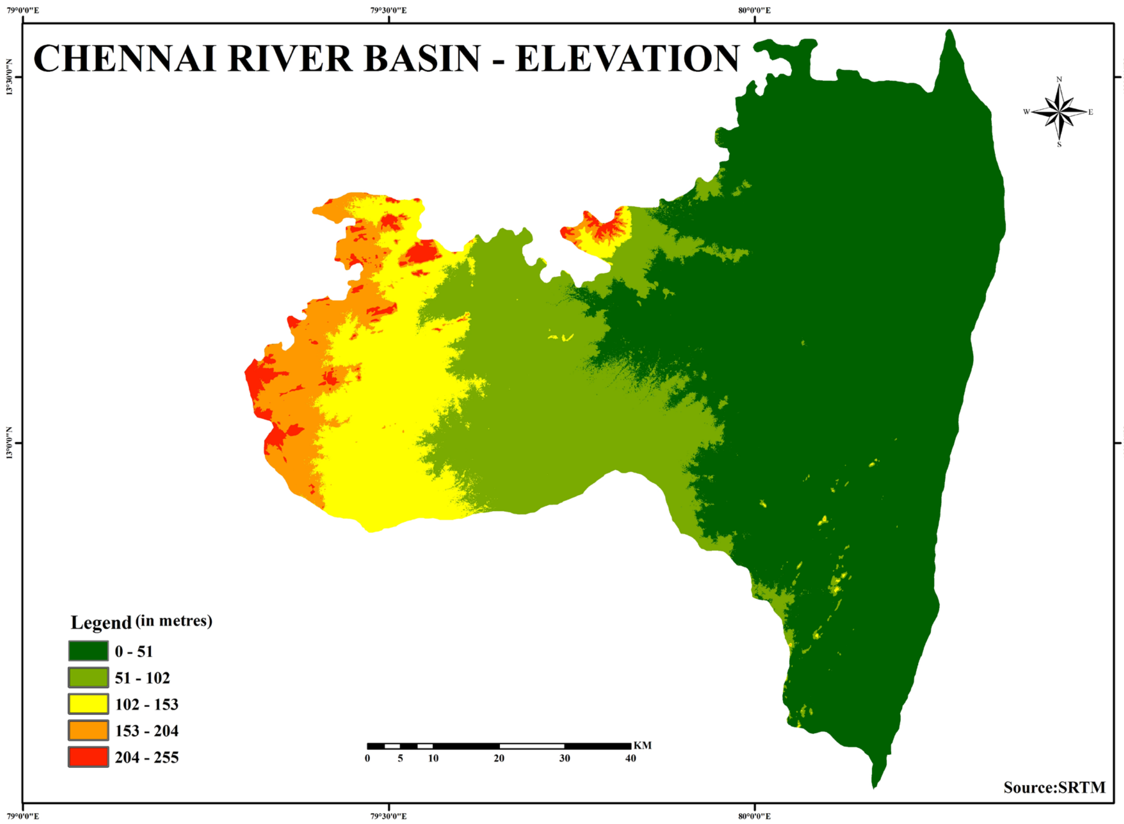

Figure 4.4: Elevation map of Chennai River Basin

4.4.1.3.3 Relief Ratio (Rh)

Relief ratio (Rh) is useful in the comparison of the relative relief of any basin irrespective of scale. Relief ratio is explained as the ratio of the total relief to the maximum basin length (Lb). Rh shows a decrease with increasing basin area and size of the given drainage basin (Gottschalk 1964). This ratio measures the steepness of the basin and obviously used as an indicator to detect the intensity of erosional processes. Rh values in the Chennai Basin are 0.002, showing gentle to moderate slope.

4.4.1.3.4 Relative relief (Rhp)

Relative relief (Rhp) is measured as a ration of R to the basin Perimeter (p), representing variation in altitude in a unit area to its local base level (Vandana 2013) (see Table 1). This index gives vital information about the structural, as well as lithological, control of the basin (Al Saady et al., 2016). The Rhp value of the Chennai Basin is 0.48 (see Table 4.5).

4.4.1.3.5 Slope

Slope is a crucial factor of a basin that controls runoff characteristics and water flow in an area. Higher slope increases the chances for flood peaks. The slope map generated for the Chennai Basin is shown in Figure 4.5. A wide variation in slope from 0° to 90° is observed in the basin. Gentle slope is found in a majority of the study area; however, the western parts and some of the SE region show very high slopes.

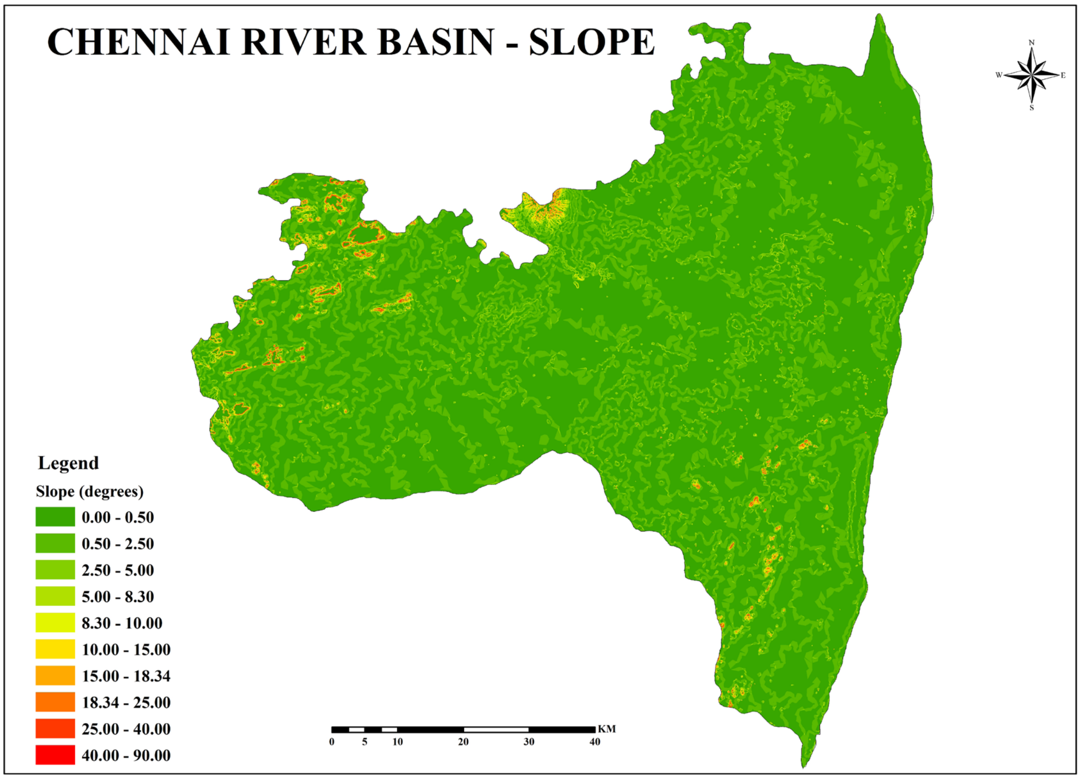

Figure 4.5: Slope map of Chennai River Basin

4.4.1.3.6 Ruggedness number (Rn)

The product of basin relief and drainage density is known as ruggedness number (Rn). This dimensionless number combines slope and basin lengths in a single value and basically explains the structural complexity of the drainage basin (Aher et al., 2014). Steep – long slopes are normally characterized with a high ruggedness number.

4.4.3 Hypsometric analysis

Strahler (1952) defined hypsometric analysis as a study of the distribution of the ground surface area, or horizontal cross-sectional area, of a landmass with respect to elevation. However, the study of hypsometry was initiated by Langbein (1947), with an intention to calculate the slope and land forms of a drainage basin. Hypsometric analysis gives vital information about the geographic evolution of land forms even without information about their origins (Gajbhiye et al., 2014). This analysis is comprised of the relation of altitude and area, which is effective in providing information about the development of the watershed (Gopinath et al., 2016). Topographic analysis of the basin is generally done with hypsometric curve and hypsometric interval of the basin under consideration (Ramu and Mahalingam 2002; Gajbhiye et al., 2014).

The hypsometric curve can infer the total volume of soil mass available in a basin and the extent of erosion that happened in a basin against the remaining soil mass (Hurtrez et al., 1999; Gajbhiye et al., 2014). The shape of the hypsometric curve is an indication of the degree of dissection and relative age. It also shows the relative area either below or above a specified altitude (Strahler 1952). In general, three shapes for the hypsometric curves can be found in the literature. As Convex-up curves with high integrals represent young, undissected (disequilibrium stage) landscapes, while smooth, S-shaped curves crossing the center of the diagram characterize mature (equilibrium stage) landscapes, and concave-up with low integrals typifies old and deeply dissected landscapes (Strahler 1952).

Convex type curves represent less erosion, while concave type curves indicate strong erosion (Hurtrez et al., 1999; Prasannakumar et al., 2013). Hypsometric analysis of the Chennai River Basin has been performed using the hypsometric extension tool in the ArcGIS software program. This analysis generated the hypsometric curve for the entire basin, which is shown in Figure 4.6. The results of the hypsometric curve analysis for the 11 sub-basins indicate that sub-basins 1, 6 & 7 are matured stage with an almost S-shaped hypsometric curve. All remaining sub-basins have concave shaped curves representing the old (monadnock) stage. In terms of elevation, most of the sub-basins have relatively lower elevations, which decreases the effect of erosion.

Hypsometric integral (HI) is the second most important parameter which usually represents the cycle of erosion. It is the total time required for erosion to bring the land area to the base level (Strahler 1952; Gajbhiye et al., 2014). Further, the cycle of erosion is classified into (i) Hsi < 0.3: monadnock (old stage), (ii) Hsi (0.3 to 0.6): watershed is matured and stabilized, and (iii) Hsi > 0.6: young stage, highly susceptible to erosion (Strahler, 1952). The hypsometric integral values of the 11 sub-basins in the Chennai River Basin are shown in Table 4.6. Results show that the HI values vary from 0.089 (SB-9) to 0.42 (SB-7). Sub- basins 1, 6 and 7 have HI > 0.3, showing mature stages, while the remaining sub-basins are all classified as old stage.

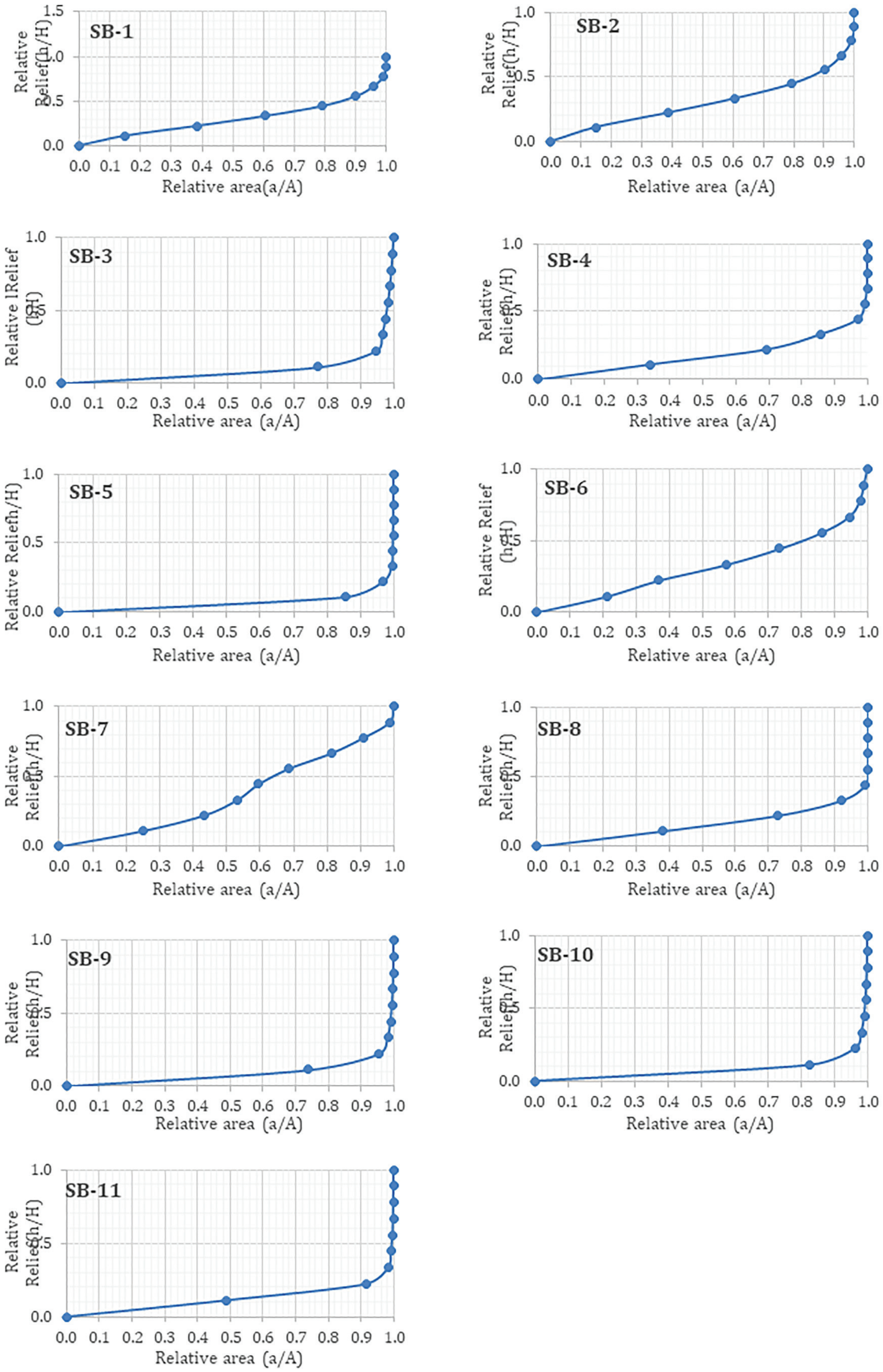

Figure 4.6: Hypsometric curves for the 11 sub watersheds in the Chennai River Basin.

Table 4.6: Hypsometric Integral values of 11 sub watersheds in the Chennai River Basin.

Sub-water-sheds	Area (km²)	Elevation-Relief ratio (HI)	Geologic Stage
1	210.76	0.3445	**Mature**
2	194.92	0.2718	**Old**
3	421.62	0.1199	**Old**
4	90.02	0.2175	**Old**
5	39.85	0.1263	**Old**
6	2659.86	0.3307	**Mature**
7	611.90	0.4221	**Mature**
8	821.38	0.2254	**Old**
9	291.48	0.0892	**Old**
10	210.19	0.0907	**Old**
11	**228.15**	**0.1476**	**Old**

4.5 Conclusions

Morphometric and hypsometric analysis of CRB has been carried out using GIS and remote sensing techniques. 11 sub-basins were demarcated and linear, areal and relief characteristics were calculated. CRB is a 7th order basin and basin length shows that the basin is elongated. Stream length of the sub basin were higher in the first order (3295 Km^2) and lowest in the 7th order (3.4 Km^2). The total perimeter of the CRB is 534 Km^2. As the basin area of CRB is very big (6112 Km^2), which is an indication of high- water holding capacity. Drainage density of the basin is low and drainage texture is coarse, may be due to the high permeable formations. Constant of Channel maintenance is 0.87 and circularity ratio was 0.085. The elongation ratio is 0.98, showing the presence of steep slopes and which is evident from total relief 255 and may affect the infiltration rates. Hypsometric curves were drawn and hypsometric integral (HI) were calculated. HI values ranged between 0.089 and 0.42. analysis of the hypsometric curves and hypsometric integral suggests that the sub-basins 1,6 and 7 were matured stages and the remaining has monadnock (old stage). This study shows that GIS based morphometric and hypsometric analysis can draw vital information about the hydrological and terrain characteristics of the river basin.

CHAPTER 5

Geographical Information System (GIS) and Analytical Hierarchy Process (AHP) based Groundwater Potential Zones delineation in Chennai River Basin, India.

5.1 Abstract

Groundwater depletion is one of the most important concerns for users and policy makers. Information on the locations where groundwater potential is high or low is the key factor that helps them to do proper planning. Application of new technologies and methods are essential in this situation. This study has used the possibilities of Geographical Information System (GIS), Remote Sensing and, of course, field data to delineate the groundwater potential zones in the Chennai River Basin (CRB). To provide accurate results, 11 controlling factors such as geology, water level, drainage, soil, lineament, rainfall, land use, slope, aspect, geomorphology, and depth to bed rock, were brought into a digital GIS environment and appropriate weightage given to each layer depending on their effect on potential. The weightage is given based on Multi-Criteria Decision Making (MCDM), namely Analytical Hierarchal Process (AHP). Groundwater potential zones in the CRB were mapped as very poor, poor, moderate, good, very good using weighted overlay analysis. The results were compared with actual specific capacity from the borehole data. The accuracy of prediction was found to be 78.43%, indicating that in most of the locations, the predicted potential map agrees with the bore hole data. Thus, AHP aided GIS-RS mapping is a useful tool in groundwater prospecting in this region of the world.

5.2 Introduction

According to availability and ease of access, surface water may be the most depended upon source of water for drinking and domestic purposes. However, with increased industrialization and urbanization, surface water faces serious threats in terms of quality. On a global scale, groundwater serves 50% of drinking and 43% of irrigation needs (FAO 2010). India is one the largest users of groundwater resources and the usage is increasing drastically (Postal 1999). As an agriculturally lead economy, 80% of the groundwater in India is used for irrigation (Dhavan 2017), and remaining is used for drinking, domestic and industrial purposes. Uncontrolled pumping has lowered the groundwater level severely and reported as overexploited in many parts of India (Dhavan 2017).

Chennai is the fourth largest metropolitan area in India and the biggest urban area in the Chennai River Basin (CRB). One of the earliest acts on the regulation of groundwater use and policy in India was the Chennai Metropolitan Area Groundwater (Regulation) Act in 1987, which banned the extraction of groundwater at 229 locations (Jenifer and Arul 2102). Further amendments to this restriction were made in 1995 and 2008. Rapid increase in population, industrialization, urbanization and irrigation have resulted in a huge demand of water from the Chennai Basin. Geographically, the eastern boundary of the basin is long coastline of the Bay of Bengal. Sea water intrusion into the freshwater zones and groundwater quality deterioration has been reported (Elango and Manickam 1986; Sajil Kumar et al., 2013; Nair et al., 2015). In this region, groundwater depletion and pollution affect the population and the economy, calling for sustainable water resources management. Previous studies suggests that most of the studies in this region focusing on groundwater quality, saline intrusions, hydrochemical investigations, managed aquifer recharge etc., (Elango et al., 1992; Senthik Kumar et al., 2001; Sathish et al., 2011, Parimala and Elango 2013; Raicy and Elango 2017). All these studies were performed at a watershed or sub-basin level. A more holistic approach is needed because the groundwater supply to the city also includes the well fields located north of Chennai. Thus, a study must be performed on the complete basin, with a special emphasis on the urban area.

