HYDROLOGICAL AND HYDROGEOLOGICAL EVALUATION OF MHADEI RIVER WATERSHED – IN GOA AND KARNATAKA

A THESIS SUBMITTED TO

GOA UNIVERSITY

FOR THE AWARD OF THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN GEOLOGY

BY

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DEPARTMENT OF EARTH SCIENCE
GOA UNIVERSITY

2012

'Gurur Brahma, Gurur Vishnu, Gurur Devo Maheshwara

Guru Sakshat Parabrahma Tasmai Shree Guruveh namah'

(Shri Guru Charitra)

To

All My Teachers

CERTIFICATE

This is to certify that the thesis titled, "HYDROLOGICAL AND HYDROGEOLOGICAL EVALUATION OF MHADEI RIVER WATERSHED – IN GOA AND KARNATAKA" submitted by Mr. Manoj M. Ibrampurkar for the award of degree of Doctor of Philosophy in Geology is a record of research work done by him during the period of study and is based on the results of experiments carried out by him independently. The thesis or a part thereof has not previously formed the basis for the award to the research scholar for any other degree, diploma, associateship, fellowship or other similar titles.

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STATEMENT

I hereby state that this thesis titled, HYDROLOGICAL AND HYDROGEOLOGICAL EVALUATION OF MHADEI RIVER WATERSHED – IN GOA AND KARNATAKA" for the award of Ph.D. degree is my original contribution and that the thesis or any part thereof has not previously formed the basis for the award of any other degree, diploma or other similar titles of any university or institute. To the best of my knowledge, the present study is the first comprehensive study of its kind from the study area. The literature pertaining to the investigated problem has been duly acknowledged. Facilities availed from other sources have also been duly acknowledged.

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ACKNOWLEDGEMENTS

I owe a deep debt of gratitude to my Guide Prof. A. G. Chachadi, Head, Department of Earth Science, Goa University, for his continued inspiration and efficient guidance throughout the course of this research work. His thorough understanding of the subject of Hydrogeology and his ability to get the best out of his students is highly appreciated. I take this opportunity to express my deep respect and gratitude to him for his constant involvement in the study, valuable suggestions, critical evaluation of the findings and patient review of the manuscript.

I am thankful to the University Grants Commission, Government of India, for providing financial assistance in the form of Minor Research Project and award of Teacher Fellowship under the Faculty Improvement Programme.

I sincerely thank Mr. S.D. Sayanak, former Chief Engineer (Mandovi Basin), Mr. S. T. Nadkarni, Chief Engineer (WRD), Mr. N. Somasundaram, Senior Hydrogeologist and Mr. S. V. Prabhavalkar, SE (CPO) of the Water Resources Department , Government of Goa for providing the necessary data about the water resources of Goa and the proposed water retention projects by Karnataka. I am also thankful to India Meteorological Department, Altinho, for providing the rainfall data and Dr. D. Mayekar and Mr. S. Sawant of Department of Mines and Geology, Govt. of Goa for their support and co-operation. I am grateful to Mr. V.B. Saxena, Joint Director, Department of Planning, Statistics and Evaluation, Govt. of Goa for providing necessary information about the Minor Irrigation schemes.

I express my deep gratitude towards Dr. B. K. Purundara and Dr. B. Venkatesh of National Institute of Hydrology, Belgaum and Dr. Davithuraj of Central Ground Water Board, Belgaum for their valuable inputs and encouragement.

I am thankful to the Principal Dr.(Mrs) Y. Modassir, former Principal Dr. S.V. Deshpande and Management of Dhempe College of Arts and Science for providing all the necessary facilities in the college during the research work. Special thanks to Dr. K.G. Hiremath, Dr. S.R. Ganihar, Dr. S Powar, Dr. Ramu Murthy, Dr. S. Samant, Dr. W. Manual and Dr. R. Karmali for their co-operation and guidance at various stages of the work. Similarly, I express my gratitude to all the teaching and non-teaching staff of Department of Earth

Science, Goa University and the administrative staff and authorities of Goa University for their constant guidance and co-operation during the study period.

I am also grateful to my colleagues at the Geology Department of Dhempe College of Arts and Science, Prof. A.G. Agshikar, Prof. D.S. Parab, Prof (Ms). M.A. Miranda and Mr. V. Kurundwad for their constant support and co-operation during the research work. Special thanks to Ms. Shilpa Khandolkar for assisting me in the preparation of all the figures in GIS platform. I gratefully acknowledge Late Prof. O.A. Fernandes who inspired me to study Geology. I also thank Prof. M.S. Katti of Chowgule College, Margao for his constant encouragement and advice.

I am also grateful to all the students of geology at Dhempe College and Goa University for their assistance during the field work and data processing. Special thanks to Anuj, Sachit, Zuber, Pooja, Rohit, Poornima, Shivam, Sapresh, Shaibaz, Francisco, Yogita, Samantha, Sonia, Vishwajit, Ambarish, Renfred and Shruti for their valuable contributions at various stages of the work.

I am also grateful to my friends Simon, Ajinkya, Mohan, Rajesh, Satish, Siddhesh, Mendes, Inas, Walter, Bapat, Amruta, Manjit and Aulito for being with me during good as well as difficult times.

I express my profound gratitude to my parents who raised me with love, care and values, and safeguarded me from all the troubles of life. I am also thankful to my sisters and brothers for their support and love. I also thank all those people who directly or indirectly helped me in completion of this work.

Last but not the least, with immense pleasure, I express my gratitude to my wife Pallavi for providing a great support in times of distress, continual encouragement and taking care of our daughter Ira single-handedly. Her patience, understanding and untiring care kept me going.

Above all, I thank the Almighty for being with me all the time.

Manoj Ibrampurkar

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ABSTRACT

The present study titled, 'Hydrological and Hydrogeological Evaluation of Mhadei River Watershed – In Goa and Karnataka' comprises of groundwater assessment of an interstate river watershed located along the West coast of India.

The Mhadei River is an interstate river, the watershed of which extends in Goa and Karnataka. The river has been at the crux of a controversy since last one decade due to the proposed river water retention and diversion projects in the upper reaches of the river by Karnataka government. The state of Goa has expressed concern about the likely effects of such river water retention and diversion structures on the hydrological regime, ecological balance and economic development in the lower reaches of the Mhadei River watershed. Environmentalist and social activists have been often raising the issue of negative impacts of the projects entirely based on qualitative information about the natural resources of the Mhadei River watershed.

Literature survey revealed lack of scientific and quantitative information about Mhadei River watershed, particularly the groundwater and surface water resources. It was observed that most of the studies in Goa on hydrogeology were carried out on a regional scale with administrative boundaries as study units while others focused on the influence of open cast mining on the local groundwater regime. Even the regional studies related to hydrology and hydrogeology of the

Mhadei River watershed have never been carried out. Therefore, assessment of the groundwater and surface water resources with watershed as a unit for its development in a sustainable manner becomes important. With the constitution of the Interstate water dispute tribunal it becomes essential to generate field based primary data which is scientifically valid and technically acceptable. Thus, it was decided to carry out a detailed and comprehensive hydrological and hydrogeological evaluation of the Mhadei River watershed.

The primary data regarding the occurrence, distribution and availability of surface and groundwater resources in the interstate Mhadei River watershed has been collected and processed. The surface water contributions from watersheds lying in Goa and Karnataka have been estimated separately using long term rainfall data. The total volume of rain water received in the Mhadei River watershed is 3538 MCM. Of this, 67% is contributed from the Goa region and 33% is contributed from the Karnataka region of the watershed. Baseflow contribution from the watershed lying in Karnataka has been estimated by using *unit area base flow* derived from stream flow measurements carried out at the Goa-Karnataka boundary and river discharge data of the Mhadei River measured at Ganje river-gauging station. The Karnataka watershed contributes about 109 MCM (38%) of the total non-monsoon baseflow (285 MCM) of the entire Mhadei River watershed. The *bandharas* built across the Mhadei River channel accumulate this baseflow and a large population depends on this water for their domestic and agricultural requirements during the non-monsoon season.

Morphometric analysis of the Mhadei River watershed as well as the entire Mandovi River basin has been carried out to understand the drainage development in the basin and its implications on the water resources of the basin. The drainage development in the Mhadei River watershed is partially controlled by the underlying rock structure and allows moderate infiltration conditions. It is estimated that the Mhadei River will have an extended but flat peak flow.

Laterite constitutes the most widespread aquifer in the Mhadei River watershed containing groundwater at shallow depths. Valley fill deposits, iron ore bodies, weathered and fractured basalts and metamorphic rocks at depth constitute local aquifers in different regions of the watershed. Two major domains of groundwater, one in the low lying region in Goa and other in the Karnataka plateau, have been identified in the watershed. The analysis of flow-nets indicates that the major part of the Mhadei River is effluent in nature and a major recharge zone is found to occur around village Dhave. The groundwater domain in the Goa region shows gentle hydraulic gradients indicating slow groundwater flow velocities and relatively higher hydraulic conductivity of the saturated zone. On the other hand, the ground water domain in Karnataka region, which is situated at higher topographic level has closely spaced equi-potential lines indicating steep hydraulic gradients and lower hydraulic conductivity and higher groundwater velocities. The analysis of the pumping test data carried out in the area indicates that the transmissivity and specific yield of the unconfined aquifer vary from place to place emphasizing the heterogeneous nature of the aquifer. The aquifer recharge estimated using water table fluctuation method is 41.86 MCM which is less than 1.5% of the total rainfall received by the watershed. The rainfall infiltration factor worked out for the Mhadei River watershed is found to be 2%. Well hydrograph analysis indicates that the groundwater levels remain within the limits of seasonal fluctuation during the study period. A new approach has been developed for identifying groundwater potential zones. The approach makes use of the parameters *specific recharge, relative fall in groundwater level and percentage thickness of saturated aquifer zone.* The overlay of the groundwater potential map on the geological map indicate that the laterites formed on metabasalts and metagreywackes of the Vageri Formation give better yield followed by laterites developed on phyllites. On the other hand, the groundwater potential on the Karnataka plateau is mainly governed by the intensity of fracturing and weathering of the rocks.

The possible implications of proposed river water development projects on the downstream hydrological regime of Mhadei River watershed have also been assessed and analysed. It is estimated that the watersheds of the proposed river water retention structures will retain 21% of the annual monsoon discharge of the Mhadei River and 22% of the non-monsoon baseflow. The reduced flows are expected to affect the hydrological and ecological regimes in the downstream reaches of the river. The influence of the reduced river flows on sediment and nutrient loads, flood hazards, groundwater discharge, baseflow retention structures and biological activity have been discussed. The reduced river flow may enhance silt accumulation in the river bed reducing river bed infiltration which may enhance flood events. Reduction in the baseflow may also enhance groundwater discharge into the main river as the river is found to be effluent throughout. The baseflow retention structures (bandharas) are expected to receive about 22% less base flow that was supposed to enter into Goa. The erodibility capacity of the river water may get reduced due to reduction in sediment load arising from reduced flows and flow velocities. The proposed retention of the flows would influence the biological equilibrium and may also affect possible bio-diversity commensurate with the changes. The contribution of the nutrients to the downstream flows would also get reduced due to retention of the river flows.

The thesis has been presented in six chapters followed by bibliography.

CHAPTER 1

INTRODUCTION

1.1 General

The State of Goa is located along the West Coast of India with a geographical area of 3702 km^2. It is situated between the latitudes N14°53′ 57″ and N15° 47′ 59″ and between longitudes E73° 40′ 54″ and E74° 20′ 11″. The north to south length of the State is about 100 km while the east to west width is about 55 km. It is bounded in the north by the Sindhudurg district of Maharashtra, in the north-east by Belgaum district of Karnataka, in the east and south by Uttar Kannada district of Karnataka and in the west by the Arabian Sea (Fig. 1.1). Major part of Goa form a part of the Konkan- Kanara coastal lowland region which is bounded in the east by the Western Ghats escarpment (Sahyadri mountain range). The State is well connected to the rest of the country by road with NH17 and NH4A highways, by rail with Konkan Railway and South Western Railway and by air through Dabolim Airport. The Mormugao port located on the coast of Goa is a premier hub for maritime trade of India and ranks among the top ten iron ore exporting ports of the world. Renowned for its beautiful beaches, places of worship and world heritage architecture, Goa is visited by large numbers of international and domestic tourists every year.

The State is divided into two districts, namely North Goa and South Goa district with their headquarters at Panaji and Margao respectively. The

North Goa district comprises of six talukas, namely Pernem, Bardez, Tiswadi, Bicholim, Ponda and Sattari while the South Goa district comprises of five talukas, namely Mormugao, Salcete, Quepem Sanguem and Canacona. Panaji is the capital city of the State. As per Census 2011 (Provisional), the population of the State is 14.57 lakhs with a population density of 394/km^2. The coastal talukas are more populous compared to the inland talukas. There are 14 statutory towns, 56 census towns and 334 villages in the State. Goa has emerged as one of the developed States of India with high per capita income, high literacy rate, better health care facilities and better standard of living.

Goa is endowed with rich natural resources such as forests, navigable rivers, valuable mineral ore deposits like iron and manganese, fertile agricultural land, abundant rainfall, considerable marine and inland fishing potential, beautiful coastline and an important natural harbour.

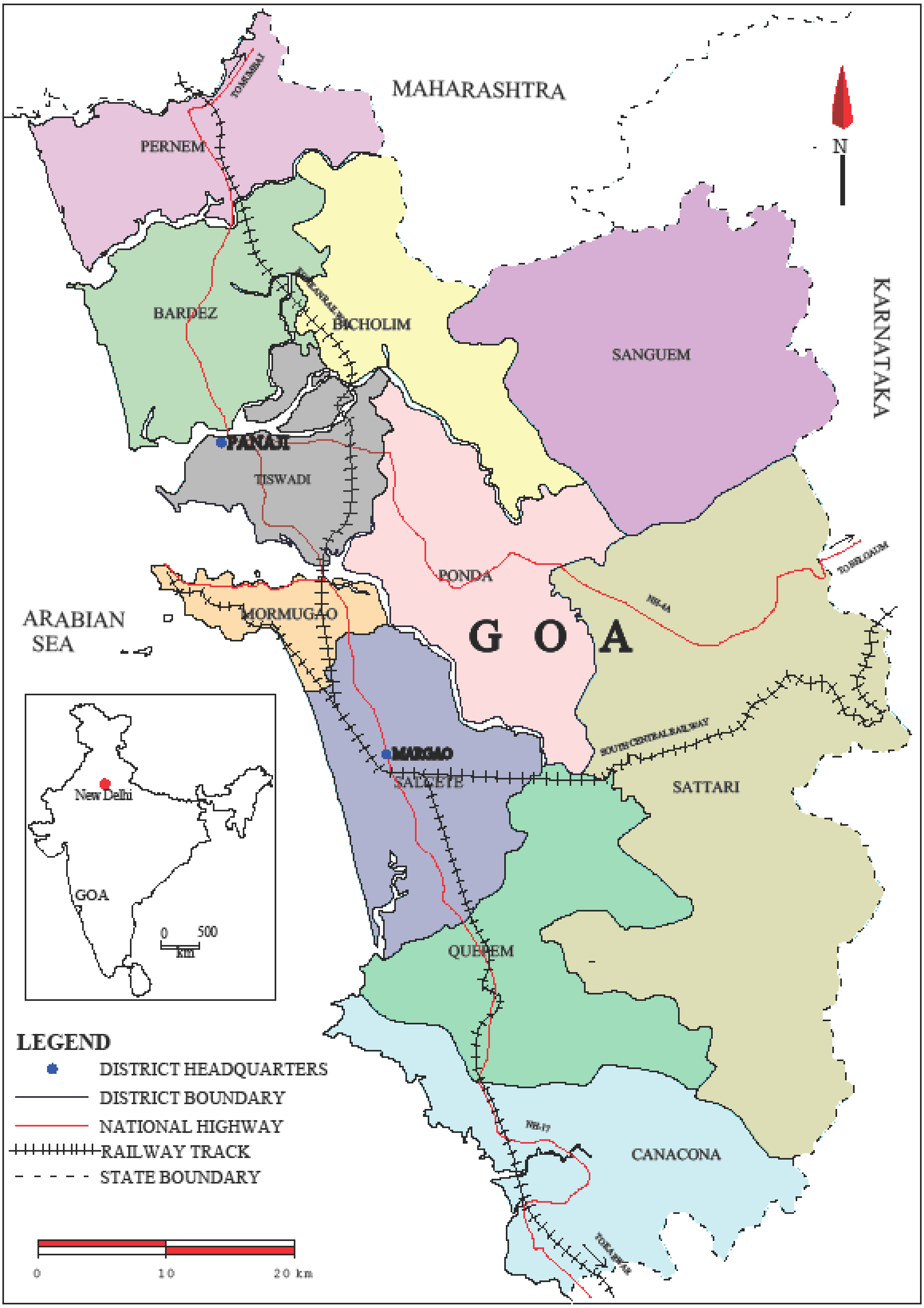


Figure 1.1 Location map and administrative set up of Goa State (source: www.mapsofindia.com)

Owing to its location along the Western Ghats, it has rich flora and fauna and is classified as a biodiversity hotspot. About 60% of the total area of the State is under forest (Forest Survey of India, 2011) while almost 36% is net sown area (Ministry of Agriculture, 2012). Agriculture and fishing have been the key sources of livelihood in Goa since ages. However, owing to its extensive iron ore deposits and beautiful sandy beaches, mining and tourism form the backbone of Goa’s economy. Industrial development is confined to the 21 industrial estates in the State. Rice is the staple food and paddy is the principal agricultural crop while pulses, ragi and other food crops are also grown. Coconut, cashewnut, arecanut, mango and sugarcane are the major cash crops.

1.2 Physiography and Drainage of Goa

Goa forms a part of the coastal tract of the mid-West coast of India. Physiographically, Goa is divided into three broad zones namely the Coastal plain in the west, the Midland region in the centre and the Western Ghats in the east (Fig. 1.2). The Coastal plain consists of sandy beaches, sand dunes, estuarine alluvium, tidal mudflats, saltpans, *Khazan* lands and marshes. The Coastal plain is often interrupted by low dissected laterite capped tablelands. The central Midland region consists of moderately high, elongated, denudational hills trending in NW-SE direction separated by undulate tracts of deeply weathered etch-plain. Finally, the high imposing hills and steep escarpment of the Western Ghats in the east runs in a general north-south direction. Further east, the Karnataka plateau borders the State. The Coastal plain ranges between 2 m to 15 m above mean sea level (amsl) while the flat tops of the coastal tablelands are elevated 50-80 m amsl. The ridges of the Midland vary in elevation from 100 to 400 m while the intermountain etch-plain ranges between 30 to 60 m amsl. The Western Ghats have an average elevation of about 800 m amsl in Goa (Fig. 1.3).

The entire State is drained by a network of nine estuarine rivers, namely Terekhol, Chapora, Baga, Mandovi, Zuari, Sal, Saleri, Talpona and Galgibag River (Fig. 1.4). Most of the rivers originate in the Western Ghats but soon lose their energy as they wander through the Midlands and the Coastal plains to discharge into the Arabian Sea. They are characterised by imperceptible gradients in the lower reaches resulting in the tidal waters entering several kilometres inland. Central Water Commission (CWC, 2005) has estimated the surface water resources of Goa to be 8437 million cubic meters (MCM). The basin wise breakup of this resource is given in Table 1.1.

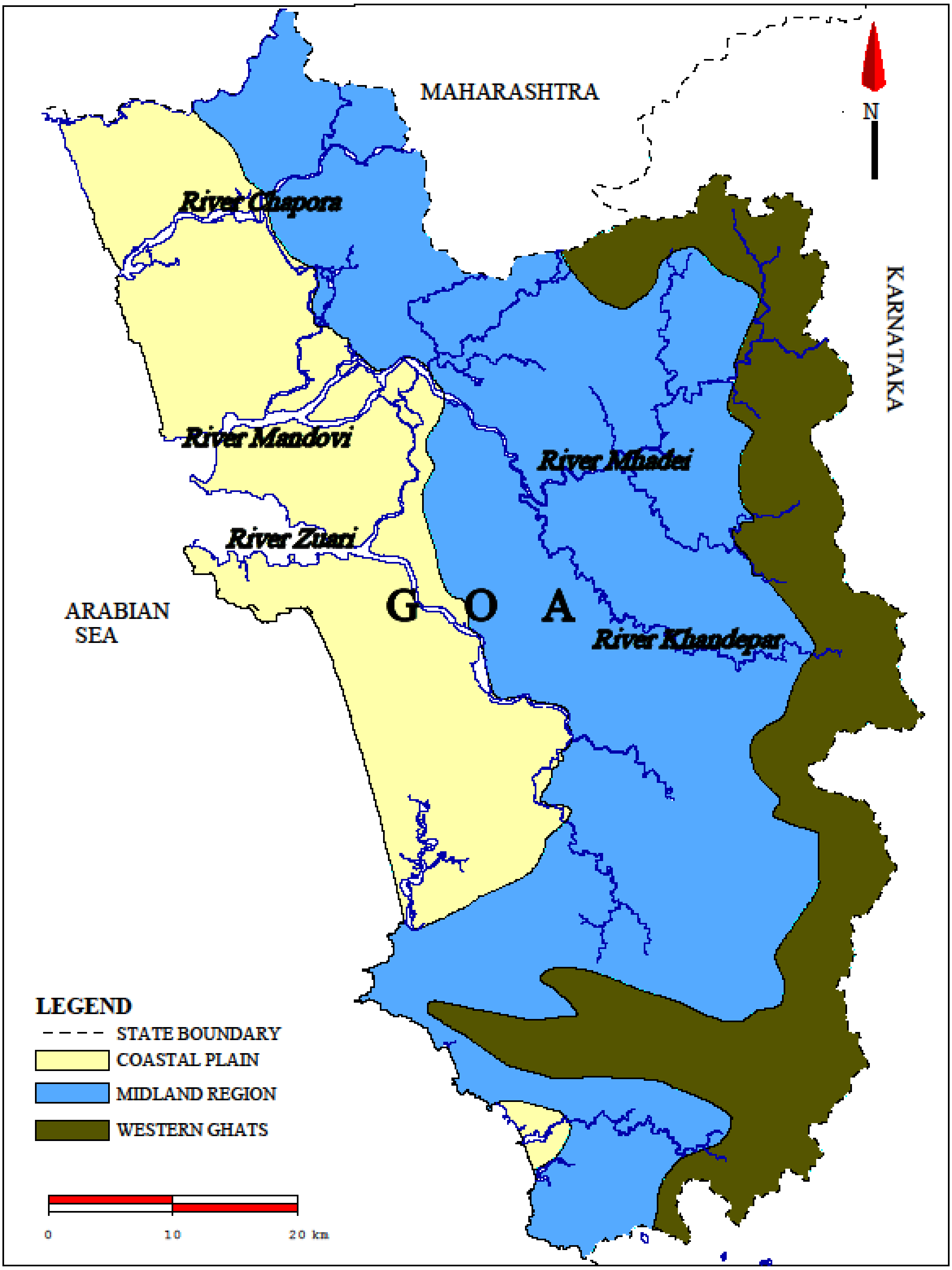


Figure 1.2 Map showing broad physiographic divisions of Goa (source: Fernandes, 2009)

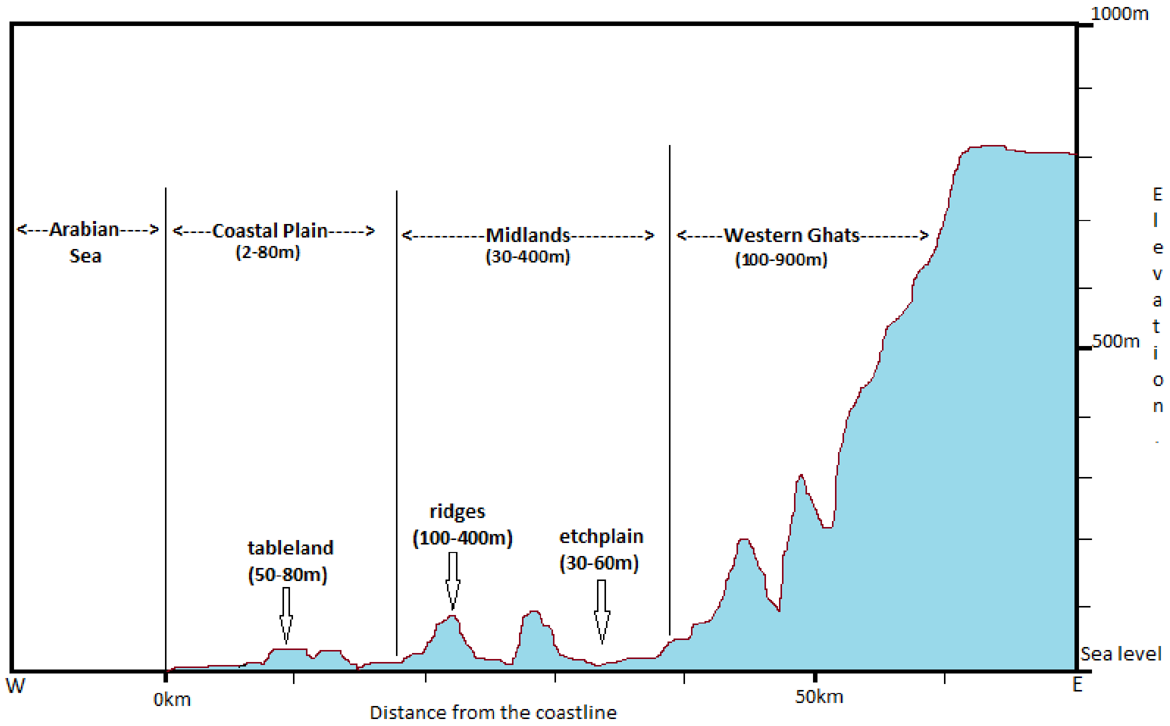


Figure 1.3 A schematic profile of Goa along east- west direction showing the various physiographic units

Table 1.1 Salient features of the river basins in Goa

Sr. No.	River Basin	Catchment Area (km^2)	Surface run-off (MCM)	Length of river within State (km)	Length within the salinity zone (km)
1	Terekhol	71	164.25	26	26
2	Chapora	255	588.35	32	32
3	Baga	50	116.42	10	10
4	Mandovi	1580	3580.04	52	36
5	Zuari	973	2247.40	145	42
6	Sal	301	694.39	40	14
7	Saleri	149	343.04	11	5
8	Talpona	233	515.59	32	7
9	Galgibag	90	187.11	14	4
	Total	3702	8436.59		

Source: CWC and Water Resource Department (WRD), Goa.

Figure 1.4 Watershed map showing river basins of Goa (source: Water Resources Department, Government of Goa)

The two major rivers of Goa, namely the Mandovi and the Zuari River along with Kumbharjua Canal, that links the two rivers naturally, are navigable up to 40 km inland and thus play an important role in the export of the iron ore by providing efficient and economically cheaper means of transport. The Mandovi River has been regarded as the lifeline of the State as its watershed covers about 42% of the total area of the State and its water is extensively used for drinking, transportation, agriculture, fisheries, etc. It has five main tributaries, namely Mhadei, Khandepar, Valvanti, Mapusa and Sinquerim River.

Drinking, industrial and irrigation water supply potential created through 8 schemes as on 2010 is 354 million litres per day (MLD) (Table 1.2). Salaulim dam is a major irrigation project located on Zuari River in South Goa while Anjunem dam is a medium irrigation project located on Mandovi River in North Goa.

The total irrigation potential created in the State through Minor Irrigation Schemes is 31098 hectares (ha) till March 2008 (WRD, 2009). Various schemes such as irrigation wells, lift irrigation schemes, minor irrigation tanks, surface flow irrigation and *bandharas* are implemented by the State government to cover maximum area under irrigation. The details of minor irrigation schemes existing in Goa is given in Table 1.3.

Table 1.2 Water supply schemes created in Goa as on 2010 (WRD, Goa)

Sr. No.	Water supply scheme	Capacity in MLD		Catering to		
		Existing	Proposed	Talukas	Towns	Villages
1	Opa	75	40	Tiswadi, Ponda	4	53
2	Podocem	40	-	Bicholim, Bardez	-	11
3	Sanqueli	12	-	Bicholim, Sattari	2	22
4	Assnora	42	30	Bardez, Bicholim	2	-
5	Chandel	15	-	Pernem	-	-
6	Dabos	5	10	Sattari	-	
7	Salaulim	160	220	Sanguem, Salcete, Marmugao, Quepem	4	71
8	Canacona	5	5	Canacona	1	-
9	Ambeshi-Mhadei	-	25	Sattari, Bicholim	1	4
	Total	354	330		14	161

Table 1.3 Irrigation by different sources in Goa as per Third (2000-01) and Fourth (2006-07: Provisional) Census of Minor Irrigation Schemes

Sr. No	Irrigation Source	Third Census		Fourth Census		% change	
		No. of schemes	Area(ha) irrigated	No. of schemes	Area(ha) irrigated	No. of schemes	Area irrigated
1	Dug wells	5116	3482	4271	4961	-16.52	+37.73
2	Shallow tube wells	30	60	105		+250	
3	Deep tubewells	60	60	47		-21.67	
4	Lift irrigation scheme	984	3545	910	6891	-7.52	-34.51
5	Surface flow irrigation	3861	6978	1741		-54.91	
	Total all sources	10051	14125	7074	11852	-29.62	-16.09

Minor irrigation tanks are constructed at Panchwadi in Ponda taluka, Amthane in Bardez taluka and Chapoli in Canacona taluka. The State has undertaken construction of a series of *bandharas* for augmentation of water resources. A *bandhara* is a hydraulic structure across a river for holding dry weather flow within the limits of river banks without submerging the adjacent land. The *bandharas* in Goa have been effectively harvesting dry weather flows for many beneficial uses. A total number of 158 *bandharas* have been completed as on 2009 with a storage capacity of 47 MCM (WRD, Goa).

1.3 Climate and Rainfall

Goa has a tropical monsoon climate and the region is generally warm and humid throughout the year. The temperature ranges from 20°C to 34°C. The diurnal range of temperature during the day is not large being 4 to 6°C during monsoon season and increases to 10 to 20°C during December and January. The temperature is highest during pre-monsoon months of April and May and lowest during January. Due to proximity of the State to the Arabian Sea the humidity is high throughout the year. The relative humidity varies from 60% to 90%.

The State receives abundant rainfall from the Southwest monsoon during June to September. There are thirteen rain-gauging stations of India Meteorological Department (IMD) in Goa. The average annual rainfall received in the State is about 3200 mm. As a result of the orographic influence the rainfall increases progressively from the coast to the Western Ghats from about 2500 mm to over 4500 mm (Fig. 1.5). Over 90% rainfall occurs during the monsoon months with Valpoi and Sanguem stations recording maximum rainfall (Fig. 1.6) while the remaining 10% rainfall is received during the non-monsoon months (Fig. 1.7). The low lying coastal areas receive minimum rainfall while the inland hilly terrain receives maximum rainfall (Fig. 1.8). Highest rainfall is received during the month of July (Fig. 1.9) followed by a gradual decrease in subsequent monsoon months. Rainfall is the main source of groundwater recharge in the State.