Estimating groundwater reserve and the demarcation of prospective zones is the preliminary step of any water resources management project. Accurate calculation of inputs (recharge) and outputs (discharge) is essential at this stage. Systematic planning of groundwater exploitation using modern techniques is necessary for the proper utilization and management of this precious but shrinking natural resource (Chowdhury 2007). The use of conventional techniques like geological, geophysical, geostatistical and numerical modeling is expensive, laborious and time consuming (Elbeih 2014). The rapid growth of space technology has played a vital role in groundwater studies. Remote Sensing (RS) and Geographic Information System (GIS) are promising tools for efficient planning and management of groundwater resources (Machiwal 2007). NRSA in India is one of the pioneers in using the integrated study of RS and GIS for delineating groundwater recharge potential in an area (NRSA 1987). Geospatial technologies provide cost-effective solutions for the aquifer management and integration of multi thematic data sets to a uniform scale.

The use of RS and GIS extensively used in India for the mapping and montoring of the groundwater potential zones and locating the suitable locations for the artificial groundwater recharge (Prasad et al., 2008; Singh et al., 2013; Nagaraju et al., 2011 ; Magesh et al., 2012; Nag and Gosh 2013; Murthy et al., 2013 and many more)

There are many studies found in many parts of India (Kurmapalli watershed Andhra Pradesh), (Bist Doab Basin, Punjab), (Chamarajnagar District, Karnataka), (Bankura District, West Bengal), (Vamshadhara basin, Andhra Pradesh), (Theni district Tamil Nadu) and many more., on groundwater potential zone delineation using GIS techniques. The present study is concentrated mainly on the estimation of groundwater reserve and mapping groundwater potential zones in Chennai River Basin (CRB). We aim to create a basic platform for the sustainable groundwater management in future.

5.3 Data and Methods

Factors influencing groundwater recharge are determined based on literature survey, field analysis and expert opinion. Based on this preliminary investigation geomorphology, geology, lineament, annual rainfall, pre-monsoon water level, depth to bed rock, soil, land use, aspect and slope were chosen as main factors. All these maps where digitized and integrated into a GIS platform using ArcGIS 10.2. The map layers used, and their hydrogeological significance are summarized in Table 5.1. Conventional data sets, such as topographical maps and field data, were used along with advanced data sets, such as satellite data. Corresponding topographic maps were collected from Survey of India (SOI), with a scale of 1:150,000. These maps were digitized in the GIS environment using ArcGIS 10.2. A geological and geomorphological map for the study were prepared from the SOI maps and soil map from the National Bureau of Soil Science and Land Use Planning (NBSS and LUP). SRTM -DEM were used to derive the slope maps. A flow chart of the adopted methodology is shown in Figure 5.1.

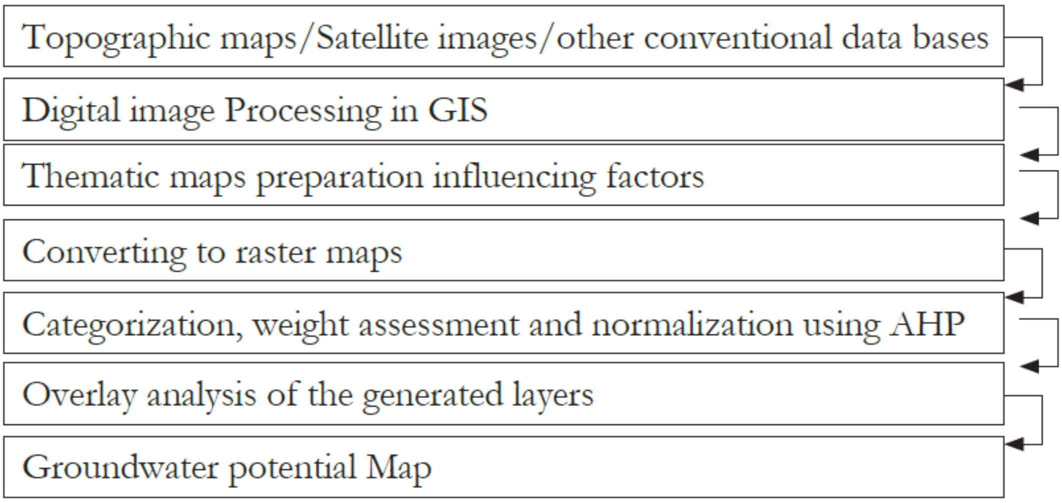

Figure 5.1: Flow chart showing the methodology adopted in the study

Table 5.1: Phenomenon and need for the thematic layers

No.	Map Layer	Phenomenon	Need
1	Geomorphology (GM)	Physical processes on the earth's surface that produce different landforms	A geomorphic unit is a composite unit that has specific characteristics
2	Geology (GEOL)	Different lithological formations	The aquifer characteristics of different geology is varied considerably
3	Lineament (including Fault & Shear zone) (Ln)	Planes/Zones of structural weakness in the rocks	Easy movement of water along weak planes
4	Rainfall (RF)	Rainfall	Major source of water
5	Groundwater level (GWL)	Depth at which water occurs in the unconfined zone (top zone) below ground level	Accessible of water
6	Soil (Sl)	Soil	Result of physical surface processes and the lithology
7	Landuse (LU)	Purpose for which land has been put to use	Indicates the state of current use.
8	Depth to Bed rock (DBR)	Massive rock below the soil and the weathered zone	Indication of the thickness of the unconfined aquifer
9	Slope (Sp)	Slope	Controls the movement of water (surface and ground)
10	Drainage (D)	Drainage	
11	Aspect (A)		

Data for the analysis was available in vector (from existing maps) and raster (interpolated from point data or classified from satellite images) formats. For rainfall, depth to bed rock, water level, and elevation, layers were created from the point data sources by the Inverse Distance Weighted (IDW) interpolation method. In the IDW method, the unknown data points are calculated from the four surrounding known data points. We opted for IDW over distance threshold methods, because the point data was sparse and distributed. The slope map was derived from the elevation contours from the Survey of India topographical maps of the study area.

Analytical Hierarchical Process (AHP), which was originally proposed by Saaty (1990), were used for assigning the weights for each thematic layer used in this study. AHP is one of the most commonly used multi criteria decision making technique in the field of environmental and groundwater studies (Das and Mukhopadhyay 2018; Rahmati et al., 2015).

In this method a pairwise comparison matrix is generated by comparing the assigned scores for each layer. The scores are generally assigned between 1 (equal importance) and 9 (extreme importance) (Table 5.2; Saaty 1990). In the AHP model, a pairwise comparison matrix for the 11 layers was created. The normalized weights of the individual layers were created using the eigen vector method.

Table 5.2: Saaty´s scale for assignment of weights and the pairwise comparison process (Saty 1980)

Less Important				**Equally important**	**More Important**			
Extreme-ly	Very Strongly	Strongly	Moderat-ely	Equally	Moderately	Strongly	Very Strongly	Ex tremely
1/9	1/7	1/5	1/3	1	3	5	7	9

The weight of each thematic layer is derived from the maximum eigen value in the normalized eigen value in the pairwise comparison matrix. The reliability of the judgment is dependent on the Consistency Ratio (CR) and its value must be less than or equal to 0.1. In case it exceeds this limit, it is suggested to revise the process. CR is calculated as follows,

$$CR=CI/RI \tag{5.1}$$

Here RI is the Random Consistency Index (see Table 5.3) and CI is the Consistency Index, which is calculated as follows,

$$CI = \frac{\lambda_{max} - \mathrm{n}}{n-1} \tag{5.2}$$

In this equation, λ is the principal eigen value of the matrix and n is the number factors used in the estimation (Saaty 1980).

Table 5.3: Random indices for matrices of various sizes

Matrix Size	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Groundwater potential zones were derived from 11 thematic layers integrated into the GIS environment to calculate the groundwater potential index (GWPI). This is done by Weighted Linear Combination (WLC), as suggested by Malczewski (1999).

$$GWPI = \sum_{w=1}^{m} \sum_{1}^{n} (Wj \times Xi) \tag{5.3}$$

Here GWPI is the Groundwater Potential Index, Xi is the normalized weight of the ith feature of the thematic layer, Wj is the normalized weight of the jth thematic layer, m represents total number of themes, and n is the total number of classes in a theme.

5.4 Results and Discussion

5.4.1 Thematic Layers and Features in the CRB

5.4.1.1 Mapping and analysis of slope

Slope is an important geomorphological feature that affects the groundwater potential of a region and an important parameter in identifying groundwater recharge prospects (Fasche et al., 2014). Groundwater potential is greater in gentle slopes as more infiltration occurs due to the increased residence time. On the other hand, the increased runoff rate for steep slopes makes them less suitable for groundwater recharge. In this study, slope varies from 0 to 80.44%, the majority of the area having a slope between 0 to 4.73 %. The highest slopes were found mostly in the western region of the study area. Based on this, the slope range of 0-4.73% was given a weightage of 7 (very good) with 4 (moderate), 3(moderate) and 2 (poor) given to subsequent classes (see Figure 5.2). Generally, steep slopes are given lower weights and gentle slope with higher weights (Agarwal and Garg 2016).

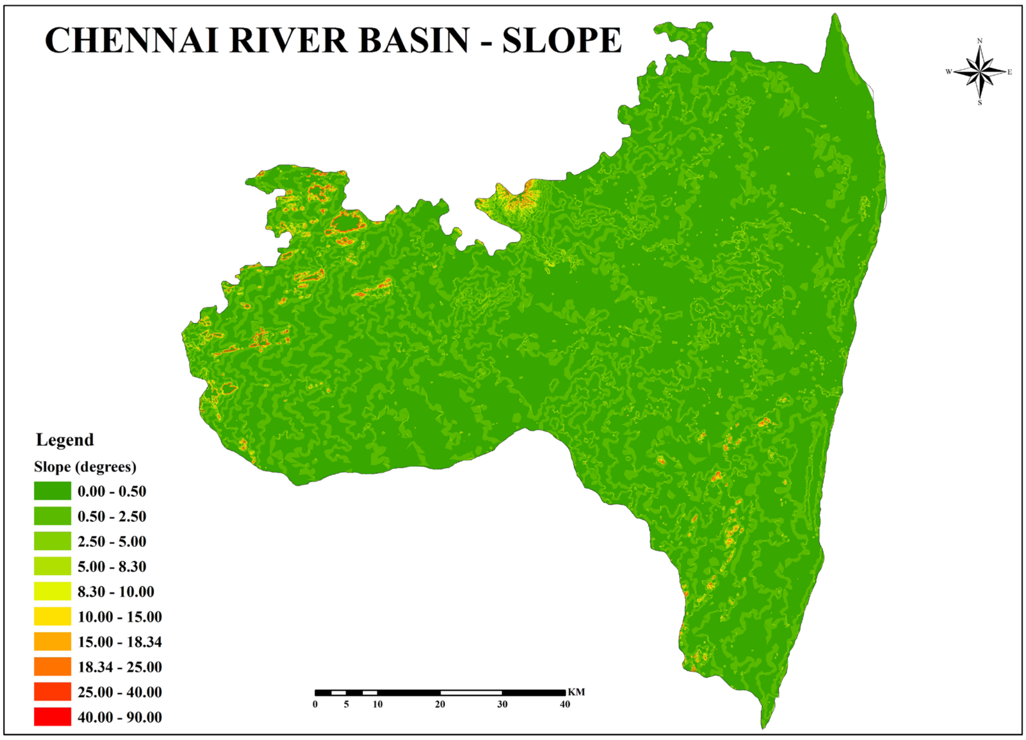

Figure 5.2: Slope Map

5.4.1.2 *Mapping and analysis of aspect*

Aspect is an important terrain characteristic that affects the groundwater recharge characteristics of a basin. It is the direction of slope usually measured clockwise from 0 to 360°. Zero means the aspect facing north, 90 ,180 is south-facing, and 270 is west-facing. In arid and semi-arid regions, microclimatic changes are dependent on slope exposure direction and drainage basin development. Thus, aspect has a direct influence on the microclimates (Hadley 1961; Al-Saady et al., 2016). An aspect map of the study area is shown in Figure 5.3. The aspect of CRB is trending towards all the directions, however higher weightage is given to the flat terrains and the lowest to those areas trending north.

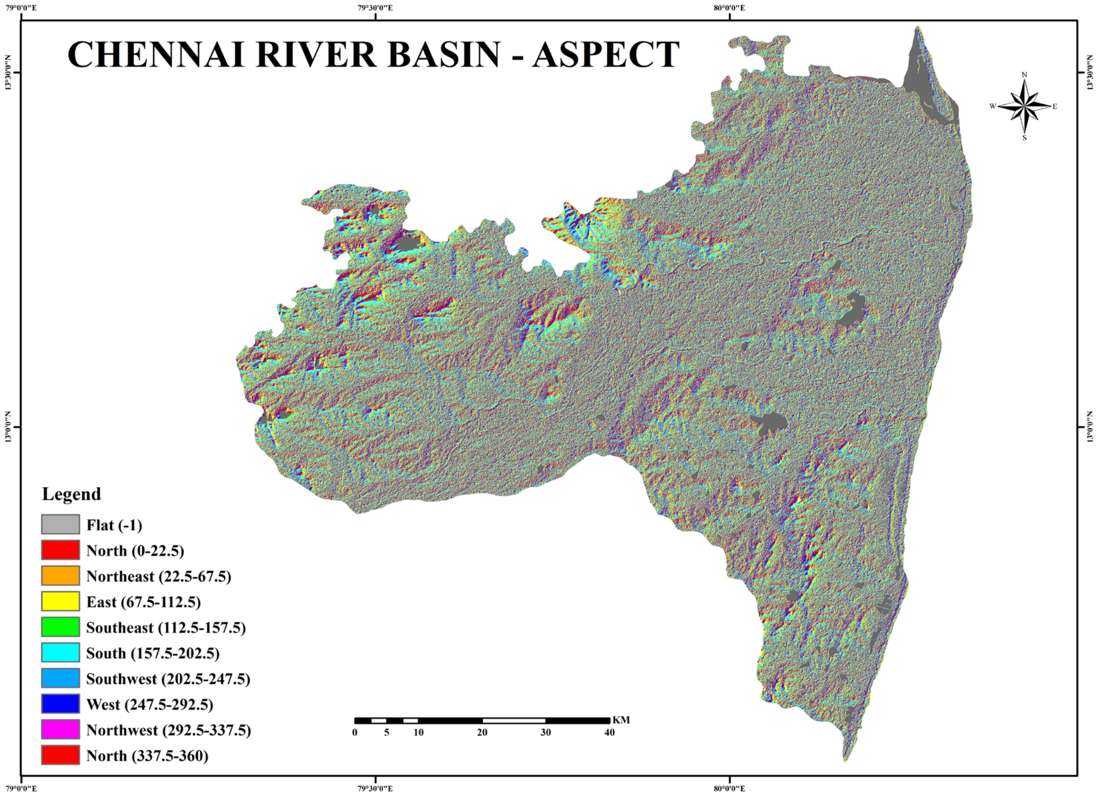

Figure 5.3: Aspect Map

5.4.1.3 *Mapping and analysis of groundwater level*

In unsaturated conditions, the upper level of saturated underground surface in which water pressure equals the atmospheric pressure is known as groundwater table (Freeze and Cherry 1979). Depth to the water table is a measure of groundwater recharge or discharge. When the water table is deep, the flow is towards the water table via percolation and infiltration. On the other hand, when the water table meets the land surface, the flow is away from the water table. (Poehls and Smith 2009). So, for potential recharge zones, the higher depth to the water table is an essential factor. The groundwater level in the study area varies from 0 to 21m below ground level. Most of the region in the study area falls between 6 and 11m below ground level(mbgl) (Figure 5.4). As the depth to the water table increases, the possibility of recharge increases because of the increased storage in aquifers. Greater weight is given to those regions where the depth to the water table is high and vice versa.

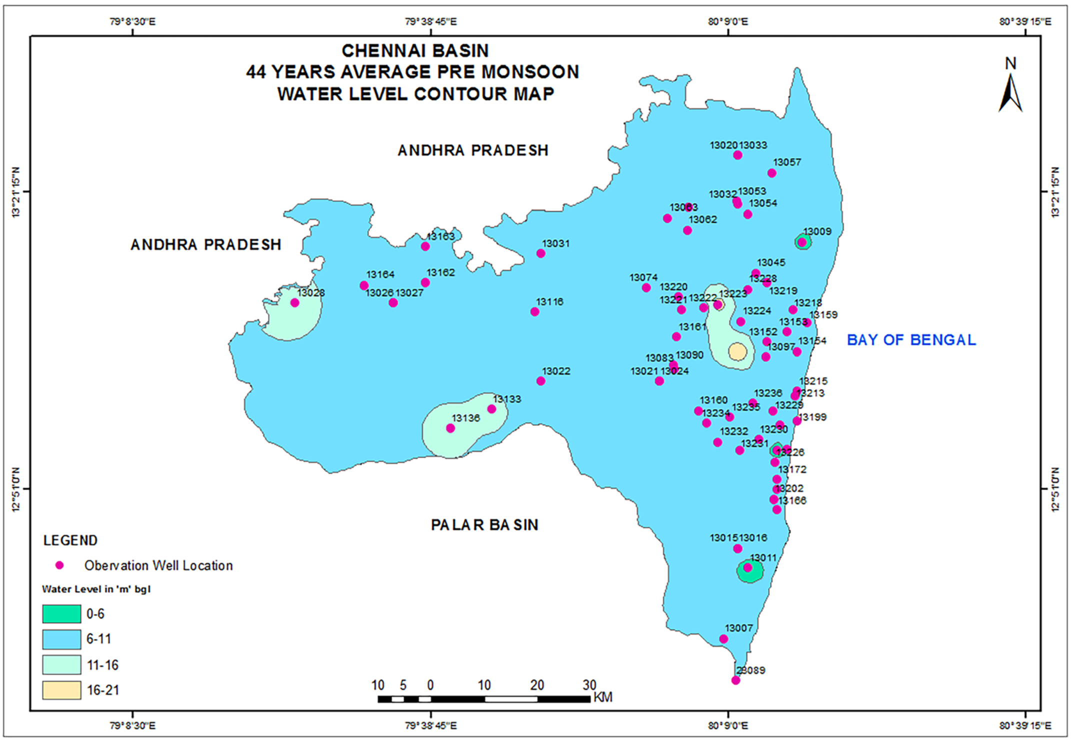

Figure 5.4: Groundwater Level Map

5.4.1.4 Mapping and analysis of rainfall

Rainfall data for the past 44 years has been collected by the India Meteorological Department (IMD). A spatial variation map of the rainfall was created with the IDW interpolation method. The minimum and maximum rainfall received in the Chennai Basin were 770 and 1570 mm, respectively. The coastal part of the basin is receiving a high amount of rainfall, compared to the western part. A spatial map of rainfall in the Chennai Basin is given in Figure 5.5.

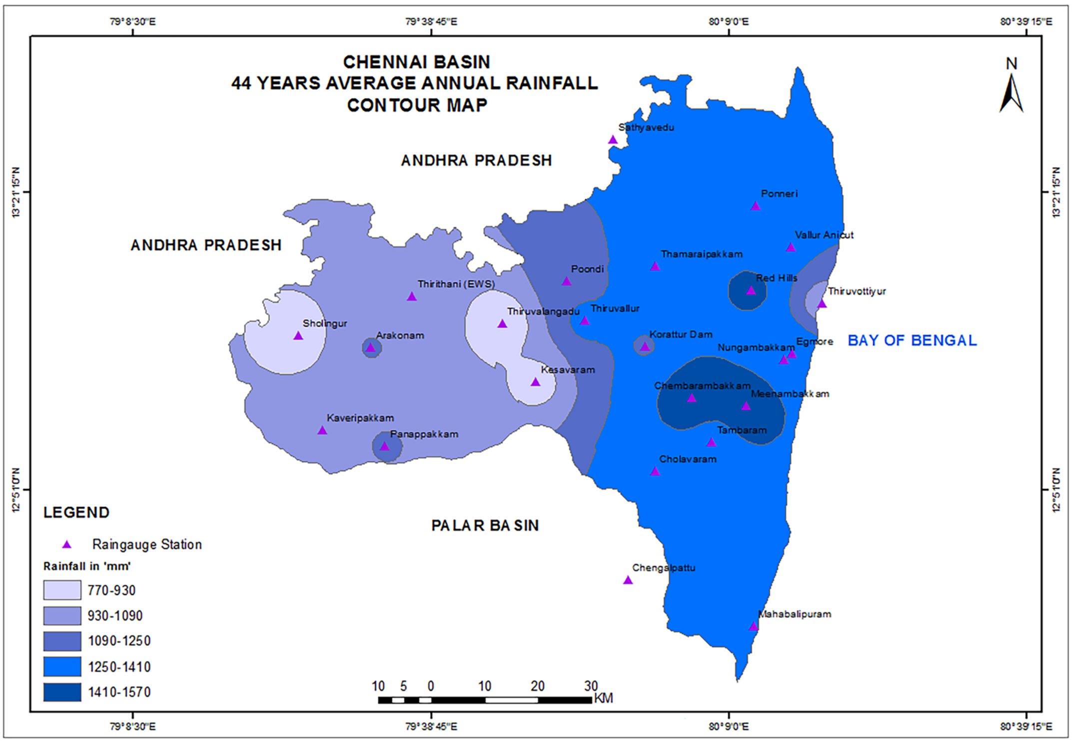

Figure 5.5: Rainfall map

5.4.1.5 Mapping and analysis of Lithology

The geology of an area is one of the key factors in groundwater potential zone delimitation. Various geological formations have different water bearing capacities and subsurface flow characteristics. A considerable variation in the water bearing capacities may be found between sedimentary to Igneous and metamorphic rocks of recent to Precambrian periods(see Figure 5.6). The other principal factor is the weathering of the rocks, which increase the groundwater potential of the area. The Chennai basin exhibited a wide range (sedimentary-Metamorphic-Igneous) of geological formations. Starting from the eastern coastal region, a long stretch of coastal Alluvium is observed throughout the study area and charockites in the southern edge. From the middle to north alluvial formation begins and extend to greater areas towards the west. Laterites are found in the northern part of the basin and also spread in between the alluvial formations. In the southern part, just near to the charnockite, there are thick shale sandstone formations. The western end of the area is marked by biotite- hornblende-gneiss, with lengthy patch of hornblende-epidote. Geology of the area suggests that the possible high groundwater bearing formations are alluvium and sandstones. Considering the geology of the area, alluviums, sandstone are promising locations for groundwater development. However, the degree of weathering, lineament and fractures determine the same for the hard rock formations.

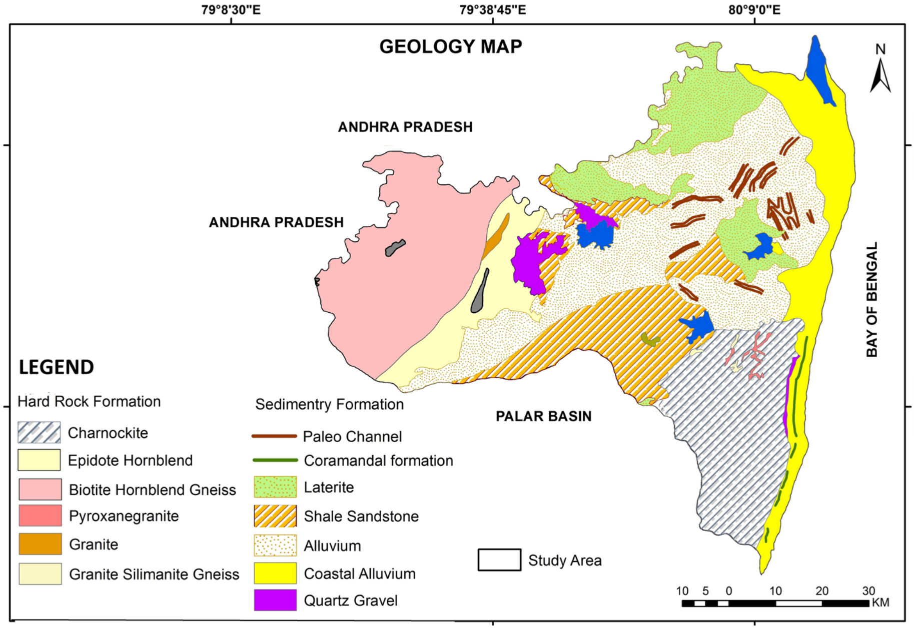

Figure 5.6: Geological map of the study area

5.4.1.6 Mapping and analysis of Drainage

The drainage network map of the Chennai basin is shown in Figure 5.7. The Chennai Basin has many rivers, tanks and reservoirs. Since the basin has mostly permeable formations as well as built-up areas, the drainage density of the basin is very low. Thus, the main features are classified as rivers, tanks/reservoirs and others. Suitable ranking is given to each feature depending on their groundwater potentiality.

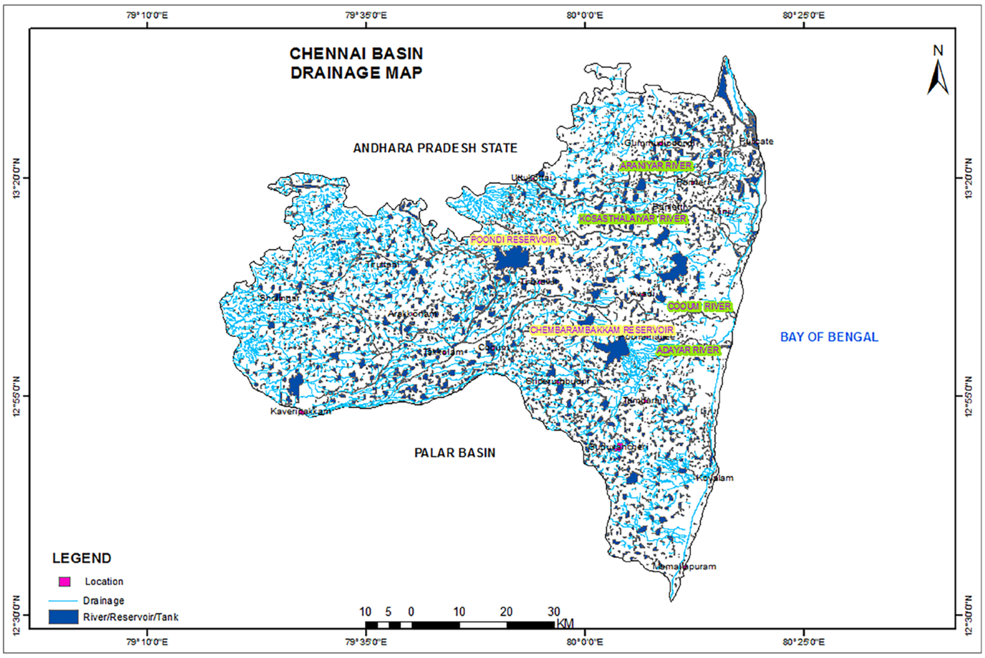

Figure 5.7: Drainage Map

5.4.1.7 Mapping and analysis of soils

Soils in the study area can be classified into Clay, clay loam, loamy sand, Sand, Sandy Clay, Sandy-clay- loam, Sandy loam, as shown in Figure 5.8. Along the beeches sandy and sandy clay loam types are present, and these formations are permeable and can be a aquifer. These formations are extensively found along the East Coast Road (ECR), and holds good for agricultural activities.

Clayey soils are found in northern region, namely Gummidipoondi, Ponneri, Minjur, Madhavaram and Manali, and in the western portion of the East Coast Road around Thiruporur. These soils have much lower infiltration rates. Weights assigned for the soil layer are mainly based on the infiltration rate. As a result, clayey soils have been given the lowest weights, while sandy soil receives the highest.

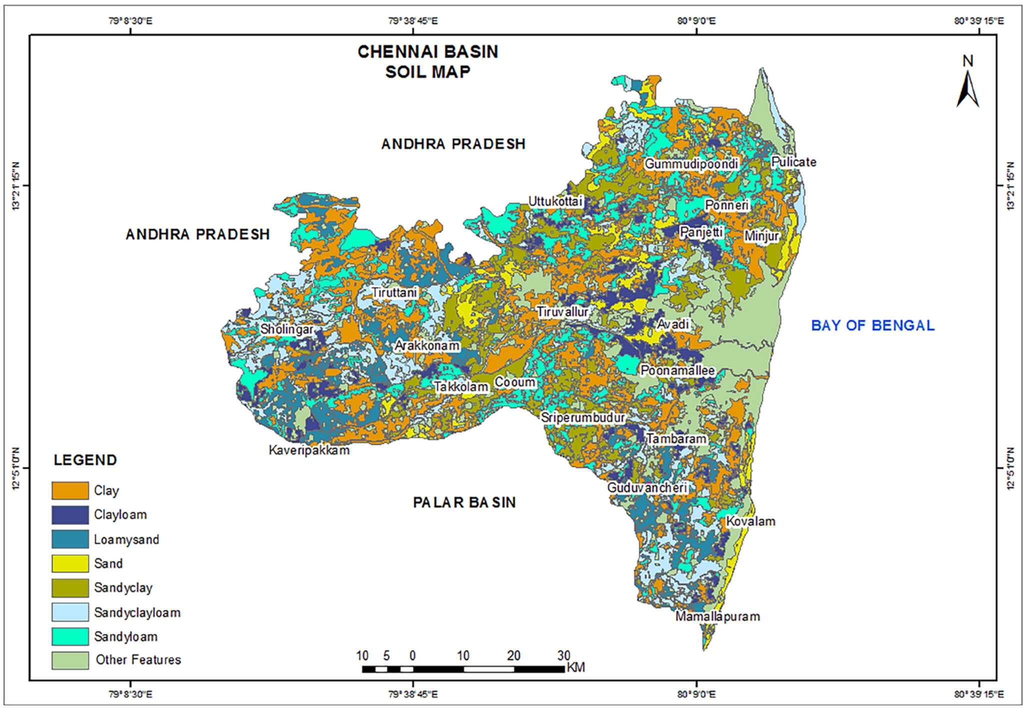

Figure 5.8: Soil map

5.4.1.8 Mapping and analysis of land use

The rapid increase in population resulted in extensive changes in the land use pattern of the CRB. Groundwater recharge is largely controlled by the landuse. Hence, a proper understanding of land use is necessary for the sustainable groundwater development. Overexploitation of water resources for various purposes has a severe impact on the water system. Increased water exploitation has led to a reduction in water recharge and groundwater storage of the area. The various land use patterns of the study area are presented in Figure 5.9. Cropland, mangroves, shrubs, and casuarina cover a majority of the study area.

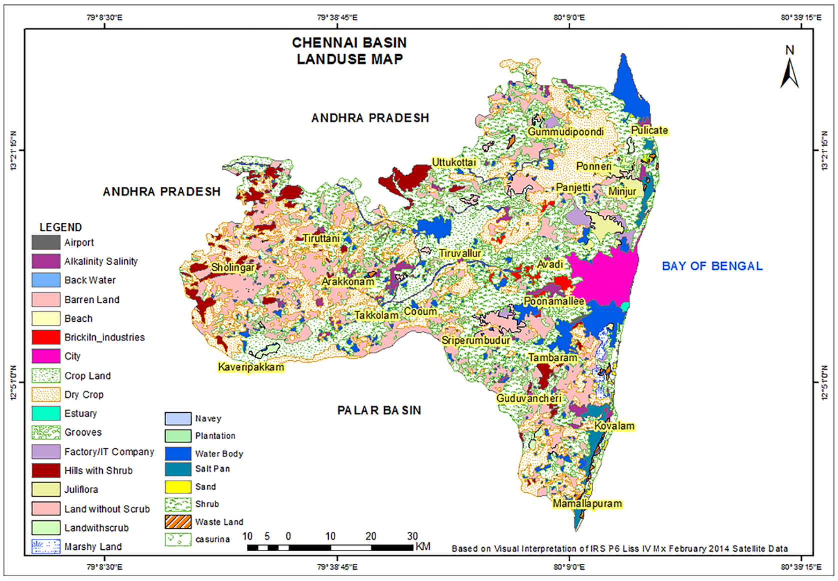

Figure.5.9: Land-use map of Chennai Basin

5.4.1.9 Mapping and analysis of Lineaments

Lineaments are rectilinear alignments observed on the surface of the earth, which are representations of geological or geomorphological events. They can be observed as straight lines in digital data, which represent a continuous series of pixels having similar terrain values. Large scale lineaments can be identified from remotely sensed images. Lineaments are the primary indicators of secondary porosity and also for potential sources of water supply. The presence of lineaments is observed in all directions in the study area. The lineament density seems to be very high in Takkolam, Cooum, Sriperumbudur, Thiruvallur, Thiruthani, etc., (Figure 5.10).

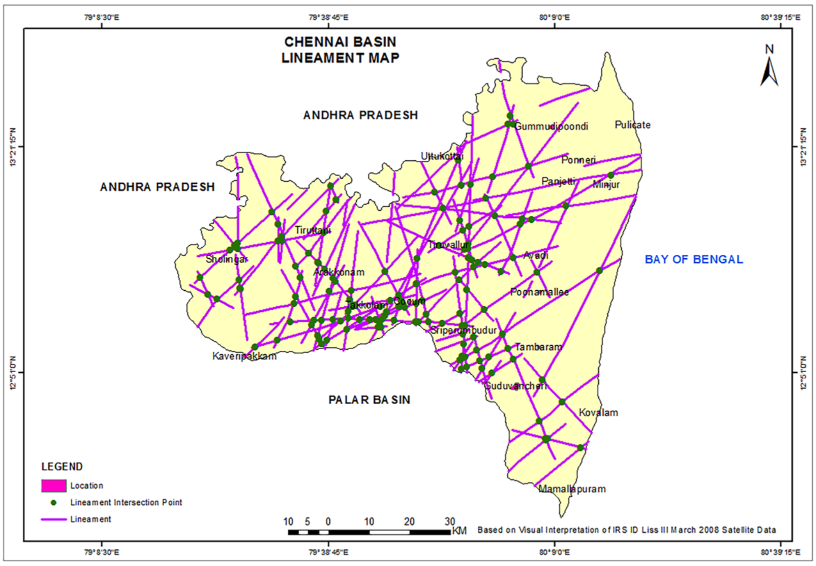

Figure 5.10: Lineaments Map

5.4.1.10 Mapping and analysis of geomorphology

The Chennai Basin has exceptionally versatile geomorphological features with beaches, Beach Ridges, Beach terraces, Buried Pediments, Wash Plains, Salt Pans, Swamps, Swale, Deltaic Plains, Deep Pediment, Pediment and Shallow Pediment, Buried Course & Channels, Tertiary Uplands, Flood Plains, Piedmont, Inter Fluveo. The presence of rivers, coastal regions, hills and plain land make this area an example of a complex geomorphological set up. It has a long coastal belt on the eastern boundary where the city of Chennai is located, with one of the thickest populated regions in southern India. The NE boundary of the study area has a long portion with Duricrust, a hard mineral layer on top of the sedimentary formations. Tertiary laterites are found as patches all along the basin. In the western part structural hills are visible. Lower Gondwana formations are seen in the southern and central parts. Upper Gondwana formations are Pediments seen in the Tambaram region of the city. At the northern part, along the state boundary of Andhra Pradesh, tertiary uplands form a larger area and the same is present in available north of the city. A detailed geomorphological map of the study area is shown in Figure 5.11.