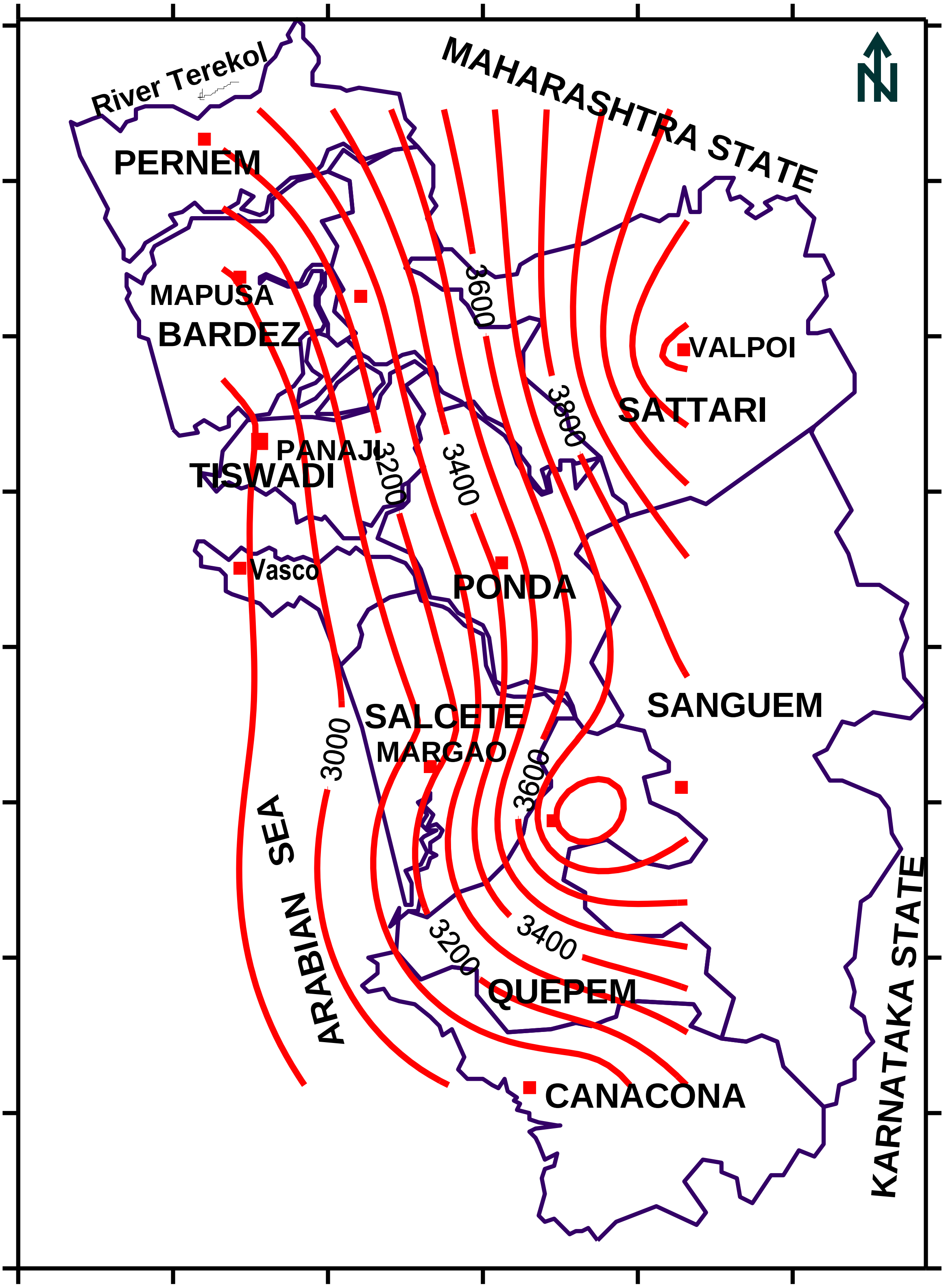


Figure 1.5 Isohyetal map showing normal annual rainfall (mm) in Goa

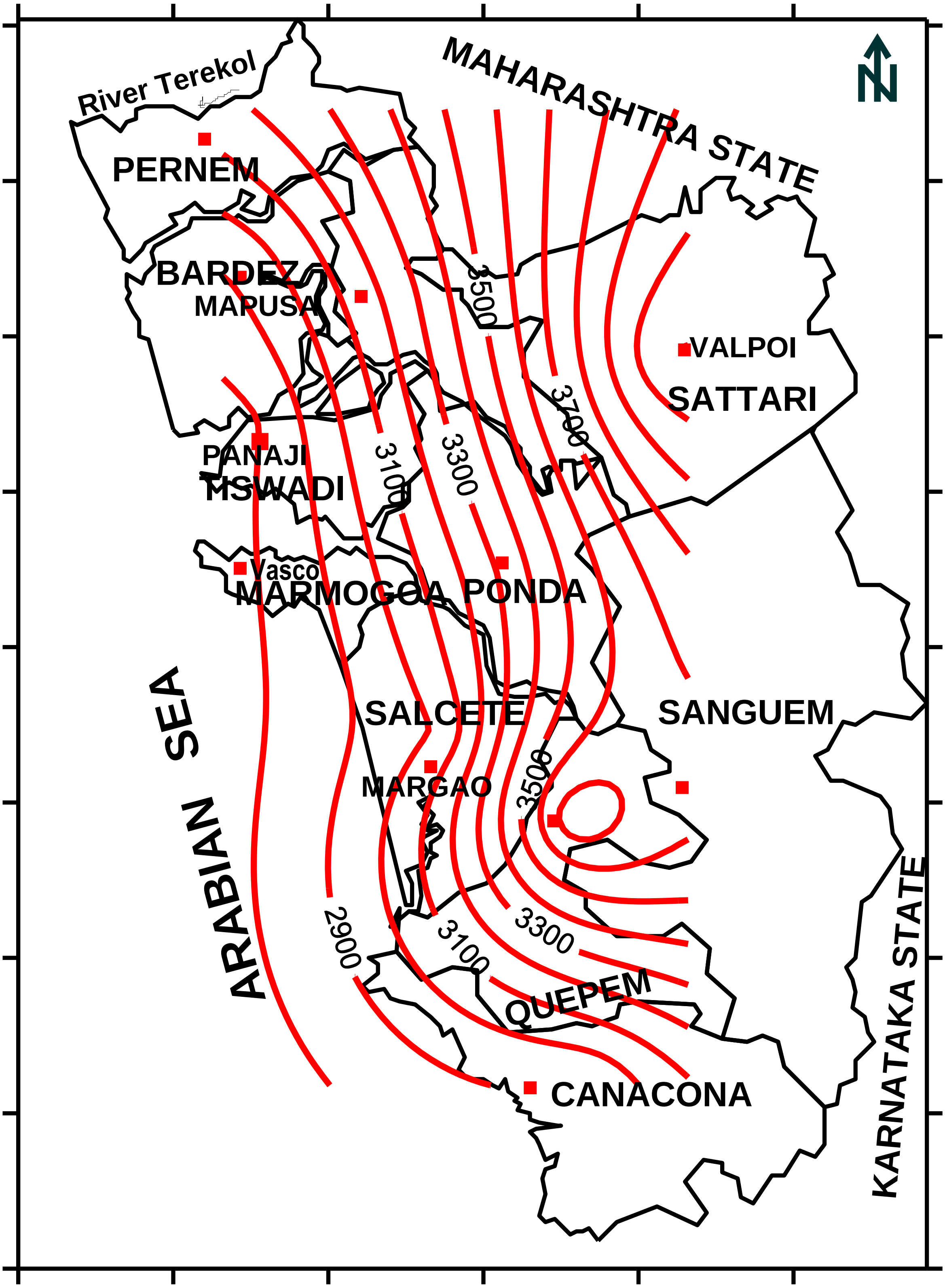


Figure 1.6 Isohyetal map showing normal monsoon rainfall (mm) in Goa

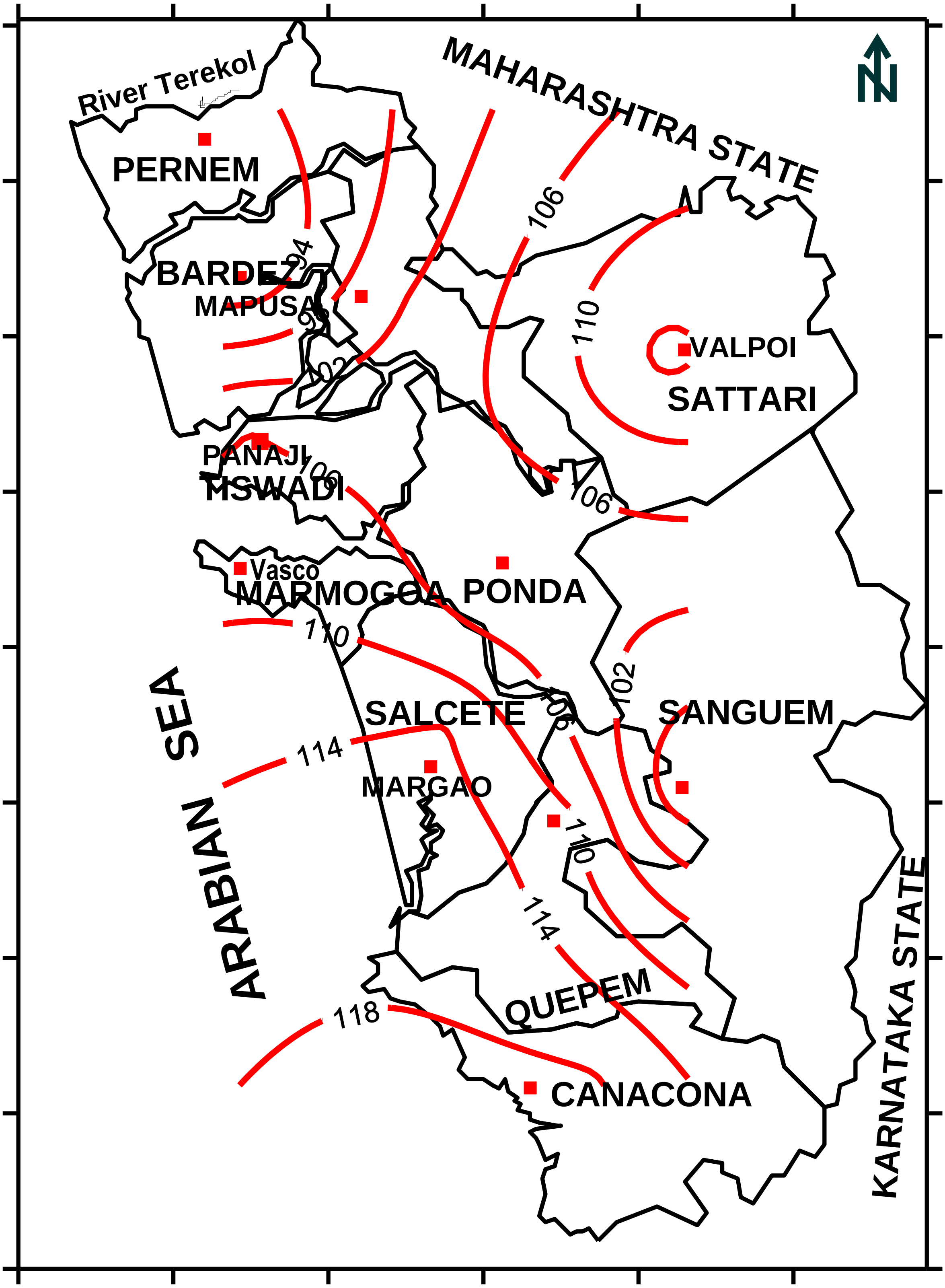


Figure 1.7 Isohyetal map showing normal non-monsoon rainfall (mm) in Goa

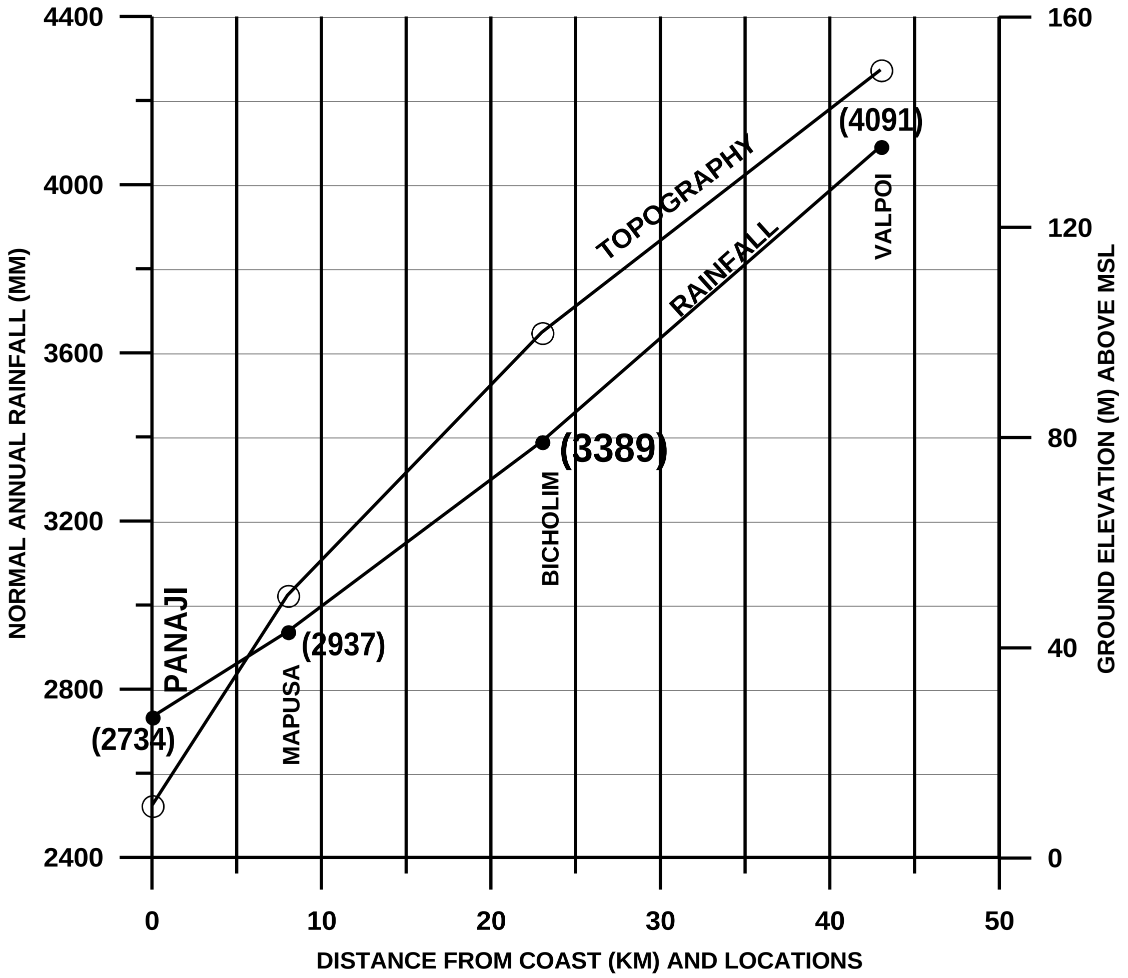


Figure 1.8 Graph showing relationship between topography and rainfall in Goa

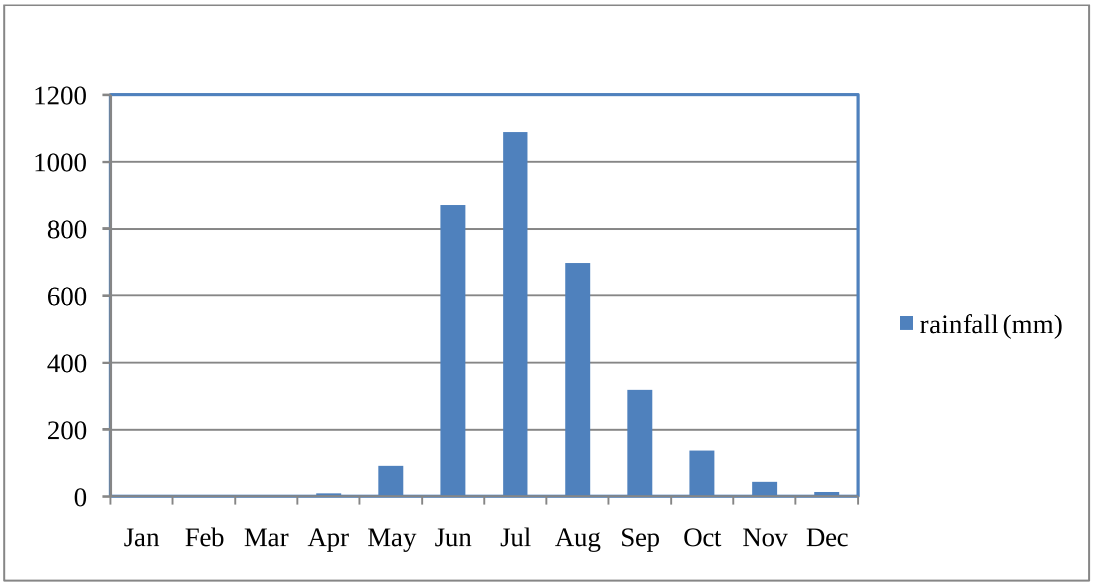


Figure 1.9 Histogram showing normal monthly rainfall in Goa

1.4 General Geological Setup of Goa

The regional geology in general and local geology in particular is very important in understanding hydrogeological characters of an area. The occurrence and movement of groundwater directly depends on the openings within the rock formations. The nature of rock type, the degree of rock deformation and the extent of weathering play a significant role in the formation of porosity.

The State of Goa is located on the Western Dharwar craton. It constitutes the north-westerly extension of the greenstone-granitoid terrain of Karnataka, comprising rocks of the Peninsular Gneissic Complex (PGC) and Dharwar Supergroup of Precambrian age. The PGC is well exposed along the Western Ghats in North Goa and around Chauri and Quepem in the South Goa. The rocks of the Dharwar Supergroup are represented by the northern extension of the Shimoga schist belt locally classified as 'Goa Group' (Gokul et al, 1985). The rocks of the PGC and the Goa Group are intruded by mafic-ultramafic complexes, younger granites and mafic intrusives. A narrow strip in the north eastern corner of the State is covered by Deccan Traps of late Cretaceous-lower Eocene age (Fig. 1.10). Most of these rocks are often hidden below a thick weathered lateritic cap and/or a soil cover of varying thickness.

The oldest known rock found in Goa is the Anmod Ghat Trondhjemitic Gneiss (3400$\pm$140Ma, Dhoundiyal et al, 1987). The Peninsular gneisses are grey, medium to coarse grained, banded or migmatitic and grade in composition from Tonalite- Trondhjemite- Granodiorite. These gneisses form the basement for the Goa Group of rocks.

The Goa Group of rocks consists of meta-volcanic and meta-sedimentary rock assemblage characterized by greywackes, argillites, tuffs, agglomerates, mafic lavas and banded iron formation. It has undergone greenschist facies of regional metamorphism and is broadly comparable to the Chitradurga Group of Karnataka (Gokul et al, 1985). The Goa Group is divided into four formations, namely the Barcem, Sanvordem, Bicholim-Rivona and Vageri Formations in the ascending order of superposition (Table 1.4).

The PGC and the Goa group of rocks have been intruded by Bondla mafic-ultramafic complex and granites which occur as plutons, plugs and apophyses (GSI, 1996), the most important being the porphyritic Canacona Granite and the Dudhsagar Granite. These are followed by mafic intrusives. These rocks are overlain by Deccan Traps represented by horizontally disposed massive and vesicular basaltic lava flows. During the late Cenozoic period the rocks were subjected to intense chemical weathering resulting in a laterite cover of varying thickness (Widdowson, 2009). Beach sands, sand dunes and alluvium occurring along the low lying coastal area and narrow alluvial strips along rivers and streams are of sub-recent to recent age. Laterite constitutes the most widespread and important water bearing formation in the State.

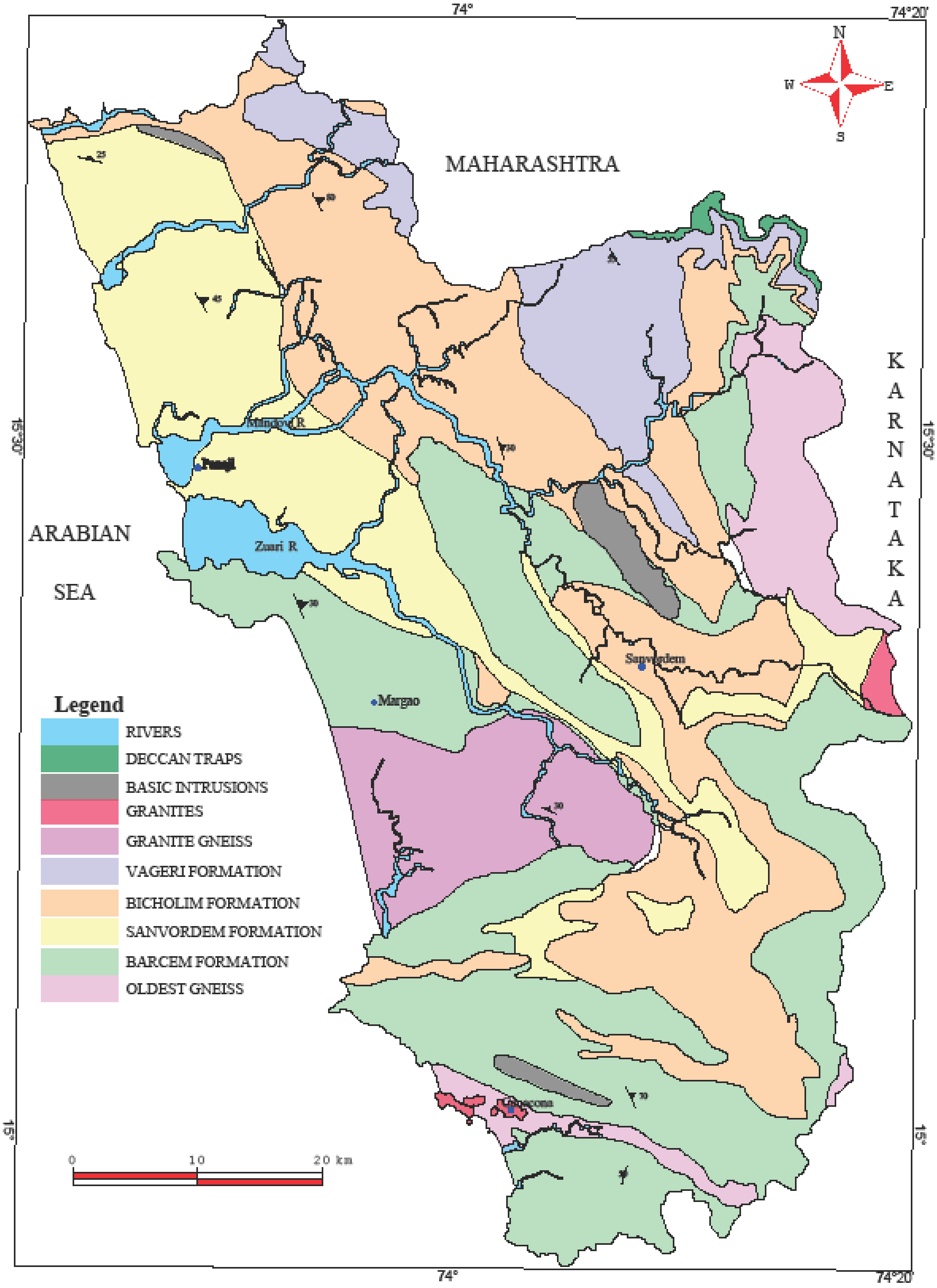


Figure 1.10 Geological map of Goa (modified after GSI, 1996)

Table 1.4 Stratigraphic sequence of rock formations in Goa

Late Cenozoic to Recent	Sand, alluvium, lateritic soil and laterite
Upper Cretaceous to Lower Eocene	Deccan Trap volcanics and dolerite dykes
Early Proterozoic (<2500 Ma)	Acidic and basic intrusives including granites, gabbros, dolerite dykes and ultramafics
Archean (3000-2500 Ma) **Goa Group** (Dharwar Supergroup)	Vageri Fm: Carbonate-quartz-chlorite schist and metagreywacke with some quartzite and metavolcanics
	Bicholim Fm: Qtz-chlt-biotite schist, chert, Fe and Mn oxides, metabasalt, metagabbro, BIF, qtz-sericite schist, Mg- limestone
	Sanvordem Fm: Quartzite, qtz-chlorite schist, metagreywacke with conglomerate
	Barcem Fm: Metabasalt, metagabbro, meta-acid volcanics, quartzite, qtz-chlorite schist
Archean (>3000 Ma)	Basement Peninsular Gneiss

(Adopted from Gokul et al, 1985 and GSI, 2006 with modifications)

The Dharwarian rocks were folded, fractured and faulted in several episodes of tectonic activity. Gokul, et al (1985) have noted three phases of folding in the rocks of the Goa Group. The first fold movement, F1, resulted in a general WNW-ESE trend preserved in the south western part of Goa. The second cycle of folding, F2, which was the most powerful movement imparted the NW-SE Dharwarian trend to these rocks. The third fold movement, F3, which was relatively milder and is noticed only in the north-eastern part of the State, has resulted in a northwest plunging broad open synclinal fold. In the eastern margin of the territory, along the Western Ghats, rocks exhibit evidences of intense shearing and mylonitisation which are related to the upliftment of Karnataka plateau on the east.

1.4.1 Laterite

The laterites of Goa constitute a significant geological formation as it forms the most important aquifer in the State covering a large geographical area. One of the most remarkable aspects of laterites in Goa is their ubiquitous development on a wide range of rock types. They have developed upon the variety of Dharwar schists and metasediments, the more mafic gneisses, the mafic- ultramafic intrusives and the Deccan basalts. However, laterite is often absent in those areas where granite is exposed and is sparsely developed over most Peninsular gneisses. Laterites are either developed *insitu* (autochthonous) on crystalline rocks and on alluvial valley fills or of detrital origin (allochthonous) which are generally occupying hill slopes and valley portions.

Laterite is a manifestation of intense tropical deep weathering of rocks that occurs when favourable climatic conditions exist. The degree of weathering typically diminishes with depth producing a weathering profile (Fig. 1.11). The top of the weathering profile is characterised by hard, massive, highly indurated iron-rich material called 'duricrust', followed downward by a semi-indurated mottled zone comprising iron segregations. These zones have vermiform or tubular texture that promotes a good vertical drainage of percolating water. These zones are followed downward by lithomarge clay called 'saprolite' in which structures and/or individual crystal pseudomorphs from the parent rock may still be recognised. It is dominantly composed of kaolinite along with unaltered core-stones of the protolith (Widdowson, 2009). The saprolite is generally devoid of voids, conduits or fissures and therefore has a poor permeability. However, occasionally it contains sand mixed clays which are porous and permeable. The lithomarge clay gradually progresses into the unaltered basement rock.

The coastal tablelands which are an important geomorphic feature of the State are invariably made up of a thick sequence of autochthonous laterite. They are generally capped by a hard duricrust of typically 5-10 m thickness followed downward by the less indurated lower layer of the weathering profile which is susceptible to preferential erosion when exposed. The faster erosion of this lower layer at the edges of the tablelands results in topographic cambering and subsequent sliding of the overlying duricrust fragments which get accumulated at the foot and steep slopes of the tablelands. The steep slopes of the tablelands are mantled with detrital lateritized debris and clays resulting in the development of allochthonous laterite. The denudational ridges and the intermountain etch-plains of the Midland region of Goa are also covered by a thick layer of laterite. However, the high hills of the Western Ghats are often devoid of laterite cover. The laterites and the crystalline rocks are often covered by a thin soil cover.

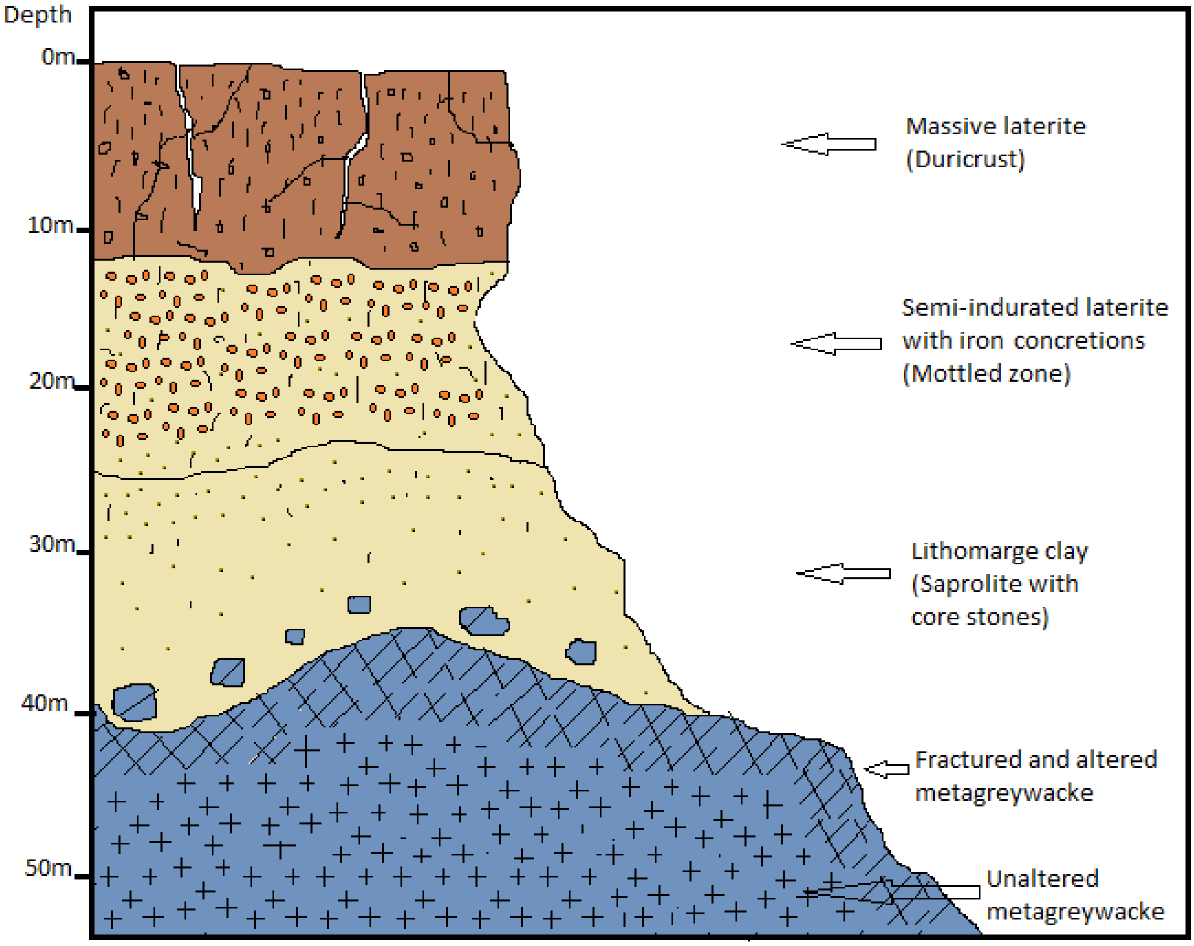


Figure 1.11 Idealised vertical section of a laterite weathering profile (adoted and modified after Widdowson, 2009)

The National Bureau of Soil Survey and Land Use Planning (NBSS & LUP, 1999) have identified 25 soil series units in the soils of Goa and classified them into 4 orders, 7 sub-orders, 12 great-groups and 18 subgroups. The thickness of soil cover is generally between 0.25 m to 1.5 m. The soil texture of 38% of the soil cover is silty clay to gravelly silty clay, 26% soil cover has gravelly clay to clayey texture while about 20% of the soil cover has sandy loam to loamy sand texture. Most of the soils are well drained to excessively drained.

1.4.2 Lineament Map of Goa

Lineaments are representations of linear physiographic features related to structural features of rocks such as joints, faults, fractures, shear zones, dykes or folds. These weak zones in the rocks form favourable areas for groundwater occurrence and hence study of lineaments gives valuable information about the groundwater potential of an area.

Two major trends of lineaments viz., NW-SE and NE-SW have been identified in Goa by Kunte, 1990 using advanced image processing techniques (Fig. 1.12). The NW-SE trend corresponds to the regional Dharwarian trend while the NE-SW trend is perpendicular to the Dharwarian trend corresponding mostly to incised fractures, joints, faults and dykes (Dessai and Peshwa, 1978; Wagle, 1982; Iyer, et al, 1989).

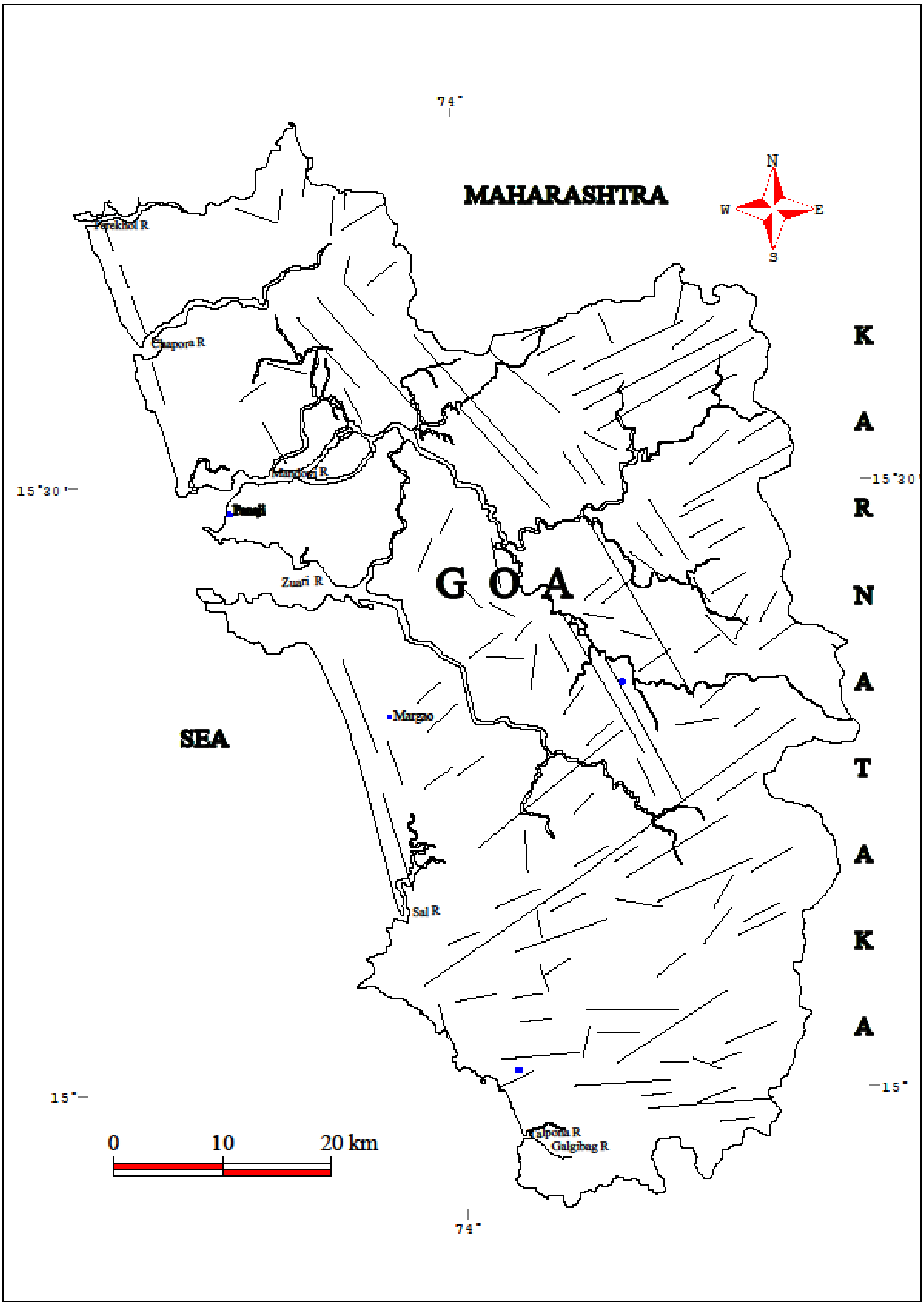


Figure 1.12 Lineament map of Goa (adopted and modified after Dessai and Peshwa, 1978 and Kunte, 1990)

1.5 General Hydrogeological Setup of Goa

The hydrogeological framework of Goa is essentially controlled by the geological and geo-morphological setup. Laterites, alluvium, iron ore bodies, meta-sedimentaries, meta-volcanics, granites and gneisses are the groundwater bearing formations of the State (Chougula, 1999). Laterites, coastal alluvium and fractured and weathered basement rocks constitute the major groundwater bearing formations of the State.

The common aquifer comprising of fine to coarse sands with intercalations of sandy loam, silt and clay forms an important unconfined aquifer along the coastal plains (Fig.1.13). Groundwater occurs under water table condition in the sandy alluvial matrix with moderate to high permeability (Chachadi, 2009). The thickness of the coastal alluvium varies from 5 m to 22 m. Depth to water level generally varies from 1 m to 6 m below ground level (bgl) (CGWB, 2002). The coastal alluvial aquifers are considered to be non-sustainable due to their high drainability. The water levels in the coastal areas drop rapidly during the post monsoon both due to high drainability of these aquifers and excessive groundwater extraction leading to sporadic incidence of sea water intrusion.

Laterites constitute an important shallow aquifer covering about 70% area of the territory (Chougula, 1999). They occur as an extensive, semi-continuous belt capping the tablelands of the coastal plains and the elongated hills and etch plains of the midlands.

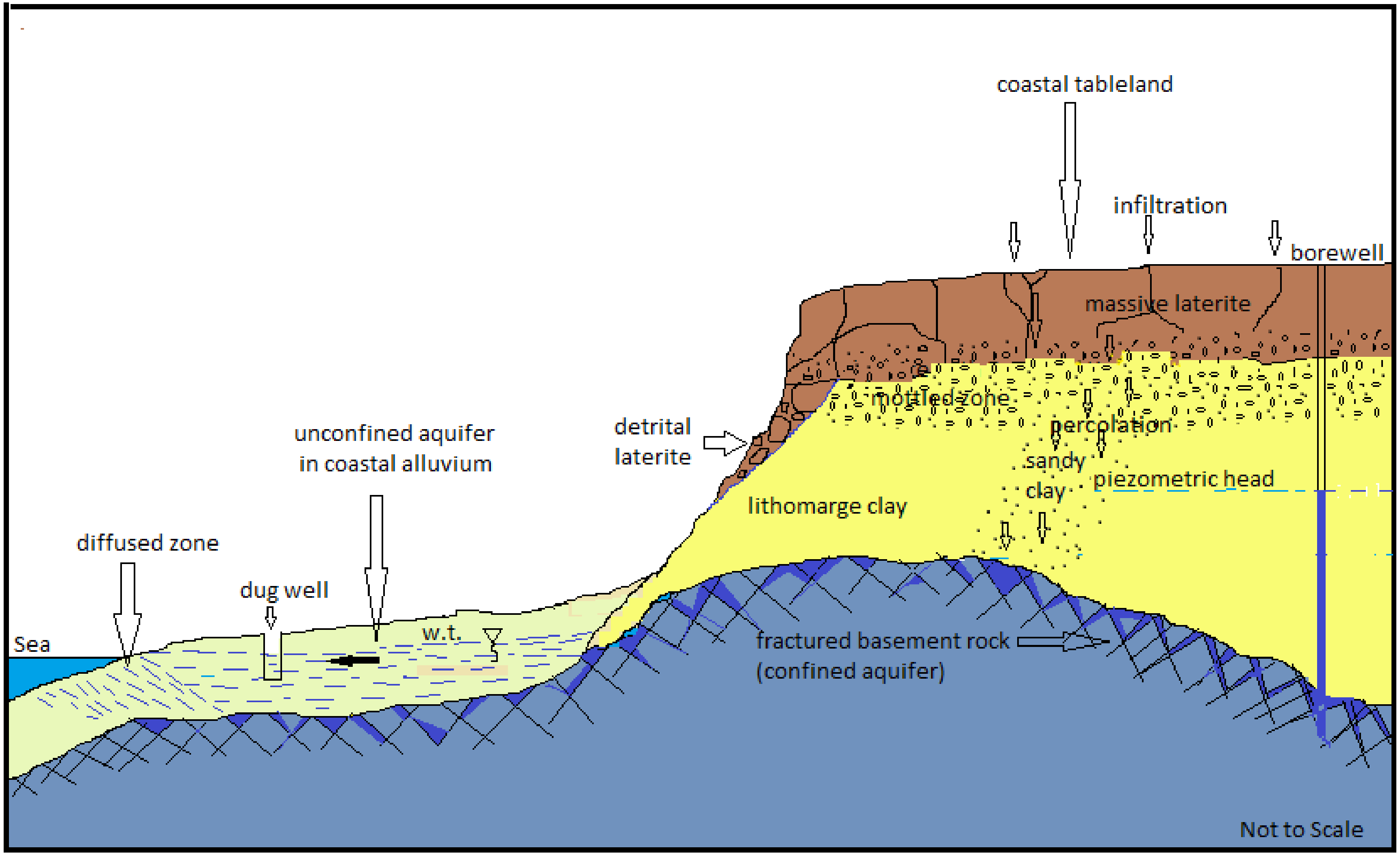


Figure 1.13 A schematic vertical section showing unconfined aquifer in coastal alluvium and confined aquifer in fractured basement rock below coastal tableland

The laterites vary in thickness from less than 5 m to more than 30 m and are underlain by a thick sequence of lithomarge clay followed downward by the fractured basement rock (Chachadi, 2009). Rainwater that infiltrates through the soil cover and percolates downwards after saturation of soil zone is stored in the openings in the laterites. Groundwater generally occurs in laterites under phreatic (water table) condition in the intricate network of voids, fissures and sinuous conduits. In addition to their inherent porosity they are often jointed and fractured which increases their water bearing and transmitting capacity. However, the topographic setting of laterites mainly controls their groundwater potential and occurrence. The laterites occurring in the low lying areas of the Midlands and some coastal areas, form potential water table aquifers with sustainable yields throughout the year. They are recharged annually through rainfall. A large number of open wells are dug in these laterites. Irrigation dug wells tapping laterite range in depth from 3m to 10m and depth to water levels varies from 1 to 7 m bgl (CGWB, 2002).

Contrastingly, the laterites capping the tablelands in the coastal region generally lack groundwater due to their unfavourable topographic setting which renders faster surface runoff to the low lying area. Part of the infiltrating water reappears in the form of springs around the slopes of the plateaus. However, vast plateaus with a depression on top often form laterally limited water table aquifers. In addition, the layer of the fractured and weathered basement rock lying between the lithomarge clay and the fresh compact basement rock form an important confined to semi-confined aquifer (Fig 1.13). It has been observed that the water levels in the boreholes drilled on the plateaus penetrating the fractured basement rock show 20 to 25 m of groundwater elevation above mean sea level. The ground water bearing layer in the fractured aquifer under the coastal plateaus (tablelands) is often found below the sea level (Chachadi, 2009). Bore-wells dug in this aquifer vary in depth from 50m to 120m.

The iron ore bodies, particularly powdery iron ore layers, constitute another confined aquifer that occurs in the elongated hills of the Midlands of the State. The iron ore bodies occur in the Bicholim Formation of the Goa Group and are bounded on both sides by variety of clays which are mostly impervious thereby rendering the ore bodies as confined aquifers. Primary unaltered, compact, impermeable phyllites and BIF occur towards their base. The iron ore bodies are highly folded and dominantly composed of powdery ore which is highly permeable and often saturated with water. The ore bodies are covered by laterite on the crests of the hills and are recharged by vertical seepage through this laterite cover (Pahala Kumar et al, 1994). These ore body aquifers may extend up to the basement rocks. However, the laterite capping the elongated hills in the Midland region is generally devoid of groundwater due to their unfavourable topographic setting.

A limited areal extent unconfined aquifer composed of silty loam with pebbles at the bottom occurs in the intermountain valleys and etch-plains in the hinterland. These are the areas extensively used for paddy cultivation in the post monsoon season as groundwater occurs at shallow depth and the contact springs supply water from the adjoining hills.

Groundwater occurs under unconfined condition in the weathered mantle of the gneisses, meta-volcanic and meta-sedimentary rocks. However, fractures and joints in the underlying fresh rock also render secondary porosity to these rocks resulting in semi-confined to confined aquifers. Bore-wells drilled in these rocks range in depth from 37m to 200m and indicate that productive zones exist up to 119m bgl (CGWB, 2002).

The WRD, Goa and CGWB, Bangalore (2011) has assessed the net annual groundwater availability of the State at 132 million cubic meters (MCM) and the annual groundwater draft is 43 MCM as on March 2009 (Table 1.5). The stage of groundwater development is 33% and the entire state has been categorised under safe category (WRD & CGWB, 2011). However, these macro level estimates of groundwater reserves and utilization are approximations only and cannot be put to use entirely because of their typical spatial and temporal distribution (Chachadi, 2009). Micro-watershed level studies carried out by Chachadi et al. (2001) in the coastal areas and Chachadi (2003) in the mining belt have indicated moderate to severe water stress conditions in majority of the sub-watersheds.

There are 53 National Hydrograph Network Stations and 58 Exploratory Tube wells constructed in Goa by CGWB as on 2009. On the basis of long term groundwater level trend (1995-2005) pre-monsoon trend of 40% of the observation wells in Bicholim taluka and 16% in Sattari taluka have recorded declining trend (CGWB, 2010).

Table 1.5 Dynamic groundwater resource of Goa as on 2009

Sr. No.	Assessment unit	North Goa	South Goa	Goa
1	Net annual groundwater availability (MCM)	78.01	54.72	132.74
2	Total annual groundwater draft (MCM)	25.46	18.36	43.83
3	Projected demand for domestic and industrial uses up to 2025 (MCM)	24.13	18.74	42.87
4	Stage of groundwater development	33%	34%	33%

(Source: WRD and CGWB, 2011)

The quality of groundwater in Goa has been classified as Calcium-Bicarbonate type and in general, the quality of groundwater in the State is good (CGWB, 2010). However, about 5% area along the coast and tidal river courses has been affected by the sea water ingress (CGWB, 2002). There are quite a few reported examples where groundwater and surface water have been seriously contaminated due to industrial effluent disposals and urban sewage and solid waste disposals. Mining has resulted in declining groundwater levels and bacteriological contamination of groundwater around the mining belt in Bicholim and Sattari talukas (Chachadi, 2002). Acute shortage of drinking water supply during the summer months of March, April and May is a common situation in the State.

In order to meet the ever growing demand for water the exploitation of groundwater resource has increased manifold recently in the urban areas with random sinking of bore wells. Though groundwater represents the largest available source of fresh water in the hydrologic cycle, its overexploitation can detrimentally affect the quality and quantity of this valuable resource. Keeping all these aspects in view, assessment of the groundwater and surface water resources in a scientific manner and managing their development for sustainable supplies becomes utmost important.