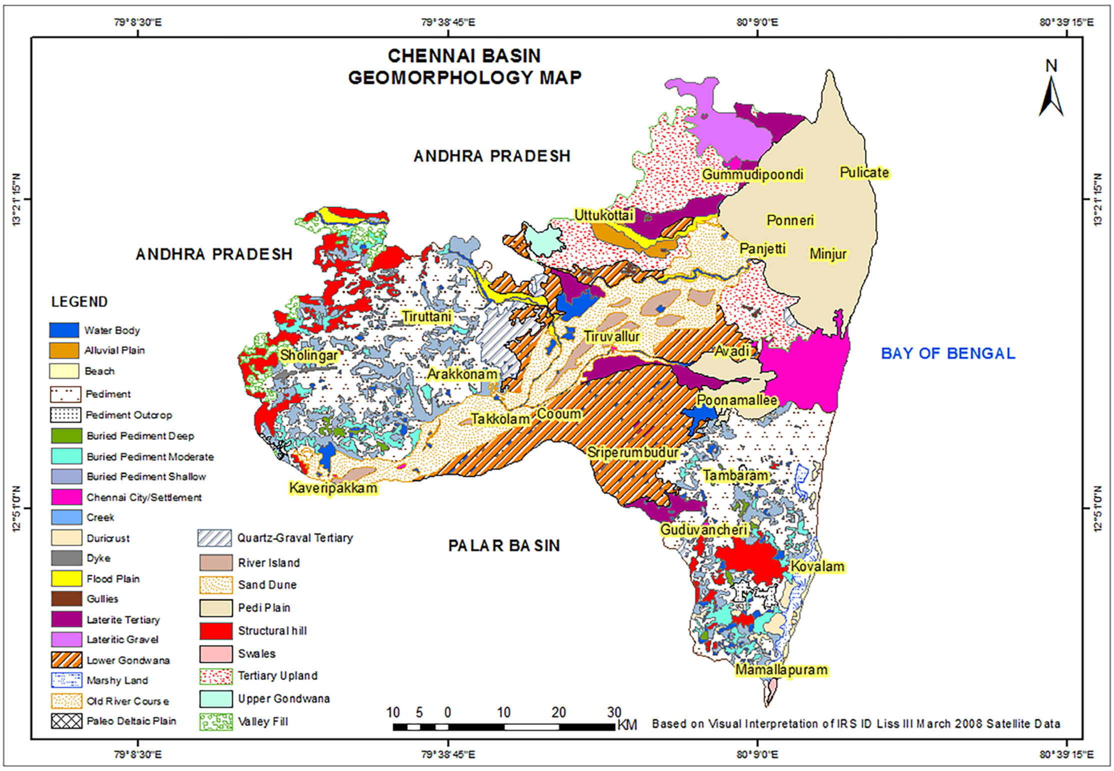

Figure 5.11: Geomorphology map of the study area.

5.4.1.11 Mapping and analysis of Depth to bed Rock

Depth to bed rock is a representation of the thickness of unconsolidated or weathered formations in the area. The depth to bed rock of CRB varied from 11 to 829m (Figure 5.12). Southern coastal regions and western part of CRB has weathered thickness upto 45m. The deepest depth to bed rock is found in the extreme north region. Based on these values, three major categories such as poor, moderate and very good, with corresponding weights 5 ,6 and 8 were assigned for the layer.

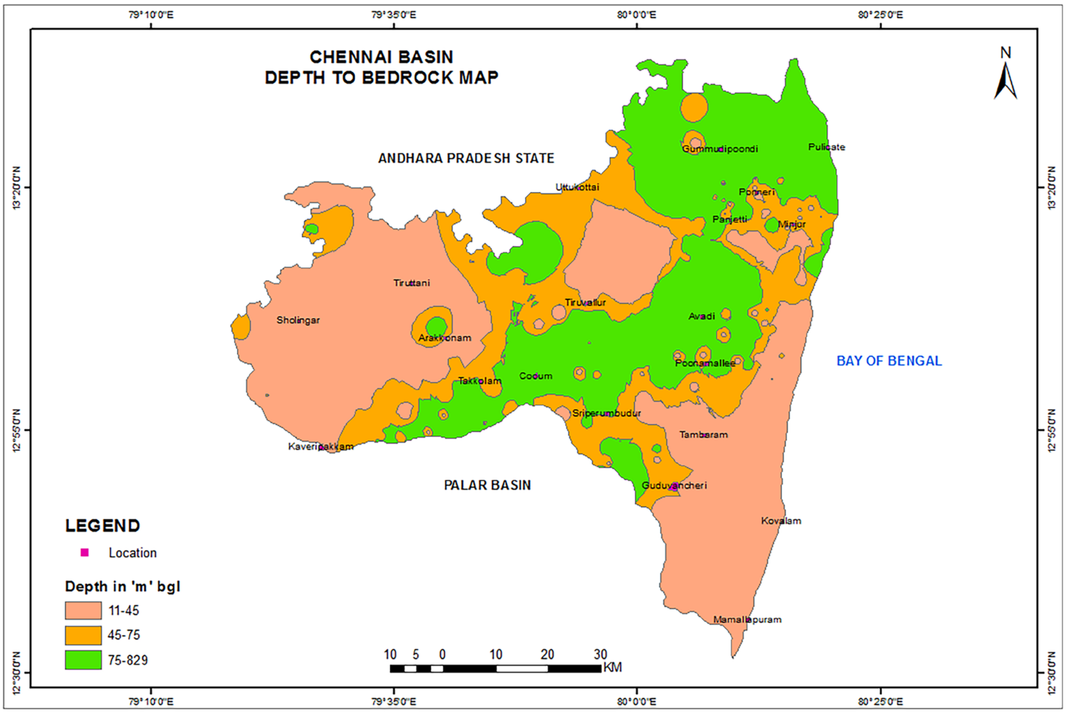

Figure 5.12: depth to bed rock

5.4.2 Normalized weights for thematic maps

The pairwise comparison matrix of the groundwater prospecting thematic layers were derived based on the AHP method. The weights were normalized and the weights for individual thematic layers are calculated by eigen vector method (Table 5.4).

Table 5.5 shows the normalized weights of each layer and their corresponding total weightage. The maximum weightage shows the most influential parameter, and the minimum weightage represents the least influential parameter. In the CRB, depth to bed rock or aquifer thickness play the most important role with 20.33% weightage. With 15%, geomorphology was the second most important parameter. The relative importance of the other parameters are as follows, lineament (12.37%), land use (12%), soil (9%), drainage (8.2%), geology (6.6%), rainfall (4.9%), aspect (4.5%), water level (4.2%), and slope (2.6%).

To check the consistency of the assigned weights, the consistency ratio was calculated using the formula mentioned in the methodology. For the 11 layers (n=11), the consistency ratio was found as 0.098, which is <0.10. This means that the weight assessment was consistent.

Table 5.4: Pairwise comparison matrix of 11 groundwater prospecting parameters for AHP

Thematic Layer	Sp	A	GWL	RF	GEO	D	Sl	LU	Ln	GM	DBR
Slope (Sp)	1.00	0.33	0.33	0.50	0.50	0.33	0.33	0.20	0.25	0.25	0.25
Aspect (A)	3.00	1.00	0.50	0.50	0.33	0.33	0.50	0.50	0.50	0.33	0.50
Ground Water level (GWL)	3.00	2.00	1.00	0.25	0.25	0.25	0.25	0.33	0.25	0.25	0.50
Rainfall (RF)	2.00	2.00	4.00	1.00	0.33	0.25	0.33	0.25	0.50	0.25	0.25
Geology (GEOL)	2.00	3.00	4.00	3.00	1.00	0.50	0.33	0.33	0.50	0.33	0.25
Drainage(D)	3.00	3.00	4.00	4.00	2.00	1.00	0.50	0.25	0.50	0.33	0.33
Soil (SL)	3.00	2.00	4.00	3.00	3.00	2.00	1.00	0.50	0.33	0.50	0.33
Landuse (LU)	5.00	2.00	3.00	4.00	3.00	4.00	2.00	1.00	0.33	0.50	0.33
Lineament (Ln)	4.00	2.00	4.00	2.00	2.00	2.00	3.00	3.00	1.00	0.50	0.25
Geomorphology (GM)	4.00	3.00	4.00	4.00	3.00	3.00	2.00	2.00	2.00	1.00	0.50
Depth to bed rock (DBR)	4.00	2.00	2.00	4.00	4.00	3.00	3.00	3.00	4.00	2	1.00
SUM	**34.00**	**22.33**	**30.83**	**26.25**	**19.42**	**16.67**	**13.25**	**11.37**	**10.17**	**6.25**	**4.50**

Table 5.5: Calculation of normalized weights for 11 thematic layers of CRB

	Sp	A	GWL	RF	GEO	D	Sl	LU	Ln	GM	DBR	Normalized weight
Sp	0.03	0.01	0.01	0.02	0.03	0.02	0.03	0.02	0.02	0.04	0.06	0.0257
A	0.09	0.04	0.02	0.02	0.02	0.02	0.04	0.04	0.05	0.05	0.11	0.0455
GWL	0.09	0.09	0.03	0.01	0.01	0.02	0.02	0.03	0.02	0.04	0.11	0.0429
Rf	0.06	0.09	0.13	0.04	0.02	0.02	0.03	0.02	0.05	0.04	0.06	0.0491
GEOL	0.06	0.13	0.13	0.11	0.05	0.03	0.03	0.03	0.05	0.05	0.06	0.0665
D	0.09	0.13	0.13	0.15	0.10	0.06	0.04	0.02	0.05	0.05	0.07	0.0822
Sl	0.09	0.09	0.13	0.11	0.15	0.12	0.08	0.04	0.03	0.08	0.07	0.0911
LU	0.15	0.09	0.10	0.15	0.15	0.24	0.15	0.09	0.03	0.08	0.07	0.1188
Ln	0.12	0.09	0.13	0.08	0.10	0.12	0.23	0.26	0.10	0.08	0.06	0.1237
GM	0.12	0.13	0.13	0.15	0.15	0.18	0.15	0.18	0.20	0.16	0.11	0.1512
DBR	0.12	0.09	0.06	0.15	0.21	0.18	0.23	0.26	0.39	0.32	0.22	0.2033
	1	1	1	1	1	1	1	1	1	1	1	1.000

Table 5.6: Weight assessment and normalization of different features of groundwater prospecting thematic layers

Factor	Class	Value	Normalized weight of features	Level of Suitable
Geomorphology	Chennai City	2	0.0122	Poor
	Pediment	2	0.0122	Poor
	Buried Pediment Shallow	2	0.0122	Poor
	Buried Pediment Moderate	3	0.0183	Moderate
	Tank	8	0.0488	Very Good
	Buried Pediment Deep	6	0.0366	Very Good
	Structural hill	2	0.0122	Poor
	Valley Fill	8	0.0488	Very Good
	River	9	0.0549	Very Good
	Flood Plain	9	0.0549	Very Good
	Lateritic Gravel	3	0.0183	Moderate
	Duricrust	2	0.0122	Poor
	Marshy Land	7	0.0427	Very Good
	Tertiary Upland	5	0.0305	Good
	Sand Dune	6	0.0366	Good
	Pediment Outcrop	2	0.0122	Poor
	Settlement	2	0.0122	Poor
	Swales	2	0.0122	Poor
	Beach	5	0.0305	Good
	Paleo Deltaic Plain	7	0.0427	Very Good
	Quartz-Graval Tertiary	4	0.0244	Moderate
	Upper Gondwana	8	0.0488	Very Good
	Pulicate Lake	7	0.0427	Very Good
	Alluvial Plain	8	0.0488	Very Good
	Laterite Tertiary	4	0.0244	Moderate
	Creek	5	0.0305	Good
	B Canal	7	0.0427	Very Good
	River Island	7	0.0427	Very Good
	Lower Gondwana	7	0.0427	Very Good
	Dyke	2	0.0122	Poor
	Gullies	2	0.0122	Poor
	Pedi Plain	2	0.0122	Poor
	Old River Course	9	0.0549	Very Good

Table 5.6 Continued

Factor	Class	Value	Normalized weight of features	Level of Suitable
Geology	Biotite Hornblende Gnies	4	0.0727	Poor
	Quartz Gravel	5	0.0909	Moderate
	Sandstone Conglomerate	5	0.0909	Moderate
	Laterite	7	0.1273	Good
	Shale Sandstone	5	0.0909	Moderate
	Waterbodies	4	0.0727	Poor
	Alluvium	8	0.1455	Very Good
	Epidote Hornblend	5	0.0909	Moderate
	Granite	5	0.0909	Moderate
	Charnockite	7	0.1273	Good
Drainage	River	8	0.4000	Very Good
	Tank/Reservoir	9	0.4500	Very Good
	Others	3	0.1500	Poor
Water Level	0-6	2	0.1429	Poor
	6-11	5	0.3571	Moderate
	6-21	7	0.5000	Good
Soil	Sandy loam	3	0.0667	Moderate
	Loamy sand	3	0.0667	Moderate
	Habitation	2	0.0444	Poor
	Waterbody	8	0.1778	Very Good
	Sandy clay loam	6	0.1333	Good
	Sandy clay	6	0.1333	Good
	Clay	3	0.0667	Poor
	Sand	6	0.1333	Good
	Clay loam	6	0.1333	Good
	Misce	2	0.0444	Poor
Rainfall	770-930	1	0.1000	Poor
	930-1090	2	0.2000	Moderate
	1090-1250	3	0.3000	Good
	1250-1410	4	0.4000	Very Good

Table 5.6 Continued

Factor	Class	Value	Normalized weight of features	Level of Suitable
Landuse	Barren Land	2	0.0211	Poor
	Brickiln_industries	2	0.0211	Poor
	Beach	3	0.0316	Moderate
	HF Ind_IT	4	0.0421	Moderate
	Airport	2	0.0211	Poor
	Alkalinity Salinity	2	0.0211	Poor
	Back Water	2	0.0211	Poor
	casurina	3	0.0316	Moderate
	City	2	0.0211	Poor
	Estuary	2	0.0211	Poor
	Groves	4	0.0421	Moderate
	Crop Land	5	0.0526	Good
	Juliflora	4	0.0421	Moderate
	Marshy Land	5	0.0526	Good
	Navey	2	0.0211	Poor
	Plantation	5	0.0526	Good
	Pulicat Lake	5	0.0526	Good
	River	8	0.0842	Very Good
	Salt Pan	2	0.0211	Poor
	Sand	8	0.0842	Very Good
	Shrub	5	0.0526	Good
	Waste Land	3	0.0316	Moderate
	Landwithscrub	4	0.0421	Moderate
	Land without Scrub	2	0.0211	Poor
	Hills with Shrub	2	0.0211	Poor
	Dry Crop	7	0.0737	Good
Lineament	Buffer 500	6	0.4000	Good
	Buffer 750	8	0.5333	Very Good
	Others	1	0.0667	Poor
Depth to Bed Rock	11-45	5	0.2632	Poor
	45-75	6	0.3158	Moderate
	75-829	8	0.4211	Very Good

Table 5.6 Continued

Factor	Class	Value	Normalized weight of features	Level of Suitable
Aspects	Flat	9	0.1957	Very Good
	North 0-22.5	7	0.1522	Very Good
	Northeast 22.5-67.5	5	0.1087	Good
	East 67.5-112.5	6	0.1304	Good
	Southeast 112.5-157.5	8	0.1739	Very Good
	South 157.5-202.5	4	0.0870	Moderate
	Southwest 202.5-247.5	3	0.0652	Moderate
	West 247.5-292.5	2	0.0435	Poor
	Northwest 292.5-337.5	1	0.0217	Poor
	North 337.5-360	1	0.0217	Poor
Slope	0-2.42	7	0.4375	Very Good
	2.42-7.58	4	0.2500	Moderate
	7.58-15.61	3	0.1875	Moderate
	15.61-38.81	2	0.1250	Poor

5.4.3 Groundwater Potential Zones

In this study, groundwater potential zones were identified using AHP aided methodology. The output map generated by Weighted Linear Combination (WLC) shows five different classes such as very poor, poor, moderate, good and very good potential for groundwater. The results are presented in Table 5.7 and the spatial variation map for the groundwater potential is shown in Figure 5.13.

The groundwater potential is very poor in the western regions especially the northwestern region and the coastal region of the Chennai and Kancheepuram area. It is 15.4% of the total area with a land area of 930.9 km^2. Geologically, the western region is mostly charnockite formation and the coastal region is alluvium deposits. It is obvious that the massive charnockite is not a good aquifer unless there are factures or joints. In general alluviums have good water bearing capacity, but the potential is showing low in the analysis. This can be explained by the over-exploited aquifer system, especially in the South Chennai coastal aquifer. Increased urbanization and population growth directly affect the groundwater potential of these regions. These results agree with the land use map of the study area. There are many barren lands in the western region, and this is also a reason for the poor potential of this area. The second classification of groundwater potential was "poor", it is also located mostly in the same geographic regions of the very poor category and possess the same geological and geomorphological characteristics. This category is second largest among the five classes, with a share of 22.86% spread over 1379.2 km^2 in the CRB. Moderate potential zones are dominant among all classes with an area of 1636 Km^2, 27% of the total land area of the CRB. Moderate potential is observed throughout the basin, however, it is largely located in the SE and NE regions, as well as the central part. The major geology for this group is alluvium, coastal alluvium, and charnockite formations. There is a patch in the middle area of the basin extending north from Gummidipoondi in the Thiruvallur district to south in Kaveripakkam in the Vellore district which has good and very good groundwater potential. This includes some bordering portions of the Chennai district as well. Both these classes together constitute 34% of the study area and spread over 2100 km^2. This area is mostly covered by alluvial formations resulting from the river system and its deposits.

Table 5.7: Classification of Groundwater Potential Zones in CRB

Groundwater potential class	Area (Km^2)	% Of Area
Very Poor	930.9	15.4
Poor	1379.3	22.8
Moderate	1636.2	27.00
Good	1369.1	22.6
Very Good	743.9	12.3

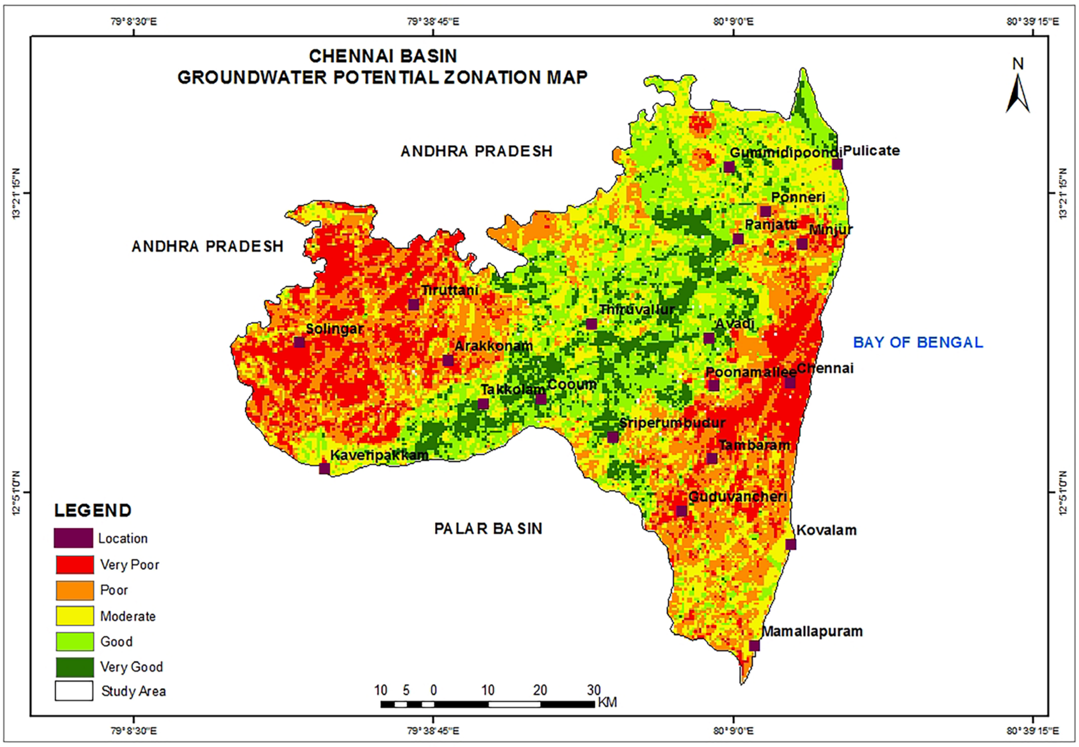

Figure 5.13: Spatial variation map of Groundwater potential in CRB

5.4.4 Cross verification of the Groundwater potential zones with Bore hole data

The groundwater potential map is created based on the available maps of different factors using GIS based AHP method. However, it is necessary to verify the results using actual data collected from the field. This study used 51 bore holes, in which the specific capacity was compared with the groundwater potential mapped using GIS based method. The Yield data from the field is classified into low yield (<3 lps), moderate yield (3-6 lps) and high yield (> 6 lps). The details of the procedure and the results of the comparison are provided in Table 5.8.

The accuracy calculations were done as follows:

- Number of boreholes = 51
- Number of boreholes agreed with the result of mapping = 40
- Number of boreholes disagreed with the result of mapping = 11
- Accuracy of the potential mapping = 40/51 ×100 = 78.43%

This suggests that among the 51 wells, the prediction was reliable in 40 wells. This means that 78% of the potential delineation agreed with the actual data from the field. The use of AHP based groundwater potential zonation thus proved to be successful and can be adopted as a cost-effective groundwater prospecting method.

Table 5.8: Comparison of Groundwater potential zones with actual field data

Location name	X	Y	Actual Specific Capacity	Interference on actual yield	Expected yield from map	Suitability Agreement
Velachery	80.23	12.98	2.71	Low	Low to moderate	Agree
Ayyanavaram	80.23	13.10	4	Moderate	moderate	Agree
Tandiarpet	80.28	13.13	0.61	Low	Very low to low	Agree
Mandaiveli	80.25	13.01	0.56	low	Very low to low	Agree
Besent Nagar	80.27	13.00	12	high	Moderate to high	Agree
Arumbakkam	80.21	13.07	3.47	Moderate	Very low to low	disagree
Redhills	80.19	13.19	1	low	Moderate	disagree
Tirumalisai	80.06	13.05	1.5	low	Moderate	disagree
Pallavaram	80.15	12.97	2.11	low	Low to moderate	Agree
Pallikaranai	80.20	12.94	3.11	Moderate	Low to moderate	Agree
Solinganallur	80.23	12.90	4.66	Moderate	Low to moderate	Agree
Alathur	80.18	12.69	2.28	low	low to moderate	Agree
Sembakkam	80.13	12.71	2.9	low	poor to moderate	agree
Thaiyur	80.20	12.78	1.5	low	Low to moderate	Agree

Table 5.8 Continued

Location name	X	Y	Actual Specific Capacity	Interference on actual yield	Expected yield from map	Suitability Agreement
Ottivakkam	80.12	12.70	2.5	low	Low to moderate	Agree
Melakottaiyur	80.15	12.84	2.11	low	Very low to low	Agree
Madampakkam	80.05	12.83	1.9	low	Very low to low	Agree
Ponmar	80.17	12.84	4.1	Moderate	moderate	Agree
Padappai	80.03	12.88	1.42	low	Very low to low	Agree
Sriperumbadur	79.94	12.95	1.82	low	Good to very good	disagree
Purisai	79.75	12.99	2.24	low	moderate to high	disagree
Kunrathur	80.10	13.00	5.47	Moderate	Moderate to high	Agree
Thandalam	80.00	13.10	3	Moderate	Moderate to high	Agree
Ambattur	80.15	13.11	2.37	low	low	Agree
Arani	80.09	13.33	3.3	Moderate	Moderate	agree
Avadi	80.10	13.12	2.4	low	Low to moderate	agree
Ennore	80.24	13.22	1.9	low	Low to moderate	Agree
Gummidipoondi	80.13	13.40	1.12	low	moderate	disagree
Kaverirajapuram	79.75	13.17	2	low	Low to moderate	Agree
Korattur	80.01	13.08	4.5	Moderate	Moderate to high	Agree
Madhavaram	80.23	13.15	3.16	Moderate	Low to moderate	Agree
Nabalur	79.70	13.20	3.02	Moderate	poor to moderate	Agree
Nandiambakkam	80.28	13.27	7.41	high	poor to moderate	disagree
Pallipattu	79.44	13.34	2.8	Low	Low to moderate	agree
Pazhverkadu	80.33	13.42	5.02	Moderate	moderate to good	Agree
Pondeswaram	80.07	13.19	4.75	high	moderate to good	agree
Red Hills	80.18	13.19	2.47	Low	moderate to good	agree
Thandarai	80.06	13.11	2.4	Low	Low to moderate	agree
Thervoy	79.92	13.37	3.01	Moderate	Low to moderate	Agree
Thirumullaivoyal	80.13	13.13	2.26	Low	Low to moderate	Agree
Tiruthani(taluk)	79.61	13.18	3.14	Moderate	Low to moderate	agree
Tiruvotriyur	80.30	13.15	2.11	Low	moderate	disagree
Uthukkottai	79.90	13.33	3	Moderate	Low to moderate	Agree
Veppampattu	79.98	13.13	3.66	Moderate	moderate to good	Agree
Arakkonam	79.67	13.08	4.3	Moderate	Low to moderate	disagree
RK Pet	79.44	13.17	2.7	Low	Low	Agree
Panapakkam	79.57	12.92	3.23	Moderate	Low to moderate	Agree
Sumaithangi	79.44	12.90	4.34	Moderate	moderate to good	Agree
Kunnattur	79.53	13.06	4.81	Moderate	low	disagree
Sholingur	79.42	13.11	3.6	Moderate	low	disagree

5.5 Conclusions

This study used GIS, remote sensing, multi-criteria decision-making techniques, and analytical hierarchy process (AHP) for the delineation of groundwater potential zones in the Chennai River Basin (CRB). Eleven different thematic layers that has direct influence on groundwater potential were used in this study and the weights were given using AHP methodology. The resultant thematic layers were merged using overlay analysis and the groundwater potential maps were generated. According to these maps, 35% of the study area has good to very good groundwater potential, 27% has moderate potential and 38% has poor to very poor groundwater potential. Groundwater in the coastal region and the urban area shows very poor potential and the high potential is observed in the central regions. The resultant potential map was compared with the bore hole discharge data collected from the field. The specific capacity of the wells was used for comparing the potential. This analysis shows that more than 78% of the field data is matched with the predicted map. This suggests that the method has greater accuracy in mapping the groundwater potential zones with comparatively less cost.

CHAPTER 6

Climate change induced water stress evaluation in the Chennai Basin using water stress indicators

6.1 Abstract

In the Chennai River Basin (CRB), groundwater is the most important source for drinking and irrigation. This study aims to assess the water stress and drought condition characteristics over a long-term period (1971 to 2014). Rainfall - atmospheric temperature relationships, meteorological drought (with SPI) and agricultural drought using NDVI, NDWI and VCI were studied. Precipitation amount showed a positive correlation with temperature increases, suggesting the possible impact of an accelerated evaporation rate. Though there are certain exceptions, SPI values generally showed that the basin is mostly under near normal condition with SPI values ranging from -0.99 to +0.99. Results show that the values were negative in the January to July period, and positive in the August to December period. For agricultural droughts, the results were varied among the indexes. Healthy vegetation was observed in the northern and southern regions, however, more than 40% of the area was found to be water stressed. NDWI values showed that the water stressed area decreased from 90% (1991) to 57 % (2018). VCI showed that agricultural drought is prevailing and the decadal changes were found to be 40% (1991), 50% (2000), 80% (2010) and 60% (2018). The highest was in 2010. It has been found that the CRB has not severely affected by meteorological drought, but there is definite stress on agricultural sector.

6.2 Introduction

Water stress is a condition that happens when the demand for water exceeds its availability during a certain period (EEA 2018), causing deterioration of both quality and quantity. Water stress is caused natural and anthropogenic influences such as by climate change, , drought and anthropogenically by over exploitation, pollution, and landuse changes., (Mehran et al., 2017).

Climate change either positively or negatively affects water resources (Emmanuel et al., 2013). Climate change is a complex environmental phenomenon collectively affecting the environmental components such as atmosphere, lithosphere and hydrosphere. The expected outcomes of climate changes are a continuous increase in temperature, changes in precipitation patterns, a rising sea level due to the melting of arctic ice, variation in the duration of seasons and more droughts and water stress (NASA https://climate.nasa.gov/effects/). The 5th assessment report of the Intergovernmental panel on climate change (IPCC) on climate change reported in 2013 that the

Global Mean Surface Temperature (GMST) has increased since the 19th century. This agrees with earlier reports (3rd IPCC report, Houghton et al., 2001) of increased summer drying in mid-latitude continental interiors in the 20th century. Similarly, Dai et al., (2004) found that very dry areas (defined in terms of the PDSI) around the globe have more than doubled since the 1970s. There are also different opinions on the same, as Lloyd-Hughes and Saunders (2002) reported not much change in extreme and/ or moderate drought conditions during the 20th century and the same result was reported by Schrier et al., (2006) in their studies related to summer moisture availability over Europe between 1901 and 2002. However, water stress is a fact and the reasons must be quantified and an appropriate remedy must be taken.

India faces severe water shortage with its never-ending population growth (1.2 billion as of 2011, GoI) and subsequent increase of agricultural production, industrialization and urbanization. Erratic distribution of rainfall causing floods and droughts, overexploitation of groundwater resources, water pollution, poor sanitation and poor management of water resources are also major contributing factors of the water crisis (Cronin et al., 2014). The situation is no different in the Chennai Basin, which includes the Chennai Metropolitan Area (CMA) and fast-growing peri-urban areas. However, water stress is an age-old problem in Chennai, mainly due to the lack of perennial rivers. At present, the requirement of the city is 1,100 MLD (million liters of water a day), while the supply is just 550 MLD (Times of India 2017).

Chennai receives approximately 1290 mm of rainfall each year, more than the national average (Janakarajan et al., 2006). The main rainy season is the northeast monsoon. Of the total rain received, only 5% reaches groundwater while the rest drains to the Bay of Bengal. The reduction in the total recharge against the extraction resulted in over exploitation of 80% of groundwater reserves (Janakarajan et al., 2006). However, rainfall patterns have changed recently and more frequent floods and droughts have been observed in the past decade. This is the principle reason for conducting this study at a large scale. While there have been hydrological, meteorological, agricultural and socioeconomic droughts, this study focus on meteorological droughts.

Several researchers have studied increased drought and water stress all over the world specifically central Europe (Smith et al., 1996), Mediterranean region (Watson et al., 1997); Mexico (Giddings et al., 2005), Aravalli India (Bhuniyan et al., 2006), Czechia (Trnka et al., 2009), Elbe Basin (Krysanova et al., 2008), China (Zhai et al., 2010). Cameroon (Cheo et al., 2013) and many more. There are several indices which have been suggested by these researchers over the years for the quantification of water stress. A detailed summary of drought concepts is provided in the classical paper by Mishra and Singh (2010).

In this chapter, a detailed analysis of seasonal drought dynamics was made with an aim to understand the spatio-temporal, meteorological and vegetative drought patterns in the Chennai River Basin (CRB). This study used the standardized Precipitation Index (SPI), the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI), and the Vegetation Condition Index (VCI) for a better understanding of drought scenarios over a long-term period. Geographical Information Systems (GIS) were also employed in the mapping of spatial variation of droughts over the years.

6.3 Materials and Methods

6.3.1 Data collection and sources

To study the water stress of the CRB, monthly rainfall data and average annual temperature data were used. A total of 28 rain gauge stations were found with different governmental agencies such as the Indian Meteorological Department (IMD), the Institute of Water Studies, Chennai and the Central Groundwater Board (CGWB) (see Table 6.1). Most of the stations are maintained by the IMD. Among the available stations, however, few were excluded due to the missing and heterogeneous nature of the data. For ease of understanding, five representative rain gauge stations were selected from, one each from north, south, east, west and central parts of the basin. The climatic data was collected from the Thiruthani Climatic Station, located in the Thiruvallur District, which represents the whole Chennai Basin.

Table 6.1: Locations of the selected rain-gauge stations in the Chennai River Basin

Name of Station	Longitude (X)	Latitude (Y)	Location
Numgampakkam	80.24	13.07	East of CRB
Mahabalipuram	80.18	12.61	South of CRB
Ponneri	80.20	13.33	North of CRB
Thiruvallur	79.91	13.14	Middle of CRB
Sholingur	79.42	13.11	West of CRB

6.3.2 Time Series Analysis

Time series analysis was conducted for variation in temperature and precipitation at the regional level. This procedure is performed by the Microsoft Excel program and the results were compared and discussed using standard methods.

6.3.3 Drought indices

6.3.3.1 Meteorological Drought assessment using Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) is a measure of precipitation shortages and related drought characteristics or an extreme wet event for a specific time-period of the given area. SPI convert the total aggregated precipitation for a selected period, generally 1 to 24 months (Dubrovsky et al., 2009). Long term (>30 years) precipitation data is required for the calculation of SPI and which is fitted to a probability distribution. The calculation of SPI (McKee et al., 1993; Hughes and Saunders 2002) is as follows,

1. In the initial step, the probability density function representing the time-series of the observed rainfall is calculated.
2. The time series of rainfall can be chosen according to the need of the study like, 3, 6, 9, 12, and 24 months
3. After the probability density function is calculated, the cumulative probability of the observed precipitation is evaluated.
4. To the cumulative probability distribution, the inverse normal (Gaussian) function (mean=1 and variance=1), is applied and results in SPI.

A positive SPI value represents precipitation excess with respect to median precipitation of the region while negative SPI shows the precipitation deficit. So drought is characterized by an acute negative value of SPI, from moderately dry conditions ($-1.0 > SPI > -1.49$) to severely dry ($-1.5 > SPI > -1.99$) and extremely dry conditions ($SPI < -2.0$). The breaking point of drought based on SPI is -1.0, which is considered as the beginning of a drought (McKee et al., 1993). A detailed classification of SPI values is provided in Table 6.2.

Table 6.2: Standard drought classification using SPI

SPI Value	Drought Classification
2.0 and more	Extremely Moist
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

6.3.3.2 Normalized Difference Vegetation Index

Normalized Difference Vegetation Index (NDVI) is the most commonly used vegetation index, indicating the volume of vegetation cover in the land. NDVI was first suggested by Rouse et al., (1973) as an index of vegetation health and density. It is calculated as,

$$NDVI = (b_{NIR} - b_{RED})/(b_{NIR} + b_{RED})$$

where b_{NIR} and b_{RED} are the reflectance in the NIR and red bands respectively. NDVI values vary from -1 to +1. This value is dependent upon the reflectance from the red and NIR channels. High values of NDVI suggest healthy vegetation and lower values suggest comparatively little or no vegetation.

6.3.3.3 Normalized Difference Water Index (NDWI)

The Normalized Difference Water Index (NDWI) is a modified version of the NDVI, initially proposed by Gao (1996). As with others, this index is also calculated from the satellite data from Near-Infrared (NIR) and Short Wave Infrared (SWIR) channels. SWIR is controlled by variation in the water content of vegetation as well as spongy mesophyll structure in vegetation covers. On the other hand, NIR does not depend on water content, but largely depending on the internal leaf structure and dry matter (http://edo. jrc.ec.europa.eu/documents/factsheets/factsheet_ndwi.pdf). As NDWI is calculated from these two, better accuracy in monitoring vegetation water content is possible (Biswal et al., 2014). It is calculated as follows,

$$NDWI = (\lambda_{NIR} - \lambda_{SWIR})/(\lambda_{NIR} + \lambda_{SWIR})$$

where λ_{NIR} = spectral reflectance in near infrared region and λ_{SWIR} = spectral reflectance in shortwave infrared region. The variation of NDWI is also varied between -1 to +1, representing the lower to highest leaf water content.

6.3.3.4 Vegetation Condition Index (VCI)

Kogan (1995) suggested the Vegetation Condition Index (VCI) as an indicator of moisture content and difference in vegetation. This index is derived from the NDVI values and is calculated as follows,

$$\mathrm{VCI} = \frac{\mathrm{NDVIi} - \mathrm{NDVImin}}{\mathrm{NDVImax} - \mathrm{NDVImin}} \times 100$$

where NDVIi is the smoothed 10-day NDVI, and NDVImax and NDVImin are the absolute maximum and minimum NDVI, respectively. This modified version of NDVI can indicate the drought condition, which was not possible by NDVI (Patel and Yadav 2015). The other advantage is that VCI is not dependent on geographical locations, time or the type of vegetation, thus a comparison of the results from different locations is possible (Bhuiyan et al., 2006).

VCI values are expressed in percentages in which zero percentage representing bad vegetation while 100 is the optimal. The general classification is as follows i.e., stress (<50%), fair (50%), above normal (50- 100%) (Kogan 1995). In extreme cases the value equals 100%, indicating that the NDVI value of that decade equals NDVImax.

6.4 Results and Discussion

6.4.1 Time Series Analysis of Temperature and Precipitation

The two important parameters that are considered here are temperature and precipitation. For the whole basin, the main climate data station is Thiruthani in the Thiruvallur district. Monthly average temperature data is available for 40 years, starting from 1974. This data was used to plot a time series graph for yearly temperature variations. The annual average temperature varied between 27.15 and 35.68°C, with an average of 32.12°C. The trend line for the temperature shows that the temperature of the basin is increasing gradually (see Figure 6.1).

On the other hand, the Chennai Basin has more than 26 rain gauge stations which measure daily rainfall. This study has calculated the annual rainfall for years between 1974 to 2014. The average rainfall varied between 626 and 1763 mm, with an average of 1067 mm. There were considerable fluctuations in rainfall observed over the years. However, a slightly positive trend was shown by the precipitation curve (Figure 6.2).