1.6 Scope of the Present Work

Hydrological and hydrogeological evaluation of surface water and groundwater resources with watershed as a unit is a prime requirement for sustainable development and management of water resources. The Mhadei River is an interstate river, the watershed of which extends in Goa and Karnataka. The river has been at the crux of a controversy since last one decade due to proposed river water retention and diversion projects in the upper reaches of the river by Karnataka government. The State of Goa has expressed concern about the likely effects of such river water retention and diversion structures on the hydrological regime, ecological balance and economic development in the lower reaches of the Mhadei River watershed. Environmentalist and social activists have been raising the issue based on qualitative information about the natural resources of the Mhadei River watershed.

Literature survey revealed lack of scientific and quantitative information about Mhadei River watershed, particularly the quantum of groundwater and surface water resources. It is observed that most of the studies in Goa on hydrogeology were carried out on a regional scale with administrative boundaries as study units while others focused on the influence of open cast mining on the local groundwater regime. The studies related to the hydrology and hydrogeology of the Mhadei River watershed on a regional scale has never been carried out. With Mhadei River watershed at the peak of its water resource development strategy it becomes essential to generate field based primary data which is technically valid and scientifically acceptable. Thus, a detailed and comprehensive evaluation of hydrological and hydrogeological aspects of the Mhadei River watershed becomes essential.

1.7 Aim and Objectives of the Present Study

The primary aim of the present study is to acquire, generate and analyse comprehensive hydrological and hydrogeological data of the interstate Mhadei River watershed. In order to fulfil this primary aim of the study the following objectives have been setup:

1. To carry out a comprehensive literature review of the earlier studies about the hydrological and hydrogeological aspects of the entire State of Goa and the study area in particular.
2. To carry out a detailed rainfall analysis and quantification of surface run-off and baseflow components from the respective watersheds lying in the two States.
3. To carry out a systematic morphometric analysis of the entire Mandovi River basin and Mhadei River watershed in particular.
4. To carry out a comprehensive study of the groundwater occurrence, its distribution and movement in the sub-surface, delineate potential recharge and discharge areas, mapping of groundwater potential areas, estimation of groundwater resources, estimation of rainfall infiltration factor, estimation of aquifer properties and evaluation of soil infiltration properties besides evaluating the nature of groundwater occurrence.
5. To assess possible environmental and ecological impacts of the proposed upstream surface water development projects on the lower reaches of the Mhadei River watershed lying in Goa.

1.8 Location of the Study Area

The study area i.e., the Mhadei River watershed is a sub-catchment of the Mandovi River basin. The Mhadei River and the Khandepar River are the two major tributaries of the Mandovi River which drains into the Arabian Sea. The other minor tributaries of the Mandovi River include the Valvanti River, the Mapusa River and the Sinquerim River.

The Mhadei River watershed can be located on Survey of India toposheet numbers: 48 I/2, 48 I/3, 48 I/6 and 48 I/7 drawn on 1:50,000 scale. It lies between latitudes N15° 22′ 14″ and N15° 42′ 08″ and longitudes E74° 02′ 25″ and E74° 25′ 00″. The watershed extends over a total area of 899 km^2 of which 573 km^2 (64%) lies in Goa and 326 km^2 (36%) lies in Karnataka (Fig. 1.14) making it an interstate watershed. It is bounded by the watershed of Valvanti River in the northwest, Khandepar River in the southwest, Pandhri Nadi in the southeast and Malaprabha River in the northeast. It is a mountainous watershed of Western Ghats region that extends over the Midland region of Goa and the Karnataka plateau. The national highway NH4A connecting Panaji to Belgaum runs on the southern side of the watershed.

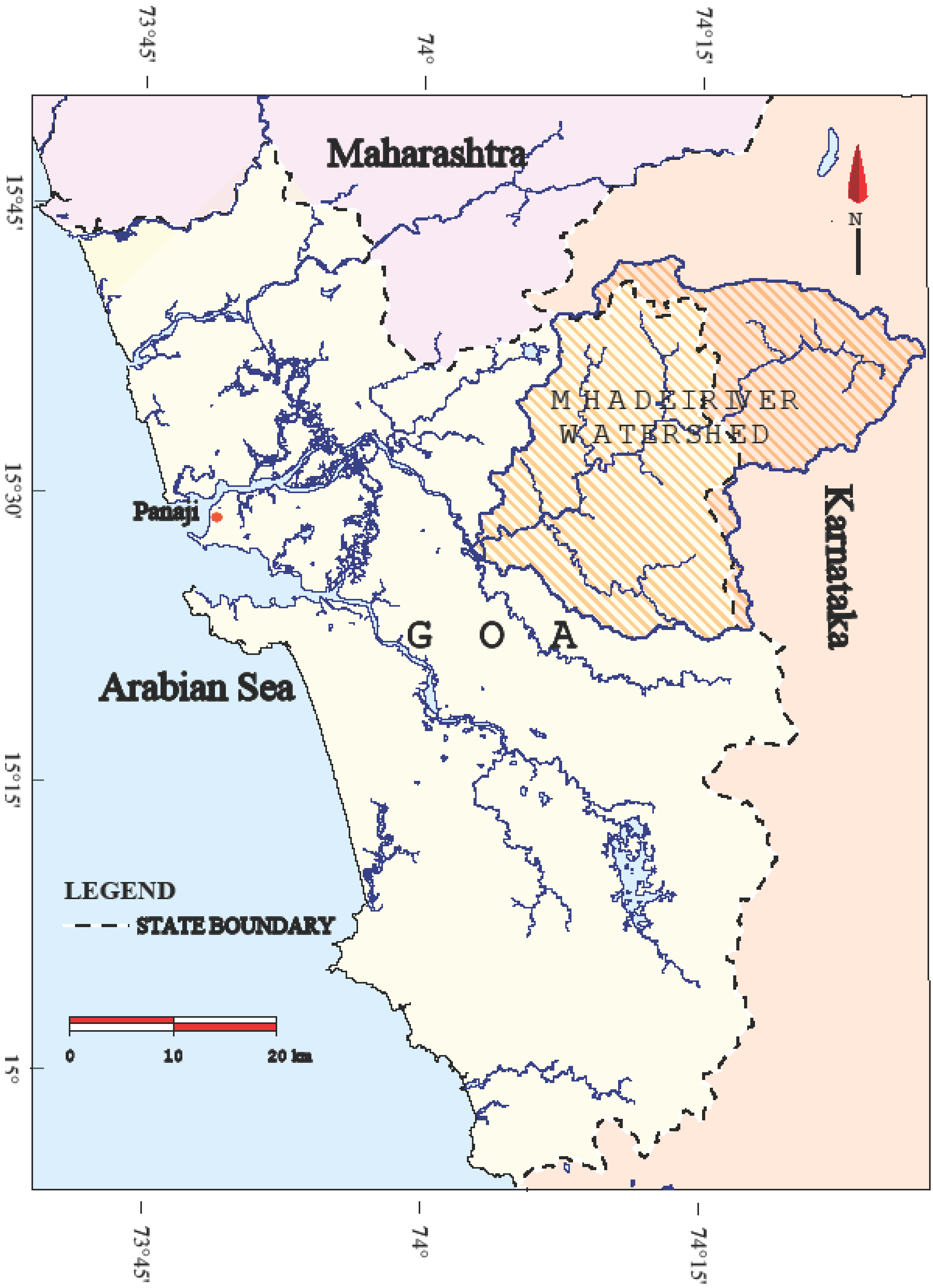


Figure 1.14 Location map of the study area- Mhadei River watershed

1.9 Salient Features of the Study Area

The study area, Mhadei River watershed, is dominantly located in the North Goa district of Goa. Valpoi is the only major town of Goa that is located within the watershed along with 68 villages. Out of these, 62 villages are located in Sattari taluka, 3 villages in Sanguem taluka, 2 villages in Ponda taluka and 1 village in Bicholim taluka. The eastern part of the watershed is located in the Khanapur taluka of Belgaum district in Karnataka. Kankumbi is the main settlement area of Karnataka located on the northern boundary of the watershed along with 14 villages. Almost 85% of the area of the watershed is covered by forest while about 4% is agricultural land (Table 1.6). Few iron ore mines are located in the southern and south-western part of the watershed around Pale and Sancordem villages. Cultivation, mining and small scale industrial activities form the major occupations of the local population. Cashew and coconuts are the major cash crops of the region and paddy forms the conventional food crop.

Table 1.6 Distribution of various land use – land cover types in Mhadei River watershed (Based on SOI maps and satellite imageries)

Land Type	Area (km^2)	Area %
Settlement area	16.40	1.82
Agricultural land	32.21	3.58
Mining area	4.77	0.53
Plantations	71.43	7.94
Water bodies	8.71	0.96
Forest area	765.97	85.16
Total	899.49	100

The Mhadei River watershed, can be topographically divided into three parts, the western part of the watershed lies in the central Midland region of Goa, this region consists of elongated hills having elevations below 400m amsl separated by the etch plain having elevation between 30 m to 60 m amsl, the central part of the watershed comprises of steep imposing hills of the Western Ghats ranging in elevation between 500 m to 900 m amsl while the eastern part of the watershed lies on the plateau region of Karnataka (Mysore Plateau) (Figs. 1.15 and 1.16). The highest elevation in the watershed is 1026 m amsl at Darsingha while lowest elevation is 5 m at the outlet of the river near Usgao.

The Mhadei River originates in the Degao village of Khanapur taluka in Belgaum district, located on the western fringe of the Karnataka plateau. Initially for some distance it flows towards northeast and then takes a turn due southwest and flows down the Western Ghats to enter the Sattari taluka of Goa. At Usgao, the Mhadei River meets the Khandepar River and further it is called as the Mandovi River. Kotrachi Nadi (also called Veluz Nadi), Surla Nadi (also called Nanoda Nadi) and Ragda Nadi form the main tributaries of the Mhadei River (Fig. 1.15). A number of smaller streams like Bail Nadi, Kotni Nadi, Doli Nadi and Bhandura Nadi also join the Mhadei River. The total length of the Mhadei River is 77 km of which 34 km flows in Karnataka and 43 km flows in Goa. The watershed receives abundant rainfall from the southwest monsoon during the months of June to September.

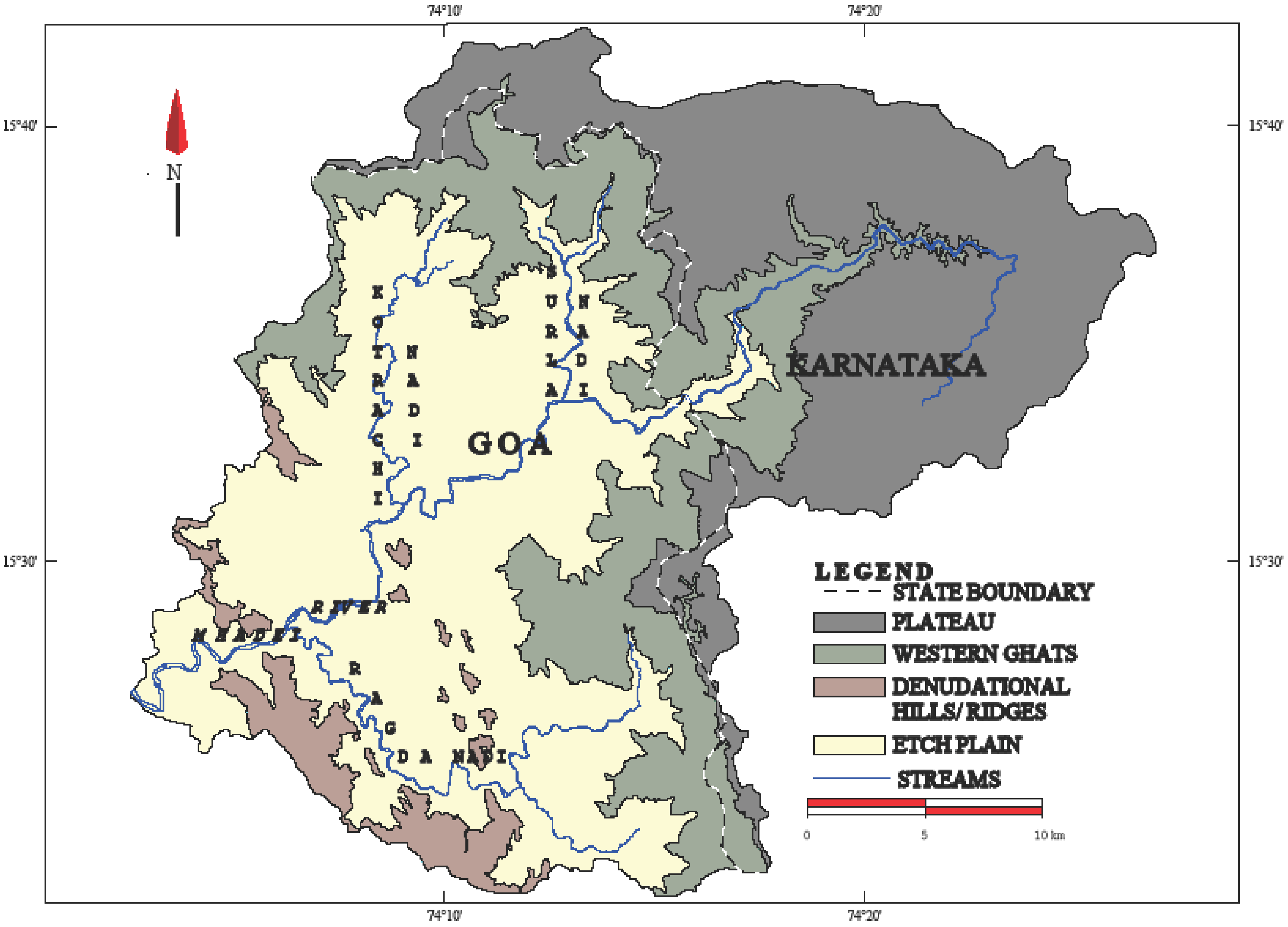


Figure 1.15 Physiographic map of the Mhadei River watershed

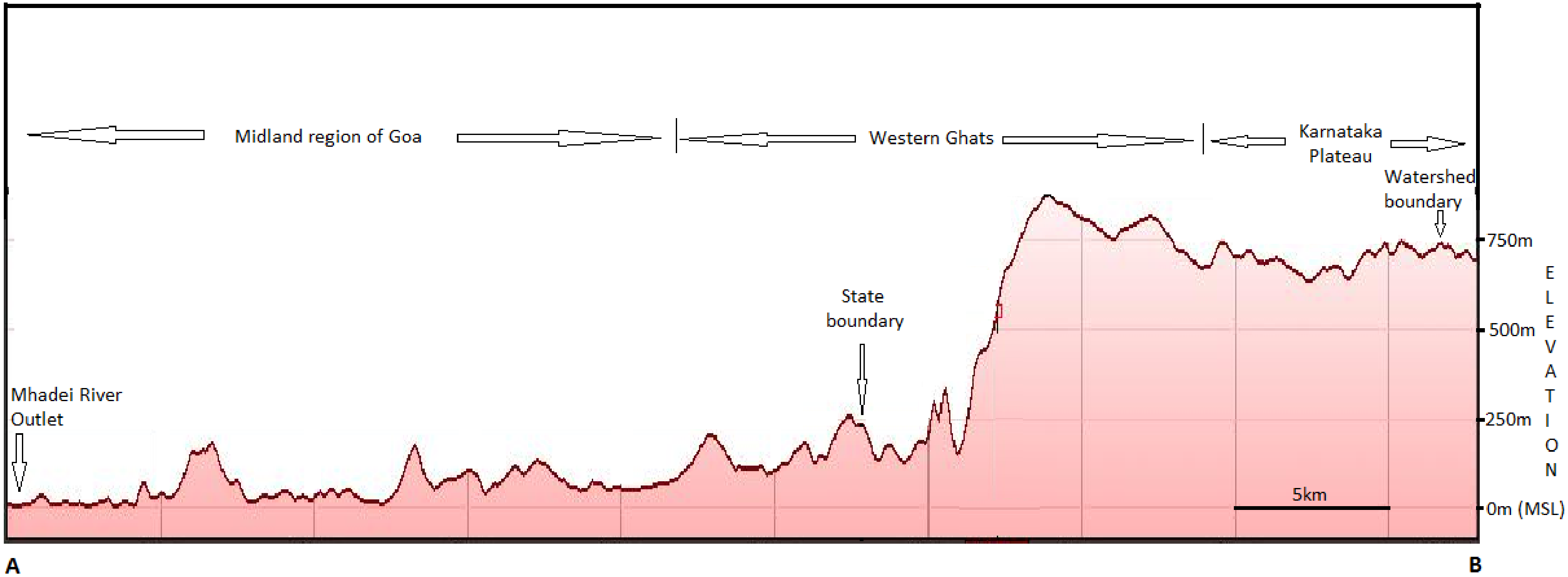


Figure 1.16 Topographic profile of Mhadei River watershed along the length of the river (NE-SW direction).

Geologically, the study area mainly comprises of the rocks of the Goa Group and the Peninsular Gneiss. Three formations of the Goa Group namely Barcem, Bicholim and Vageri Formations are exposed in the study area. They exhibit a general NW-SE trend. The rock types exposed in the study area includes gneiss, meta-basalt, quartz-sericite schist, quartz-chlorite schist, pink ferruginous phyllite, limestone and metagreywacke. Minor intrusive gabbro bodies along with a small portion of the Bondla mafic-ultramafic complex represented by gabbro and peridotite are also exposed. Deccan Traps occur along the northern margin of the study area comprising of horizontally laid basaltic flows (Fig. 1.17). All these rocks have undergone lateritisation to varying extent.

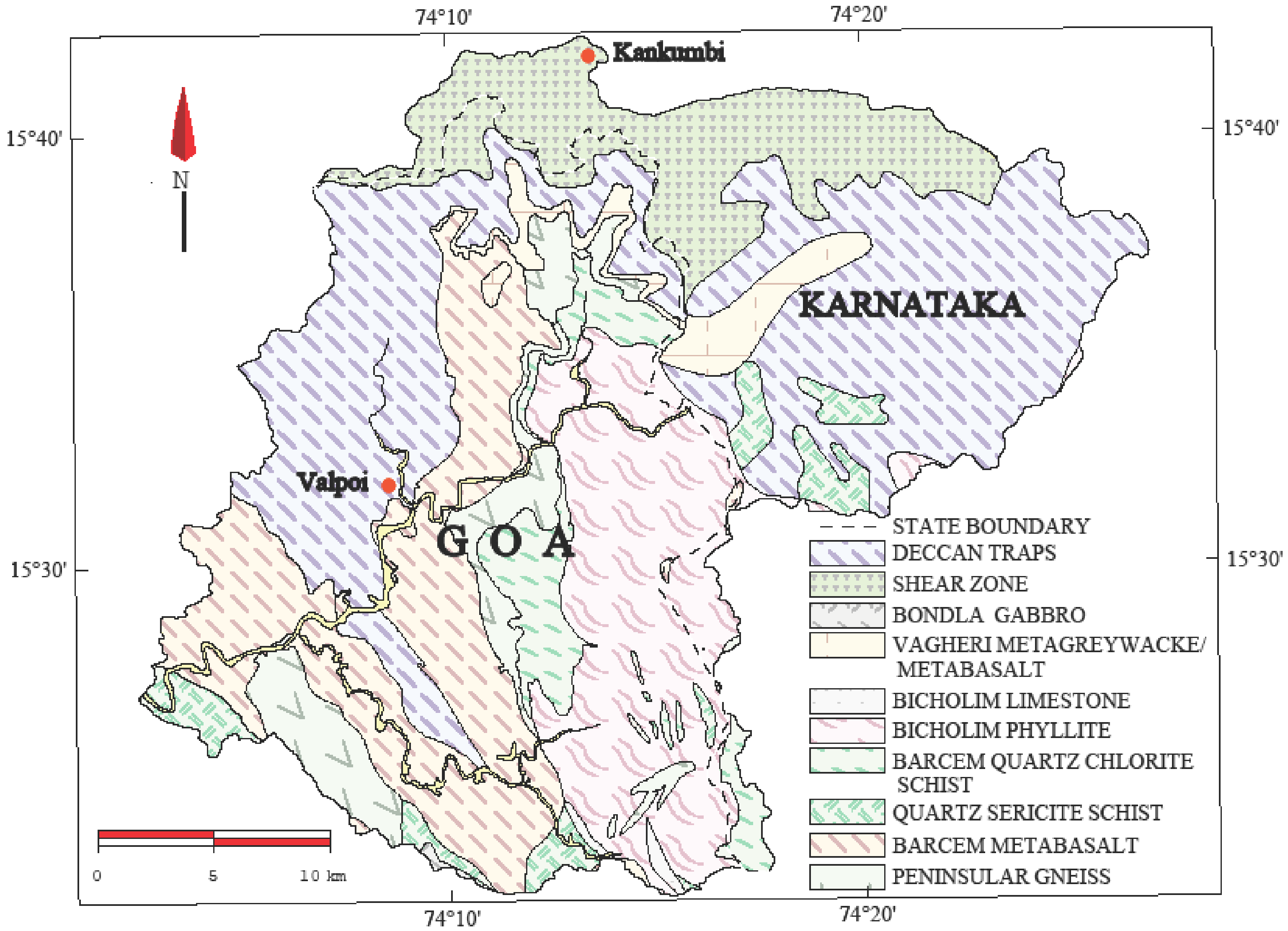


Figure 1.17 Geological map of the study area- Mhadei River watershed

1.10 Previous Work

Oertal (1958) published the first geological map of Goa based on mapping of the region. The Geological Survey of India (GSI) mapped the Goa State during the years 1962-1969 and brought out an updated map of the geology of Goa. Subsequently Gokul et al (1985) classified the Precambrian schistose rocks of Goa as the 'Goa Group' resting on the Peninsular Gneissic Complex. Later the Geological Survey of India (GSI) published the Geological and Mineral map of Goa in 1996.

Systematic hydrogeological survey was carried out for the first time by Subramanian (1971) in the northern part of Goa. Joseph (1975) carried out the reconnaissance hydrogeological survey in parts of Goa. Sharma (1977) undertook systematic hydrological studies in parts of southern Goa. Later, Adyalkar and Sharma (1978) highlighted the importance of laterite as significant hydrogeological unit. Subramanian (1985) concluded from his study that the rivers and their perennial tributaries in Goa retain high discharges in the post monsoon season mainly due to effluence of the leaky aquifers of laterite all along their courses. Adyalkar (1985) studied the hydrogeology of Goa with special reference to the lateritised midlands and the coastal landforms. He found that the groundwater occurs under water table condition in the shallow zones of beach sand, laterite and weathered crystalline rocks and under semi-confined condition in the crystalline rocks underneath the laterite. Pathak (1981) confirmed that groundwater occurs under phreatic condition in the laterite which is the most important water bearing formation of Goa. Pahala Kumar et al (1994) observed that the iron ore bodies are important aquifers bounded on both sides by impermeable formations.

Studies pertaining to aquifer properties and groundwater balance were also carried out in Goa. The GSI conducted pumping tests in open dug wells at Arambol to estimate Transmissivity and Storativity of laterites (Subramaniam, 1981). Marathe and Shah (1987) computed the hydraulic conductivity of different grades of iron ore and few other rock types. Ghosh (1985) quantified the rainfall contribution to groundwater recharge as 16%, to evapo-transpiration as 32% and to surface runoff as 52%. Chachadi (2003) published a technical report on groundwater balance studies in mining belt of Goa. Chachadi et al (2004) estimated surface runoff and groundwater recharge in mining area of Goa using daily sequential water balance model – BALSEQ. Sharma (1991) carried out few infiltration tests on a laterite-topped tableland along the coast of Goa.

Central Ground Water Board (CGWB) prepared Master Plan for development of groundwater in Goa State in 1997. The CGWB also published two reports on the studies related to groundwater in Goa in1999 and 2002.

Various studies investigating influence of open cast mining on local groundwater domains have been carried out by Anonymous (1983), Marathe (1985), Venkataraman (1994), Pahala Kumar et al (1994), TERI (1997), Chaulya et al (1999), Chachadi (2002), Chachadi and Choudri (2004), Chachadi (2005) and some by private mining companies.

The spatial variability of rainfall in Mandovi basin has been mapped by Suprit and Shankar, 2008.

Morphometric and geomorphological studies were mostly carried out on a regional scale. Dikshit (1976) studied the forms and characteristics of the drainage basins of Konkan. Dessai and Peshwa (1978) studied the drainage and drainage anomalies in Maharashtra and Goa. Sriram and Prasad (1979 and 1980) described some aspects of the geomorphology of Goa. Wagle (1982) described geomorphological features of the coastal Goa using aerial photographs and reported three sets of lineaments. Iyer and Wagle (1987) carried out morphometric analysis of the river basins in Goa. Kunte (1990) applied advanced image processing techniques to study lineaments in Goa. Widdowson and Cox (1996) studied the laterites and drainage patterns of the Western Ghats and Konkan Coast.

However, most of these studies were carried out on a regional scale with administrative boundaries as study units while others focused on the influence of open cast mining on the local groundwater domains. Groundwater domains are often governed by the topographic configuration of a region in hilly areas. Thus, boundaries of river watersheds invariably coincide with that of groundwater domains. Therefore, assessment of the groundwater resource with watershed as a unit and its development in a sustainable manner has become utmost important.

1.11 Methodology

The study area, Mhadei River watershed is included in Survey of India (SOI) Toposheets No. 48 I/2, 48 I/3, 48 I/6 and 48 I/7 on 1:50,000 scale. Using these toposheets the watershed boundary has been delineated and base maps have been prepared in a GIS environment (TNT mips software).

Thirteen rain gauging stations located in and around the Mhadei River watershed were identified and long term rainfall data has been collected. This data was processed using Thiessen polygon and Isohyetal methods to compute average rainfall for the watersheds and quantify volume of rainfall contributions from Goa and Karnataka regions of the watershed. Long term (17 years) river discharge data from river-gauging station of CWC located at Ganjem (N15°28’10”; E74°05’33”) has been collected and analysed for estimating run-off components.

Stream flow measurements were carried out at Goa-Karnataka State boundary to estimate baseflow from the watershed lying in Karnataka.

The boundary of the entire Mandovi River basin has been delineated using SOI toposheets drawn on 1:50000 Scale. Drainage network of the

Mandovi River basin has been digitised from the toposheets and morphometric parameters have been computed in a GIS platform. The various morphometric parameters pertaining to the linear, areal and relief aspects include Stream Order, Stream Number, Stream Length, Channel Sinuosity, Bifurcation Ratio, Form Factor, Circularity Ratio, Elongation Ratio, Drainage Density, Drainage Frequency, Ruggedness Number, Constant of Channel maintenance, Compactness Constant, Texture Ratio, Relief Ratio, Relative Relief, Time of Concentration, etc. The input parameters such as area, perimeter, elevation, stream lengths, etc. have been computed using GIS software (TNT mips).

Eighty two observation wells (open dug wells) were established to monitor changes in groundwater levels during pre-monsoon, monsoon and post-monsoon seasons. The groundwater levels were measured on seasonal basis from May 2007 till November 2009 in sixty nine observation wells located in the western low lying (Goa) region of the watershed. Thirteen observation wells located on the Karnataka plateau in the eastern part of the watershed were monitored for three seasons of the year 2007. The details of the well locations and dimensions of the wells were also recorded and the field data was then transferred on to the base maps.

Using the groundwater level data, water table fluctuation in the watershed has been computed and analysed. Well hydrograph analysis has been carried out to identify groundwater potential zones using a new approach. Pumping tests were carried out on ten open dug wells to estimate aquifer properties namely, transmissivity and specific yield. Infiltration studies using Double-ring Infiltrometer were carried out at nine locations spread over various land –use/ land-cover types. The groundwater recharge estimation has been carried out using procedures recommended by Groundwater Estimation Methodology Committee (GEC, 1997). Finally, based on the data generated, impact assessment of the proposed river water retention and diversion projects have been carried out.

CHAPTER 2

RAINFALL RUN-OFF AND BASEFLOW ESTIMATION

2.1 Introduction

The west coast of India receives abundant rainfall from the southwest monsoon. The Western Ghats escarpment (Sahyadri mountain range) that runs parallel to the west coast plays an important role in its distribution. The monsoon causes heavy rainfall on the windward side of the escarpment, distinguishing it from the much drier leeward side (Suprit and Shankar, 2008). This results in high discharge from the small rivers originating on the Ghats and draining into the Arabian Sea in the west. The Mhadei River is a tributary of the Mandovi River that originates in the Western Ghats and drains into the Arabian Sea. It has been grouped under Bhatsol Basin (Sub-basin: Vasishti and Others) by CGWB on the Watershed Atlas of India.

2.2 Rainfall Analysis

The Mhadei River watershed receives abundant rainfall due to the southwest monsoon during the months of June to September. Thirteen rain-gauge stations in and around the watershed have been identified and normal monthly rainfall data has been collected (Table 2.1). Over 90% rainfall occurs during the monsoon months from June to September while the remaining 10% rainfall is received during the non-monsoon months. Highest rainfall is received during the month of July followed by a gradual decrease in subsequent monsoon months. There is also a considerable variation in rainfall increasing from the coast towards the Western Ghats. Rainfall during the monsoon consists of several bursts with weak spells and sometimes monsoon breaks in between (Rao, 1976). In the present study both Isohyetal and Thiessen polygon methods have been used to compute the average normal rainfall for the Mhadei River watershed.

2.2.1 Thiessen Polygon Method

In this method, the watershed is divided into polygons with the rain gauge station in the middle of each polygon assumed to be representative for the rainfall on the area of land included in its polygon. Thiessen polygons are obtained by drawing perpendicular bisectors to the lines joining adjacent rain gauge stations on a base map. Each polygon area is assumed to be influenced by the rain-gauge station inside it (Fig 2.1). An area factor is computed for each station as a ratio of the land area influenced by that station to the area of the entire watershed. Large area factor implies that the rainfall of that station is manipulated over a larger area and therefore less accurate.

The average annual rainfall computed using Thiessen polygon method for the Mhadei River watershed is 3955mm (Table 2.2). The Valpoi rain-gauge station has the maximum influence (39%) on the Mhadei River watershed followed by Amgao, Collem and Kankumbi station.

2.2.2 Isohyetal Method

In Isohyetal method, the point rainfalls are plotted on a suitable base map and the lines of equal rainfall (isohyets) are then drawn as contours giving consideration to orographic effects and storm morphology (Fig. 2.2).

The average annual rainfall using Isohyetal Method for the Mhadei River watershed is 3933mm (Table 2.3). There is not much difference between the Thiessen polygon and the Isohyetal averages. However, Isohyetal method gives consideration to orographic effects and storm morphology (Raghunath, 1992), and the Mhadei River watershed is a mountainous watershed, therefore Isohyetal method has been adopted for further computations. As a result of the orographic influence the rainfall increases progressively from the western boundary of the watershed towards the Western Ghats located in east from about 3500mm to over 5000mm (Fig. 2.2). However, further east on the Karnataka plateau it decreases rapidly to about 2500mm.

Table 2.1 Normal monthly rainfall (mm) of the rain-gauge stations in and around Mhadei River watershed.

Stations in Karnataka	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual
Amgao	710	1385	969	249	109	6	0	1	1	1	3	11	3445
Castlerock	1112	2304	1643	543	176	7	4	0	0	1	1	1	5792
Chapoli	821	1266	957	203	106	22	0	0	0	0	0	8	3384
Gavali	833	1468	1268	321	78	8	0	0	0	0	1	4	3979
Jamagao	495	792	685	179	69	9	0	0	0	0	0	1	2230
Jamboti	318	594	416	104	55	9	0	1	2	2	5	13	1520
Kankumbi	1019	1725	1268	348	160	24	0	0	0	2	11	21	4578
Khanapur	331	728	377	129	116	40	6	1	1	5	27	80	1840
Tilariwadi	1076	1538	1045	355	156	27	3	0	0	0	0	35	4236
Stations in Goa													
Bicholim	924	1284	674	325	187	48	4	1	0	0	9	86	3542
Colem	1015	1825	1098	550	257	52	10	1	0	1	18	112	4938
Ponda	857	1200	797	383	165	71	13	2	0	0	10	88	3586
Valpoi	978	1505	946	397	200	55	7	1	0	1	14	97	4200

Source: IMD, Master Plan for Mhadei/Mandovi River basin, 1999

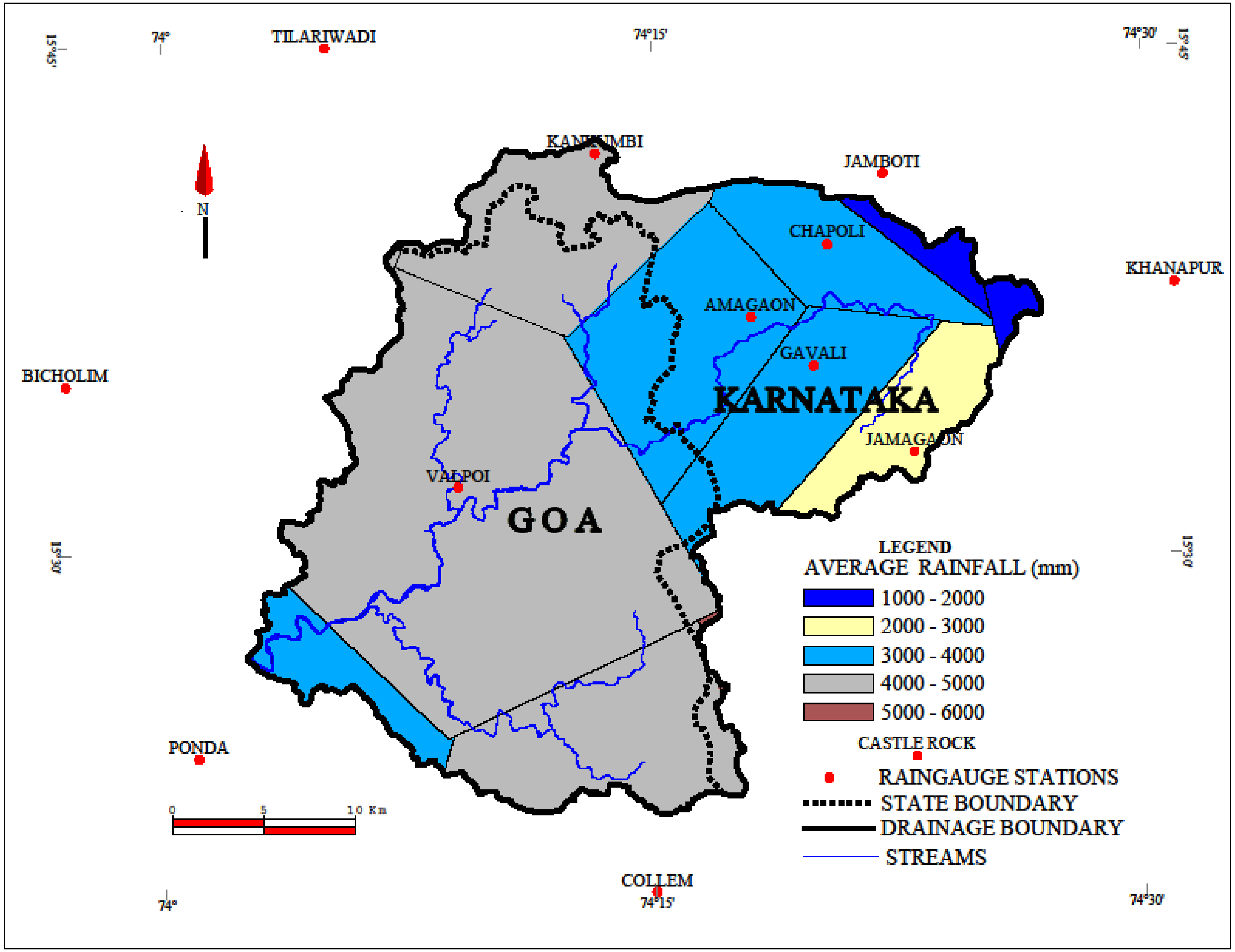


Figure 2.1 Map showing Thiessen polygons for Mhadei River watershed

Table 2.2 Average rainfall using Theissen polygon method

Rain-gauge station	Area of polygon (km^2)	Area Factor	Normal annual rainfall (mm)	Rainfall in Mhadei (mm)
Jamagaon	51.04	0.057	2230	127
Colem	100.05	0.110	4938	543
Ponda	33.40	0.037	3586	133
Valpoi	351.90	0.390	4200	1638
Amgao	107.23	0.119	3445	411
Castlerock	0.94	0.001	5792	6
Chapoli	58.60	0.065	3384	220
Gavali	81.63	0.091	3979	361
Jamboti	13.68	0.015	1520	23
Kankumbi	92.93	0.103	4578	473
Khanapur	6.98	0.008	1840	14
Tilariwadi	1.08	0.001	4236	4
Bicholim	0.00	0.000	3530	0
Total	899.46	0.998		3955

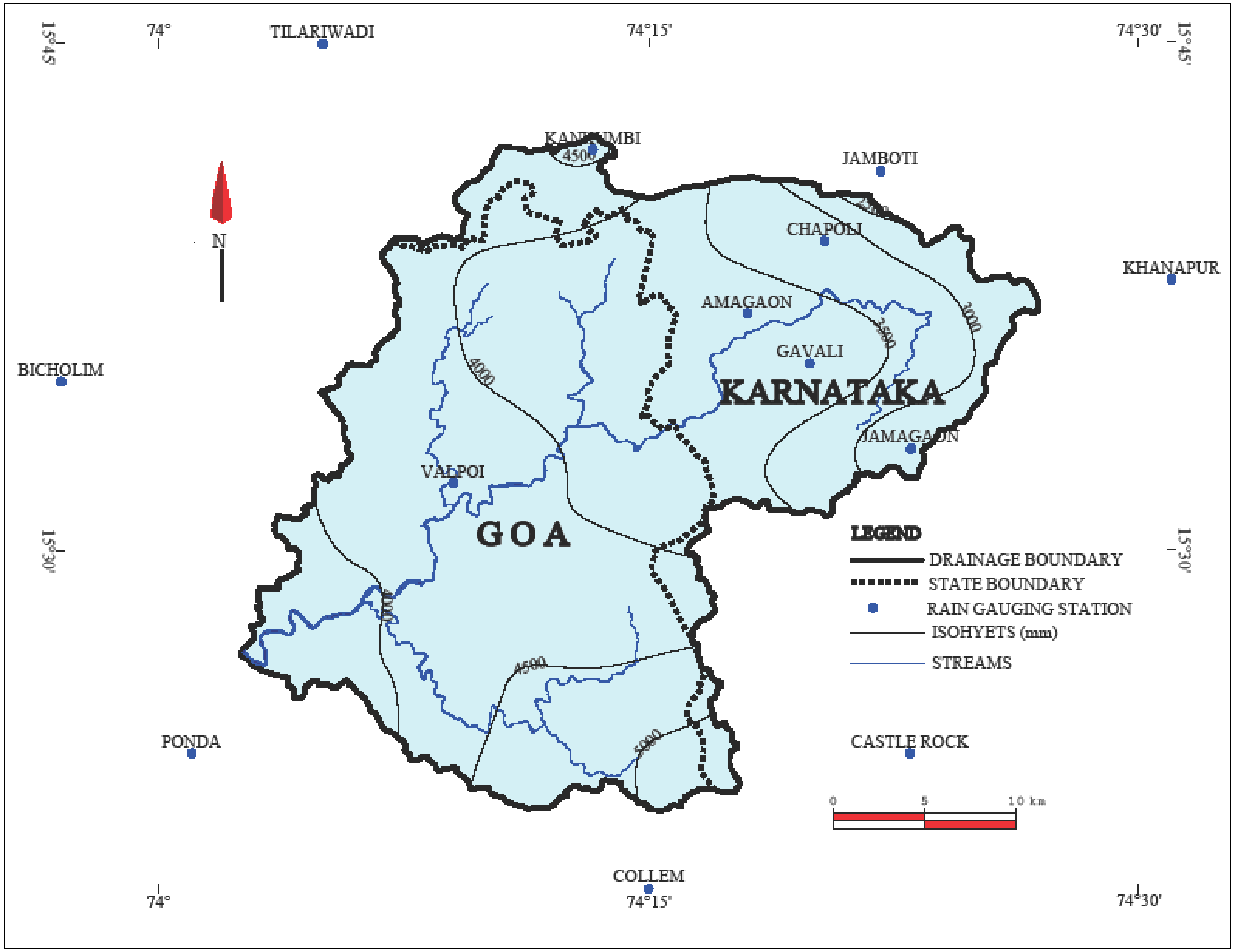


Figure 2.2 Isohyetal map for Mhadei River watershed

Table 2.3 Average rainfall using Isohyetal method

Sr. No.	Isohyetal Interval (mm)	Mean Rainfall (mm)	Area in Mhadei watershed (km^2)	Area Percent	Area Factor	Average rainfall (mm)
1	5500-5000	5250	19.85	2.21	0.0221	116
2	5000-4500	4750	76.95	8.56	0.0856	406.6
3	4500-4000	4250	323.83	36.00	0.3600	1530
4	4000-3500	3750	326.59	36.31	0.3631	1361.6
5	3500-3000	3250	101.33	11.27	0.1127	366.3
6	3000-2500	2750	49.36	5.49	0.0549	151
7	2500-2000	2250	1.54	0.01	0.0001	0.2
		Total	899.45	100	1.0000	3933

2.3 Rainfall Run-off Estimation

The average annual rainfall and the resulting rainfall volume for Goa and Karnataka regions using Isohyetal method have been computed separately (Table 2.4).