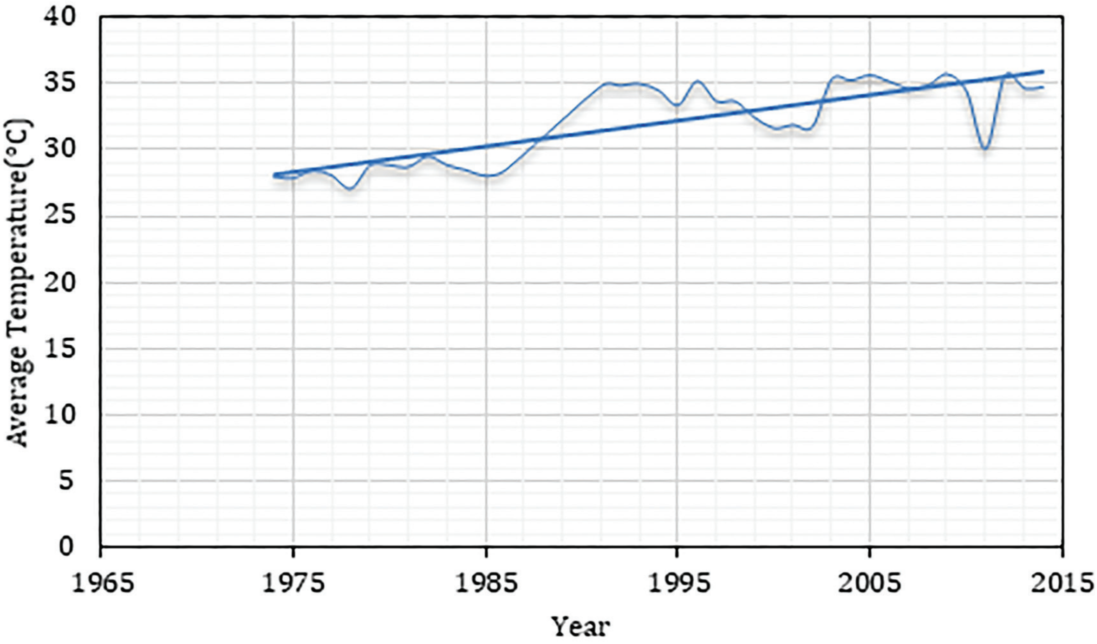

Figure 6.1: Annual Average Temperature (1974 to 2014) in the Chennai River Basin

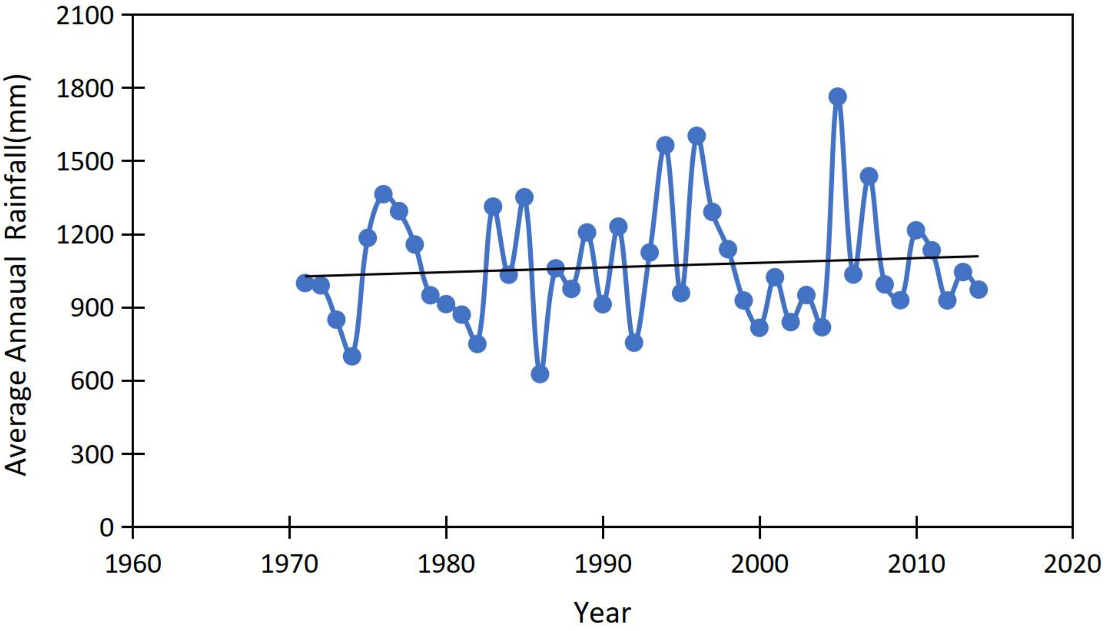

Figure 6.2: Annual Average Rainfall (1971 to 2014) in the Chennai River Basin

A relationship between temperature and rainfall in the CRB were established (see Figure 6.3). Studies show that, while minimum temperatures may not correlate with rainfall, maximum temperatures do (Nicholls et al., 1996). The most commonly observed impact for rising temperatures is an intensification of the water cycle and a subsequent increase in evaporation (https://pmm.nasa.gov/resources/faq/how- does-climate-change-affect-precipitation). As seen from Figure 6.3, precipitation in the CRB has a positive trend along with the increasing temperatures. Similar observations were made by Nicholls et.al. (1996) in Australia. In general, if there is an increase in atmospheric temperature, the rate of evaporation increases. This will result in the accumulation of water vapours in the atmosphere and increase the rainfall amount (Emmanuel et al., 2013). However, this may be restricted to storm affected areas, where the increased rainfall and flooding may occur. Usually, a storm follows a course while moving on the land or towards the sea, generally known as a storm-track. So, the possibility of high rainfall is mostly confined to storm tracks and those areas away from this may get comparably less rainfall and, thus, are prone to drought.

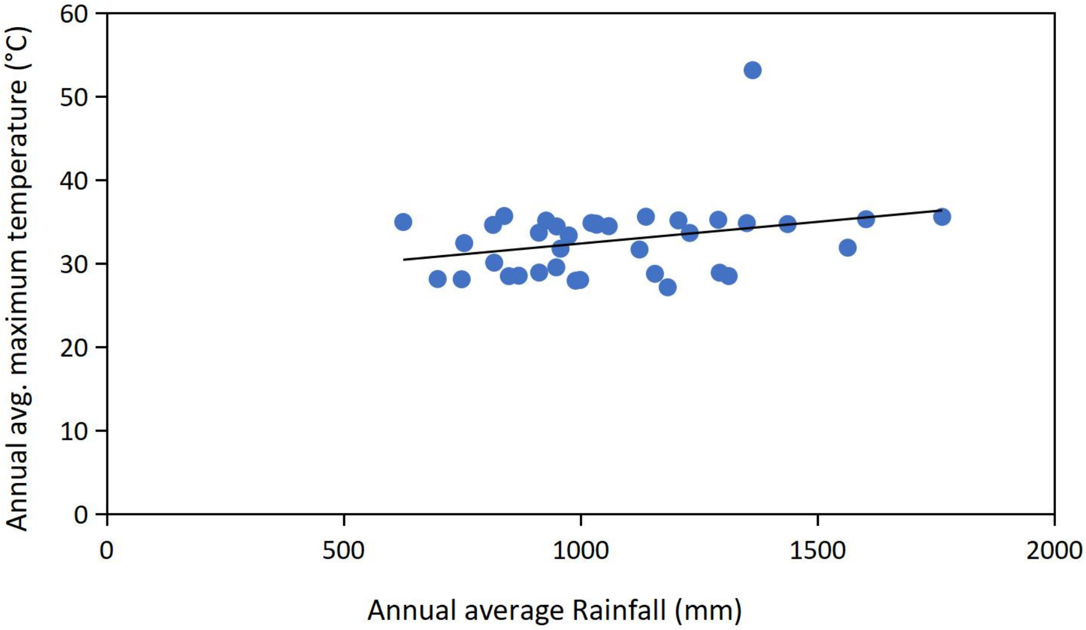

Figure 6.3: Correlation between Rainfall and Temperature in CRB

6.4.2 Hydrological and Vegetation Drought analysis

6.4.2.1 Standardized Precipitation Index (SPI)

To calculate the SPI, five rain gauge stations were selected depending on their geographical locations in the CRB: Numgampakkam (east), Mahabalipuram (south), Ponneri (north), Thiruvallur (middle) and Sholingur (west). In the CRB, the rainy season extends from August/ September to October/December, though in exceptional cases, it extends until the beginning of January. Monthly and yearly SPI values have been calculated. Monthly and yearly SPI values were calculated. Bivariate plots of SPI values for post- monsoon season (January), pre-monsoon (July) and the yearly SPI from 1971 to 2014, were drawn for each selected rain-gauge stations

In the Nungampakkm station (see Figure 6.4), the SPI value for all 44 years falls in the near normal class (-0.99 to 0.99), in other words, neither wet nor dry. This trend is more or less followed by pre- and post- monsoon seasons, with some exceptions. For example, i.e., the year 1972, January SPI was 1.38 suggesting moderately wet category this may be due to the extended rainy season to January in this year. Likewise, the years 1975, 1981, 2007 and 2011 were moderately wet in the pre-monsoon (July) season.

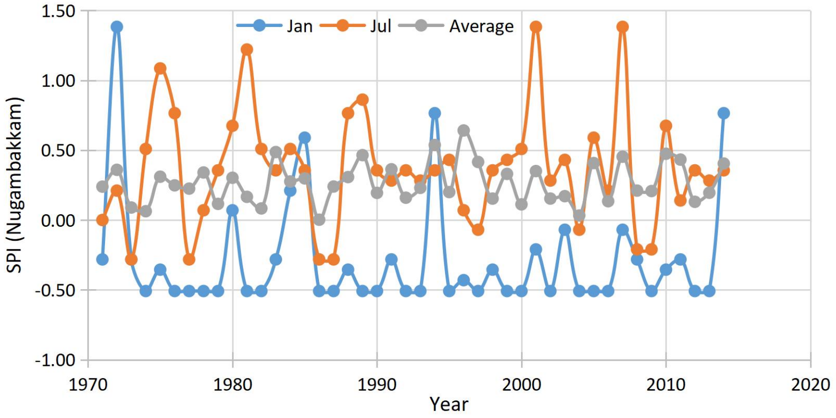

Figure 6.4: SPI of Nungambakkam Station

The Mahabalipuram station is located south of the CRB and the SPI values of this station are shown in Figure 6.5. In the post-monsoon season, SPI values for most years were negative, though they stayed within the limits of the near normal class. Only in the years 1985 and 1996 was this limit exceeded with the moderately wet category. For the pre-monsoon season, the years 1981, 1984, 2003, 2007 and 2013 were moderately wet and the remaining years were near normal condition. As observed in the Nungambakkam, the yearly average values of the SPI for Mahabalipuram show near normal.

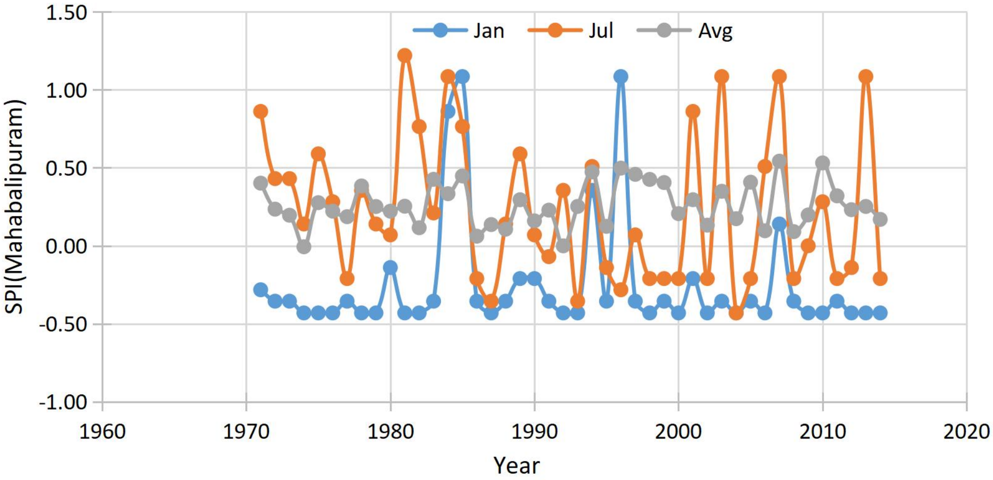

Figure 6.5: SPI of Mahabalipuram Station

The Ponneri Rain Gauge Station represents the northern region of the study area. Throughout the 44 years considered, the average values of the SPI suggest that the region was near normal condition. While post monsoon 1985 and pre-monsoon 1976, deviated from this trend with the average SPI value (see Figure 6.6).

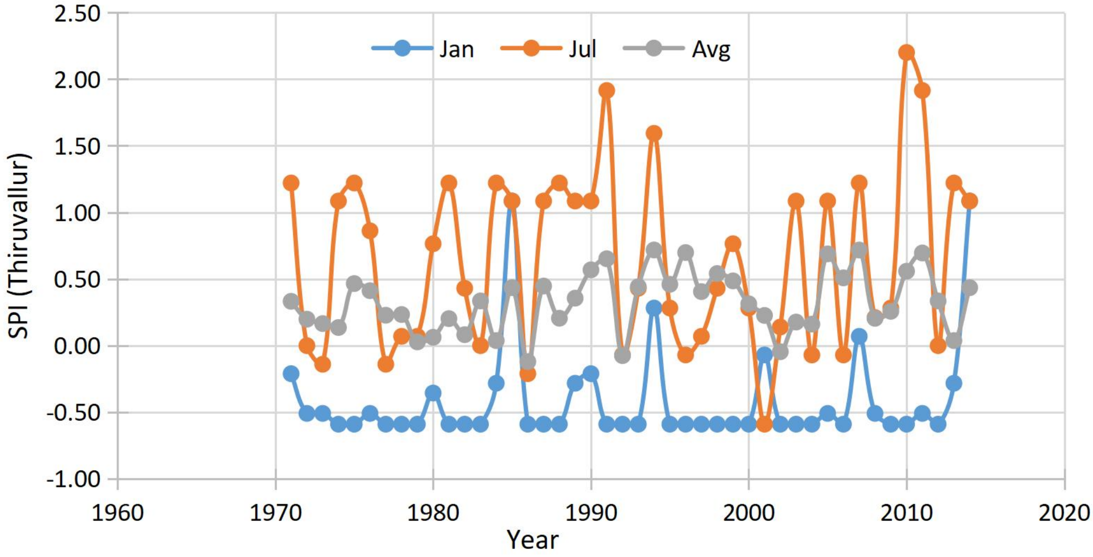

Figure 6.6: SPI of Ponneri station

The SPI value of Sholingur (representing the western region of the CRB) is presented in Figure 6.7. Values in January were mostly zero, with exceptions in some years. Both the seasonal as well as yearly SPI were near normal category. Extremely wet conditions were observed in the pre-monsoon season of the year 2003, while moderately wet conditions were seen in the years 1971, 1984 and 1989.

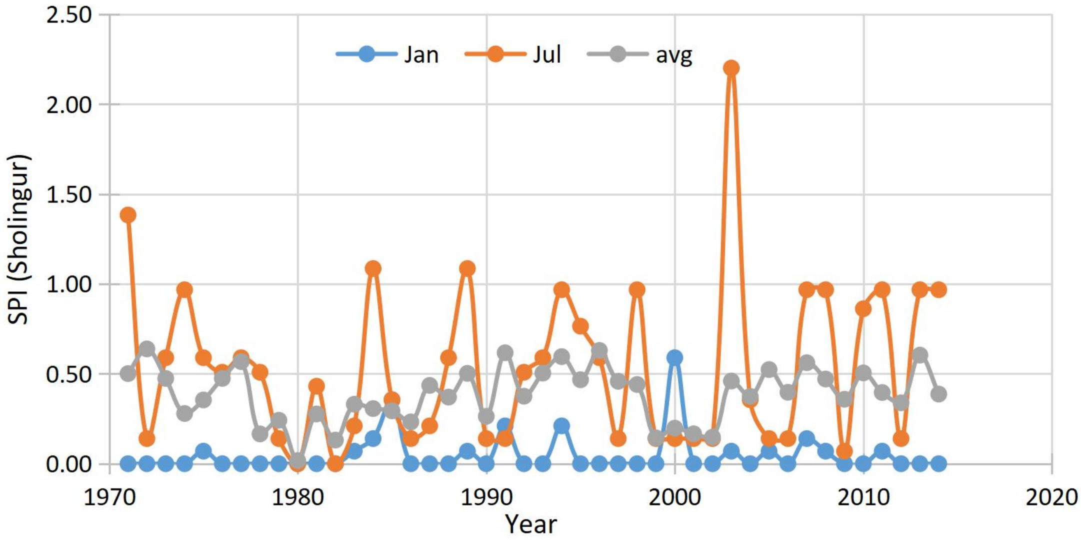

Figure 6.7: SPI of Sholingur station

The results of SPI in Thiruvallur Station also followed the same pattern as the other four stations (Figure 6.8). This station is in the central part of the CRB. Post- monsoon, pre-monsoon and the yearly average SPI were near the normal category. However, in the month of July, moderate wet conditions were observed in the years 1971, 1974, 1975, 1984, 1985, 1987, 1988, 1989, 1990, 1991, 1994, 2003, 2005, 2007, 2011, 2013, and 2014 and extremely wet conditions were observed in 2010.