The total area of the Mhadei River watershed is 899 km^2. The area of the Mhadei River watershed that lies in Goa State is 573 km^2 (64%) while the area of the Mhadei River watershed that lies in Karnataka State is 326 km^2 (36%). The average rainfall in the entire Mhadei River watershed using Isohyetal method is 3933 mm. The average rainfall in the Goa region of the Mhadei River watershed is 4160 mm while that in the Karnataka region of the Mhadei River watershed is 3536 mm. As seen from Table 2.4, about 2383 MCM i.e., 67% of the rain water is received by the Goa region of the watershed while 1155 MCM i.e., 33% of rain water is received by the Karnataka region of the watershed. The total volume of rain water received in the Mhadei River watershed is therefore 3538 MCM.

The average monthly rainfall (mm) has also been computed for Mhadei River watershed and the resulting volume of monthly rainfall is shown in Table 2.5.

Table 2.4 State-wise average annual rainfall and volume of rainfall using Isohyetal method.

Isohyetal Interval (mm)	Average annual Rainfall (mm)	Area in the Mhadei watershed (km^2)	Area in Goa (km^2)	Area in Karnataka (km^2)	Resulting volume of rainwater (MCM)		
					In Mhadei River watershed	In Goa region	In Karnataka region
5500-5000	5250	19.85	13.55	6.3	104	71	33
5000-4500	4750	76.95	70.81	6.14	365	336	29
4500-4000	4250	323.83	288.2	35.81	1376	1224	152
4000-3500	3750	326.59	200.39	126.2	1225	752	473
3500-3000	3250	101.33	0	101.33	329	0	329
3000-2500	2750	49.36	0	49.36	136	0	136
2500-2000	2250	1.51	0	1.51	3	0	3
	Total	**899**	**573**	**326**	**3538**	**2383**	**1155**

Table 2.5 Average monthly rainfall and resulting volume of rainfall in Mhadei River watershed

Period	Month	Average rainfall (mm)	Volume of rainfall (MCM)
Monsoon	June	871	783
	July	1450	1304
	August	991	891
	September	351	316
Non-monsoon	October	161	145
	November	35	32
	December	4	4
	January	1	1
	February	0	0
	March	1	1
	April	10	9
	May	58	52
	Total annual	**3933**	**3538**

Thus, the total volume of monsoon rainfall received in the Mhadei River watershed is 3294 MCM while the total volume of non-monsoon rainfall is 244 MCM.

2.4 River Discharge Analysis

The Mhadei River discharge is gauged by Central Water Commission (CWC) at Ganjem station located close to the outlet of Mhadei River (Fig 2.3). The average monthly river discharge data for 17 years measured at Ganjem river-gauging station on the Mhadei River outlet is given in Table 2.6. The same is graphically represented in Fig. 2.4 along with the normal monthly rainfall in the Mhadei River watershed.

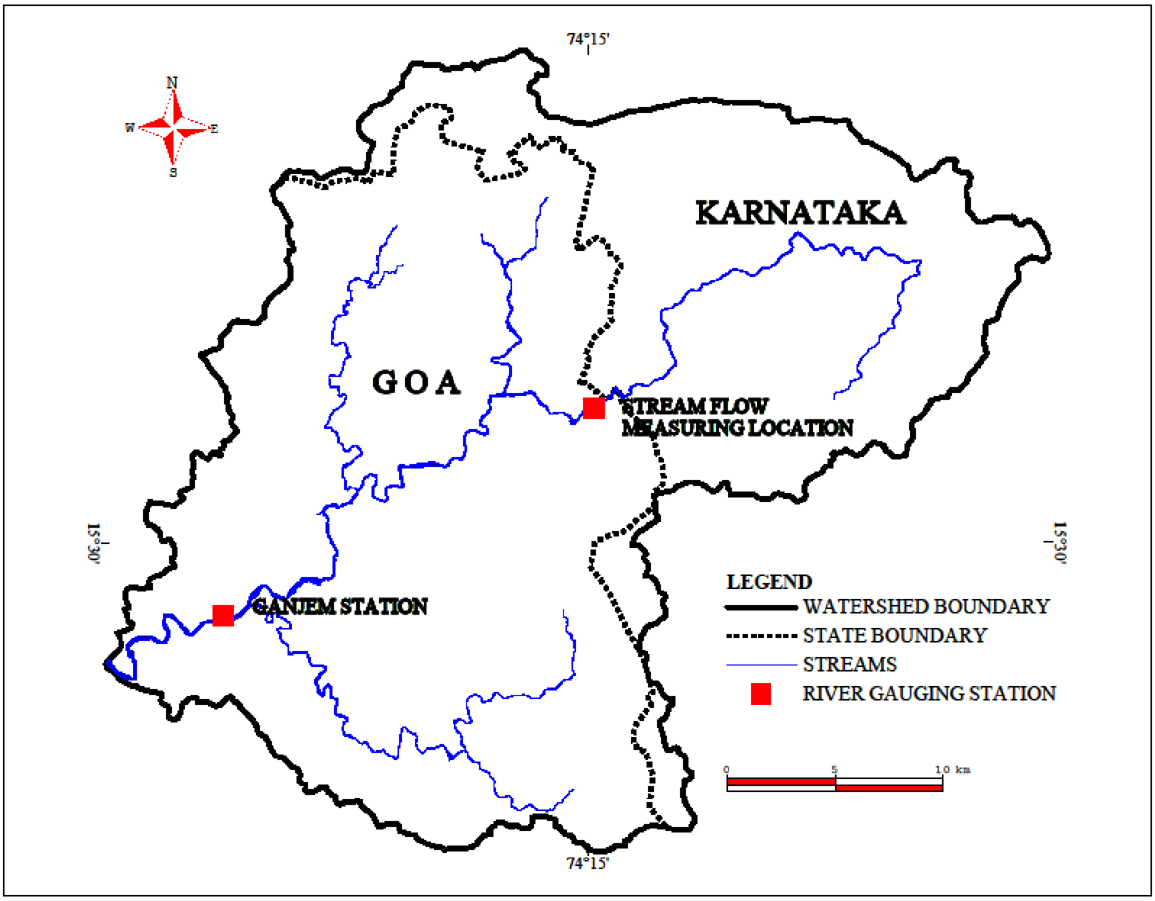


Figure 2.3 Map showing Ganjem river-gauging station of CWC and location of stream flow measurements carried out during the present study.

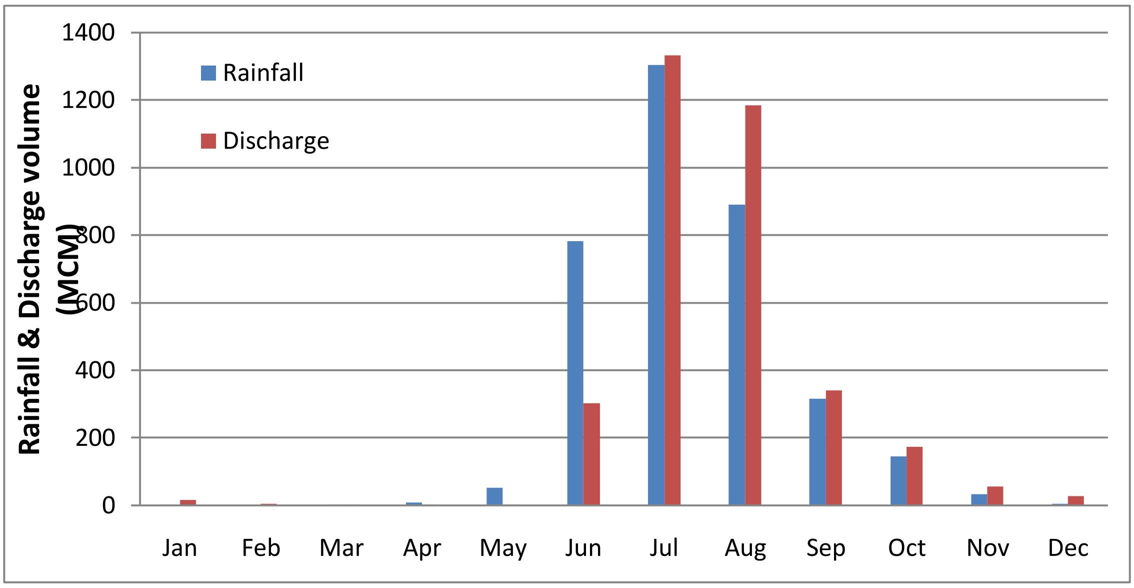


Figure 2.4 Histogram showing average monthly discharge of Mhadei River measured at Ganjem station and normal monthly rainfall volume in Mhadei River watershed

Table 2.6 Monthly average discharge data measured at Ganjem River-gauging station on Mhadei River (Source: CWC).

Month	Discharge (MCM)
June	303.24
July	1333.36
August	1184.56
September	340.35
October	173.45
November	54.61
December	27.15
January	16.33
February	5.05
March	3.42
April	2.52
May	2.52
Total annual	**3446**

As seen from Fig. 2.4, during the beginning of the monsoon season, i.e., during May and June the rainfall dominates the run-off. This is due to the antecedent moisture conditions in the ground which allows large portions of the rainfall as soil moisture saturation and storage followed by groundwater recharge. During the month of July a marginal increase in the surface runoff is witnessed which increases substantially during the month of August. During July little of groundwater contributes to the surface runoff components whereas during August the component of baseflow to the surface run-off becomes significant. That means the soil moisture retention and groundwater recharge continues in the first three months of the rainy season. The baseflow contribution sustains till January as seen from the figure indicating higher groundwater levels during these months. The average annual discharge of Mhadei River watershed at Ganjem river-gauging station is 3446 MCM which is 97% of the total volume of annual rainwater (3538 MCM) received by the watershed. Thus, only 3% of the total annual rainfall is attributed to groundwater recharge.

2.5 Baseflow Estimation

Rainfall on a catchment is considered to partition between overland flow, ground infiltration and evapo-transpiration. Overland flow is that part of the total run-off which travels over the land surface to reach a stream channel. The ground infiltration further gets distributed into soil moisture storage, interflow and groundwater recharge. Interflow is water moving laterally within the zone of aeration in the direction of the topographic slope. The interflow combines with the overland flow to represent the surface run-off. The groundwater recharge is subsequently, totally or partially, discharged into streams in the form of springs or seepages and is called baseflow. Baseflow supports the stream discharge during dry weathers when there is little or no rainfall. Thus, the total run-off is a function of three components namely, overland flow, interflow and baseflow. These three components of total run-off are shown schematically in Fig. 2.5.

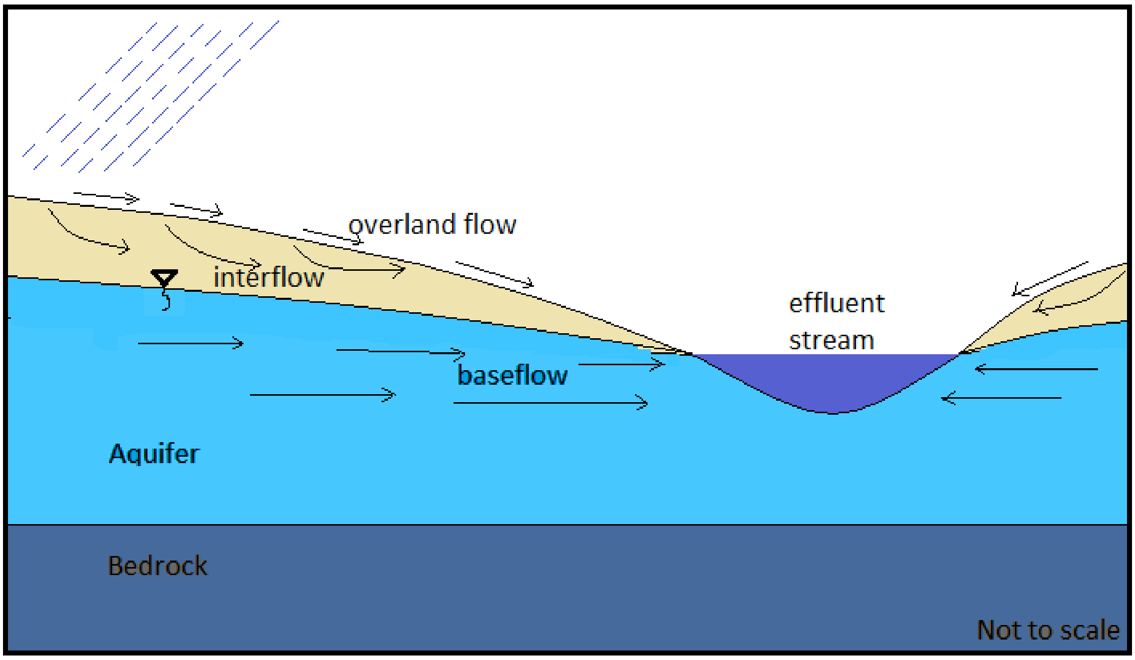


Figure 2.5 A schematic section showing the various components those contribute to the total discharge of a stream.

In order to quantify the baseflow volumes in Mhadei River watershed, stream-flow measurements were carried out on a single stream at Goa-Karnataka State border (Fig. 2.3) for the months of December and April. As it is not feasible to physically measure the baseflow volume from all the streams coming from Karnataka due to inaccessibility, it is proposed to derive ***unit area baseflow*** using the field measured values. Using this unit area baseflow, the total non-monsoon baseflow coming from all the streams from Karnataka is computed on monthly basis. Further, the stream hydrograph analysis has been used to quantify the annual baseflow contribution in Mhadei River watershed.

2.5.1 Stream Gauging Measurements

Stream-flow measurements were carried out on Mhadei River at the Goa- Karnataka State boundary near village Uste in the months of

December 2007 and April 2008 using Velocity-Area method. The method requires the choice of a length of river reach sufficient to allow accurate timing of a float released in the middle of a channel and far enough upstream to attain ambient velocity before entering the reach. By measuring the distance of the reach and the time taken for the float to travel the length of the reach, the water velocity can be calculated by dividing the length by the time (Hiscock, 2005). The procedure is repeated a number of times to obtain the average maximum surface velocity, which is then converted to mean velocity using coefficients (Table 2.7). By measuring the flow area upstream and downstream of the reach and taking the average value, the mean cross-sectional area of flow for the reach is obtained (Plate 2.1). The river discharge is then found by multiplying the mean velocity by the cross-sectional area of flow (Tables 2.8 and 2.9).

Table 2.7 Coefficients to obtain mean velocity of a river from the surface velocity (Hiscock, 2005)

Average Depth in Reach (m)	Co-efficient
0.3	0.66
0.6	0.68
0.9	0.70
1.2	0.72
1.5	0.74
1.8	0.76
2.7	0.77
3.7	0.78
4.6	0.79
≥ 6.1	0.80

Plate 2.1 Stream-flow measurements being carried out at Goa-Karnataka State boundary

Table 2.8 Stream-flow measurements on Mhadei River at Goa-Karnataka State boundary in the month of December 2007

1	**Upstream River Section**	
A	Location	**Latitude: N15°33’20”** **Longitude:E74°15’10”**
B	Total width of the section	**35.60 m**
C	Average depth of the section	**0.57 m**
D	Cross-sectional area	**20.29 m^2**
2	**Downstream River Section**	
A	Location	**Latitude: N15°33’19.5”** **Longitude: E74°15’04”**
B	Total width of the section	**36.57 m**
C	Average depth of the section	**0.54 m**
D	Cross-sectional area	**19.75 m^2**
3	**Average cross-sectional area**	**20.02 m^2**
4	**Surface velocity**	
A	Distance between upstream and downstream section	**160.5 m**
B	Average time taken by float to travel the above distance	**9min 25 sec**
C	Surface velocity of river water	**0.257 m/sec**
5	**Mean velocity of stream flow** **= 0.257 x 0.68**	**0.174 m/sec**
6	**Stream flow (Discharge)** **= 20.02 x 0.174**	**3.48 cumec**

Thus, the discharge measured in the month of December is 3.48 cubic meters per second (cumec). This is equal to 9 MCM per month. The contributing area to the above measured discharge is estimated to be 296 km^2 from the Karnataka region of the watershed.

It is noted that the average discharge measured at Ganjem river-gauging station for the month of December is 27.15 MCM/month. The area contributing to the above measured discharge at Ganjem station is 880 km^2 which is 98% of the entire Mhadei River watershed.

Table 2.9 Stream flow measurements on Mhadei River at Goa-Karnataka State boundary in the month of April 2008

1	**Upstream River Section**	
A	Location	**Latitude: N15°33′20″** **Longitude:E74°15′9.4″**
B	Total width of the section	**13.7 m**
C	Average depth of the section	**0.342 m**
D	Cross-sectional area	**4.6854 m^2**
2	**Downstream River Section**	
A	Location	**Latitude: N15°33′19.7″** **Longitude: E74°15′8.8″**
B	Total width of the section	**22.19 m**
C	Average depth of the section	**0.4412 m**
D	Cross-sectional area	**9.791 m^2**
3	**Average cross-sectional area**	**7.2382 m^2**
4	**Surface velocity**	
A	Distance between upstream and downstream section	**126 m**
B	Average time taken by float to travel the above distance	**36 min**
C	Surface velocity of river water	**0.0583 m/sec**
5	**Mean velocity of stream flow** **= 0.0583 x 0.68**	**0.04 m/sec**
6	**Stream flow (Discharge)** **= 7.2382 x 0.04**	**0.289 cumec**

Thus, the discharge measured in the month of April 2008 is 0.289 cumec. This is equal to 0.75 MCM per month. The contributing area to the above measured discharge is 296 km^2 from the Karnataka region of the watershed.

It is noted that the corresponding average discharge measured at Ganjem river-gauging station for the month of April is 2.52 MCM/month. The area contributing to the above measured discharge at Ganjem station is 880 km^2 which is 98% of the entire Mhadei River watershed.

2.5.2 Quantification of Baseflow

Baseflow for December: The discharge measured for the month of December from the Karnataka region of the watershed is 9 MCM per month and the area contributing to this discharge is 296 km^2. Thus, the unit area baseflow from the Karnataka region of the watershed for the month of December can be calculated as:

$$\text{Discharge/Area} = 9 \text{ MCM} / 296 \text{ km}^2 = 0.0304 \text{ MCM/km}^2$$

Since the total area of the Mhadei River watershed that lies in the Karnataka state is 326 km^2 therefore, the total baseflow from the Karnataka region for the month of December 2007 can be calculated as:

$$\text{Unit area base flow X total area} = 0.0304 \text{ X } 326 = 9.9 \text{ MCM}$$

Similarly, the average discharge measured at Ganjem river-gauging station for the month of December is 27.15 MCM. The area contributing to the above measured discharge at Ganjem station is 880 km^2. Thus, the unit area baseflow for the entire Mhadei River watershed for the month of December can be calculated as:

Discharge/Area= 27.15 MCM / 880 km^2 = 0.0308 MCM/km^2

Thus, the value of the unit area baseflow computed for the entire Mhadei River watershed for the month of December is in close agreement with the value of the unit area baseflow computed for the Karnataka region by stream flow measurements during the present study.

Thus, the baseflow measured for the month of December from the Karnataka region of the watershed (9.9 MCM) is 37% of the base flow measured for the entire Mhadei River watershed (27.15 MCM) in the month of December.

Baseflow for April: The discharge measured for the month of April from the Karnataka region of the watershed is 0.75 MCM and the area contributing to this discharge is 296 km^2. Thus, the unit area baseflow from the Karnataka region of the watershed for the month of April can be calculated as:

Discharge/Area= 0.75 MCM / 296 km^2 = 0.0025 MCM/km^2

Since the total area of the Mhadei River watershed that lies in the Karnataka State is 326 km^2 therefore, the total baseflow from the Karnataka region for the month of December can be calculated as:

Unit area base flow X total area = 0.0025 X 326 = 0.826 MCM

Similarly, the average discharge measured at Ganjem river-gauging station for the corresponding month of April is 2.52 MCM. The area contributing to the above measured discharge at Ganjem station is 880 km^2. Thus, the unit area baseflow for the entire Mhadei River watershed for the month of April can be calculated as:

Discharge/Area= 2.52 MCM / 880 km^2 = 0.0028 MCM/km^2

Thus, the value of the unit area baseflow computed for the entire watershed for the month of April is in close agreement with the value of the unit area baseflow computed for the Karnataka region by stream flow measurements during the present study.

The baseflow measured for the month of April from the Karnataka region of the watershed (0.826 MCM) is found to be 33% of the baseflow measured for the entire Mhadei River watershed (2.52 MCM).

Baseflow computation for non-monsoon period: The baseflow contribution for the other non-monsoon months from Karnataka region has been computed by linearly extrapolating the values of December and April months to the remaining months of non-monsoon period from October to May (Table 2.10). Further, using the monthly baseflow volume unit area baseflow has been computed for each month of non-monsoon period.

Table 2.10 Baseflow computation for non-monsoon season from Karnataka

Month	Discharge measured at Ganjem station (MCM)	Linearly extrapolated baseflow proportion from Karnataka (%)	Baseflow volume from Karnataka (MCM)	Unit area baseflow calculated for non-monsoon months
October	173.45	39	67.65	0.2075
November	54.61	38	20.75	0.0637
December	27.15	37	9.90	0.0304
January	16.33	36	5.88	0.0180
February	5.05	35	1.77	0.0054
March	3.42	34	1.16	0.0036
April	2.52	33	0.826	0.0025
May	2.52	32	0.806	0.0025
Total	**285**		**109**	

The total non-monsoon baseflow contribution from Karnataka region computed using unit area baseflow works out to be 109 MCM which is 38% of the total non-monsoon baseflow (285 MCM) of the entire Mhadei River watershed. As seen from Table 2.8, the baseflow drastically decreases from January onwards and the river cannot sustain sufficient water to meet the water demands on its banks. There are several patches of agricultural lands and settlements which heavily depend on the available baseflow. The dry weather flow is utilised extensively in the downstream region of the watershed by storing the water within river banks by constructing *bandharas* across the streams.

The contribution of baseflow from Karnataka region compared to the baseflow measured at Ganjem station for the non-monsoon months is shown graphically in Fig. 2.6.

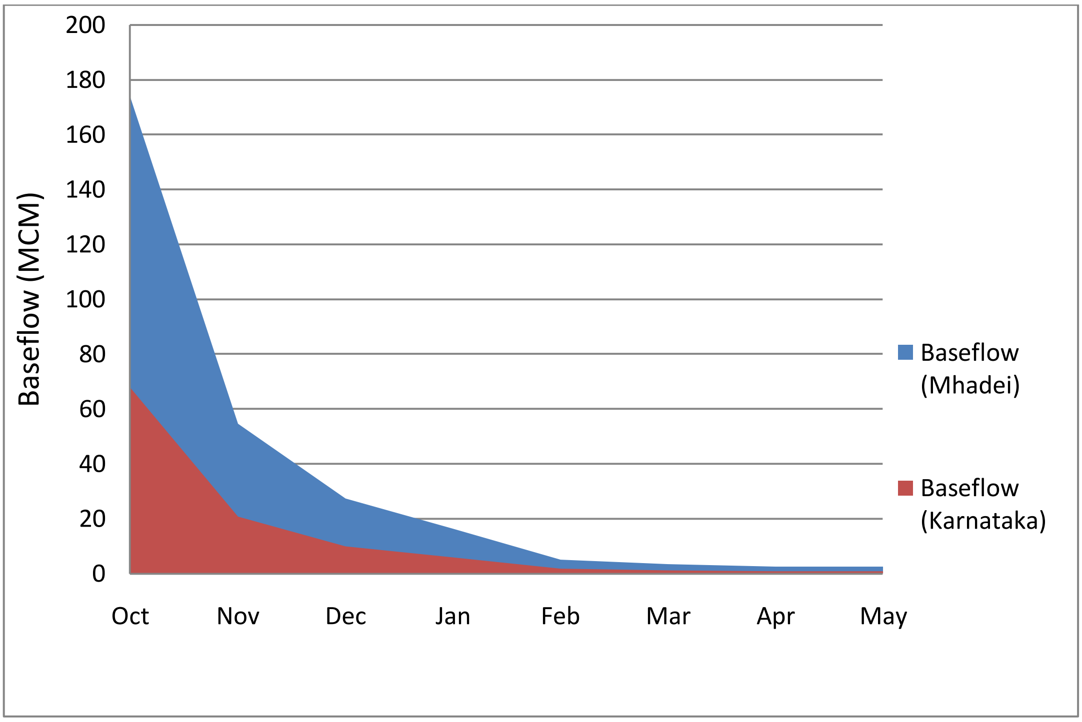


Figure 2.6 Comparison of non-monsoon baseflow (MCM) contributed from Karnataka region with non-monsoon baseflow (MCM) of the entire Mhadei river watershed

2.5.3 Baseflow Computation using Stream Hydrograph Analysis

A stream hydrograph is described as a graphical plot showing measured stream discharge as a function of time. Surface run-off and baseflow components of total run-off combine to generate a stream hydrograph. The baseflow represents the relatively steady contribution to stream discharge from groundwater return flow while the surface run-off represents the additional discharge contributed by rainfall event. A stream hydrograph may be plotted as storm hydrograph, seasonal hydrograph or long-term hydrograph. Storm hydrograph is plotted when a relatively short interval of time spanning the approach and passing of a storm is involved. Seasonal hydrograph is plotted when longer time interval representing the full range of seasonal flow is involved. A time span extending over a period of many years enables plot of long-term hydrograph.

In the present study, stream hydrograph analysis of the seasonal (monthly) discharge data of Ganjem river-gauging station has been carried out. The baseflow can be separated either using Constant discharge method, Concave method or Constant slope method. The Constant discharge method assumes that baseflow is constant throughout the rainfall period while the Concave method assumes that the declining hydrograph trend prior to the onset of rainfall continues till the occurrence of peak flow (Linsley et al, 1975). Since it is unlikely that the baseflow will remain constant after the onset of rainfall in Mhadei River watershed given the high infiltration occurring in the months of May and June (as indicated in Fig. 2.4) and the highly drainable nature of the aquifers in the watershed (as brought out later in Chapter 4), the Constant slope method has been adopted for separation of the baseflow (Fig. 2.7 and Table 2.11).

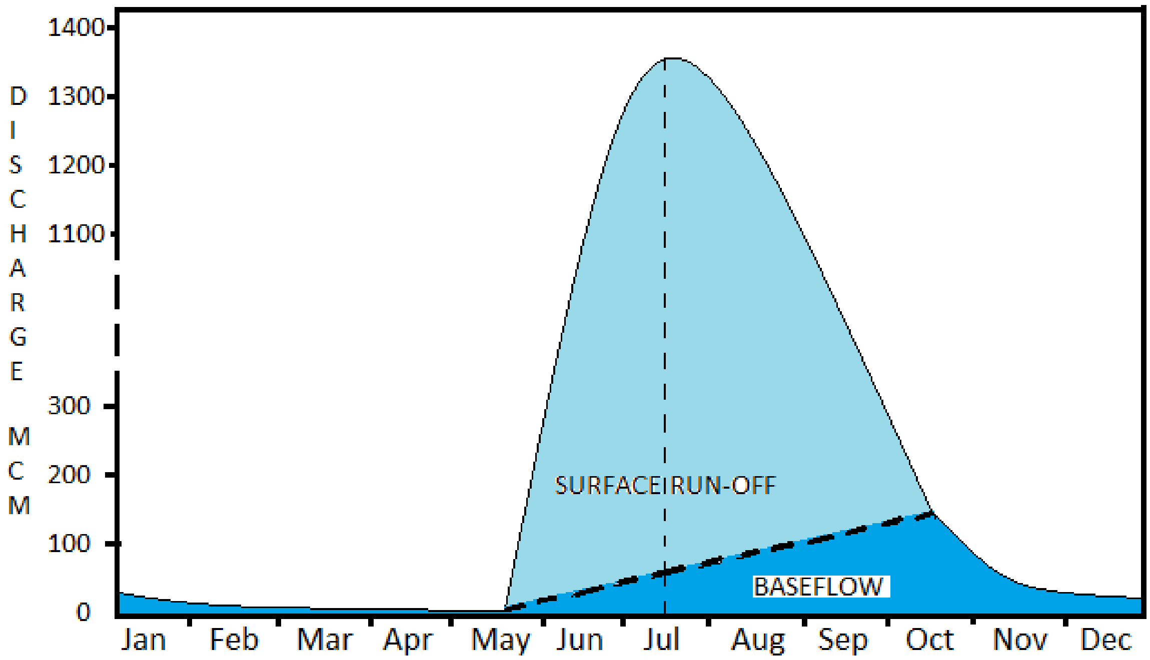


Figure 2.7 Mhadei River hydrograph separation using Constant slope method

As seen in Fig. 2.7, the hydrograph indicates a slow decline in the flow prior to the onset of rainfall. This is typical of a stream relying on baseflow (groundwater) for its discharge (Watson and Bernett, 1993). Then, as the surface run-off begins to reach the stream in ever increasing amounts the hydrograph rises sharply (June to July). Further, as the intensity of rainfall diminishes, the hydrograph moves over a peak and declines steeply till the surface run-off ceases to reach the stream (July to October). Here onwards the trend of the hydrograph is again governed by the baseflow.

Table 2.11 Baseflow computation of Mhadei River watershed using Stream hydrograph separation (Constant slope method)

Months	Volume of rainfall (MCM)	River discharge (MCM)	Monsoon baseflow (MCM)	Non-monsoon baseflow* (MCM)
January	1	16	-	16
February	0	5	-	5
March	1	3	-	3
April	9	3	-	3
May	53	3	-	3
June	783	303	37	-
July	1303	1333	71	-
August	891	1185	105	-
September	315	340	140	-
October	146	173	-	173
November	32	55	-	55
December	4	27	-	27
Total	**3538**	**3446**	**353**	**285**
			638	

* All the flow volume measured during non-monsoon months is considered as baseflow

As seen in Table 2.11, it is estimated that 638 MCM (19%) of the total discharge measured at Ganjem station is baseflow component. The total discharge of a stream is a function of the surface run-off component and baseflow component. Therefore, the surface run-off component can be calculated by subtracting the total baseflow from the total discharge. This works out to be 2808 MCM per annum for the Mhadei River watershed. As the total rainfall received by a catchment gets partitioned into surface run-off, groundwater recharge and evapo-transpiration, the volume available for the two later components is 730 MCM (volume of rainfall - surface run-off). Assuming 1% (35 MCM) of the total rainfall received in the catchment is lost as evapo-transpiration, the groundwater recharge works out to be 695 MCM. Of this 638 MCM is discharged as baseflow, therefore the effective groundwater recharge works out to be 57 MCM. The groundwater recharge computed using water table fluctuation method works out to be 41.86 MCM (Chapter 4). Therefore, the effective evapo-transpiration loss amounts to 50 MCM i.e., 1.5%. of the total rainfall.

2.6 Discussion

The Mhadei River watershed receives abundant rainfall to the tune of more than 3900 mm from the southwest monsoon from June to September. This value is more than the average rainfall (3200 mm) for the entire Goa State. However, the presence of Western Ghats in the watershed causes uneven distribution of the rainfall resulting in higher rainfall on the Goa side of the escarpment and relatively less rainfall on the Karnataka plateau. The rainfall also exhibits a systematic spatial pattern from west to east. It increases moving from western boundary of the watershed towards the Western Ghats and further shows a uniform decline moving from the Western Ghats towards the eastern boundary of the watershed. The total volume of rain water received in the Mhadei River watershed is 3538 MCM. Of this, 67% is contributed from the Goa region and 33% is contributed from the Karnataka region of the watershed. The total volume of monsoon rainfall received in the entire Mhadei River watershed works out to be 3294 MCM while total volume of non-monsoon rainfall is 244 MCM.

The average annual discharge of Mhadei River watershed at Ganjem river-gauging station is 3446 MCM which is 97% of the total volume of annual rainwater (3538 MCM) received by the watershed. Thus, only 3% of the total annual rainfall is attributed to groundwater recharge. Histogram of the monthly rainfall and discharge data indicate that the groundwater recharge dominantly takes place during the first three months of the monsoon season.

It is estimated that 638 MCM (19%) of the total discharge measured at Ganjem station is baseflow component. The total non-monsoon baseflow contribution from Karnataka region computed using *unit area baseflow* works out to be 109 MCM which is 38% of the total non-monsoon baseflow (285 MCM) of the entire Mhadei River watershed.

CHAPTER 3

MORPHOMETRIC ANALYSIS

3.1 Introduction

Morphometric characteristics of a river basin reflect its hydrological behavior and are useful in evaluating the hydrologic response of the basin. Quantitative morphometric analysis facilitates understanding of the drainage development, surface run-off generation, infiltration capacity of the ground and groundwater potential. The watershed of the Mhadei River is an integral part of the Mandovi River Basin (Fig. 3.1) and hence the morphometric setup of the entire Mandovi River basin has been studied.

3.2 Mandovi River Basin

River Mandovi is an interstate river that originates in the Western Ghats and flows down the entire width of the State of Goa to discharge into the Arabian Sea. The Mandovi River basin extends over an area of 2017 km^2, of which 1551 km^2 (77%) lies in Goa, 394 km^2 (19.5%) lies in Karnataka and the remaining 72 km^2 (3.5%) lies in the State of Maharashtra (Fig. 3.1). It is regarded as the lifeline of the State of Goa as its watershed covers about 42% of the total area of the State resulting in extensive use of its water for drinking and agriculture purposes. It also serves as an important internal navigation route for commercial purpose. The basin of the Mandovi River extends over all the physiographic divisions of Goa, namely the Coastal plain, the Midland region and the Western Ghats, as well as on the Karnataka plateau. The river originates in the Khanapur taluka of Belgaum district located on the western fringe of the Karnataka plateau. Here it is called as the Mahadayi or Mhadei (meaning the Great Mother). Initially, for some distance it flows due north-east, then takes a turn and flows due south-west. The Kotrachi nadi, the Surla nadi and Ragda nadi form the main tributaries of the Mhadei River. At Usgao, the Mhadei River is joined by the other major tributary, namely, the Khandepar River. Then onwards it is referred to as the Mandovi River which flows due north-west. At Amona, it is joined by the Valvanti River which has two main tributaries, namely, the Bicholim River and the Kudne River. Further, the Mandovi enters the coastal plains where the river channel bifurcates and re-converges around the Diwar Island. Then, it is joined by the Mapusa River (which has two tributaries namely, the Asnode River and the Moida River) and the Sinquerim River on the coastal plains before it discharges into the Arabian Sea.

The Mandovi River basin has been divided into five watersheds namely Mhadei, Khandepar, Valvanti, Mapusa and Sinquerim watershed (Fig 3.2). The streams directly joining the Mandovi River have been grouped under Lower Mandovi watershed.

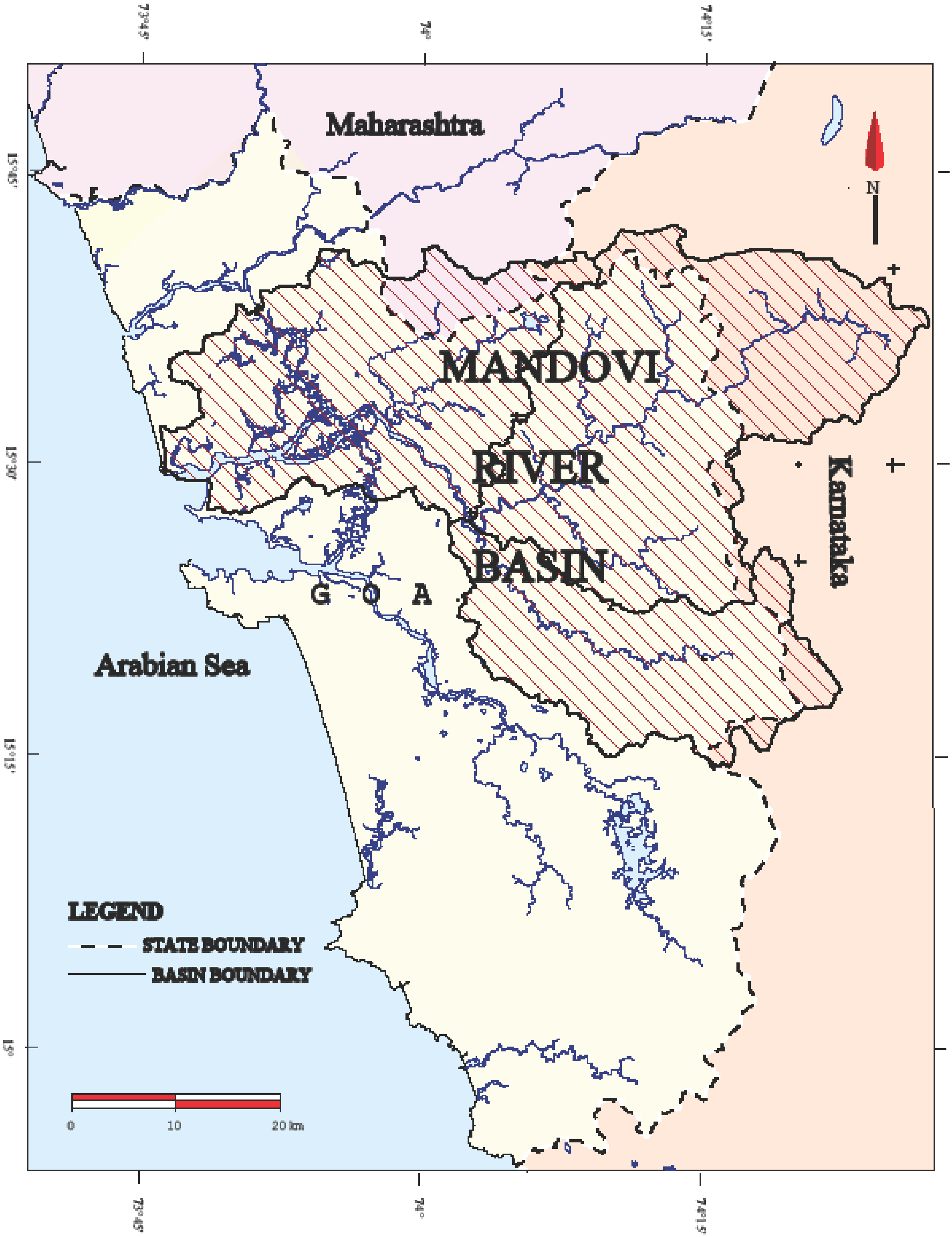


Figure 3.1 Map showing the entire Mandovi River basin.

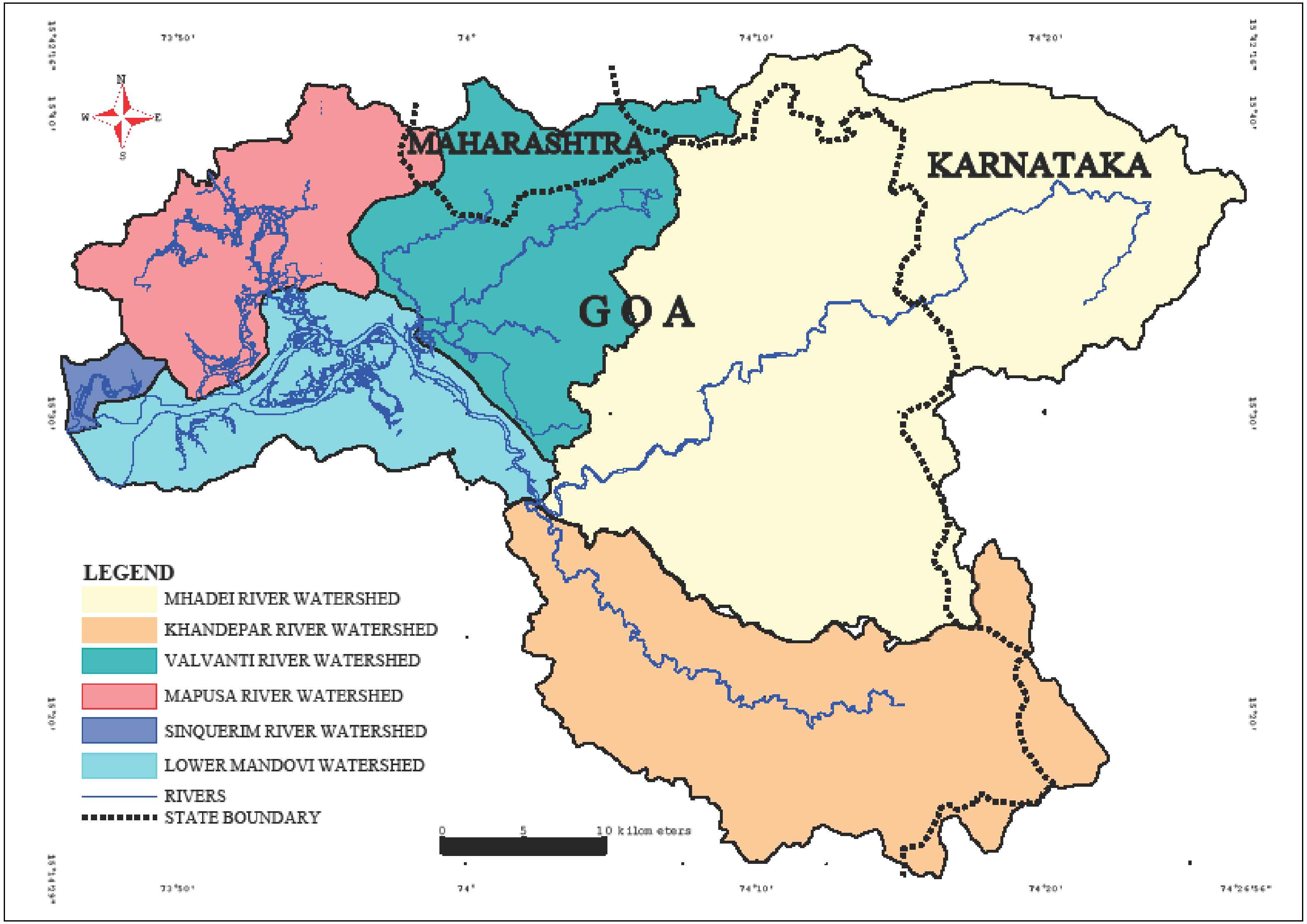


Figure 3.2 Map showing all the watersheds of Mandovi River basin.

The Khandepar and Valvanti River watersheds are partially situated in the Midland region of Goa and partially in the Western Ghats. The Mhadei River watershed is also situated on these two physiographic zones and further extends onto the Karnataka plateau. However, the Mapusa and Sinquerim river watersheds along with the Lower Mandovi watershed are situated in the Coastal plain of Goa. The drainage network of all the watersheds of Mandovi River basin has been digitized in a GIS platform (Figures 3.3, 3.4 and 3.5).

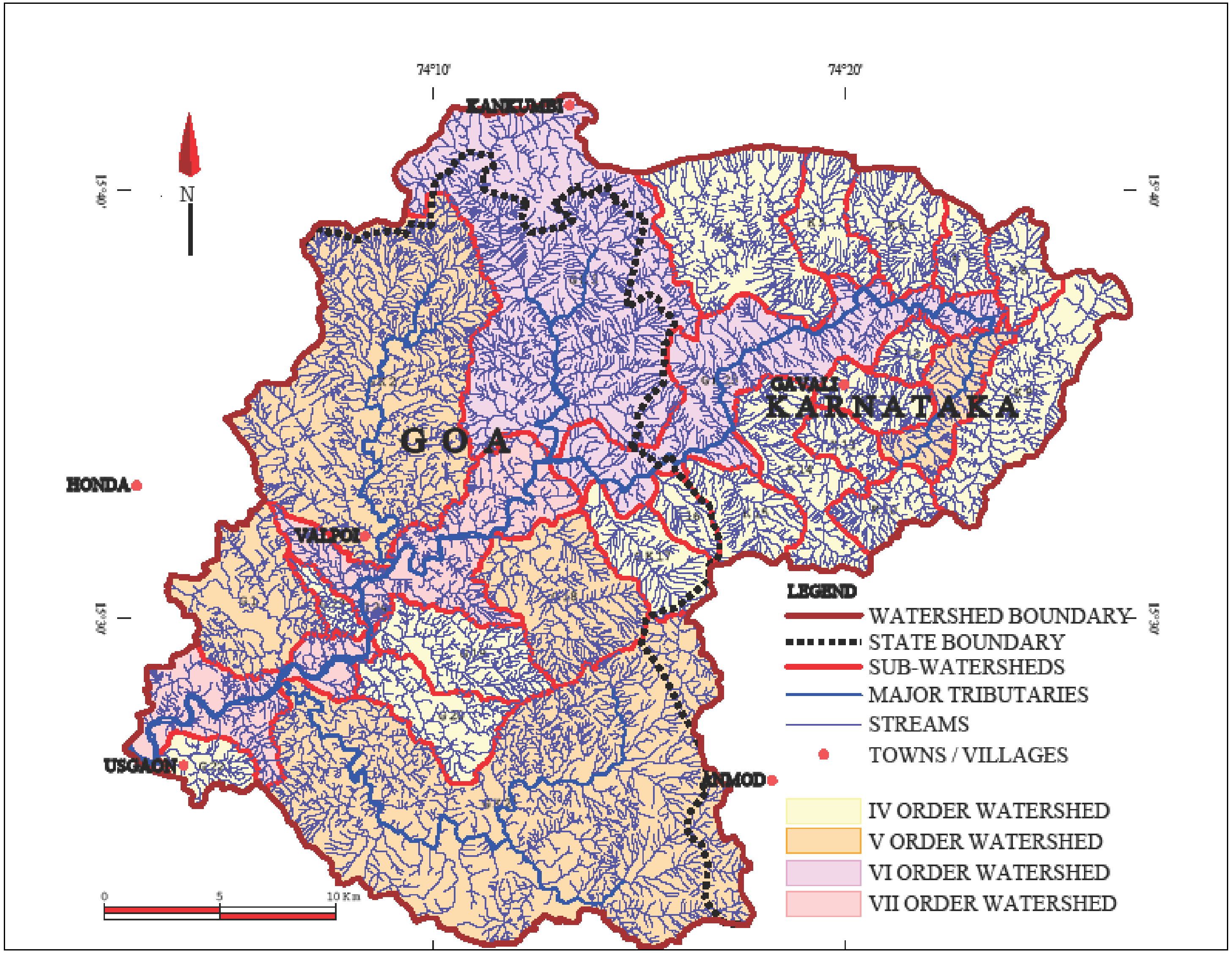


Figure 3.3 Drainage network of Mhadei River watershed

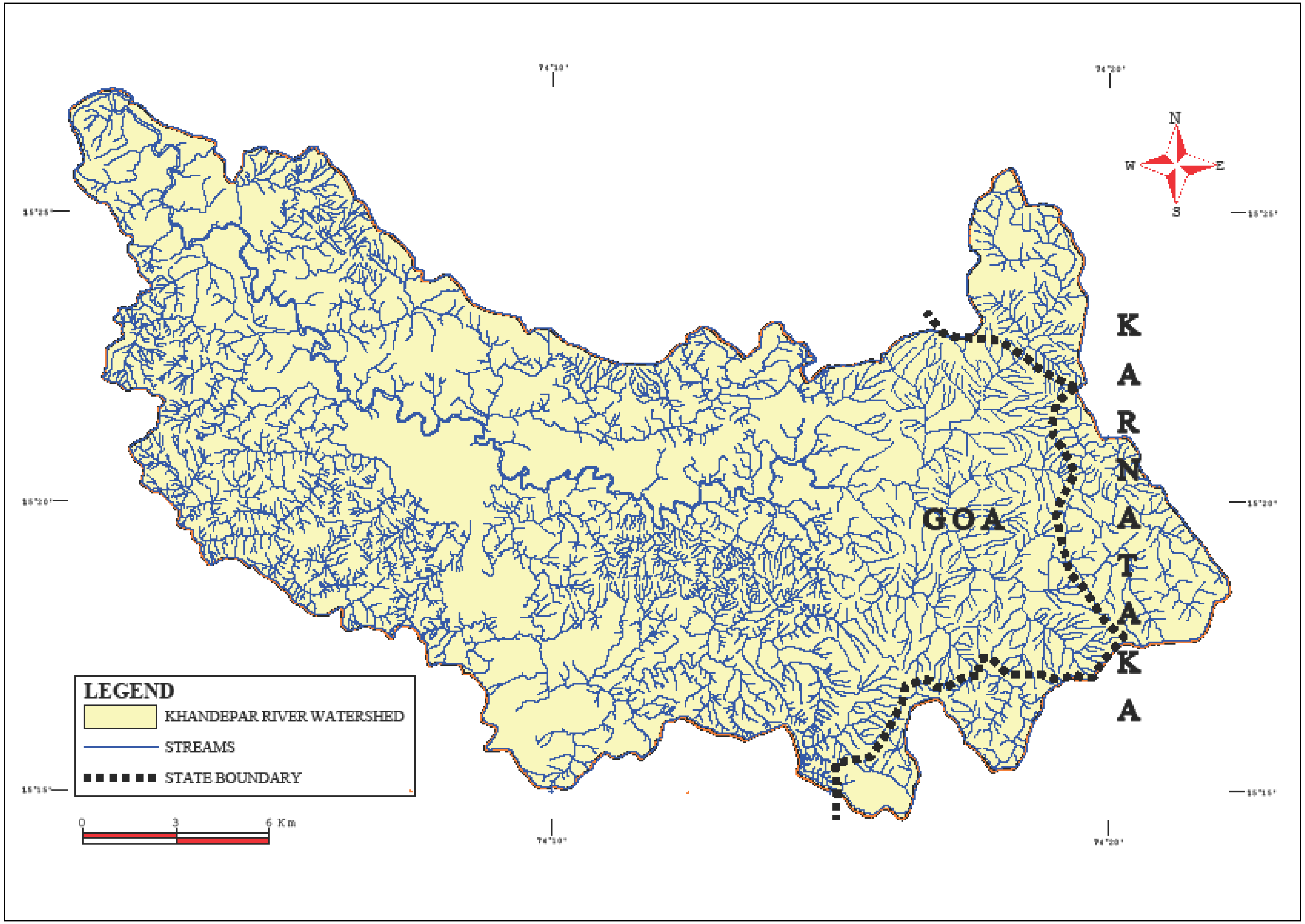


Figure 3.4 Drainage network of Khandepar River watershed

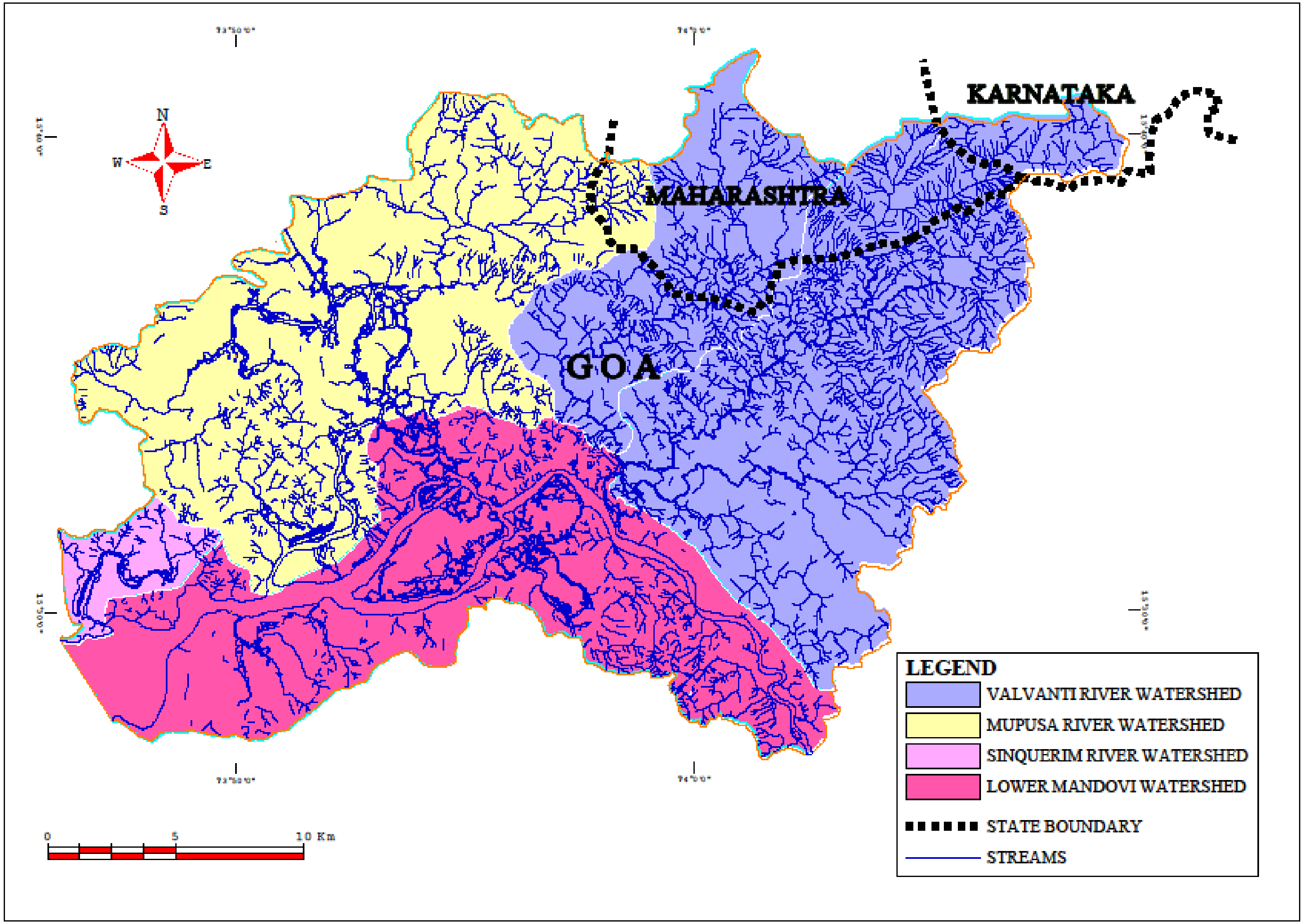


Figure 3.5 Drainage network of Valvanti, Mapusa, Sinquerim and Lower Mandovi watersheds

3.3 Morphometric Parameters:

The morphometric parameters of the Mandovi River basin have been broadly classified into two categories, namely basic parameters and derived parameters.

3.3.1 Basic Parameters

1. Basin Area (A): Basin area is the area of the catchment of the watershed of a channel network as projected onto a horizontal plane. The size of the basin affect the total volume of rainwater received, the total runoff produced and thus the stream discharge. The basin area of Mandovi River basin and its constituent watersheds are given in Table 3.1.

2. Basin Length (L_b): Basin length of a watershed is the aerial distance between the watershed outlet and the farthest point on the perimeter of the watershed (Gregory and Walling, 1973). Basin lengths of all the watersheds of Mandovi River basin and the entire Mandovi basin are given in Table 3.1.

3. Basin Perimeter (P): Basin perimeter is the length of the watershed boundary that encloses the catchment area. It is used in conjunction with the basin area to give a measure of the departure of the basin from a true circle and in conjunction with relief to give a measure of the general steepness of the basin. The perimeter of the Mandovi River basin is 283.5 km (Table 3.1).

4. Main Stream Length (S_L): The main stream length is the length of the main stream having maximum length measured along the stream course. The time of concentration is always maximum along this stream. The main stream length of the Mandovi River is 116 km. The initial 34 km of this length lies in the State of Karnataka while the later 82 km is located in the State of Goa.

5. Total Relief (H): Total relief is the difference between the highest elevation and the lowest elevation in the watershed. The highest elevation in the Mandovi River basin (1026 m amsl) is at Darsinga in the Western Ghats while the lowest elevation (0 m amsl) is at the mouth of the river at Panaji.

Table 3.1 Watershed-wise basic morphometric parameters of the Mandovi River basin.

Watershed	Area (km^2) (A)	Basin length (km) (L_b)	Perimeter (km) (P)	Main stream length (S_L) (km)	Highest elevation (m)	Lowest elevation (m)	Total relief (m) (H)
Mhadei	899.46	47.1	170.6	77	1026	5	1021
Khandepar	439.06	37.9	136.5	69	845	5	840
Valvanti	277.15	24.5	92	31.50	725	0	725
Mapusa	189.77	22.1	77.5	31	210	0	210
Sinquerim	18.68	6	17.5	13	79	0	79
Lower Mandovi	193.25	-	-	-	-	-	-
Entire Mandovi	2017.37	73.5	283.5	116	1026	0	1026

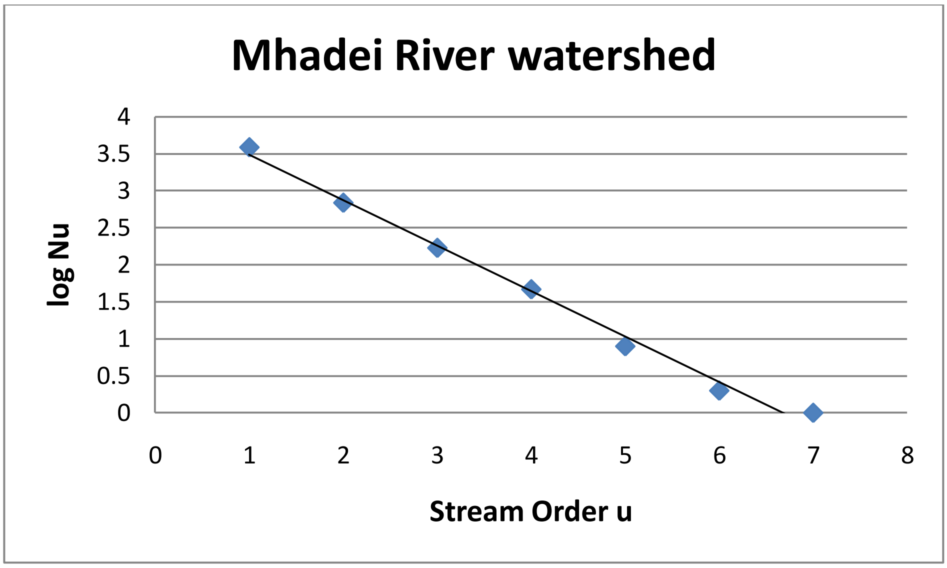
6. Stream Order (u): Stream order is the relative position or rank of a stream channel segment in a drainage network. According to Strahler's (1952) system, the smallest un-branched stream i.e. finger tip stream with no tributaries is designated as the 1st order stream, the one formed by the merging of two such 1st order segments is the 2nd order stream and so on. Stream order is a useful indicator of stream size, drainage area and discharge (Strahler, 1964). All the streams of the watersheds of Mandovi River basin have been designated according to the Strahler's system (Table 3.2).

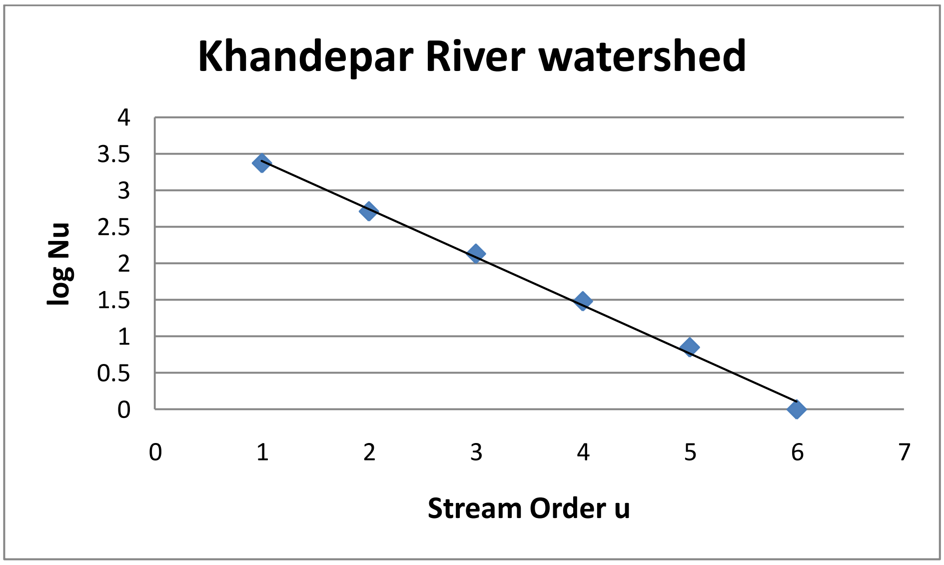
7) **Stream Number (Nu):** The number of stream segments in each order is counted separately and is called as the stream number of that order. The stream number follows Horton's (1932) law of stream number which states that the number of streams in different orders in a given drainage basin tends to closely approximate an inverse geometric series in which the first term is unity. The stream number of each order for all the watersheds of Mandovi River basin are given in Table 3.2. The lower order streams directly joining the Mandovi River have been put together as lower Mandovi streams.

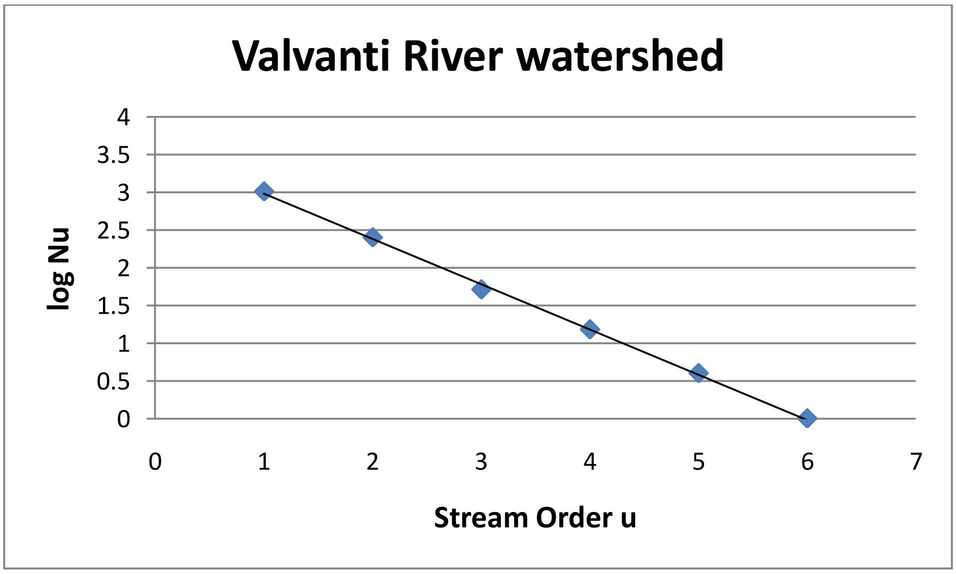
Table 3.2 Watershed-wise Stream Number of each Order

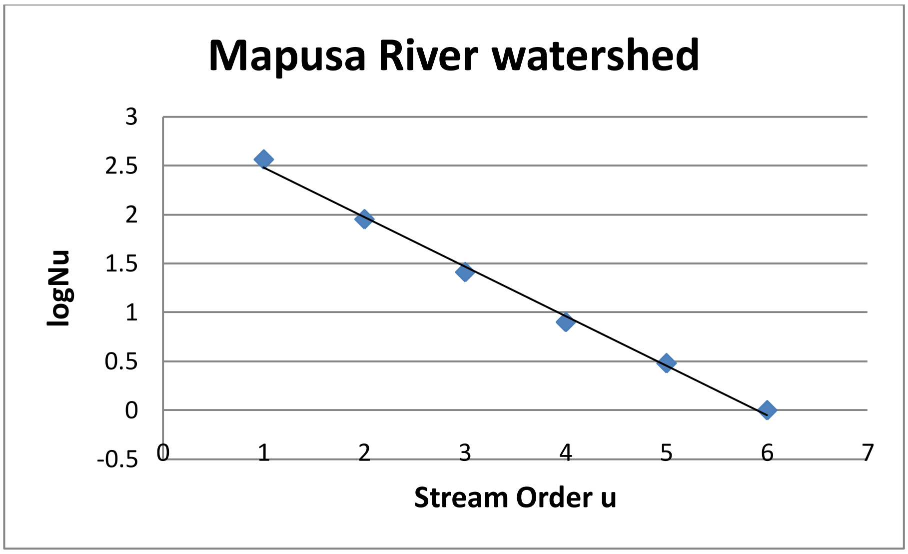
Watershed	Stream Number (Nu)							
	Ist order	IInd order	IIIrd order	IVth order	Vth order	VIth order	VIIth order	TOTAL
Mhadei	3908	692	171	47	8	2	1	4829
Khandepar	2336	514	136	30	7	1	-	3024
Valvanti	1032	252	51	15	4	1	-	1355
Mapusa	367	89	26	8	3	1	-	494
Sinquerim	30	6	1	-	-	-	-	37
Lower Mandovi	265	58	9	-	-	-	-	332
Total Mandovi	7938	1611	394	100	22	5	1	10071

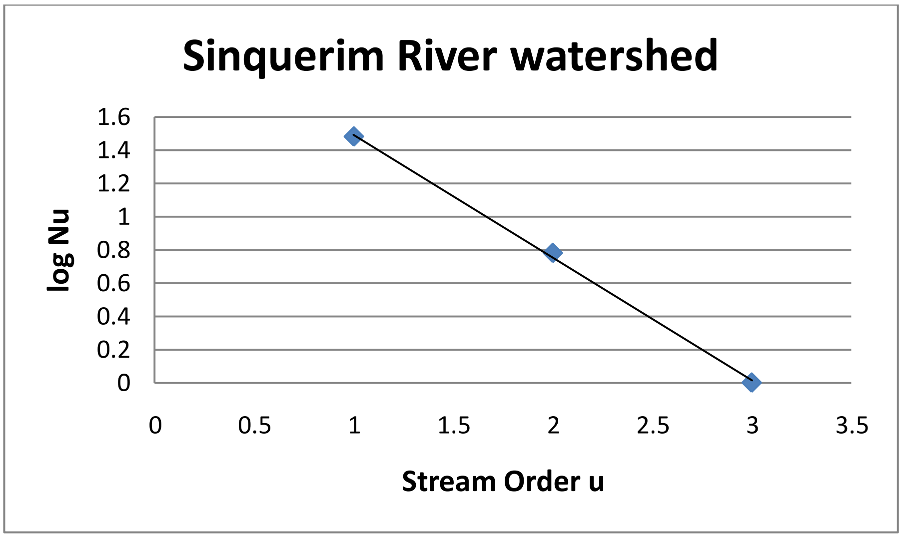
The plots of logarithm of stream number versus stream order of all the rivers are given in Fig. 3.6.


Mhadei River watershed
log Nu
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
Stream Order u


Khandepar River watershed
log Nu
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
Stream Order u


Valvanti River watershed
log Nu
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
Stream Order u





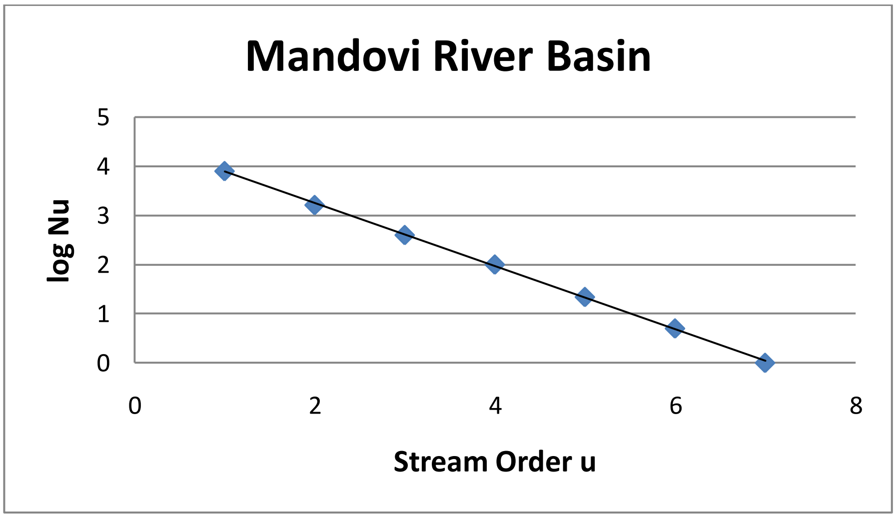


Figure 3.6 Regression of logarithm of number of stream segments (Nu) versus stream order (u) for all the watersheds of Mandovi River basin

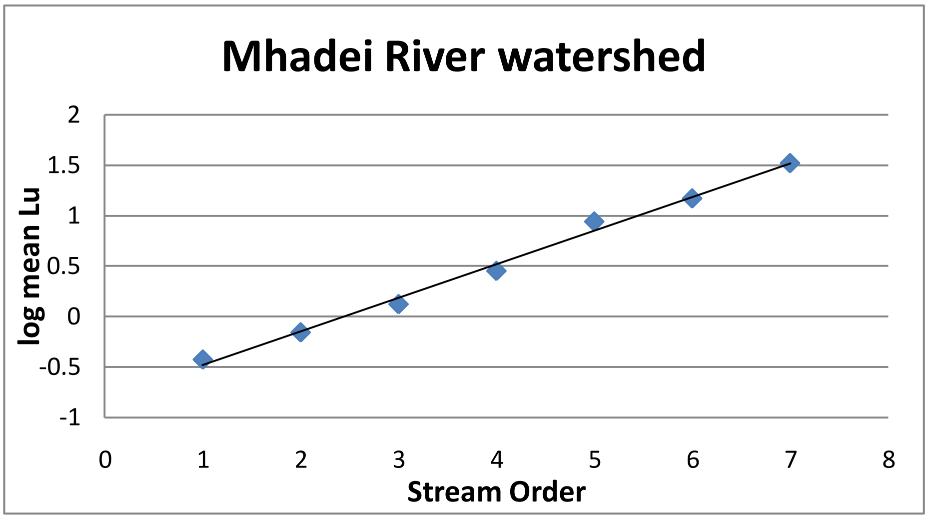
It is observed that the stream numbers of all the watersheds of Mandovi River basin and the entire basin itself follows Horton's law of Stream number. However, the higher order streams of Mhadei River watershed show some deviation from the straight line.

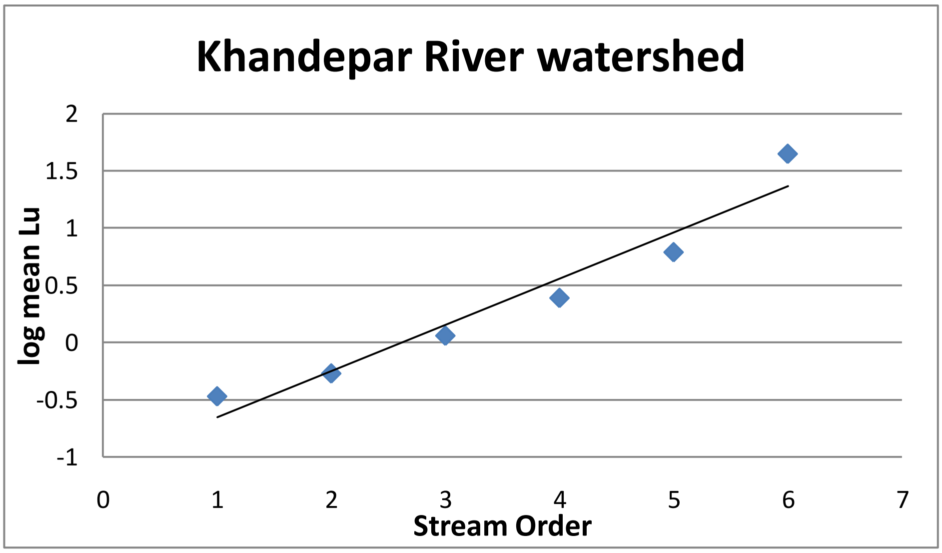
8. Stream Length (Lu): The total length of the streams in each order is referred as stream length of that order (Horton, 1945). Stream length of an order divided by its stream number gives the mean stream length of that order. The stream length follows Horton's law of stream length which states that the mean length of streams of each different order in a given drainage basin tends closely to approximate a direct geometric series in which the first term is the mean length of the streams of the first order. The stream lengths and mean stream lengths of each order of all the watersheds are given in Table 3.3.

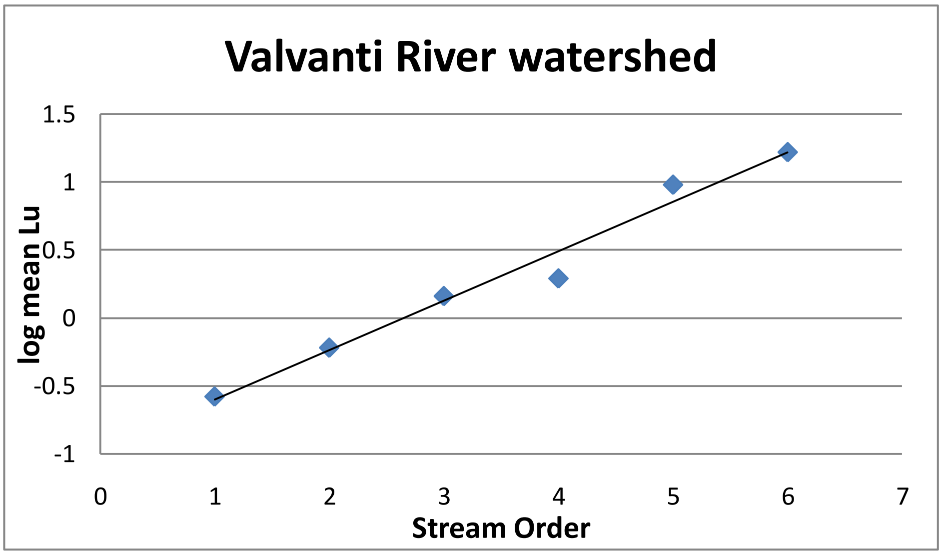
Table 3.3 Watershed-wise Stream lengths and Mean stream lengths of all the watersheds of Mandovi River basin.

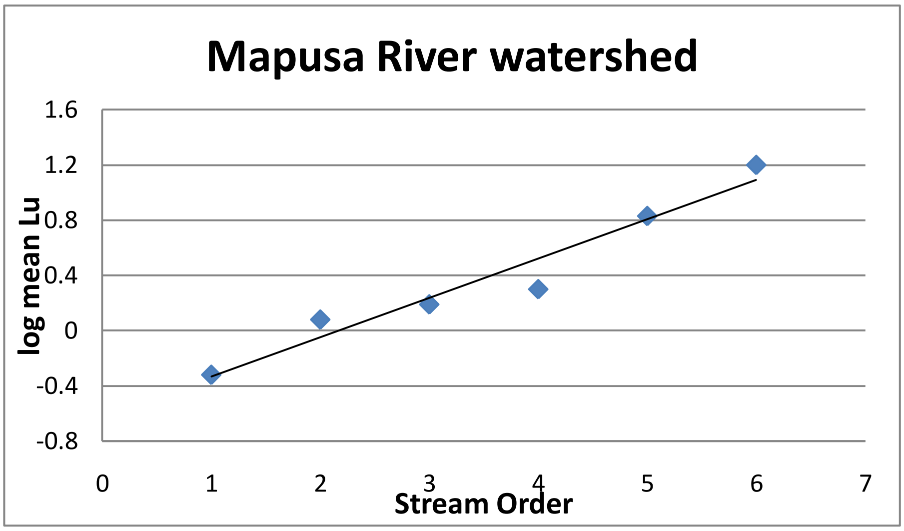
Watershed	Stream Order(u)	Stream Length (Lu) (km)	Mean Stream Length (km)
Mhadei Watershed	I	1471.00	0.37
	II	478.75	0.69
	III	228.75	1.33
	IV	134.75	2.86
	V	70.50	8.81
	VI	29.50	14.75
	VII	33.00	33.00
		$\sum L_u$ = 2446.25	
Khandepar Watershed	I	801.25	0.34
	II	280.00	0.54
	III	155.75	1.14
	IV	73.25	2.44
	V	42.75	6.10
	VI	45.00	45.00
		$\sum L_u$ = 1398.00	
Valvanti Watershed	I	267.25	0.26
	II	151.50	0.60
	III	73.50	1.44
	IV	29.50	1.97
	V	38.10	9.52
	VI	16.50	16.50
		$\sum L_u$ = 576.35	
Mapusa Watershed	I	177.50	0.48
	II	108.00	1.21
	III	40.25	1.55
	IV	16.00	2.00
	V	20.50	6.83
	VI	16.00	16.00
		$\sum L_u$ = 378.25	
Sinquerim Watershed	I	5.25	0.17
	II	5.25	0.87
	III	9.50	9.50
		$\sum L_u$ = 20.00	
Entire Mandovi Watershed	I	2796.63	0.35
	II	1072.25	0.67
	III	517.75	1.29
	IV	253.50	2.56
	V	171.85	7.83
	VI	107.00	21.06
	VII	72.00	72.00
		$\sum L_u$=4990.98	

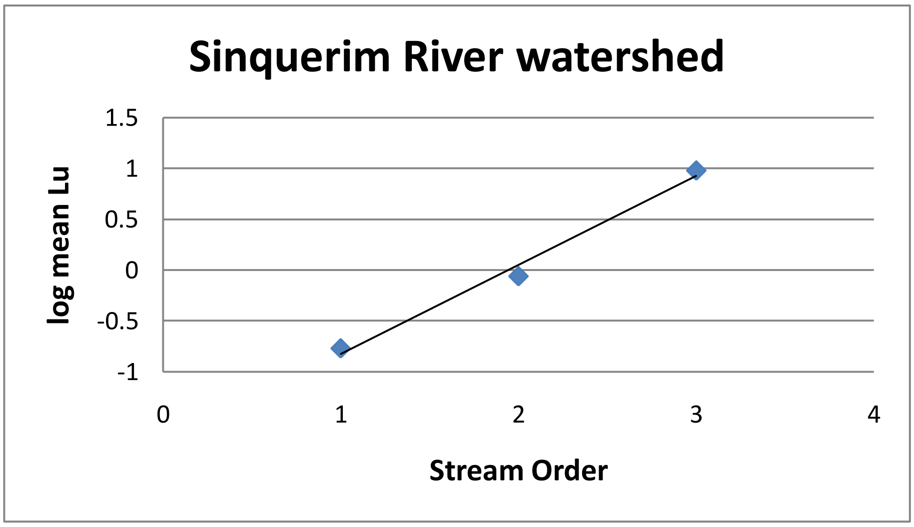
The plots of log of mean stream length versus stream order are given in Figures 3.7.