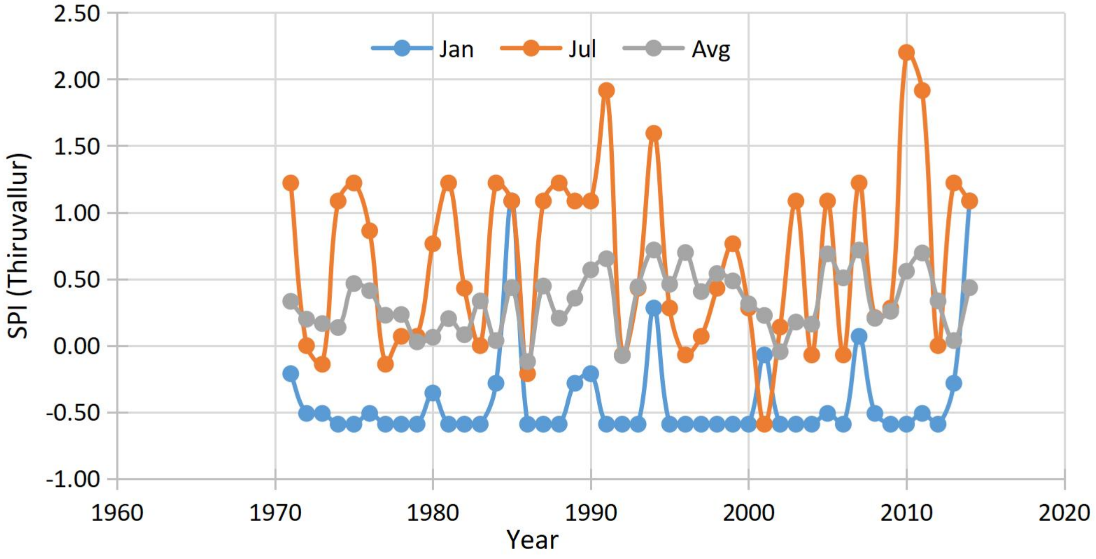

Figure 6.8: SPI of Thiruvallur Station

6.4.2.2 Water Stress Monitoring Using NDVI

In this study, long term water stress and its spatial extent is monitored by NDVI. This method is widely used for different purposes, to study the vegetation cover and structure, classification and mapping of leaf density, and monitoring the leaf water content water content. (Jensen 2007, Liang 2005; Tucker et al., 1985; Dutta et al., 2015). All these remotely sensed indices are developed based on algebraic combinations which can detect the aforementioned changes and are often sensitive to variations in spectral reflectance. Thus, it is suggested to use a combination of two or more indices. Dutta et al., (2015) reported that many researchers suggest the use of NDVI and VCI together to have more accurate results. VCI will be discussed in detail in a coming section. Based on the availability of satellite images the time intervals of 1991, 2000-01, 2010 and 2018 to were chosen to derive the NDVI values for the Chennai Basin. The observed results of NDVI for the Chennai Basin are shown in Table 6.3.

Table 6.3: NDVI results for CRB

NDVI Range	Percentage of Area			
	1991	2000	2010	2018
-0.98 to - 0.52	1.2	3.73	2.63	10.96
-0.52 to - 0.11	12.86	18.20	48.84	21.11
- 0.11 to 0.07	33.11	33.94	39-27	30.58
0.07 to 0.23	33.54	28.22	7.14	25.77
0.23 to 0.81	19.28	15.92	2.12	11.58

Based on the results, the NDVI value for the CRB can be of five classes. Figure 6.9 shows the NDVI for the selected four time periods. In 2010, more than 40% of the study area had negative NDVI values showing unhealthy vegetation and implying the existence of water stress. Very healthy vegetation is found in the northern and southern part of the basin. It is found that healthy vegetation is gradually decreasing as time goes on and the worst was in the year 2010. The transitional NDVI range (- 0.11 to 0.07) were found to be increasing in the total area till 2010 and showed a decrease in the year 2018. NDVI is a measure of vegetation health and is dependent on the climatic condition of the time when the image was taken, satellite orbital drift, satellite change and sensor errors (Kogan, 1995; Singh et al., 2003).

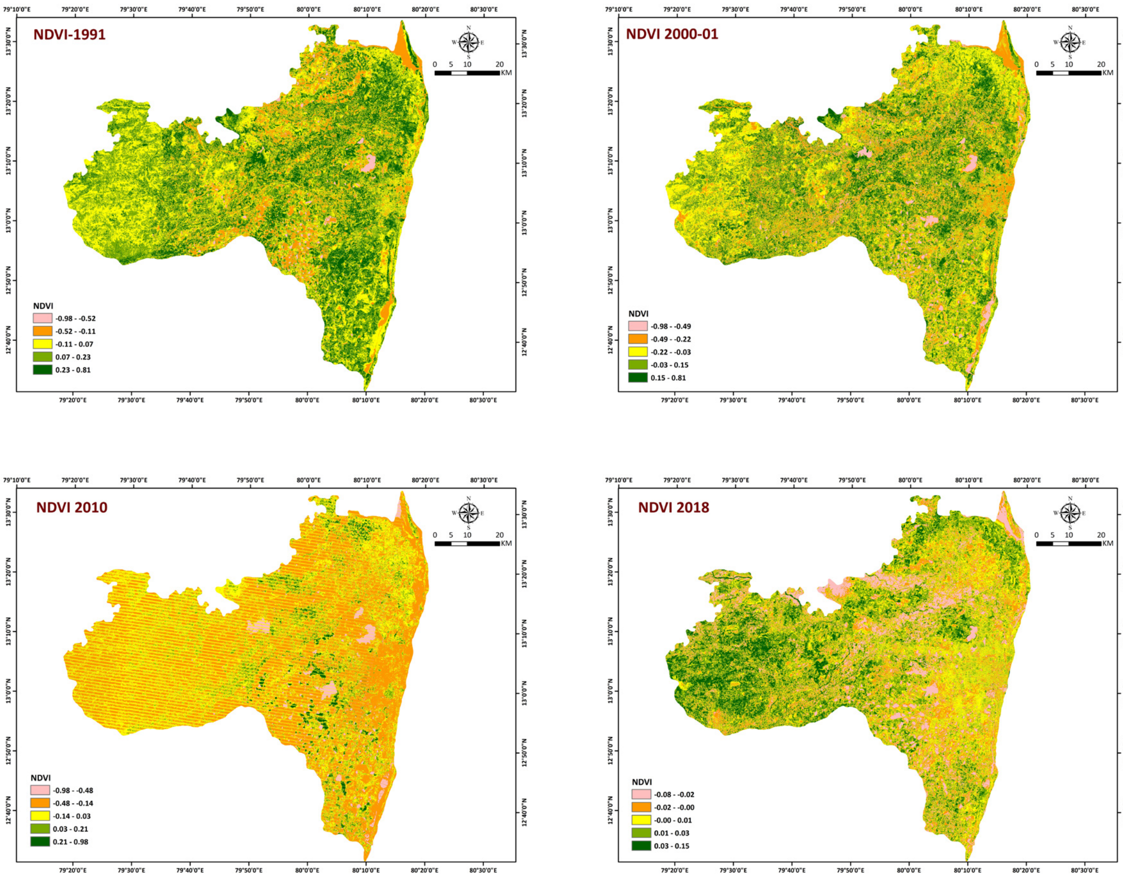

Figure 6.9: Spatial Variation of NDVI in CRB for the years 1991, 2000, 2010 and 2018

6.4.2.3 Water Stress Monitoring Using NDWI

NDWI is widely used in the detection of variation in the leaf water content of vegetation cover. This is measured between -1 and +1, without any unit. NDWI values of the CRB for the years 1991, 2001, 2010 and 2018 and is shown in Figure 6.10. Blue colour were used for the NDWI, in which high values are marked by dark blue and then, as the values lower, the blue colour fades. The statistics (see Table 6.4) show that more than 90% of vegetation in the year 1991 were negative in terms of NDWI, suggesting water stress. However, the condition has improved slightly over the decades. A considerable increase in positive NDVI values was witnessed in the year 2018, with 42% as compared to 7% in 1991. The western region of the basin is found mostly leaf water deficit. All over the basin, the western region was mostly deficit in leaf water content. The results show that the CRB does not continuously exhibit a lack of leaf water content and the NDWI results are influenced by several factors.

Table 6.4: NDWI results for CRB

NDWI Range	**Percentage of Area**			
	1991	2001	2010	2018
-0.63 to -0.25	25.58	20.02	1.43	7.46
-0.25 to -0.10	48.85	37.28	34.78	20.75
-0.10 to -0.10	18.62	27.36	46.88	29.61
0.10 to 0.53	5.85	12.36	14.07	28.20
0.53 to 0.97	1.10	2.98	2.84	13.98

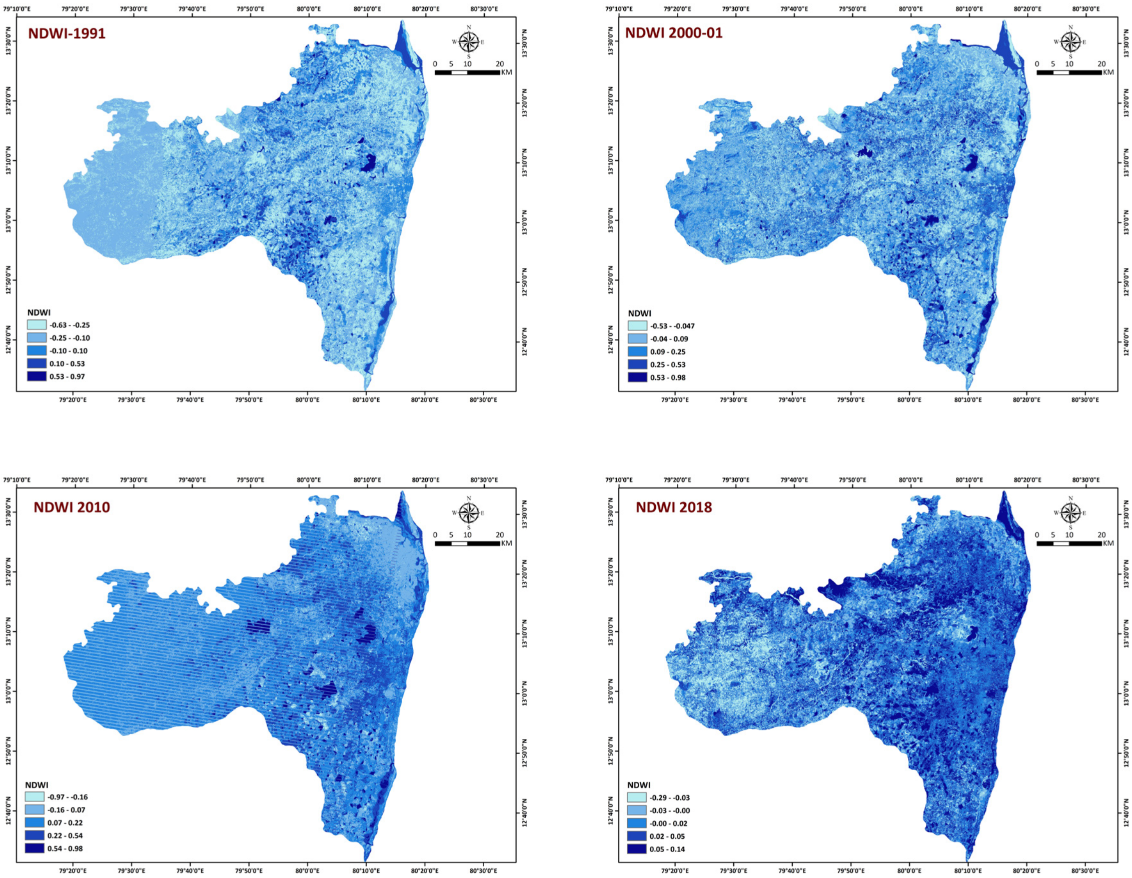

Figure 6.10: Spatial Variation of NDWI in CRB for the years 1991, 2000, 2010 and 2018

6.4.2.4 Water Stress Monitoring using VCI

VCI is a measure of percentage of NDVI in relation to maximum amplitude. In other words, it is dependent on the maximum possible variation in the amplitude of a given pixel (Liu and Kogan 1996). We used VCI as an effective tool for the drought monitoring in CRB, in combination with the other indices. Figure 6.11 shows the spatial variation of the VCI for the years 1991, 2001, 2010 and 2018. A detailed summary of the VCI results for the CRB is provided in Table 6.5. Severe drought or drought condition was experienced in more than 40% of the area in 1991, 50% in 2000, 80% in 2010 and 60% in 2018. Among the four decades considered, 2010 had the highest drought. Rainfall and atmospheric temperature play a major role in vegetation health and indirectly affect water content (Bhuiyan et al., 2017). The central and northern regions of the study area have croplands, where we received higher VCI values in almost all decades.

Table 6.5: VCI results for CRB

VCI Range	Percentage of Area			
	1991	2000	2010	2018
0 - 25.49	1,2	3.73	2.63	10.96
25.49 - 48.23	12,86	18.20	48.84	21.11
48.23 - 58.82	33.11	33.94	39.27	30.58
58.82 - 67.45	33.53	28.22	7.14	25.77
67.45 - 100	19.28	15.92	2.12	11.58

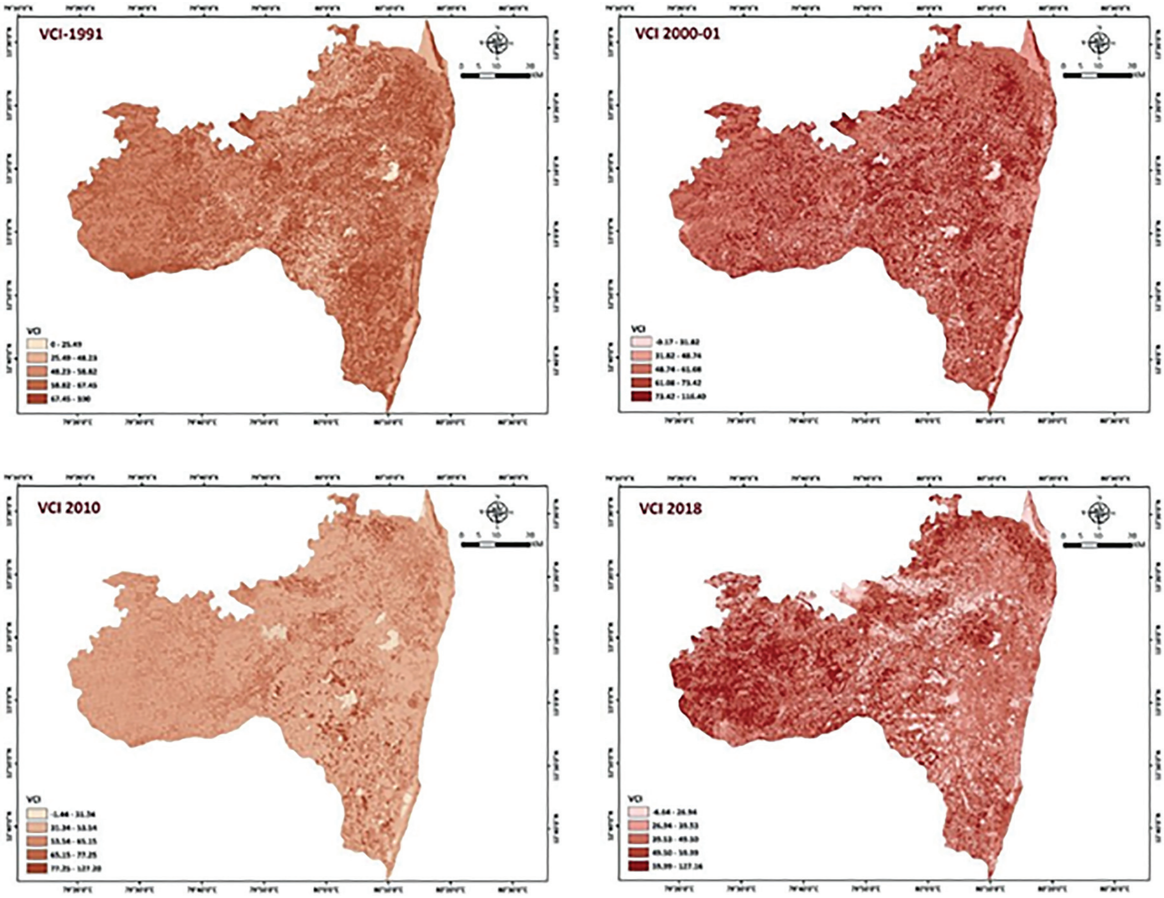

Figure 6.11: Spatial Variation of VCI in CRB for the years 1991, 2000, 2010 and 2018

6.5 Conclusions

Water stress in the Chennai River Basin (CRB) is evaluated in this chapter using conventional data mining techniques and metrological and agricultural drought indices. Time series data (1971 to 2014) suggests that temperature and rainfall are in an increasing trend. Increasing temperature has had a positive impact on rainfall, due to accelerated evaporation and precipitation. The Standardized Precipitation Index (SPI) showed that the basin generally falling under the near normal range ($-0.99 < SPI < 0.99$). However, there are exceptional years, with very wet to extreme wet condition. The SPI of the CRB varies considerably from January to December. The values of SPI were negative during January to June and positive from August to December. Still there is variation, the values are within the limit of near normal class. This suggests that, meteorologically, the area is not drought prone. Further, the agricultural drought has been evaluated using NDVI, NDWI and VCI. According to the NDVI values, the vegetation was unhealthy and showed water stress in more than 40% of the area. Northern and southern regions were found to be comparatively healthy. Within the four decades studied, the year 2010 faced the most severe water stress. In terms of NDWI, the values were negative in more than 90% of the area in 1991. On the other hand, there is an improvement observed in 2018, with 41% of the regions showing positive NDWI values, compared to 7% in 1991. VCI values indicate that severe drought or drought condition is experienced in more than 40% of the area in 1991, 50% in 2000, 80% in 2010 and 60% in 2018. The central and northern regions of the study area have croplands, where higher VCI values were observed in almost all decades. This study shows that the CRB is under agricultural drought in many areas. However, SPI values suggesting the existence of a heavy meteorological drought are not evident.

CHAPTER 7

Estimation of Natural Groundwater Recharge in Chennai River Basin (CRB)

Sajil Kumar Pazhuparambil Jayarajan, Michael Schneider & Elango Lakshmanan (2022): Estimation of natural groundwater recharge in Chennai River basin using multiple approaches, **Hydrological Sciences Journal, DOI: 10.1080/02626667.2022.2064223**

CHAPTER 8

Combined Conclusions and Recommendations

8.1 Conclusions

Groundwater usage has increased all over the world over the past few decades and has crossed all the possible limit of sustainable groundwater development. This study focused on groundwater conditions in the Chennai River Basin (CRB), including the geological and hydrogeological settings, morphometric and hypsometric analyses, groundwater potential estimation, water stress analysis, recharge estimation using different methods and the influence of these factors on groundwater recharge. Additionally, a detailed review of groundwater recharge estimation methodologies and aquifer systems in India has been presented.

The scientific value of this thesis is that groundwater recharge has been considered as the most important factor for the sustainable development of groundwater resources in order to secure the water supply. This study has employed conventional field data as well as modern satellite data and GIS mapping tools. By keeping natural recharge as the central theme, all associated factors such as hydrogeology, terrain characteristics, groundwater potential, water stress, climatic conditions have been studied extensively and used to lay a foundation for future reference. Groundwater recharge estimation tools were reviewed extensively in relation to specific conditions in India, such as appropriate methods for saturated and unsaturated zones, different geological conditions, size of the study area, and availability of reliable data. In the CRB, such an extensive study on groundwater recharge has not been conducted until now. Previous studies were too specific, focusing only on groundwater quality, contamination, and small-scale impact assessments of recharge structures on groundwater storage. Based on the literature survey, it was clearly understood that a study including the entire basin was needed. So a holistic approach is chosen which covered all the influencing factors on natural groundwater. As a result, a revised database is generated and different useful maps on groundwater potential and recharge rates were generated.