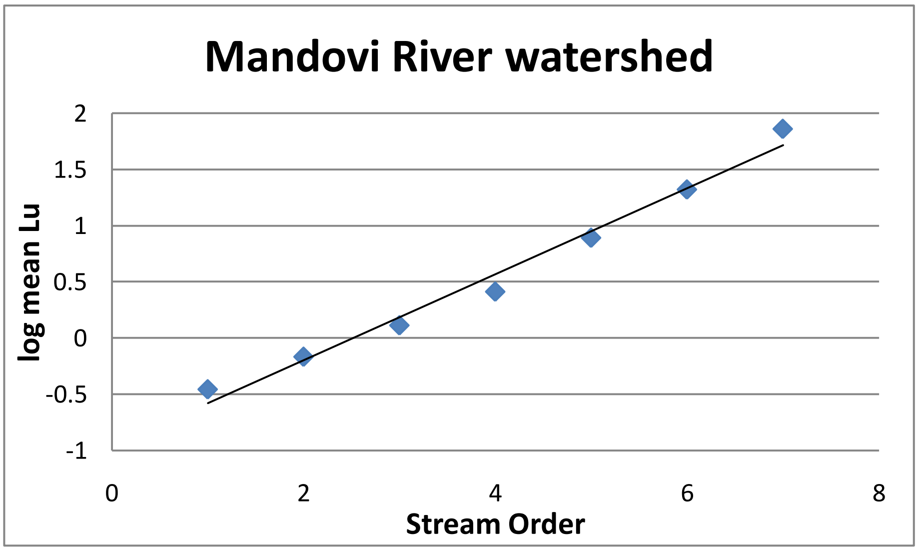


Figure 3.7 Regression of logarithm of mean stream length versus stream order for all the watersheds of Mandovi River basin.

It is observed that the stream lengths of all the watersheds of Mandovi River basin and the entire basin itself follow Horton’s law of Stream length. However, the higher order streams, particularly IVth and Vth order streams show some deviation from the straight line which according to Horton’s law is due to structural control of higher order streams.

9. Drainage Pattern: The adaptation of streams to initial slopes, inequalities in rock hardness and structural features results in the drainage network and different patterns are formed by their spatial relationships to one another. Since drainage patterns are influenced by so many factors, they are extremely helpful in the interpretation of geomorphic features and give the sum total of factors which affect the number, size and frequency of streams in a particular area.

In general, the Mandovi River basin exhibits dendritic to sub-dendritic drainage pattern (Fig 3.3, 3.4 & 3.5). However, most of the streams of fourth and fifth order in the central part of the basin (the Midland region of Goa) show a common NW-SE to NNW-SSE trend, suggesting a structural control, as the rocks in the region have a regional Dharwarian NW-SE trend. This results in a trellis type drainage pattern (smaller order streams meeting at right angle to the main stream) in some parts of the basin. Also, the first and second order streams flowing on the Karnataka plateau show parallel drainage pattern in the north-eastern corner of the basin as they flow on the horizontally laid Deccan traps.

The Mandovi River flows due west or south-west on account of the general westward slope of the Western Ghats escarpment and the Midlands. However, the initial course of the Mhadei River on the Karnataka plateau, including the Bandura nala, is due north-east which is same as that of the Haltar nala which is a tributary of Malaprabha river that flows due east on account of the eastward tilt of the Karnataka plateau, suggesting that these streams of the drainage basin have been captured by head-on erosion by the fast eroding Mhadei River.

Generally in the Mandovi River basin, the streams of the 4th and other lower orders are seasonal, whereas the 5th and above order flow throughout the year.

3.3.2 Derived Parameters

1. Bifurcation Ratio (R_b): The ratio of number of streams of any given order (Nu) to the number of streams in the next higher order (Nu+1) is called bifurcation ratio (Horton, 1932).

$$R_b = Nu/Nu_{+1}$$

It generally ranges between 3 and 5 for natural drainage basins without differential geological controls and only reaches higher values where geological controls favour the development of elongated narrow basins (Strahler, 1964). Elongated basin with high bifurcation ratio yields a low but extended peak flow while a circular basin with low bifurcation ratio produces a sharp peak flow. The bifurcation ratios of each order of all the watersheds are tabulated in Table 3. 4.

The average bifurcation ratio of the Mhadei River watershed is 4.19. The bifurcation ratio between 4th and 5th order streams is distinctly high (5.87) indicating a strong control of the structure of the underlying rocks on the development of these higher order streams. Similarly, the ratio between 1st and 2nd order streams is also relatively high (5.64).

The average bifurcation ratio of the Khandepar River watershed is 4.82 which is highest compared to all the other watersheds of the Mandovi River basin. Moreover, the ratio between the 5th and the 6th order is very high (7) suggesting a strong control of the rock structure on the development of the drainage of this watershed.

Table 3.4 Watershed-wise bifurcation ratios of all the watersheds of Mandovi River basin.

Watershed	Stream Order (u)	Stream Number (N_u)	Bifurcation Ratio (R_b)
Mhadei Watershed	I	3908	5.64
	II	692	4.04
	III	171	3.63
	IV	47	5.87
	V	8	4
	VI	2	2
	VII	1	-
		$\sum N_u$ = 4829	Av. R_b= 4.19
Khandepar Watershed	I	2336	4.54
	II	514	3.77
	III	136	4.53
	IV	30	4.28
	V	7	7
	VI	1	-
		$\sum N_u$ = 3024	Av. R_b= 4.82
Valvanti Watershed	I	1032	4.09
	II	252	4.94
	III	51	3.40
	IV	15	3.75
	V	4	4
	VI	1	-
		$\sum N_u$ = 1355	Av. R_b= 4.04
Mapusa Watershed	I	367	4.12
	II	89	3.42
	III	26	3.35
	IV	8	2.66
	V	3	3
	VI	1	-
		$\sum N_u$ = 494	Av. R_b= 3.31
Sinquerim Watershed	I	30	5
	II	6	6
	III	1	-
		$\sum N_u$ = 37	Av. R_b= 5.5
Entire Mandovi Watershed	I	7938	4.93
	II	1611	4.08
	III	394	3.94
	IV	100	4.73
	V	22	4.4
	VI	5	5
	VII	1	-
		$\sum N_u$=10071	Av. R_b=4.51

The average bifurcation ratio of the Valvanti River is low (4.04). The bifurcation ratios of all the streams of Mapusa River are very low (average 3.31) indicating no structural control on the development of the drainage of these two watersheds. The streams of Sinquerim River shows high bifurcation ratio.

The average bifurcation ratio of the entire Mandovi River Basin is 4.51. However, the bifurcation ratio is relatively high for higher order streams indicating a structural control on the development of these higher order streams.

2. Channel Sinuosity (S): Sinuosity is a quantitative index of stream meandering and a distinctive property of channel pattern. It is related to the morphological, sedimentological and hydraulic characteristics of stream channels. It can be calculated by dividing stream length by valley length (length of the basin) (Brice, 1984).

$$\mathbf{S=S_L/L_b}$$

The significance of channel sinuosity is that if S=1 indicate straight course of the stream, S=1-1.5 indicate sinuous course and S>1.5 indicate meandering course (Leopold et al, 1964).

The channel sinuosity values of both the major tributaries namely, the Mhadei and the Khandepar River, as well as for the entire Mandovi River are marginally more than 1.5 (Table 3.5) indicating that the river courses have started meandering. However, the value for the Valvanti

River is relatively low (1.28) indicating a sinuous course and a younger topography.

3. Elongation Ratio (R_e): It is defined as the ratio between the diameter of a circle of the same area as the drainage basin to the maximum length of the basin (L_b) (Schumm, 1956). The elongation ratio ranges between 0.6-1.00 over a wide variety of climatic conditions and geologic formations. The elongation ratio is equal to 1 for a circular basin and approaches 0 for a straight line. Values in the range of 0.6-0.8 are generally associated with strong relief and steep grounds. The values around 1.00 are typical of regions of very low relief. Elongated basins with high bifurcation ratio yield a low but extended peak flow while circular basins with low bifurcation ratio produce a sharp peak flow.

The elongation ratio is calculated as:

$$\mathbf{R_e = (2\sqrt{A/\Pi}) / L_b}$$

The elongation ratio for most of the watersheds as well as for the entire Mandovi river basin ranges between 0.61 to 0.8 (Table 3.5) indicating that they are moderately elongated. However, the elongation ratio for the Khandepar watershed is low (0.61) suggesting that the watershed is more elongated than other watersheds. The Valvanti and Sinquerim River watersheds have higher elongation ratio (0.76 and 0.8) suggesting that they are more circular than the other watersheds.

4. Circularity Ratio (R_c): Circulatory ratio is the ratio of the basin area (A) to the area of the circle of basin perimeter (P) (Miller, 1953). It is the measure of the degree of circularity of the given basin. High value of circularity ratio indicates old stage topography. R_c approaching 1 indicates circular shape of the basin and old stage topography. Circularity and elongation ratios may be of practical use in predicting certain hydrological characteristics of a drainage basin. The circularity ratio has been found out by using the following formula:

$$R_c = 4\pi A/P^2$$

The circularity ratio of most of the watersheds is between 0.29 and 0.41 (Table 3.5) indicating mature stage topography. However, the Sinquerim watershed has high ratio (0.76) indicating old stage topography.

5. Form Factor (R_f): Form factor is the ratio of the basin area (A) to the square of the maximum length of the basin (L_b) (Horton, 1945). Form factor varies from 0 to 1. Low form factor indicates elongated basin. Basins with low form factor have flatter peak flow for longer duration while the basins with high form factor have higher peak flows for a shorter duration.

$$R_f = A/L_b^2$$

The form factor for all the watersheds is less than 0.5 (Table 3.5) indicating elongated nature of all the basins. The form factor of

Khandepar basin is the least i.e., 0.3 emphasising its highly elongated shape while the form factor of the Valvanti and Sinquerim basin is comparatively higher emphasizing their more circular shape.

6. Compactness Constant (C_c): Compactness constant can be calculated by using the formula:

$$C_c=0.2821\ P/A^{0.5}$$

Compactness constant is unity for a perfect circle and increases as the basin length increases. Thus, it is a direct indicator of the elongated nature of the basin. The compactness constant for the Mandovi basin is 1.78 (Table 3.5) indicating its elongated shape.

Table 3.5 Watershed-wise derived morphometric parameters of the Mandovi River basin

Watershed	Channel Sinuosity	Elongation Ratio (R_e)	Circularity Ratio (R_c)	Form Factor (R_f)	Compactness Constant (C_c)
Mhadei	1.63	0.71	0.38	0.4	1.6
Khandepar	1.82	0.61	0.29	0.3	1.84
Valvanti	1.28	0.76	0.41	0.46	1.56
Mapusa	1.40	0.7	0.39	0.38	1.58
Sinquerim	2.16	0.8	0.76	0.51	1.14
Mandovi	1.58	0.68	0.31	0.37	1.78

3.3.2.1 Relationship of shape of the basin to peak discharge of stream:

The shape of the basin plays an important role in governing the discharge hydrograph of a stream. In general, elongated basin produces low but extended peak flow while circular basin yields a sharp peak flow. Typical discharge hydrographs of two basins with different shapes are shown in Figure 3.8. These patterns of hydrograph result because the elongated basin has a much broader variation in the lengths of flow path lines and hence a wide range of travel times. Whereas, a circular basin has flow path lines of more or less equal lengths resulting in high run-off accumulation at the basin outlet at the same time. However, other parameters such as bifurcation ratio, basin relief and drainage texture also play an important role in the pattern of discharge hydrograph.

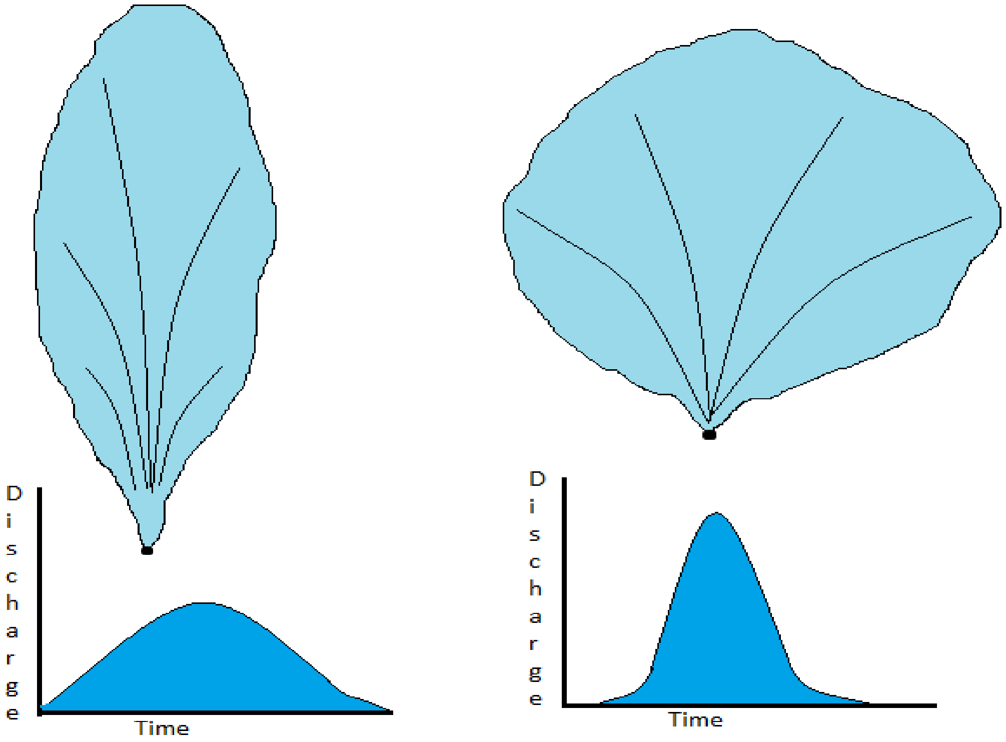


Figure 3.8 Relationships between Basin Shape and Stream Discharge

7. Drainage Density (D_d): Drainage density is the average length of streams per unit area within the basin (Horton, 1945). Drainage density may be thought of as an expression of the closeness of the spacing of channels.

Low drainage density is favoured in regions of highly resistant or highly permeable subsoil materials, under dense vegetative cover and low relief. High drainage density is favoured in regions of weak or impermeable subsurface materials, scarce vegetation, and mountainous relief. It is a valuable indicator of the relation between climate, vegetation, and the resistance of the rock and soil to erosion. Under similar climatic conditions impervious rocks support a higher drainage density compared with permeable rock. Drainage density is a useful numerical measure of land dissection and run-off potential.

$$\mathbf{D_d = \sum L_u / A}$$

Krishnamurthy et al (1996) classified drainage density as very coarse for $D_d<2$, coarse for $D_d= 2$ to 4, moderate for $D_d= 4$ to 6, fine for $D_d=6$-8 and very fine for $D_d>8$ (Jaiswal et al, 2007). The average drainage density of the Mandovi River watershed is 2.48 km/ km^2 (Table 3.5) which is, thus, classified as coarse. The drainage densities of Mhadei, Khandepar and Valvanti River watersheds are also classified as coarse. However, the drainage densities of Mapusa and Sinquerim River watersheds are classified as very coarse. Coarse drainage density gives more retention time for overland flow and hence better ground water recharge. Low drainage density in the present basin also indicates that the surface material in the drainage basin is fairly permeable and has a dense vegetative cover.

8. Stream Frequency (F): Horton (1945) defined stream frequency as the number of stream segments of all orders per unit area of the basin. High stream frequency is favoured in regions of impermeable subsoil and steep gradients. Higher the stream frequency, faster is the surface run-off and therefore less time for infiltration.

$$\mathbf{F=\sum Nu/A}$$

The average stream frequency of the study area is 4.99 per km^2 (Table 3.6). The stream frequency of the Mhadei, Khandepar and Valvanti watershed is more than 4.8 per km^2. However, the stream frequency of Mapusa and Sinquerim watershed is very low (2.6 and 1.98 per km^2 respectively). This may be attributed to the low relief and high permeability of the coastal plain in which these watersheds are situated. A plot of drainage density versus stream frequency (Fig. 3.9) of the watersheds of Mandovi basin reveals that there is a positive correlation between the two parameters.

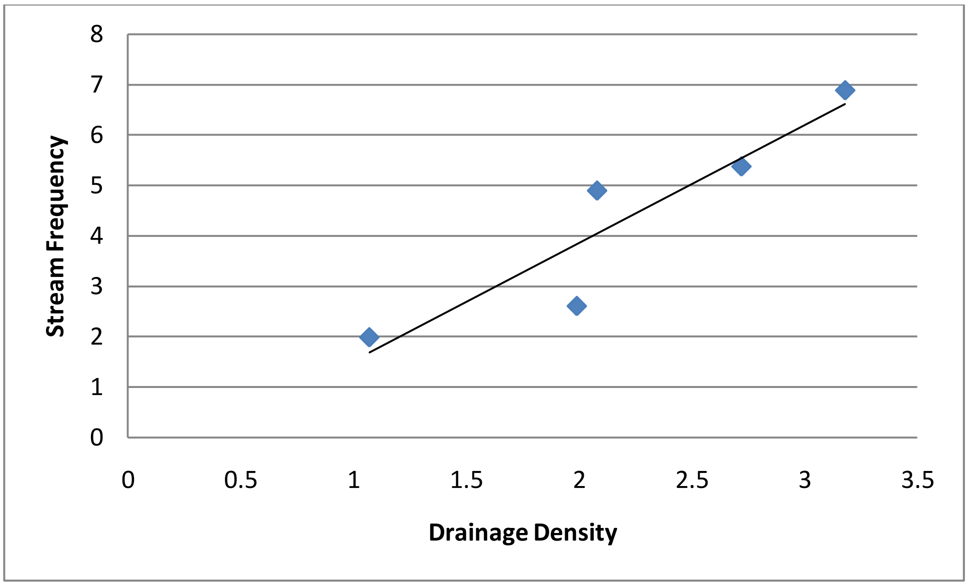


Figure 3.9 Relationship between drainage density and stream frequency.

9. Drainage Texture (T): Drainage texture is the relative channel spacing in a fluvial dissected terrain and is computed as the product of drainage density and stream frequency (Sreedevi et al, 2009; Singh and Awasthi, 2011). It depends upon a number of natural factors such as climate, rainfall, vegetation, rock/soil type, rate of infiltration, relief and stage of development of the basin.

T= Dd x F

The drainage texture of the watersheds of Mandovi River basin varies from 2.12 to 21.88 with a value of 12.37 for the entire basin (Table 3.6). Thus, the texture of Sinquerim and Mapusa watersheds may be classified as relatively coarse, that of Mhadei and Valvanti watersheds as medium while the Khandepar River watershed has relatively fine drainage texture.

10. Constant of Channel Maintenance (C_m): Schumm (1956) used the inverse of drainage density as a property termed the constant of channel maintenance which is defined as the area of the basin surface needed to sustain a unit length of stream channel.

$$C_m = 1/Dd$$

It is a function of the ground permeability. The constant of channel maintenance value for the entire Mandovi River basin is 0.4 (Table 3.6) meaning 0.40 km^2 of surface area is required to maintain each kilometre of channel length. However, the value for the Sinquerim watershed is very high (0.92) indicating higher permeability of the surface material.

11. Length of Overland Flow (L_O): Length of overland flow is the length of flow of the rain water over the ground surface before it gets concentrated in definite stream channels (Horton, 1945). It is measured as the length of non-channel flow path from a point on the water divide to a point on the adjacent stream channel and is computed as one half of the reciprocal of drainage density.

$$L_o = 1/2Dd$$

It is an important measure of erodibility affecting hydrologic response and physiographic development of watershed (Horton, 1945). Smaller the value of length of overland flow, quicker is the surface runoff and lesser erosion and vice-versa.

Table 3.6 Watershed-wise derived morphometric parameters of Mandovi River basin

Watershed	Drainage density (D_d) (km/km^2)	Stream Frequency (F) (km^{-1})	Drainage Texture (T)	Constant of (C_m) channel maintenance (km^2/km)	Length of overland flow (L_o) (km/km^2)
Mhadei	2.72	5.37	14.6	0.36	0.18
Khandepar	3.18	6.88	21.88	0.31	0.15
Valvanti	2.08	4.89	10.17	0.48	0.24
Mapusa	1.99	2.6	5.17	0.50	0.25
Sinquerim	1.07	1.98	2.12	0.93	0.46
Mandovi	2.48	4.99	12.37	0.40	0.20

12. Relief Ratio (R_h): Schumm (1956) defined relief ratio as the total relief (H) of watershed divided by maximum length of the watershed (L_b). It is an indicator of the potential energy available to move water and sediments down the slope. High value of relief ratio indicates quick runoff of water resulting in large peaked and steep limbed runoff hydrograph.

$$R_h = H/L_b$$

The relief ratio of the entire Mandovi River basin is 0.013 (Table 3.7) which indicates that the basin has relatively moderate relief. The Mapusa River watershed has the lowest ratio (0.009) indicating low relief and old stage topography. The Valvanti River watershed has the highest relief ratio (0.029) indicating steep slopes which should yield high peak flow in short time.

13. Ruggedness Number (R_N): It is defined as the product of the total relief (H) and drainage density (D_d). It gives an idea of overall roughness of a watershed.

$$R_N = H*D_d$$

The ruggedness numbers of the Mhadei and Khandepar River watershed are higher compared to that of other watersheds (Table 3.7). This may be attributed to their origin on the Western Ghats where the erosion process is still very active. However, the ruggedness numbers of the Mapusa and Sinquerim watershed are very low as the process of pediplaination is in advance stage.

14. Relative Relief (R_r): It is the ratio of the total relief (H) to the perimeter (P) of the watershed. Low relief ratio is indicative of gentle topography while high relief ratio is characteristic of steep slopes.

$$R_r = H/P$$

The relative relief of the Mandovi River basin is 0.0036 (Table 3.7). The relative relief of the Mapusa watershed is the minimum (0.0027) while the relative relief of the Valvanti watershed is the maximum (0.0079).

15. Time of Concentration (T_c): The time required to move the surface runoff from remotest point of the basin to its outlet is known as time of concentration. It is estimated based on the Kirpich (1940) equation:

$$T_c = 0.0195L^{0.77}S^{-0.385}$$

Where 'L' is the maximum length of travel of water along the water course in meters and 'S' is the slope expressed as the ratio of the difference in elevation between the remotest point and catchment outlet through the length L. High value of time of concentration will produce low run-off rate. The time of concentration for the main stream channel of the Mandovi River is 15.92 hours (Table 3.7).

16. Standard Time of Concentration (ST_c): A new factor 'standard time of concentration' has been derived by dividing the time of concentration by the main stream length. Thus, it is the time required to move the surface run-off per unit length of the main stream. It reflects the run-off potential of the watershed. It is observed that the standard time of concentration for Mhadei, Khandepar and Valvanti River watersheds are low compared to that of Mapusa and Sinquerim river watersheds implying that the run-off rate in these hilly watersheds is relatively high.

Table 3.7 Watershed-wise derived morphometric parameters of Mandovi River basin

Watershed	Relief Ratio (R_h)	Ruggedness Number (R_N)	Relative Relief (R_r)	Time of conc. (Tc) (hr)	Standard time of conc. (ST_c) (hr/km)
Mhadei	0.021	2.79	0.0060	9.919	0.129
Khandepar	0.022	2.68	0.0062	9.417	0.136
Valvanti	0.029	1.50	0.0079	4.038	0.128
Mapusa	0.009	0.41	0.0027	6.387	0.206
Sinquerim	0.013	0.08	0.0045	3.411	0.206
Mandovi	0.013	2.54	0.0036	15.923	0.137

3.4 Discussion

Mandovi River Basin: The Mandovi River is an interstate river, the watershed of which lies primarily in the territory of Goa State and remaining lies in Karnataka and Maharashtra. The Mandovi River is of seventh order and attains this order in the Mhadei watershed itself. The other major tributaries namely, the Khandepar, the Valvanti and the Mapusa River are of sixth order. However, the Sinquerim River is of third order. The streams of the Mhadei and the Khandepar River which are dominantly located in the Midland region of Goa show a high bifurcation ratio indicating that they are controlled by the trend of the underlying rock types. Thus, they can be classified as subsequent streams and the topography is in the mature stage of development. However, the bifurcation ratio of the Mapusa River is very low indicating that the rock structure has no control on the development of this watershed and the topography has reached old stage.

The Mandovi River basin in general exhibits dendritic to sub-dendritic drainage pattern. However, most of the higher order streams show a common NW-SE to NNW-SSE trend resulting in trellis drainage pattern. Thus, it is evident that the regional trend of the Goa Group of rocks (NW-SE) has a strong control on drainage development.

The shape and size of the basin affect the total volume of rainwater received, the total runoff produced and thus the stream discharge. The morphometric parameters of the Mandovi basin favor a flat but extended peak flow as seen from its shape and relief parameters. Thus, it is estimated that flood should be a rare phenomenon along this river.

The high bifurcation ratio along with low elongation ratio of the Khandepar watershed is suggestive of low but extended peak flow. The high elongation ratio coupled with high form factor and low bifurcation ratio for the Valvanti watershed suggests that the catchment is circular. Also, its high relief ratio and high relative relief suggests that the relief is strong with steep slopes. The circular shape and steep slopes favour sharp peak flow for short duration. This explains the frequent occurrence of floods during heavy rainfall in the Valvanti watershed. The low bifurcation ratio, low relief ratio, low relative relief and low ruggedness number for the Mapusa River is indicative of old stage topography that results in low peak flow. Though the elongation ratio and the circularity ratio of the Sinquerim watershed are high the catchment will not have high peak flow because its constant of channel maintenance suggests that its ground permeability is very high and also its relief ratio is very low.

The drainage density (2.48) and the stream frequency (4.99) of the entire Mandovi basin are low exhibiting coarse texture. The low drainage density in the basin could be due to the predominance of overland flow due to thick forest coverage clubbed with covering of soil surface by vegetal matter which inhibits formation of lower order streams. The stream frequency of the Mapusa and the Sinquerim River is very low which suggests high permeability of the coastal plain. Low stream frequency coupled with low drainage density favour better ground water recharge.

Mhadei River Watershed: The Mhadei River watershed has an area of 899 km^2 with aerial length of 47 km and a maximum basin width of 36 km. The Mhadei River originates in Degao village of Khanapur taluka of Belgaum District at an elevation of about 900 m amsl. The highest elevation in the watershed is 1026m at Darsinga peak on the watershed boundary in the Western Ghats. The river has a maximum length of 77 km of which the first 34 km flows in Karnataka while the later 43 km flows in Goa. The long profile of the river is concave upwards with one prominent nick point in the Western Ghats (Fig 3.10). The river channel has three prominent reaches with different gradients. The upper reach is on the Karnataka plateau with a gentle gradient, the middle reach is in the Western Ghats region with relatively steep gradient while the lower reach is in the Midland region of Goa having a gentle gradient.

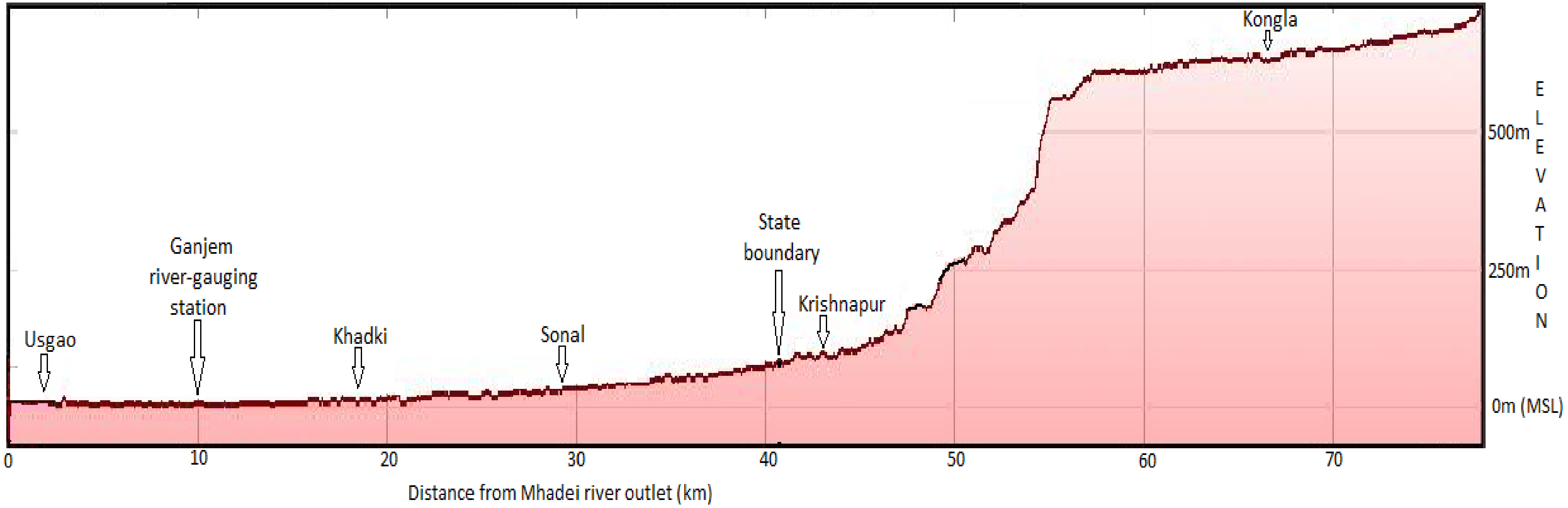


Figure 3.10 Long profile of River Mhadei showing three prominent reaches with different gradients.

The Mhadei River is of VIIth order with one major VIth order tributary, namely the Surla Nadi and two major Vth order tributaries, namely the Kotrachi Nadi and Ragada Nadi. Two minor tributaries of Vth order namely, the Advai Nala and Kumtol Nala also join the Mhadei River.

The stream numbers and stream lengths of the Mhadei River watershed follow the Horton's Laws of Stream Number and Stream Length. However, the highest order stream deviates from a linear relationship, which according to Horton's law is due to structural control of higher order streams which corroborates with the field observations.

In general, the drainage pattern in the Mhadei River watershed is dendritic to sub-dendritic indicating uniform resistance to erosion. However, the higher order streams are aligned parallel to each other (mostly in NW-SE to NNW-SSE direction) resulting in trellis drainage pattern along their courses. This indicates that the higher order streams flow through the strike valleys formed by the selective erosion of NW-SE trending Dharwarian rocks in the watershed. Further, some lower order streams are also distinctly aligned in NE-SW direction. An overlap of the lineament map of the area (Fig.3.11) indicates that these streams are controlled by the NE-SW trending lineaments. These observations are also supported by the high bifurcation ratio (5.87) between the IVth order and Vth order streams of the watershed. The main channel of the Mhadei River is highly sinuous in nature. However, it maintains an overall linearity in NE-SW direction indicating that it is also controlled by the lineaments.

The shape parameters of Mhadei River watershed indicate that the watershed is moderately elongated. The textural parameters indicate that the drainage texture is medium and the ground is moderately permeable. The relief parameters indicate that the relief is moderate with highly rugged topography.

The shape, size, textural and relief parameters of Mhadei River watershed indicate that the watershed has a mature topography and favour a flat but extended peak flow. Therefore, it is estimated that flood should be a rare phenomenon along the Mhadei River. Medium drainage texture coupled with moderate relief favour moderate groundwater recharge in the watershed.

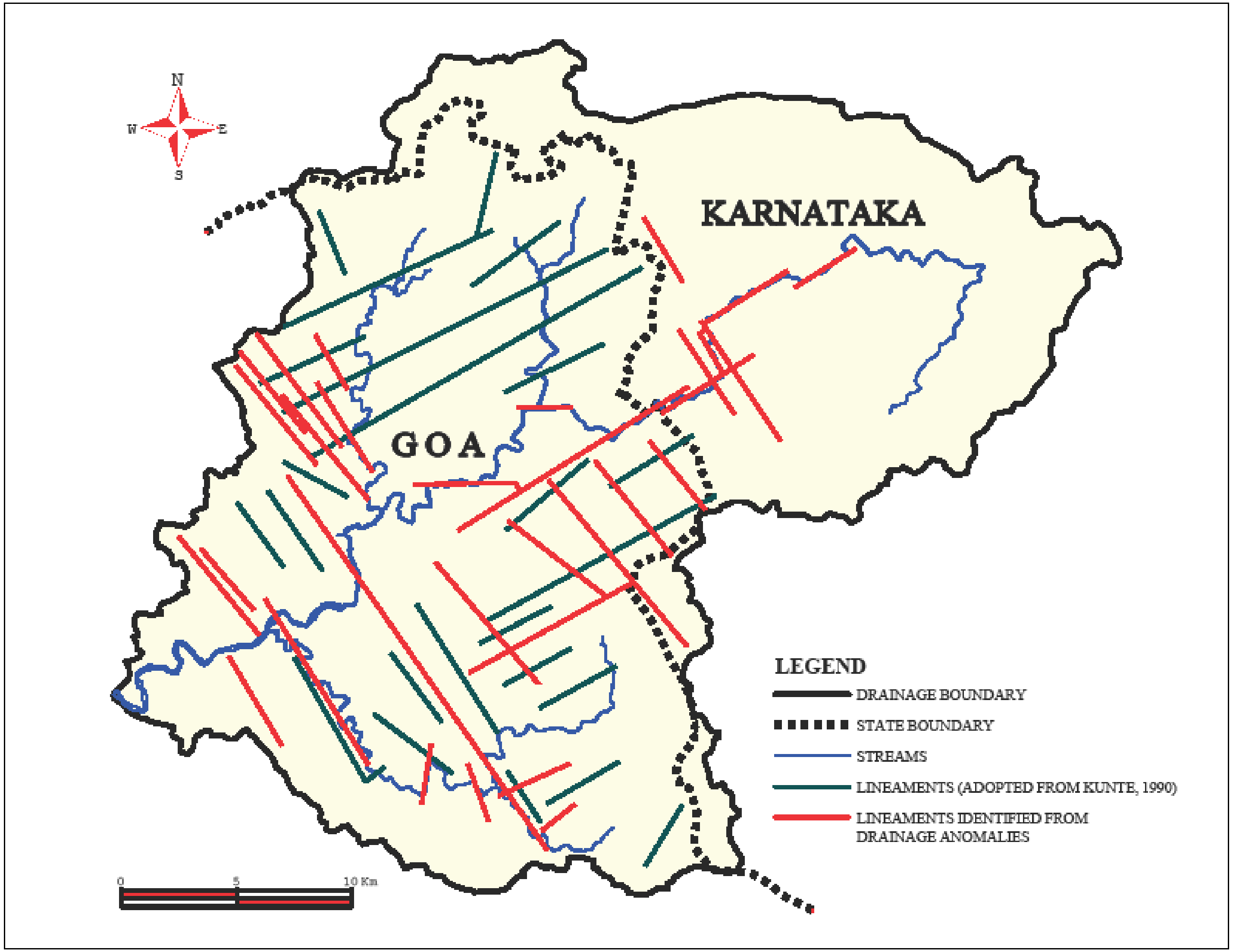


Figure 3.11 Lineament map of Mhadei River watershed

Based on this chapter, following paper has been communicated to Hydrology Journal, IAH, Roorkee:

Ibrampurkar M.M. and Chachadi A.G., (2010) Quantitative Morphometric Analysis of Mandovi River Basin in Goa & Karnataka - Western Ghats.

CHAPTER 4

HYDROGEOLOGICAL INVESTIGATIONS OF MHADEI RIVER WATERSHED

4.1 Introduction

The hydrogeological investigations are important facets of any groundwater management strategy. The groundwater potential of an area depends on the geological and geomorphologic setup, rainfall pattern, aquifer type, groundwater flow pattern, boundary conditions, aquifer properties, etc. Hydrogeological investigations indicate the status of groundwater availability in the watershed based on which management strategies can be evolved for effective and efficient use of water resources.

The Mhadei River watershed comprises of meta-sedimentary and meta-volcanic rocks of the Dharwar Supergroup and gneisses of the PGC. These rock formations have undergone multiphase tectonic activities resulting in intense fracturing and shearing of the rocks. The weak zones in the rocks coupled with heavy rainfall and other climatic factors have facilitated deep weathering of the rocks resulting in a cover of porous laterite and lateritic soils of varying thickness (Plate 4.1). Thus, the top layer of the ground in the Mhadei River watershed forms a potential zone for groundwater storage. The people dwelling in the Mhadei River watershed depend heavily on this groundwater for their domestic and agricultural requirements. Thus, scientific understanding about the occurrence, distribution, movement and sustainability of this dynamic natural resource becomes important.

4.2 Methodology of Data Collection

Dug wells are prevalent in the lateritic terrain of Mhadei River watershed (Plate 4.1). In the study area of 899 km^2, 82 observation wells were established to monitor variation in groundwater levels both in Goa and Karnataka. The wells are open dug type mostly used for domestic and agricultural purposes. The groundwater levels were measured on seasonal basis from May 2007 till November 2009 in 69 observation wells located in the western low lying (Goa) region of the watershed. The remaining 13 observation wells located on the Karnataka plateau in the eastern part of the watershed were also monitored for groundwater fluctuation for three seasons of the year 2007. Details regarding the well location, dimensions, depth to static water level, aquifer material, etc were collected and tabulated for each well. The locations of the observation wells were then transferred on to the base map in a GIS environment (TNT mips software). A point vector layer was created for plotting the observation wells using the latitude-longitude and elevation data. The well data including the assigned well numbers was stored as attribute data in the point layer. This data was further processed to prepare various thematic maps. The locations of the wells are shown in Fig. 4.1. The data regarding well locations and dimensions has been given in Table 4.1 and Table 4.2 respectively.

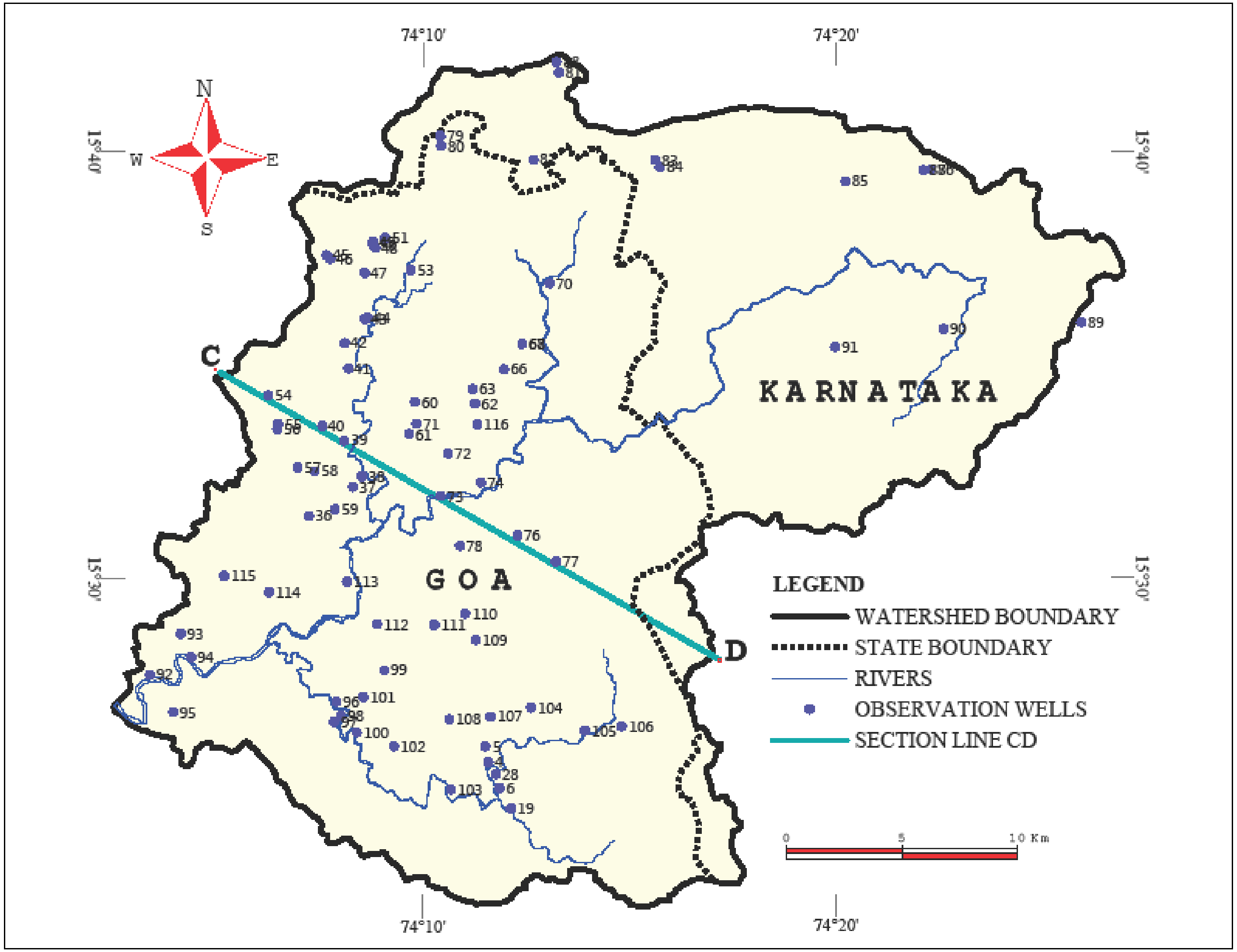


Figure 4.1 Location of groundwater observation well network established in the Mhadei River watershed

Table 4.1 Location data of observation wells established in Mhadei River watershed

Sr. No.	Well. No.	Latitude	Longitude	Ground Elevation (m) amsl	Name of the place
1	4	N 15° 25' 41.6″	E 74° 11' 35.1″	50	Bolcornem
2	5	N 15° 26' 04.2″	E 74° 11' 30.7″	70	Bolcornem
3	6	N 15° 25' 05.4″	E 74° 11' 51.1″	57	Surla
4	19	N 15° 24' 36.4″	E 74° 12' 06.9″	48	Satpal
5	28	N 15° 25' 24.9″	E 74° 11' 45.1″	58	Bolcornem
6	36	N 15° 31' 27.7″	E 74° 07' 13.3″	28	Nagre
7	37	N 15° 32' 08.1″	E 74° 08' 17.2″	28	Valpoi
8	38	N 15° 32' 23.5″	E 74° 08' 30.4″	26	Veluz
9	39	N 15° 33' 13.7″	E 74° 08' 05.1″	26	Koparde
10	40	N 15° 33' 34.6″	E 74° 07' 32.6″	48	Koparde
11	41	N 15° 34' 54.8″	E 74° 08' 10.6″	52	Pali
12	42	N 15° 35' 31″	E 74° 08' 05.1″	61	Pali
13	43	N 15° 36' 03.9″	E 74° 08' 34.9″	58	Thane
14	44	N 15° 36' 05.6″	E 74° 08' 39.5″	55	Thane
15	45	N 15° 37' 33.9″	E 74° 07' 39.7″	105	Charavne
16	46	N 15° 37' 29.1″	E 74° 07' 44.7″	110	Charavne
17	47	N 15° 37' 08.9″	E 74° 08' 34.5″	79	Hivre budruk
18	48	N 15° 37' 44.5″	E 74° 08' 50″	105	Hivre budruk
19	49	N 15° 37' 52.7″	E 74° 08' 46.8″	122	Hivre budruk
20	50	N 15° 37' 48.6″	E 74° 08' 46.9″	118	Hivre budruk
21	51	N 15° 37' 57.7″	E 74° 09' 04.1″	123	Hivre budruk
22	53	N 15° 37' 13.6″	E 74° 09' 41.3″	134	Rive
23	54	N 15° 34' 17.2″	E 74° 06' 14.8″	120	Zarme
24	55	N 15° 33' 37.4″	E 74° 06' 29.2″	51	Dabem
25	56	N 15° 33' 29.5″	E 74° 06' 27.3″	46	Dabem
26	57	N 15° 32' 35.2″	E 74° 06' 57.2″	46	Mauxi
27	58	N 15° 32' 30.5″	E 74° 07' 22.1″	30	Mauxi
28	59	N 15° 31' 37.2″	E 74° 07' 51.5″	30	Valpoi
29	60	N 15° 34' 07.2″	E 74° 09' 47.7″	50	Brahmakamali
30	61	N 15° 33' 22.3″	E 74° 09' 38.7″	48	Ambede
31	62	N 15° 34' 05.5″	E 74° 11' 14.6″	148	Malaoli
32	63	N 15° 34' 25.3″	E 74° 11' 11.3″	124	Malaoli
33	66	N 15° 34' 53.5″	E 74° 11' 57.2″	92	Nanoda
34	67	N 15° 35' 28.9″	E 74° 12' 22.9″	90	Kodal
35	68	N 15° 35' 29.1″	E 74° 12' 23.4″	83	Kodal
36	70	N 15° 36' 54.3″	E 74°13' 03.2″	120	Satrem
37	71	N 15° 33' 37.5″	E 74° 09' 56.3″	65	Ambede
38	72	N 15° 32' 55.5″	E 74° 10' 36.1″	117	Dhave
39	73	N 15° 31' 55.5″	E 74° 10' 25.3″	31	Tar
40	74	N 15° 32' 14.8″	E 74° 11' 23.5″	42	Sonal

Table 4.1 continued

Sr. No.	Well. No.	Latitude	Longitude	Ground Elevation (m) amsl	Name of the place
41	76	N 15° 31' 00.0″	E 74° 12' 16.6″	55	Kumthol
42	77	N 15° 30' 23.0″	E 74° 13' 12.8″	85	Caranzol
43	78	N 15° 30' 45.4″	E 74° 10' 52.7	88	Karambali
44	79	N 15° 40' 22.1″	E 74° 10' 24.9″	726	Surla
45	80	N 15° 40' 07.5″	E 74° 10' 25.8″	753	Surla
46	81	N 15° 41' 52.7″	E 74° 13' 16.2″	750	Kankumbi
47	82	N 15° 39' 48.3″	E 74° 12' 39.1″	792	Parvad
48	83	N 15° 39' 47.7″	E 74° 15' 36.6″	803	Chikali
49	84	N 15° 39' 37.7″	E 74° 15' 43.6″	800	Chikali
50	85	N 15° 39' 17.6″	E 74° 20' 12.7″	782	Chapoli
51	86	N 15° 39' 34.4″	E 74° 22' 16.7″	848	Kapoli
52	87	N 15° 39' 33.5″	E 74° 22' 05.4″	839	Kapoli
53	88	N 15° 42' 05.5″	E 74° 13' 13.3	750	Kankumbi
54	89	N 15° 35' 59″	E 74° 25' 55.2″	670	Nerse
55	90	N 15° 35' 50.3″	E 74° 22' 35″	646	Kongle
56	91	N 15° 35' 25.2″	E 74° 19' 58″	745	Gavali
57	92	N 15° 27' 45″	E 74° 03' 22.9″	14	Tadavado
58	93	N 15° 28' 42.5″	E 74° 04' 07.4″	54	Deoulpadi
59	94	N 15° 28' 09.6″	E 74° 04' 22.4″	22	Navarwada
60	95	N 15° 26' 51.8″	E 74° 03' 56.3″	15	Usgao
61	96	N 15° 27' 07″	E 74° 07' 53.9″	20	Vagae
62	97	N 15° 26' 38.6	E 74° 07' 50.8″	62	Poikul
63	98	N 15° 26' 46.5″	E 74° 08' 00.5″	70	Poikul
64	99	N 15° 27' 50.9″	E 74° 09' 03″	46	Myangne
65	100	N 15° 26' 23.6′	E 74° 08' 23.7″	30	Dhodo
66	101	N 15° 27' 12.7″	E 74° 08' 33.2″	37	Shail
67	102	N 15° 26' 03.8	E 74° 09' 17.1″	39	Kumbharvada
68	103	N 15° 25' 02.5″	E 74° 10' 40.3	46	Murgae
69	104	N 15° 26' 57.7″	E 74° 12' 36.3″	90	Tarade
70	105	N 15° 26' 25.4″	E 74° 13' 54.9″	88	Dharge
71	106	N 15° 26' 31.9″	E 74° 14' 48.6″	115	Tambdi Surla
72	107	N 15° 26' 45.7″	E 74° 11' 37.8″	88	Bothar
73	108	N 15° 26' 41.5″	E 74° 10' 37.5″	58	Malpona
74	109	N 15° 28' 33.2″	E 74° 11' 16″	61	Assorde
75	110	N 15° 29' 10.3″	E 74° 11' 01.2″	65	Shirungete
76	111	N 15° 28' 54.6″	E 74° 10' 15.8″	32	Shelpi
77	112	N 15° 28' 55.1″	E 74° 08' 52.6″	23	Khotade
78	113	N 15° 29' 55.3″	E 74° 08' 09′	20	Sanvarshe
79	114	N 15° 29' 40.4″	E 74° 06' 15.5″	20	Advai
80	115	N 15° 30' 03.4″	E 74° 05' 11.4″	38	Shinge
81	116	N 15° 33′ 36.3″	E 74° 11′ 17.9″	143	Hodle Dhave
82	117	N 15° 33′ 43.6″	E 74° 11′ 31.5″	170	Nanoda

Table 4.2 Dimensions of observation wells in Mhadei River watershed

Sr. No.	Well No.	Shape	Dia- meter (m)	Height of me- asuring point (MP)(m)	Total depth below MP (m)	Total depth below ground level(m)	Aquifer material
1	4	Circular	2.70	0.85	8.20	7.35	laterite
2	5	Circular	3.20	0.77	9.40	8.63	laterite
3	6	Circular	3.30	0.60	14.39	13.79	laterite
4	19	Square	3.6x3.6	0.61	8.74	8.13	gneiss
5	28	Circular	3.25	0.92	9.57	8.65	laterite
6	36	Rectangle	2.5x2.4	1.03	6.42	5.39	laterite
7	37	Circular	1.70	0.62	6.62	6.00	laterite
8	38	Circular	3.02	0.86	9.15	8.29	valley fill
9	39	Circular	3.10	1.03	8.53	7.50	phyllite
10	40	Circular	2.78	0.93	7.76	6.83	valley fill
11	41	Circular	4.10	1.04	8.93	7.89	laterite
12	42	Circular	1.90	0.00	5.76	5.76	phyllite
13	43	Circular	1.85	0.85	6.25	5.40	laterite
14	44	Circular	3.30	0.85	9.85	9.00	laterite
15	45	Circular	2.40	0.85	5.40	4.55	valley fill
16	46	Circular	3.00	1.20	7.64	6.44	valley fill
17	47	Circular	5.03	0.00	3.90	3.90	mtgrywck
18	48	Rectangle	1.8x2.0	0.00	6.50	6.50	valley fill
19	49	Circular	3.00	0.87	9.77	8.90	laterite
20	50	Circular	2.35	0.89	6.80	5.91	laterite
21	51	Circular	3.12	0.77	10.40	9.63	laterite
22	53	Circular	3.05	0.90	8.90	8.00	laterite
23	54	Circular	1.78	0.77	4.20	3.43	laterite
24	55	Circular	3.40	0.00	8.04	8.04	laterite
25	56	Circular	3.73	0.68	6.37	5.69	laterite
26	57	Circular	1.75	0.77	8.34	7.57	laterite
27	58	Circular	4.03	1.16	8.74	7.58	laterite
28	59	Circular	2.07	0.78	5.85	5.07	laterite
29	60	Rectangle	4.3x3.0	0.00	1.42	1.42	laterite
30	61	Circular	1.8	0.53	13.50	12.97	laterite
31	62	Circular	1.98	0.83	9.96	9.13	laterite
32	63	Rectangle	6.0x 9.0	0.00	4.40	4.40	laterite
33	66	Circular	Spring	0.00	1.88	1.88	laterite
34	67	Circular	Spring	0.00	2.23	2.23	valley fill
35	68	Circular	Spring	0.00	1.62	1.62	laterite
36	70	Circular	6.10	1.10	7.15	6.05	micaschist
37	71	Circular	3.68	0.75	8.52	7.77	phyllite
38	72	Circular	5.07	0.00	11.02	11.02	laterite
39	73	Rectangle	2.1x2.0	1.40	7.36	5.96	valley fill

Table 4.2 continued

40	74	Circular	2.56	0.78	6.10	5.32	laterite
41	76	Circular	5.50	0.00	3.52	3.52	valley fill
42	77	Circular	2.57	0.71	5.98	5.27	gneiss
43	78	Circular	4.17	0.81	7.22	6.41	gneiss
44	79	Circular	4.80	0.98	8.53	7.55	valley fill
45	80	Circular	4.00	0.84	7.50	6.66	basalt
46	81	Rectangle	1.8x1.4	0.80	15.85	15.05	basalt
47	82	Circular	4.00	0.71	10.46	9.75	basalt
48	83	Rectangle	2.3x1.7	0.38	6.17	5.79	basalt
49	84	Circular	1.48	0.75	4.45	3.70	basalt
50	85	Circular	3.90	1.18	3.75	2.57	basalt
51	86	Circular	1.50	0.63	3.12	2.49	basalt
52	87	Circular	1.85	0.51	2.63	2.12	valley fill
53	88	Square	2.1x2.1	0.49	12.22	11.73	basalt
54	89	Circular	2.94	0.95	3.96	3.01	laterite
55	90	Circular	Spring	Spring	0.00	0.00	laterite
56	91	Circular	1.87	0.00	5.95	5.95	laterite
57	92	Circular	2.55	0.85	4.11	3.26	laterite
58	93	Circular	1.78	0.81	8.14	7.33	laterite
59	94	Circular	2.37	0.74	8.27	7.53	laterite
60	95	Rectangle	4.2x4.1	0.72	7.65	6.93	laterite
61	96	Circular	1.84	0.81	3.24	2.43	laterite
62	97	Circular	2.50	0.78	5.57	4.79	valley fill
63	98	Circular	3.50	0.78	14.69	13.91	phyllite
64	99	Circular	4.50	0.98	8.82	7.84	Chl-schist
65	100	Circular	3.80	0.48	8.20	7.72	valley fill
66	101	Circular	3.18	0.78	12.97	12.19	laterite
67	102	Circular	2.98	0.88	7.21	6.33	laterite
68	103	Circular	2.88	0.73	13.98	13.25	schist
69	104	Circular	2.34	0.71	8.91	8.20	gabbro
70	105	Circular	3.22	0.78	7.38	6.60	valley fill
71	106	Circular	2.42	0.73	9.92	9.19	gneiss
72	107	Circular	2.13	0.71	6.48	5.77	laterite
73	108	Circular	1.88	0.68	4.71	4.03	laterite
74	109	Circular	2.81	0.67	5.20	4.53	valley fill
75	110	Circular	1.98	0.97	6.95	5.98	valley fill
76	111	Circular	4.12	0.00	2.59	2.59	valley fill
77	112	Circular	2.74	0.71	5.31	4.60	phyllite
78	113	Circular	2.54	0.71	12.42	11.71	laterite
79	114	Circular	1.66	0.73	11.41	10.68	laterite
80	115	Circular	3.12	0.77	17.00	16.23	laterite
81	116	Circular	2.25	0.67	8.00	7.33	laterite
82	117	Circular	6.00	0.50	8.50	8.00	laterite

4.3 Aquifers of Mhadei River Watershed

A rock formation, sequence of formations or part of a formation which yields appreciable quantities of groundwater is called an aquifer. The hydraulic properties of the aquifer such as porosity and permeability govern the occurrence and movement of sub-surface water.

Laterite and valley fill deposits are the important aquifers that occur in the Mhadei River watershed. Groundwater predominantly occurs in unconfined condition in these rocks. However, groundwater occurs in semi-confined condition in the fractured and weathered metamorphic rocks at depths.

Laterite occurs as an extensive layer capping the low lying area of the watershed that comprises of the etch-plain and the low elongated hills. However, it is often absent on the higher hills and the denudational hills of the Western Ghats. Generally, the thickness of the laterite is maximum, reaching over 30m, in the western region of the watershed and diminishes progressively towards the Western Ghats in the east. Nevertheless, the thickness varies depending on the type of lithology over which it has developed. The phyllites and schists show maximum lateritisation. The laterite is dominantly made up of ferruginous, aluminous and clayey minerals. It is highly porous with innumerable openings (voids) in the form of pores, cavities/vesicles, sinuous conduits, fissures, joints and/or fractures. Groundwater occurs under phreatic (water table) condition (Fig. 4.2 and Plate 4.2) in the intricate network of these openings. The porous laterite invariably grades downwards into an impermeable layer of lithomarge clay. Groundwater from the laterite aquifer is widely used through dug wells for drinking, domestic and agricultural purposes in the watershed.

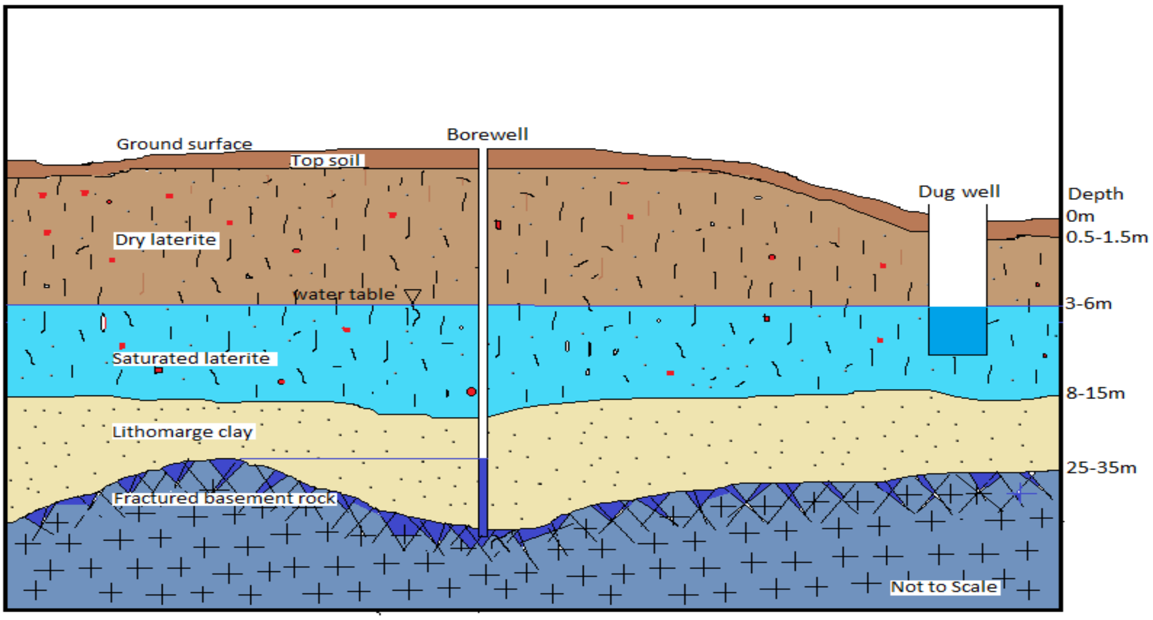


Figure 4.2 A schematic vertical section of an unconfined laterite aquifer and the deeper confined aquifer in the Mhadei River watershed.

The intermountain valley fills consisting of alluvial and colluvial deposits also behave as important groundwater reservoirs. The narrow valleys occurring between the low denudational hills in the watershed are often filled by these gravel mixed silty unconsolidated deposits. These deposits being unconsolidated and superficial have high porosity and thus store groundwater under unconfined condition (Fig. 4.3 and Plate 4.3).

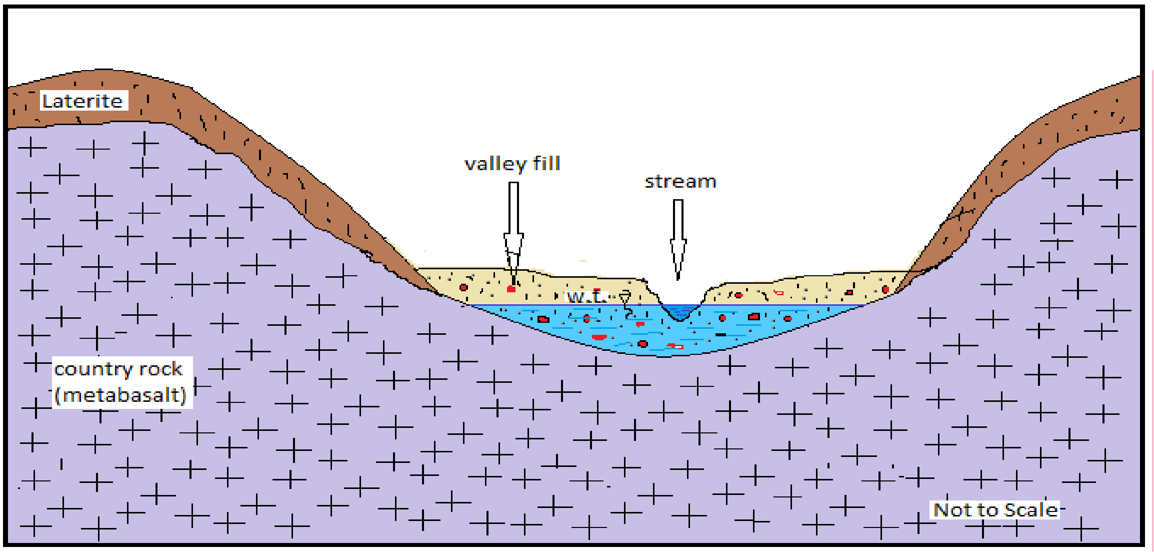


Figure 4.3 A schematic vertical section of unconfined aquifer in intermountain valley fill deposit.

Some wells dug on the hill slopes tap groundwater from the fractured and weathered schistose rocks at depth (Plate 4.4). These aquifers are of semi-confined to confined nature depending on the thickness and nature of the overlying laterite cover and occurrence of the groundwater in fractures.

Weathered basalts occurring on the Karnataka plateau also form an important aquifer in the Mhadei River watershed. The Deccan basalts occupying a large area in the north-eastern region of the watershed consists of massive, vesicular and fractured lava flows. The fractured and vesicular flows are inherently porous in nature (Sarwade, 2004). The top flows that are subjected to tropical weathering are invariably altered to clays or even weakly lateritised. Groundwater occurring in these weathered basalts is under water table condition and is the only source of fresh water for the people living in this region.

Few iron ore deposits occur in the western region of the watershed. The iron ore bodies occur in a typical geological setup composed of complex folds and embedded in clay layers all around. The ore bodies show considerable porosity and are saturated with fresh water (Fig. 4.4). Invariably these confined ore bodies are laterally limited due to numerous altered dykes composed of impervious clays. During mining they are intersected and fresh water is drained out to provide dry working conditions. Sometimes these ore bodies get recharge from percolating rain water through overlying laterites.

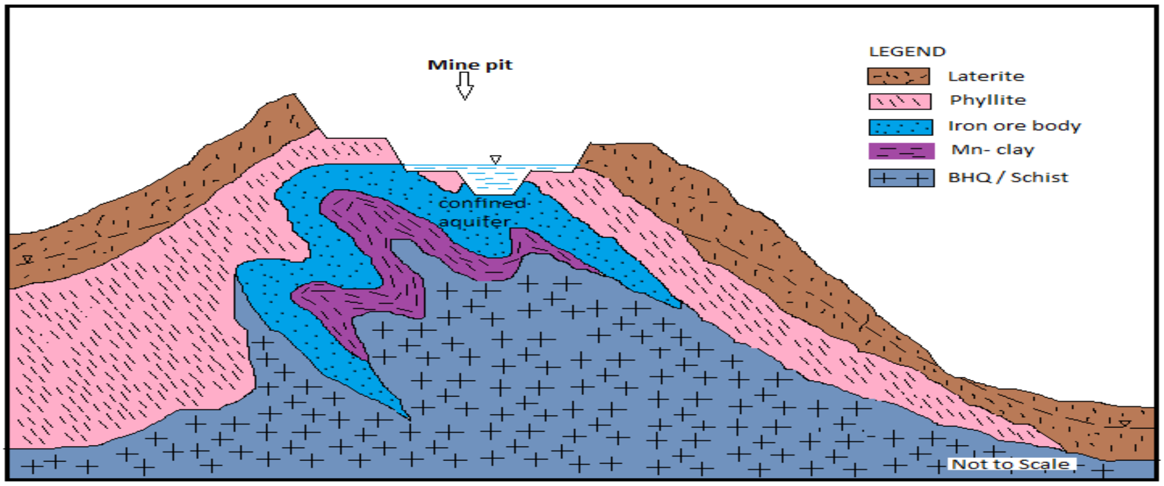


Figure 4.4 A generalised vertical section of a confined aquifer in iron ore deposits

A hydrogeological cross-section (Fig. 4.5) constructed along section line CD (refer Fig. 4.1) drawn along the entire width of the watershed depicts the occurrence of groundwater in the laterite and valley fill aquifers in the Mhadei River watershed.

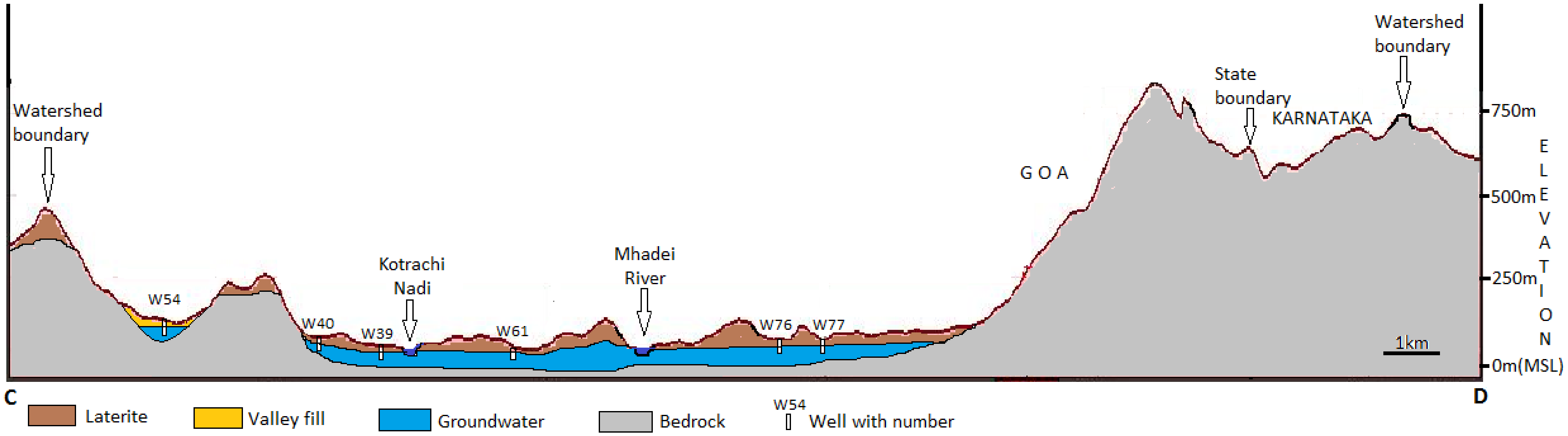


Figure 4.5 Hydrogeological cross-section depicting the occurrence of groundwater in Mhadei River watershed

Plate 4.1 A section of laterite weathering profile developed upon the metamorphic rocks (upper photo) in the Mhadei River watershed and a typical circular dug well in laterite (lower photo). Note the protection wall constructed to avoid caving in of loose laterite.

Plate 4.2 Unconfined lateritic aquifer as seen in the open dug wells in the Mhadei River watershed

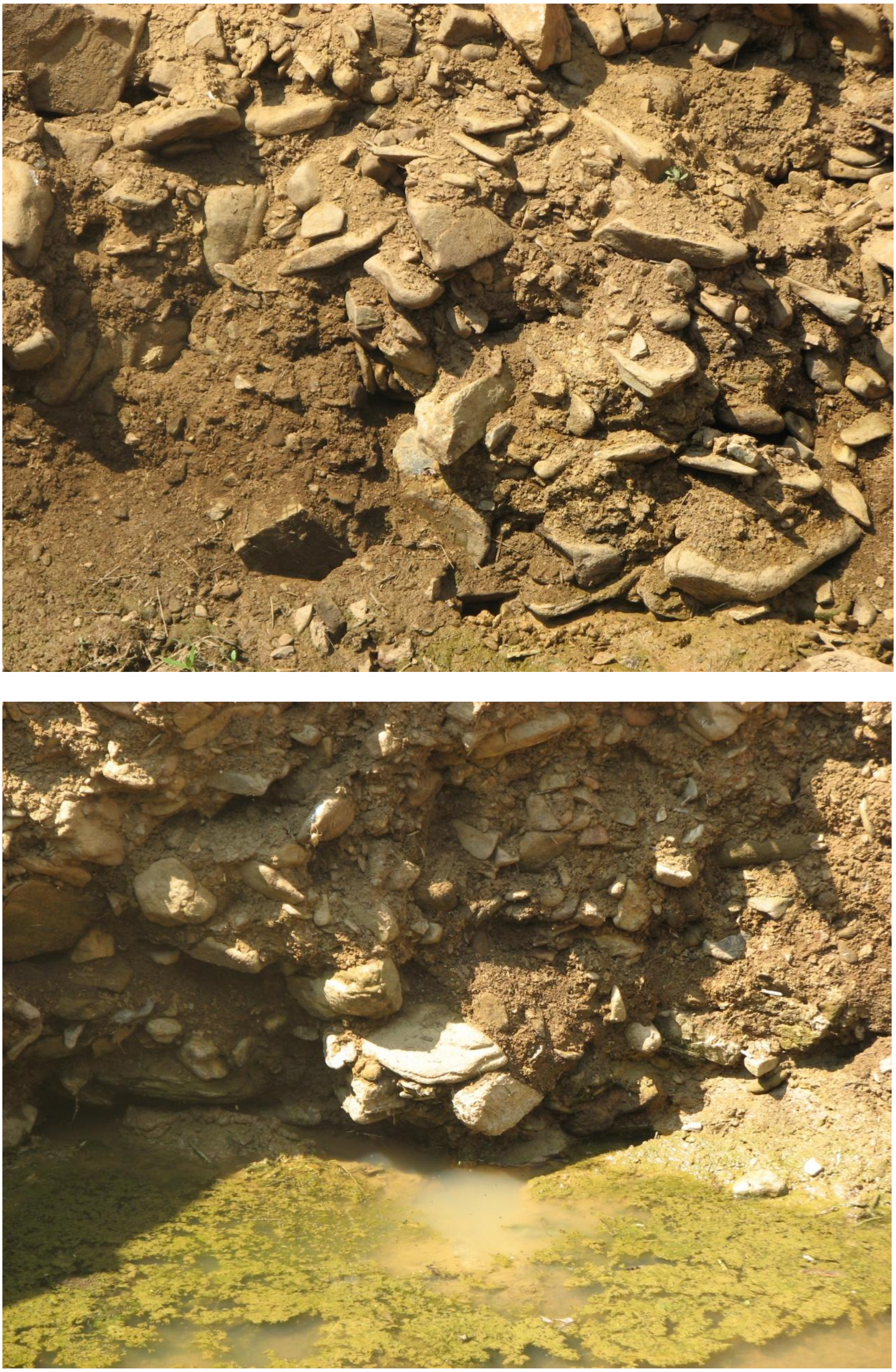


Plate 4.3 Unconsolidated gravel mixed silty material constituting the Valley-fill aquifer in the Mhadei River watershed

Plate 4.4 Photograph showing an open dug well tapping the semi-confined aquifer in the fractured and weathered schistose rocks in the Mhadei River watershed.

4.4 Depth to Static Groundwater Level

The static water level in dug well represents the water table in unconfined aquifer under undisturbed conditions and changes in its level reflect changes in groundwater storage. A rise in static water level represents recharge to groundwater storage while a decline in static water level represents abstraction or discharge of groundwater.

The depth to static groundwater level below ground in Mhadei River watershed was monitored for three consecutive year's viz. 2007, 2008 and 2009 for each season (pre-monsoon, monsoon and post-monsoon) and is given in Table 4.3.

The average depth to static groundwater level has been computed using data of the three years for each season. The dug wells have been classified on the basis of the average depth to static water levels in pre-monsoon (May), monsoon (August) and post-monsoon (November) seasons (Table 4.4).