In general, the aquifer systems in India are mostly formed by alluvial systems and crystalline rocks- most of which are in an overexploited state. Among the methods available, this review has suggested that, if the study needs to address large areas, numerical modelling or watershed modelling is the best choice. In unsaturated formations, water table fluctuation methods and water balance methods are found to be effective. Tracer techniques have application in both saturated and unsaturated formations. Overall, the usage of multiple methods for the same area is often recommended.

Morphometry of the CRB shows that the whole basin is elongated with the 7th order. As the total area is 6,112 km^2, the basin has very high-water holding capacity. On the other hand, the drainage density of the basin is low with a coarse texture. A total relief value of 255 shows that the basin has steep slopes, which may affect infiltration capacity. Hypsometric curves and the hypsometric integral suggest that the sub-basins 1, 6 and 7 were matured stages and the remaining are monadnock (old stage). In general, the terrain analysis shows that the basin has moderate to good water percolation capacity. However, it is always dependent on other factors as well.

It was necessary to understand the exiting groundwater potential of the basin and this study adopted GIS based multi-criteria decision-making techniques. 11 different thematic layers have been created and weights have been provided using the Analytical Hierarchy Process (AHP). These layers were overlaid and used to generate a groundwater potential map for the CRB. This map suggested that 35% of the study area has good to very good groundwater potential, 27% has moderate potential and 38% has poor to very poor groundwater potential. The urban as well as coastal regions showed very low groundwater potential. To confirm these results, bore hole data from the basin was compared with the potential zones and found to be a 78% match, showing these methods to be accurate enough to determine groundwater potential zones in any area.

In the next step, water stress in the basin was evaluated using data mining and drought indices. According to the time series analysis, temperature and rainfall showed a long-term positive trend, suggested the impact of evaporation on the rainfall. The Standardized Precipitation Index (SPI) of the CRB is near normal in range ($-0.99 < \mathrm{SPI} < 0.99$), and in some years exceptionally wet and dry conditions existing. Negative SPI values are seen during the period from January to June and positive values from August to December. Overall, meteorologically, the CRB cannot be considered as drought prone. On the other hand, an agricultural drought estimation using NDVI, NDWI and VCI showed wide variation in values and concluded that agricultural drought exists in many regions of the basin.

Finally, the recharge rate in the CRB was estimated using several different methods. The long-term average recharge for the Empirical (196mm/year), Water Table Fluctuation (122mm/year), and Rainfall Infiltration Factor Method (122mm/year) methods were comparable with each other. Effective recharge from rainfall is nearly 10% from the WTF and the RIF methods and 16% from the Empirical method. The overall recharge rate has been compared with the rainfall data, and it shows no direct correlation between these two components. However, the yearly recharge data of many locations correlated with the precipitation data. The geology of the area was found affect groundwater recharge. In the coastal plains, due the natural slope towards the Bay of Bengal, the recharge rate was found to be less than those in the western regions. Landuse patterns play a vital role in the recharge process as well.

The suitability of each method depends on several factors. For an approximate recharge value for a long period with multiple samples, the Empirical Method is an appropriate method in the

CRB. If spatial data is available and one is looking for a range of recharge values, the GIS based distributed model is also a suitable method to estimate recharge. The RIF method provided a recharge estimate for each data point, and this method is recommended whenever water table measurements are not possible, as long as proper understanding of the geology is available. Among the four methods studied, the WTF method has the most precise estimate as the input data is measured from the field and thus represents the actual hydrogeological conditions. If there is enough water level data to spatially represent the study area, the WTF method is suggested. Unfortunately, no estimate is 100% accurate and the use of more than one method is always recommended. For the CRB, it is suggested to have measuring wells with aquifer parameters characterized and their own rain gauge station set up, to exactly measure the recharge for each location, distributed equally to represent the whole basin.

The main achievement of this thesis is that the databases available in the different sectors have been summarized and presented in a user-friendly map. The locations identified as water stressed and those with low recharge rates must be given immediate attention and proper recharge structures need to be installed as soon as possible. Several recommendations have been proposed to improve the groundwater recharge and thus improve the availability of a safe water supply in the Chennai River Basin.

8.2 Recommendations

Groundwater recharge is a state-of-the-art procedure that requires multiple areas of expertise. In Chennai, under present conditions, the most viable method to solve the water crisis is the implementation of recharge structures. This can be done using existing structures or by creating the new ones. It is always better to restore existing structures than creating the new ones.

- Survey existing water bearing structures including those abandoned long ago and create a map of these structures. Professionally clean viable structures and install recharge shafts or similar structures according to the location and requirements necessary to improve the groundwater recharge.
- There are approximately 50 tanks in Chennai city alone. Use all possible temple tanks as mediums of recharge and install injection wells or similar structures.
- Promote rainwater harvesting structures within households.
- Use abandoned quarries for groundwater storage and recharge.
- Clean all rivers flowing through the city and control further pollution.

- Focus on improving the groundwater potential of zones identified in this study as able to benefit from governmental and non-governmental agency help in implementing appropriate methods discussed throughout this thesis.
- Spread aquifer recharge schemes, like the AK pilot study, by creating check dams throughout the basin
- According to the recharge potential analysis the best regions for the groundwater recharge is the central part of the basin including the Tirulallur till Gummidipoondi and Pulicaut lake in the far NW, Sriperumbadur in the south, parts of Avadi and southern coastal aquifer. To get the benefit for the water shortage in the urban areas these locations must be chosen and implement the appropriate recharge structures.
- The groundwater potential in the Chennai City region is poor to very poor, in which the poor regions Panjetti, Minjur, Poonamalle, Thambaran are regions that can be chosen for the groundwater recharging.
- In total, more than 50% of the CRB is categorized as poor to moderate potential zones, all of which can be converted to good potential zones with effective recharge mechanisms.
- Additionally, rainwater from rooftops can be delivered to dug wells or tube wells to ensure the recharges.
- The estimated effective recharge was highest (16%) in the empirical methods. By implementing appropriate recharge structures, the effective recharge rate can be increased to 20- 30%. This can solve a portion of the groundwater shortage problem in Chennai City and in the CRB.
- In the legal context, it is necessary to improve the environmental legislation with effective supervision of the experts from environmental sector along with the legal and political policy makers.
- Comprehensive public relation work to create awareness about the protection of water resources, starting from kindergartens, school, Colleges and finally to the public.

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APPENDIX A

APP.1: Water balance calculation for runoff classes 2 and 4 using runoff coefficient 0.2

Row	Parameters	Input Data	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Total
A	Avg. monthly pre.—PRE (mm)		29.15	5.91	15.89	11.48	39.28	119.88	156.74	257.86	176.25	376.02	617.23	87.93	157.80	**1893.62**
B	Avg. Monthly Temp.—T		24.18	26.07	28.67	31.05	33.20	31.80	30.03	29.45	29.03	27.56	25.89	24.45	28.45	
C	Potential evapotranspiration—(PET)		110.91	115.95	122.89	129.24	134.98	131.24	126.52	124.97	123.85	119.93	115.47	111.63	122.30	**1467.60**
D	Runoff coefficient—C	Refer Tables 7.4 and 7.5 (this case, C =0.2)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20		
E	Surface runoff—SR (mm)	SR = Row A × Row D	5.83	1.18	3.18	2.30	7.86	23.98	31.35	51.57	35.25	75.20	123.45	17.59	31.56	**378.72**
F	Infiltration - IN (mm)	IN = Row A - Row E	23.32	4.73	12.71	9.18	31.42	95.90	125.39	206.29	141.00	300.82	493.78	70.34	126.24	**1514.90**
G	IN - PER (mm)	IN - PET = Row F - Row C	-87.59	-111.23	-110.18	-120.06	-103.55	-35.34	-1.13	81.32	17.15	180.89	378.31	-41.29		
H	Accumulated water loss—WL (mm)	WL = Σ Neg (I - PET)														
I	Field Capacity of soil - FC (mm)	FC = 150 mm	150.00	150.00	131.60	100.50	75.50	54.90	43.00	29.20	19.70	19.70	97.60	150.00		
J	FC Change (mm)	FC actual - FC previous month	0.00	-18.40	-31.10	-25.00	-20.60	-11.90	-13.80	-9.50	0.00	77.90	52.40	0.00		
K	Water deficit - WD (mm)	WD = Row G - Row J, when Row G is negative	87.59	92.80	79.10	95.10	83.00	23.44	12.67	0.00	0.00	0.00	0.00	41.29	42.92	**514.99**
L	Actual evapotranspiration—AET(mm)	AET = Row C - Row K	23.32	23.15	43.79	34.14	51.98	107.80	113.85	124.97	123.85	119.93	115.47	70.34	79.38	**952.61**
M	Percolation P (mm)	P = Row G - Row J when Row G is positive	0.00	0.00	0.00	0.00	0.00	0.00	0.00	124.97	123.85	119.93	115.47	0.00	40.35	**484.23**

APP.2: Water balance calculation of runoff class 3. 5 and 7 using runoff coefficient 0.3

Row	Parameter	Input Data	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Total
A	Avg. monthly pre.—PRE (mm)		29.15	5.91	15.89	11.48	39.28	119.88	156.74	257.86	176.25	376.02	617.23	87.93	157.802	**1893.62**
B	Avg. Monthly Temp.—T		24.18	26.07	28.67	31.05	33.2	31.8	30.03	29.45	29.03	27.56	25.89	24.45	28.448	
C	Potential evapotranspiration—(PET)		110.91	115.95	122.89	129.24	134.98	131.24	126.52	124.97	123.85	119.93	115.47	111.63	122.298	1467.6
D	Runoff coefficient—C	Refer Tables 7.4 and 7.5 (this case, C =0.3)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.300	
E	Surface runoff—SR (mm)	SR = Row A × Row D	8.745	1.773	4.767	3.444	11.784	35.964	47.022	77.358	52.875	112.81	185.17	26.379	47.341	**568.086**
F	Infiltration - IN (mm)	IN = Row A - Row E	20.405	4.137	11.123	8.036	27.496	83.916	109.72	180.5	123.38	263.21	432.06	61.551	110.461	1325.534
G	IN - PER (mm)	IN - PET = Row F - Row C	-90.507	-111.82	-111.77	-121.21	-107.48	-47.326	-16.802	55.529	-0.477	143.28	316.59	-50.082		
H	Accumulated water loss—WL (mm)	WL = Σ Neg (I - PET)														
I	Field Capacity of soil - FC (mm)	FC = 150 mm	150	150	122.3	90.2	66.7	48.2	37.3	25.2	16.6	15.3	70.8	144.5		
J	FC Change (mm)	FC actual - FC previous month	0	-27.7	-32.1	-23.5	-18.5	-10.9	-12.1	-8.6	-1.3	55.5	73.7	0		
K	Water deficit - WD (mm)	WD = Row G - Row J, when Row G is negative	90.51	84.1	39.7	97.7	89	36.43	4.7	0	0.82	0	0	50.08	41.087	493.04
L	Actual evapotranspiration—AET(mm)	AET = Row C - Row K	20.4	31.85	83.19	31.54	45.98	94.81	121.82	124.97	123.03	119.93	115.47	61.55	81.212	**974.5618**
M	Percolation P (mm)	P = Row G - Row J when Row G is positive	0	0	0	0	0	0	0	124.97	0	119.93	115.47	0	30.031	**360.37**

APP.3: Water balance calculation for runoff classes 6, 8 and 10 with coefficient 0.4

Row	Parameters	Input Data	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Total
A	Avg. monthly pre.—PRE (mm)		29.15	5.91	15.89	11.48	39.28	119.88	156.74	257.86	176.25	376.02	617.23	87.93	157.80	**1893.62**
B	Avg. Monthly Temp.—T		24.18	26.07	28.67	31.05	33.20	31.80	30.03	29.45	29.03	27.56	25.89	24.45	28.45	
C	Potential evapotranspiration—(PET)		110.91	115.95	122.89	129.24	134.98	131.24	126.52	124.97	123.85	119.93	115.47	111.63	122.30	1467.60
D	Runoff coefficient—C	Refer Tables 7.4 and 7.5 (this case, C =0.4)	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40		
E	Surface runoff—SR (mm)	SR = Row A × Row D	11.66	2.36	6.36	4.59	15.71	47.95	62.70	103.14	70.50	150.41	246.89	35.17	63.12	**757.45**
F	Infiltration - IN (mm)	IN = Row A - Row E	17.49	3.55	9.53	6.89	23.57	71.93	94.04	154.72	105.75	225.61	370.34	52.76	94.68	1136.18
G	IN - PER (mm)	IN - PET = Row F - Row C	-93.42	-112.41	-113.36	-122.35	-111.41	-59.31	-32.48	29.74	-18.10	105.68	254.86	-58.88		
H	Accumulated water loss—WL (mm)	WL = Σ Neg (I - PET)														
I	Field Capacity of soil - FC (mm)	FC = 150 mm	150.00	150.00	113.70	81.00	58.90	42.40	32.40	21.70	14.00	11.80	45.00	93.00		
J	FC Change (mm)	FC actual - FC previous month	0.00	-36.30	-32.70	-22.10	-16.50	-10.00	-10.70	-7.70	-2.20	33.20	48.00	0.00		
K	Water deficit - WD (mm)	WD = Row G - Row J, when Row G is negative	93.42	76.10	80.70	100.30	22.40	49.31	21.78	0.00	15.90	0.00	0.00	58.87	43.23	518.78
L	Actual evapotranspiration—AET(mm)	AET = Row C - Row K	17.49	39.85	42.19	28.94	112.58	81.93	104.74	124.97	107.95	119.93	115.47	52.76	79.07	**948.82**
M	Percolation P (mm)	P = Row G - Row J when Row G is positive	0.00	0.00	0.00	0.00	0.00	0.00	0.00	124.97	0.00	107.95	115.47	0.00	29.03	**348.39**

APP.4: Water balance calculation using runoff coefficient 9 and 11, using coefficient 0.5.

Row	Parameter	Input Data	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Total
A	Avg. monthly pre. —PRE (mm)		29.15	5.91	15.89	11.48	39.28	119.88	156.74	257.86	176.25	376.02	617.23	87.93	157.80	**1893.62**
B	Avg. Monthly Temp.—T		24.18	26.07	28.67	31.05	33.2	31.8	30.03	29.45	29.03	27.56	25.89	24.45	28.45	
C	Potential evapotranspiration—(PET)		110.91	115.95	122.89	129.24	134.98	131.24	126.52	124.97	123.85	119.93	115.47	111.63	122.30	1467.60
D	Runoff coefficient—C	Refer Tables 7.4 and 7.5 (this case, C =0.5)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		
E	Surface runoff—SR (mm)	SR = Row A × Row D	14.575	2.955	7.945	5.74	19.64	59.94	78.37	128.93	88.125	188.01	308.62	43.965	78.90	**946.81**
F	Infiltration - IN (mm)	IN = Row A - Row E	14.575	2.955	7.945	5.74	19.64	59.94	78.37	128.93	88.125	188.01	308.62	43.965	78.90	946.82
G	IN - PER (mm)	IN - PET = Row F - Row C	-96.337	-113	-114.95	-123.5	-115.34	-71.302	-48.15	3.9574	-35.727	68.08	193.14	-67.668		
H	Accumulated water loss—WL (mm)	WL = Σ Neg (I - PET)														
I	Field Capacity of soil - FC (mm)	FC = 150 mm	150	137.4	96.7	66.7	47.7	34.1	25.8	17.1	10.9	8.4	19.2	41.5		
J	FC Change (mm)	FC actual - FC previous month	-12.6	-40.7	-30	-19	-13.6	-8.3	-8.7	-6.2	-2.5	10.8	22.3	0		
K	Water deficit - WD (mm)	WD = Row G - Row J, when Row G is negative	83.74	72.3	84.9	104.5	101.7	63	39.45	0	33.23	0	0	67.67	54.21	650.49
L	Actual evapotranspiration—AET(mm)	AET = Row C - Row K	27.17	43.65	37.99	24.74	33.28	68.24	87.07	124.97	90.62	119.93	115.47	43.96	68.09	**817.11**
M	Percolation P (mm)	P = Row G - Row J when Row G is positive	0	0	0	0	0	0	0	124.97	0	119.93	115.47	0	30.03	**360.37**

APP.5: Water balance calculation using runoff class 12 with coefficient 0.6.

Row	Parameter	Input Data	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Total
A	Avg. monthly pre.—PRE (mm)		29.15	5.91	15.89	11.48	39.28	119.88	156.74	257.86	176.25	376.02	617.23	87.93	157.80	**2051.42**
B	Avg. Monthly Temp.—T		24.18	26.07	28.67	31.05	33.20	31.80	30.03	29.45	29.03	27.56	25.89	24.45	28.45	
C	Potential evapotranspiration—(PET)		110.91	115.95	122.89	129.24	134.98	131.24	126.52	124.97	123.85	119.93	115.47	111.63	122.30	1589.90
D	Runoff coefficient—C	Refer Tables7.4 and 7.5 (this case, C =0.1)	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	
E	Surface runoff—SR (mm)	SR = Row A × Row D	17.49	3.55	9.53	6.89	23.57	71.93	94.04	154.72	105.75	225.61	370.34	52.76	94.68	**1230.85**
F	Infiltration - IN (mm)	IN = Row A - Row E	11.66	2.36	6.36	4.59	15.71	47.95	62.70	103.14	70.50	150.41	246.89	35.17	63.12	757.45
G	IN - PER (mm)	IN - PET = Row F - Row C	-99.25	-113.59	-116.54	-124.65	-119.27	-83.29	-63.82	-21.83	-53.35	30.48	131.42	-76.46		
H	Accumulated water loss—WL (mm)	WL = Σ Neg (I - PET)														
I	Field Capacity of soil - FC (mm)	FC = 150 mm	137.90	95.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
J	FC Change (mm)	FC actual - FC previous month	-42.10	-95.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
K	Water deficit - WD (mm)	WD = Row G - Row J, when Row G is negative	57.15	72.30	84.90	104.50	101.70	63.00	39.45	0.00	33.23	0.00	0.00	67.67	51.99	675.89
L	Actual evapotranspiration—AET(mm)	AET = Row C - Row K	53.76	43.65	37.99	24.74	33.28	68.24	87.07	124.97	90.62	119.93	115.47	43.96	70.31	**914.01**
M	Percolation P (mm)	P = Row G - Row J when Row G is positive	0.00	0.00	0.00	0.00	0.00	0.00	0.00	124.97	0.00	119.93	115.47	0.00	30.03	**390.40**