Table 4.3 Depth to groundwater level below ground (m) in the observation wells monitored for three consecutive years

Sr. No.	Well No.	May 2007	Aug 2007	Nov 2007	May 2008	Aug 2008	Nov 2008	May 2009	Aug 2009	Nov 2009
1	4	7.32	4.51	5.29	6.75	5.09	5.85	6.90	5.25	5.65
2	5	8.33	2.38	5.23	6.83	3.20	5.43	8.05	3.00	5.23
3	6	13.15	7.66	11.58	13.11	10.81	12.05	13.02	11.20	11.50
4	19	7.57	5.27	6.39	7.31	6.39	6.99	6.58	5.92	5.59
5	28	8.18	4.14	7.46	8.12	6.48	7.48	8.08	4.08	7.08
6	36	3.80	0.84	1.77	3.07	1.47	1.86	4.45	1.39	1.81
7	37	4.05	0.63	2.38	3.79	0.82	2.92	5.11	0.80	2.06
8	38	7.82	4.62	7.39	7.59	6.01	7.45	7.92	5.86	7.36
9	39	5.07	0.77	1.60	3.39	1.35	1.65	6.16	1.23	1.51
10	40	4.65	1.22	1.72	3.74	1.45	1.80	6.49	1.30	1.62
11	41	6.72	2.45	3.96	6.00	3.89	4.69	7.48	3.72	4.34
12	42	4.68	1.00	1.57	3.64	1.23	1.77	5.35	1.10	1.30
13	43	3.62	0.15	2.25	4.28	0.75	2.47	4.68	0.30	3.32
14	44	5.65	1.95	5.28	6.21	3.26	5.60	8.16	2.91	6.10
15	45	2.75	0.75	1.05	3.26	0.90	1.54	4.90	1.09	1.15
16	46	4.99	1.38	3.56	4.90	2.04	3.83	6.26	2.70	0.95
17	47	2.70	1.22	1.82	2.97	2.24	2.44	2.60	1.33	2.00
18	48	4.61	1.34	3.27	5.07	3.09	4.05	6.25	2.64	3.80
19	49	8.31	1.53	4.68	8.01	1.92	4.67	8.88	1.51	4.43
20	50	5.71	0.91	3.74	5.00	1.65	3.69	5.96	1.34	3.26
21	51	9.18	5.81	8.17	9.36	7.49	8.74	9.03	6.48	8.33
22	53	7.17	3.07	6.55	7.37	5.59	6.60	7.80	5.47	6.55
23	54	1.52	0.96	0.98	1.52	0.96	0.98	2.38	2.06	0.93
24	55	7.70	1.90	5.57	7.70	1.90	5.57	7.44	3.03	5.20
25	56	3.90	2.02	2.57	3.90	2.02	2.57	4.58	2.02	2.56
26	57	5.60	1.42	3.40	5.60	1.42	3.40	5.85	1.70	3.13
27	58	7.58	1.84	2.78	7.58	1.84	2.78	5.42	2.22	2.69
28	59	2.18	0.11	0.37	1.55	0.11	0.64	1.76	0.12	0.17
29	60	1.32	1.28	1.30	1.69	1.69	1.69	1.74	1.73	1.35
30	61	11.55	7.82	10.45	12.12	9.05	10.56	12.42	8.82	10.27
31	62	8.63	6.31	8.41	8.67	7.80	8.53	8.95	8.17	8.49
32	63	4.07	2.14	3.08	3.99	2.35	3.07	3.88	2.33	3.05
33	66	0.63	0.00	0.50	0.00	0.00	0.00	0.73	0.25	0.60
34	67	1.83	0.00	0.00	1.89	1.22	1.24	1.83	1.00	1.00
35	68	1.40	0.00	0.22	1.34	1.23	1.34	1.40	1.00	1.22
36	70	5.90	1.90	4.51	5.73	3.73	4.40	5.90	1.90	4.51
37	71	6.46	0.39	4.09	7.30	0.62	4.62	7.85	0.58	3.75
38	72	9.13	1.13	5.94	7.93	1.50	6.09	9.02	2.23	5.94
39	73	2.89	2.20	5.03	3.72	4.06	5.27	4.00	3.80	5.18
40	74	3.97	1.62	3.77	4.30	2.27	3.75	4.22	2.20	3.48
41	76	3.10	1.34	2.75	3.01	1.70	2.41	3.38	1.74	2.40

Table 4.3 continued

Sr. No.	Well No.	May 2007	Aug 2007	Nov 2007	May 2008	Aug 2008	Nov 2008	May 2009	Aug 2009	Nov 2009
42	77	3.56	0.72	2.12	3.56	0.85	1.39	5.00	2.19	1.19
43	78	3.80	0.20	0.56	3.16	0.14	0.85	4.99	0.14	0.19
44	79	3.12	1.22	1.94	NA	NA	NA	NA	NA	NA
45	80	3.48	1.18	3.22	NA	NA	NA	NA	NA	NA
46	81	13.05	4.95	10.96	NA	NA	NA	NA	NA	NA
47	82	8.68	2.60	7.71	NA	NA	NA	NA	NA	NA
48	83	4.55	0.77	3.62	NA	NA	NA	NA	NA	NA
49	84	2.66	0.00	1.56	NA	NA	NA	NA	NA	NA
50	85	1.33	0.00	0.82	NA	NA	NA	NA	NA	NA
51	86	1.90	1.04	1.81	NA	NA	NA	NA	NA	NA
52	87	1.19	0.67	1.10	NA	NA	NA	NA	NA	NA
53	88	9.73	5.26	9.54	NA	NA	NA	NA	NA	NA
54	89	0.81	0.00	1.17	NA	NA	NA	NA	NA	NA
55	90	0.00	0.00	0.00	NA	NA	NA	NA	NA	NA
56	91	4.75	2.00	3.00	NA	NA	NA	NA	NA	NA
57	92	2.70	2.72	2.70	2.68	2.67	2.68	2.75	2.72	2.70
58	93	6.07	3.56	5.16	5.15	3.77	5.08	5.99	3.56	5.09
59	94	5.93	3.36	5.75	4.76	3.58	4.51	5.36	3.36	5.36
60	95	6.59	2.36	4.96	6.18	3.71	4.79	5.93	2.36	4.60
61	96	1.87	1.13	1.62	1.78	1.08	1.64	1.79	1.13	1.49
62	97	4.12	0.77	3.71	4.07	0.82	3.82	4.06	0.77	3.77
63	98	12.40	9.23	11.57	11.98	9.16	11.78	12.64	9.23	11.16
64	99	6.90	1.18	3.54	6.46	1.12	3.86	7.25	1.18	2.96
65	100	6.62	3.88	6.59	6.42	3.76	4.87	6.72	3.88	6.52
66	101	11.82	1.35	7.34	9.29	2.23	6.54	11.65	1.35	7.37
67	102	5.67	1.97	4.86	5.54	1.93	1.67	5.72	1.97	4.94
68	103	8.58	3.42	7.28	8.16	3.32	5.87	9.67	3.42	5.04
69	104	6.79	0.61	2.66	6.89	0.97	2.82	6.54	0.61	1.73
70	105	5.90	0.47	3.36	4.69	2.21	3.36	6.55	0.47	2.97
71	106	8.55	3.61	6.50	8.01	2.26	5.59	8.84	3.61	5.97
72	107	5.35	2.42	3.48	5.05	2.55	4.71	5.77	2.42	3.29
73	108	3.08	2.71	2.79	3.08	2.71	2.79	2.82	2.71	2.77
74	109	3.72	1.02	2.33	3.44	1.05	3.25	3.93	1.02	1.13
75	110	4.64	1.29	2.53	4.10	1.17	3.59	5.57	1.29	2.38
76	111	2.42	1.32	2.10	1.83	1.04	1.72	2.42	1.32	2.10
77	112	3.82	1.45	1.47	2.87	1.43	2.49	4.36	1.45	2.96
78	113	9.68	2.41	8.41	8.41	2.76	6.42	7.75	2.41	6.41
79	114	9.36	4.29	9.19	9.36	4.29	9.19	10.31	4.29	9.06
80	115	14.23	1.14	7.65	10.60	1.23	10.21	10.48	1.14	10.09
81	116	6.33	0.53	4.03	4.79	1.36	4.35	5.53	3.43	4.03
82	117	5.01	3.00	4.67	5.01	3.00	4.67	5.01	3.00	4.67

Table 4.4 Classification of dug wells based on average depth to static water levels

Depth to static water level (m) (bgl)	Pre-monsoon		Monsoon		Post-monsoon	
	No. of wells	Percent -age	No. of wells	Percent -age	No. of wells	Percent -age
< 2m	12	15%	45	55%	22	27%
2m to 5m	27	33%	29	35%	33	40%
5m to 10m	37	45%	8	10%	23	28%
>10m	6	7%	0	0%	4	5%

It is observed that 95% of the wells have water at depths within 10 m below ground level while 67% wells have depths within 5 m below ground level indicating shallow occurrence of groundwater in the watershed in the post-monsoon season. Groundwater level reaches within 5 m depth below ground level in almost 90% of the wells during the monsoon season. Contour maps have been prepared showing the average depth to groundwater levels below ground for pre-monsoon, monsoon and post-monsoon season (Fig. 4.6, 4.7 and 4.8 respectively).

The average depth to groundwater level in the pre-monsoon season (May) is 5.53 m. However, deeper groundwater levels of about 8 to 12 m are noticed in around five regions of the watershed namely, Surla-Bolcornem, Poikul-Shail, Advai-Singne, Ambede-Dhave and Kankumbi village. The maximum depth to groundwater level does not exceed 13 m in the watershed.

The average depth to groundwater level in the monsoon season (August) is 2.37 m. Major part of the watershed area shows more than 3 m rise in groundwater levels due to the monsoon recharge as compared to the pre-monsoon levels.

The average depth to groundwater level in the post-monsoon season (November) is 4.10 m. However, deeper groundwater levels of about 8 to 10 m are noticed in the same five regions of the watershed as was noticed in the pre-monsoon season. These regions show considerable fall in the post-monsoon water levels despite good recharge during the monsoon period. This indicates higher drainability of the aquifers in these areas which may be attributed either to the higher hydraulic conductivity (permeability) of the saturated zone or unfavourable topographic setting.

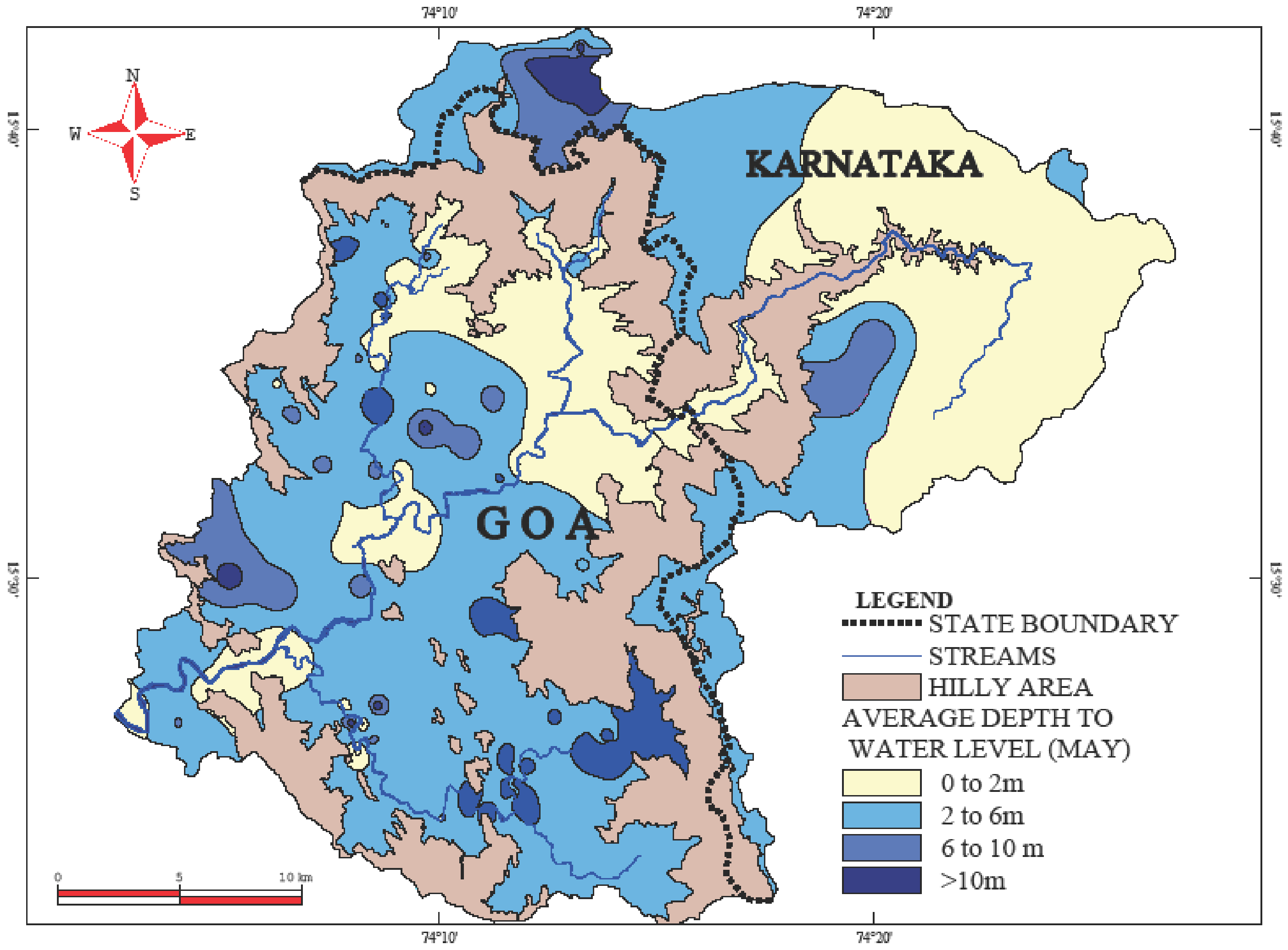


Figure 4.6 Map showing average depth to groundwater level during the pre-monsoon season in the Mhadei River watershed

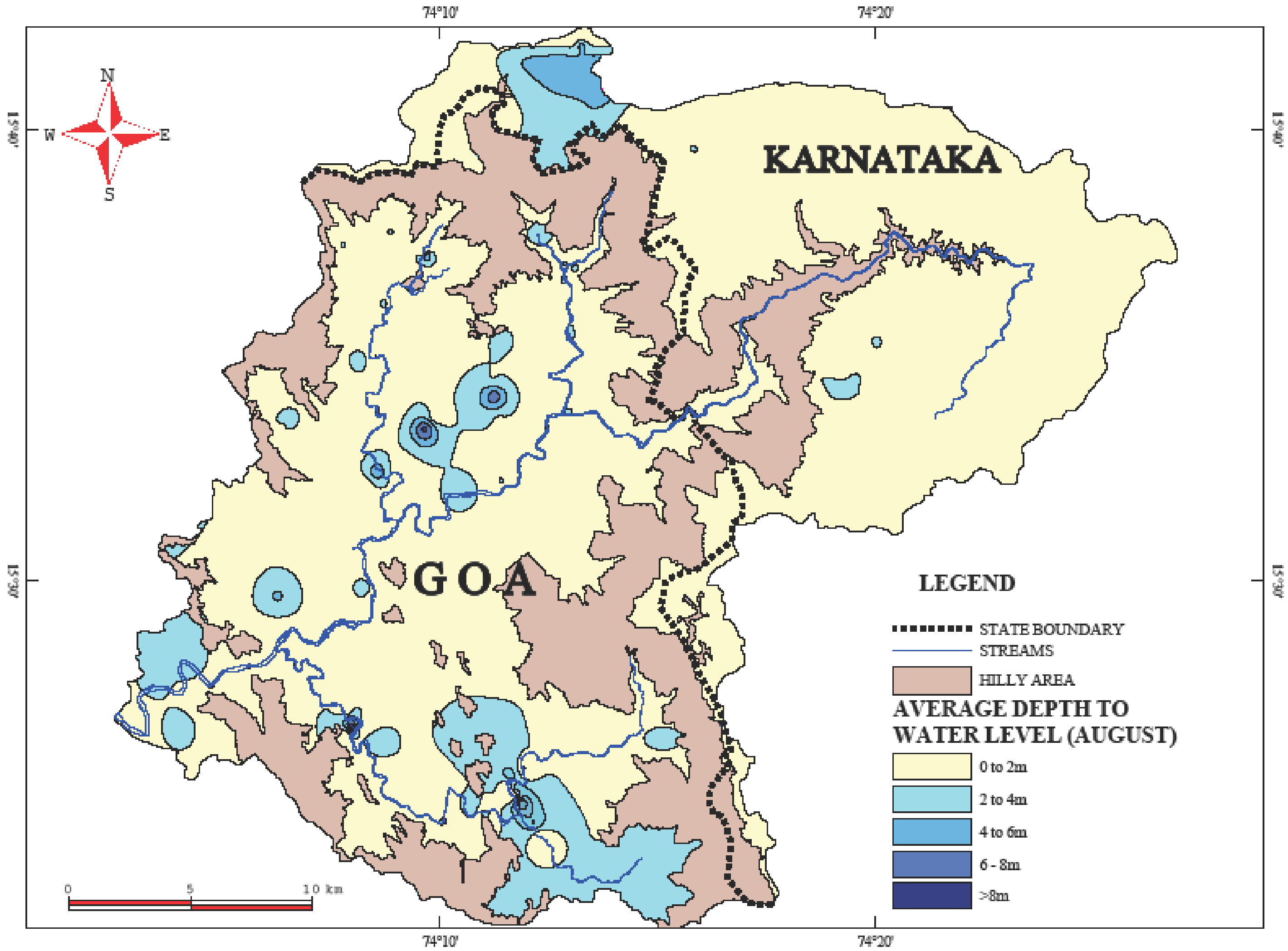


Figure 4.7 Map showing average depth to groundwater level during the monsoon season in the Mhadei River watershed

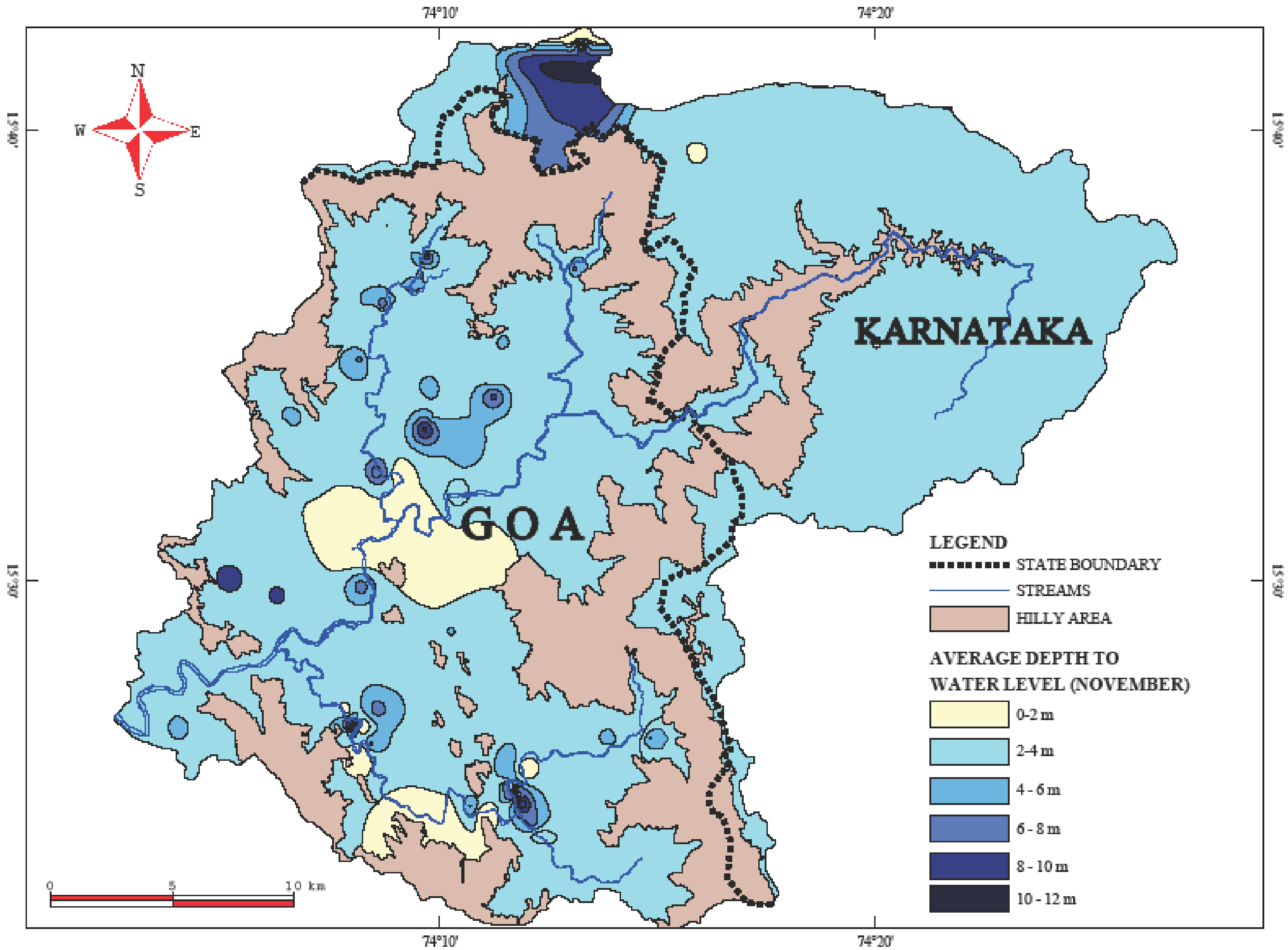


Figure 4.8 Map showing average depth to groundwater level during the post-monsoon season in the Mhadei River watershed

4.5 Water Table Fluctuation

The fluctuations in groundwater levels reflect the cumulative effects of all recharges and discharges. The difference between the pre-monsoon and post-monsoon season groundwater levels have been utilised to compute the water table fluctuation. The data has been summarised in table 4.5 and a map showing average water table fluctuation in Mhadei River watershed is shown in Figure 4.9.

It is observed that about 72% of the wells show water table fluctuations of less than 2 m while the remaining 28% show water table fluctuation of more than 2 m. The average groundwater fluctuation in the 69 wells located in the low lying region of Goa is 1.57 m while that in the 13 wells located in Karnataka region is 0.83 m. The average groundwater fluctuation in the entire Mhadei River watershed is 1.43 m. However, higher groundwater level fluctuation is seen around Koparde- Charavne, Ambede-Dhave, Kumtol-Karanzol, Myangne-Shail and Tarade-Dharge regions and Mauxi village.

Table 4.5 Water table fluctuation (WTF) in observation wells for three consecutive years (m)

Sr. No.	Well No.	WTF 2007	WTF 2008	WTF 2009	Average WTF
1	4	2.03	0.90	1.25	1.39
2	5	3.10	1.40	2.82	2.44
3	6	1.57	1.06	1.52	1.38
4	19	1.18	0.32	0.99	0.83
5	28	0.72	0.64	1.00	0.79
6	36	2.03	1.21	2.64	1.96
7	37	1.67	0.87	3.05	1.86
8	38	0.43	0.14	0.56	0.38
9	39	3.47	1.74	4.65	3.29
10	40	2.93	1.94	4.87	3.25
11	41	2.76	1.31	3.14	2.40
12	42	3.11	1.87	4.05	3.01
13	43	1.37	1.81	1.36	1.51
14	44	0.37	0.61	2.06	1.01
15	45	1.70	1.72	3.75	2.39
16	46	1.43	1.07	5.31	2.60
17	47	0.88	0.53	0.60	0.67
18	48	1.34	1.02	2.45	1.60
19	49	3.63	3.34	4.45	3.81
20	50	1.97	1.31	2.70	1.99
21	51	1.01	0.62	0.70	0.78
22	53	0.62	0.77	1.25	0.88
23	54	0.54	0.54	1.45	0.84
24	55	2.13	2.13	2.24	2.17
25	56	1.33	1.33	2.02	1.56
26	57	2.20	2.20	2.72	2.37
27	58	4.80	4.80	2.73	4.11
28	59	1.81	0.91	1.59	1.44
29	60	0.02	0.00	0.39	0.14
30	61	1.10	1.56	2.15	1.60
31	62	0.22	0.14	0.46	0.27
32	63	0.99	0.92	0.83	0.91
33	66	0.13	0.00	0.13	0.09
34	67	1.83	0.65	0.83	1.10
35	68	1.18	0.00	0.18	0.45
36	70	1.39	1.33	1.39	1.37
37	71	2.37	2.68	4.10	3.05
38	72	3.19	1.84	3.08	2.70
39	73	-2.14	-1.55	-1.18	-1.62
40	74	0.20	0.55	0.74	0.50
41	76	0.35	0.60	0.98	0.64
42	77	1.44	2.17	3.81	2.47

Table 4.5 continued					
Sr. No.	Well No.	WTF 2007	WTF 2008	WTF 2009	Average WTF
43	78	3.24	2.31	4.80	3.45
44	79	1.18	NA	NA	1.18
45	80	0.26	NA	NA	0.26
46	81	2.09	NA	NA	2.09
47	82	0.97	NA	NA	0.97
48	83	0.93	NA	NA	0.93
49	84	1.1	NA	NA	1.1
50	85	0.51	NA	NA	0.51
51	86	0.09	NA	NA	0.09
52	87	0.09	NA	NA	0.09
53	88	0.19	NA	NA	0.19
54	89	-0.36	NA	NA	-0.36
55	90	0	NA	NA	0
56	91	1.75	NA	NA	1.75
57	92	0.00	0.00	0.05	0.02
58	93	0.91	0.07	0.90	0.63
59	94	0.18	0.25	0.00	0.14
60	95	1.63	1.39	1.33	1.45
61	96	0.25	0.14	0.30	0.23
62	97	0.41	0.25	0.29	0.32
63	98	0.83	0.20	1.48	0.84
64	99	3.36	2.60	4.29	3.42
65	100	0.03	1.55	0.20	0.59
66	101	4.48	2.75	4.28	3.84
67	102	0.81	3.87	0.78	1.82
68	103	1.30	2.29	4.63	2.74
69	104	4.13	4.07	4.81	4.34
70	105	2.54	1.33	3.58	2.48
71	106	2.05	2.42	2.87	2.45
72	107	1.87	0.34	2.48	1.56
73	108	0.29	0.29	0.05	0.21
74	109	1.39	0.19	2.80	1.46
75	110	2.11	0.51	3.19	1.94
76	111	0.32	0.11	0.32	0.25
77	112	2.35	0.38	1.40	1.38
78	113	1.27	1.99	1.34	1.53
79	114	0.17	0.17	1.25	0.53
80	115	6.58	0.39	0.39	2.45
81	116	2.30	0.44	1.50	1.41
82	117	0.33	0.34	0.34	0.34

(Note: Negative value indicates higher groundwater level in pre-monsoon season as compared to that in post-monsoon season due to effects of artificial impoundment of water in the vicinity)

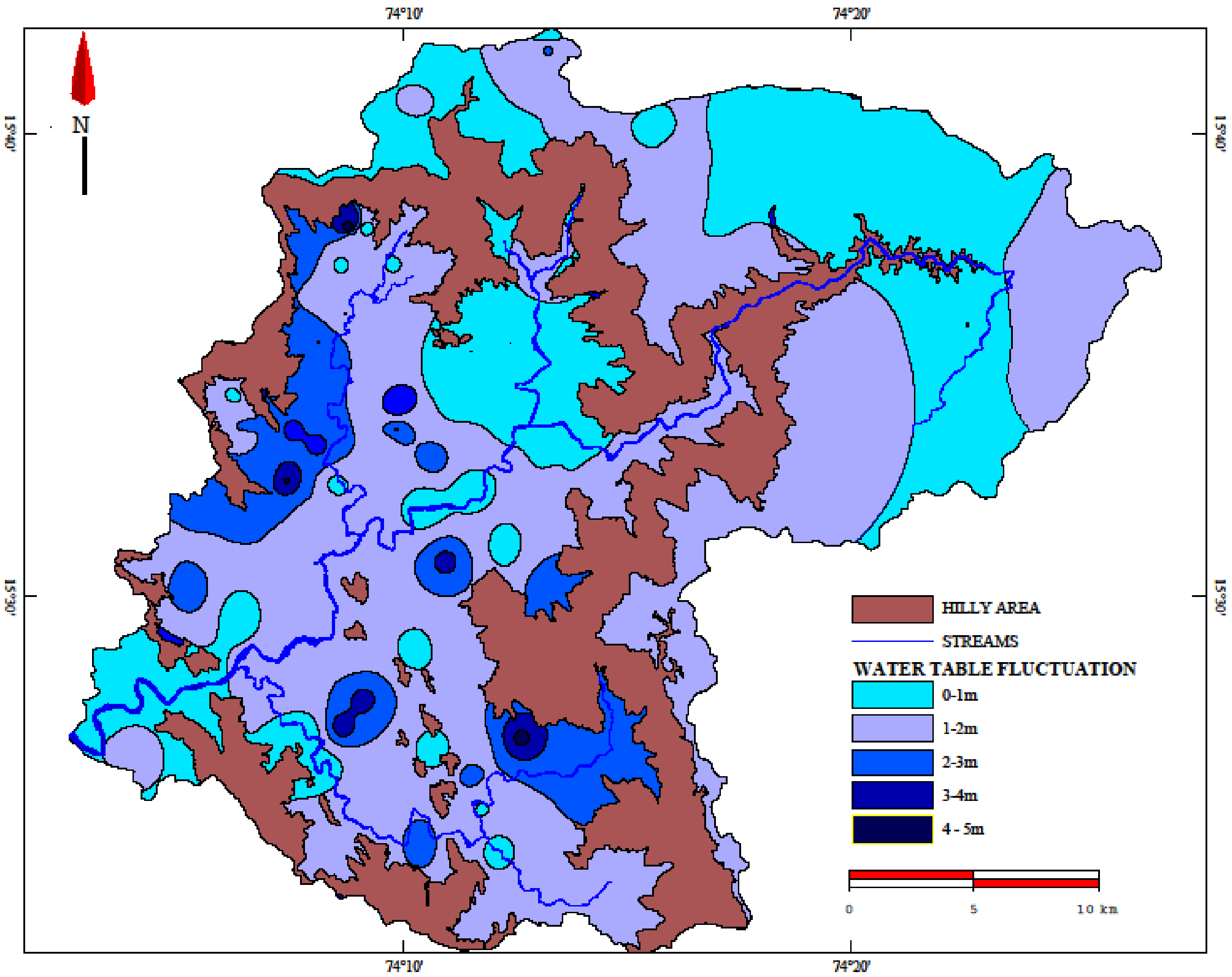


Figure 4.9 Map showing average water table fluctuation in Mhadei River watershed

4.6 Well Hydrograph Analysis

The temporal variation of groundwater levels at a given point plotted as a graph is defined as a well hydrograph. The nature of well hydrograph behaviour is influenced by the magnitude of recharge, geological formations overlying the aquifer, aquifer properties, abstractions, etc. The shape of the rising limb of a hydrograph is governed by hydraulic parameters and hydrogeological conditions of the zone of aeration whereas the recession limb is mainly influenced by hydraulic parameters of the zone of saturation and groundwater withdrawal pattern from it. These graphs when plotted with the corresponding rainfall (Table 4.6) can provide important information about aquifer potential and their sustainability besides depicting anthropogenic impacts on groundwater regime. In the present study, such well hydrographs were prepared for all the observation wells and studied. However, selected hydrographs are given in Figs. 4.10 to 4.15.

Table 4.6 Monthly rainfall received at Valpoi rain-gauging station during the study period (Source: IMD, Panaji)

Month	**2007**	**2008**	**2009**
January	0	0	0
February	0	6.3	0
March	0	123.1	0
April	9.3	0	0
May	160.7	29.4	15.7
June	1051.3	1125.0	610.6
July	1045.1	834.4	1837.8
August	1628.2	1556.2	496.8
September	1116.4	878.2	486.8
October	271.2	31.4	223.6
November	114.6	48.2	167.8
December	0	6.2	0
Annual Total	**5396.8**	**4638.4**	**3839.1**

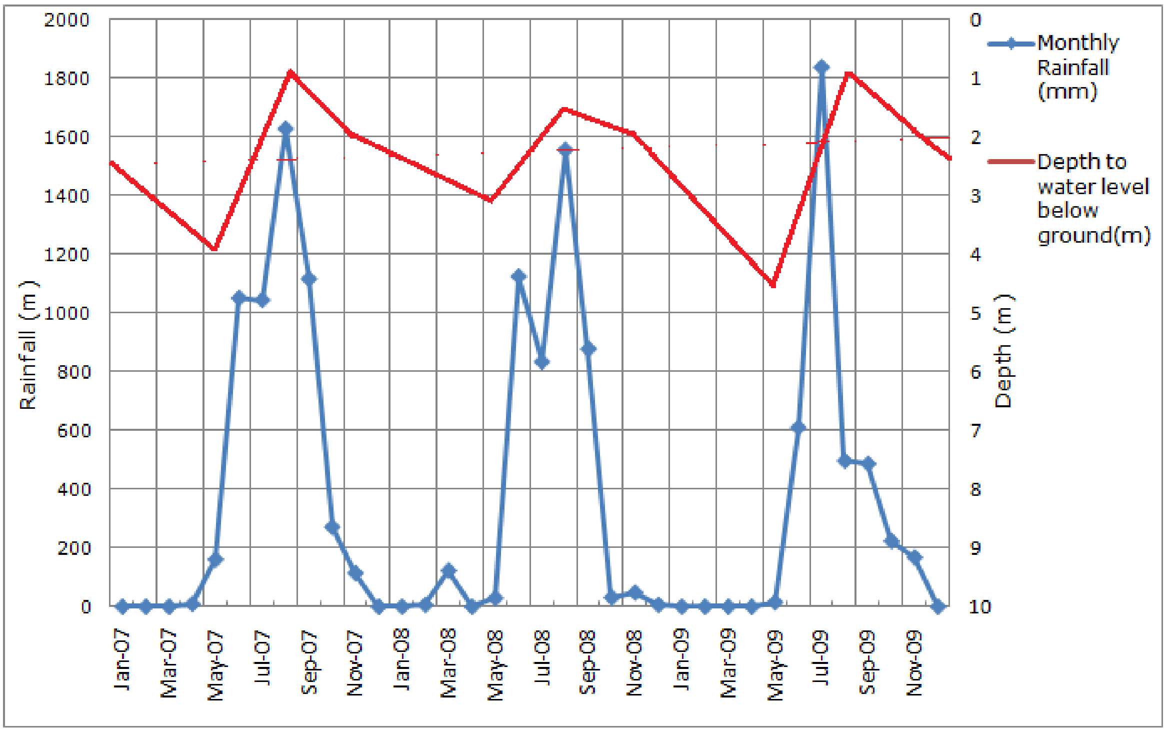


Figure 4.10 Well hydrograph and monthly rainfall for observation well no.36

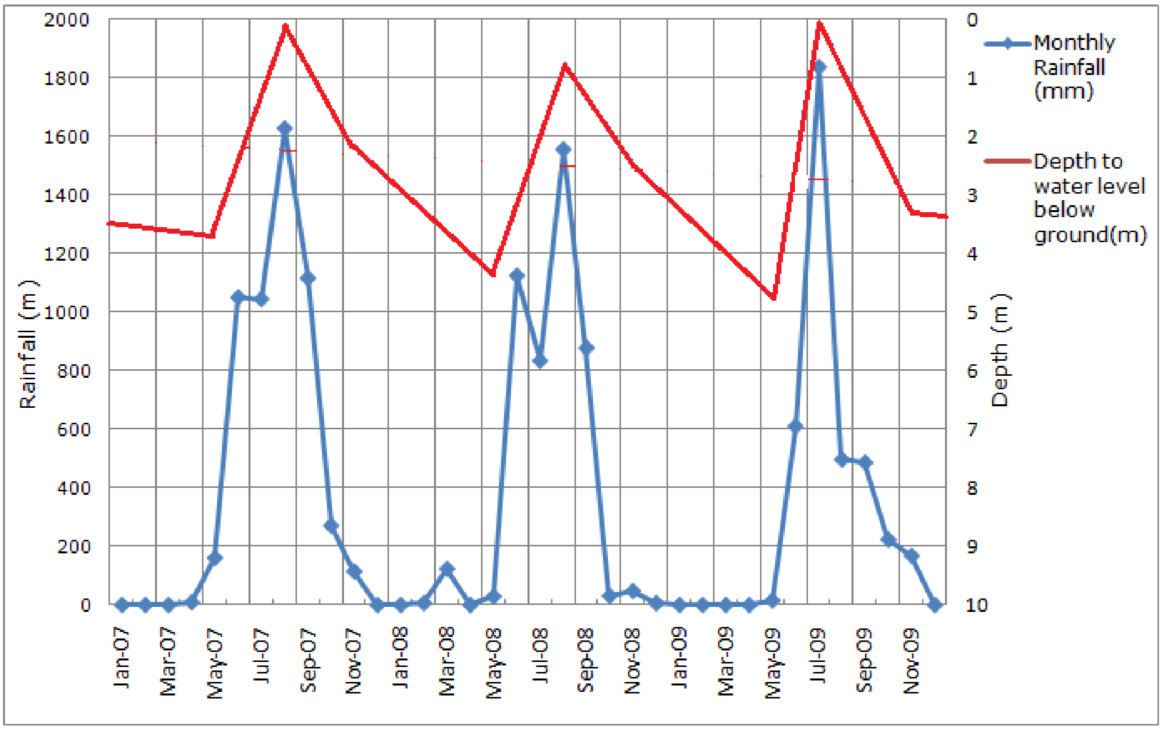


Figure 4.11 Well hydrograph and monthly rainfall for observation well no.43

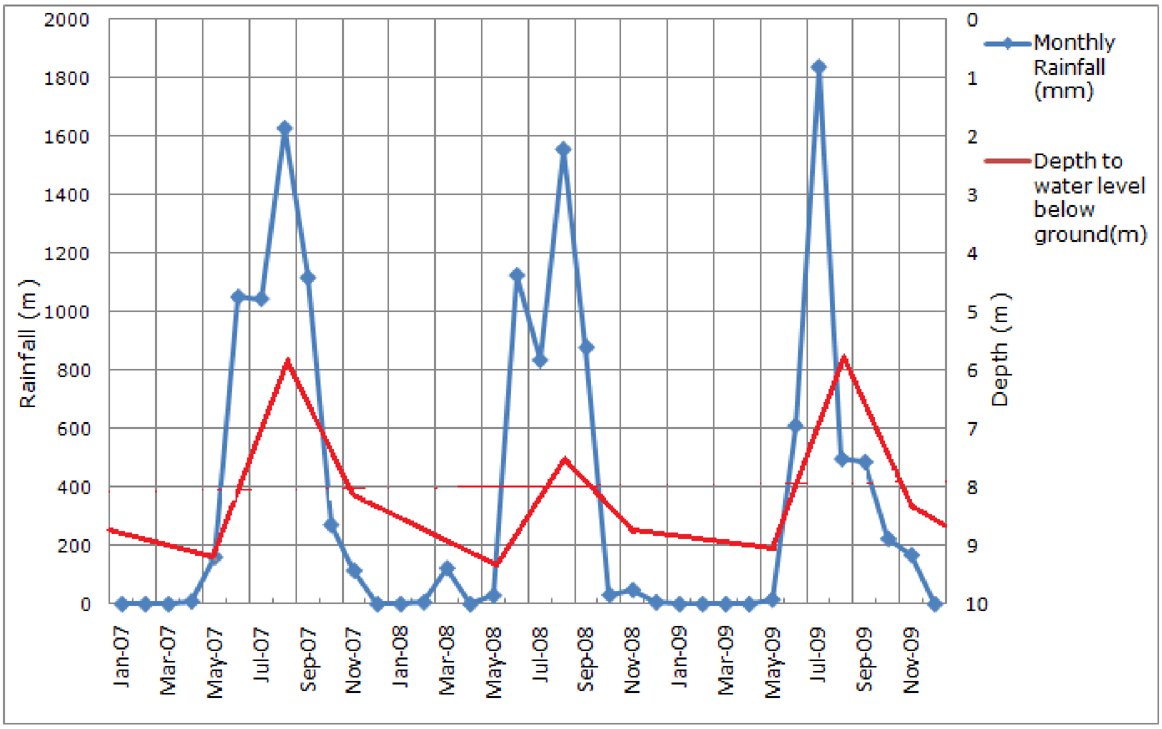


Figure 4.12 Well hydrograph and monthly rainfall for observation well no.51

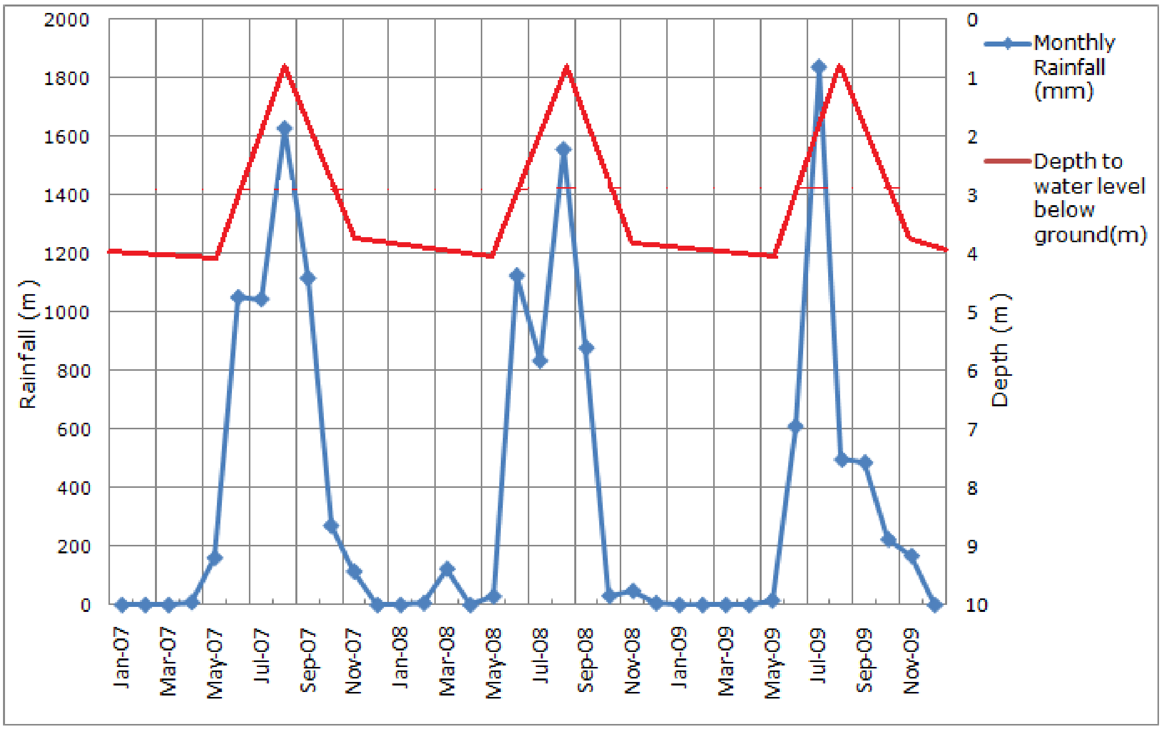


Figure 4.13 Well hydrograph and monthly rainfall for observation well no.97

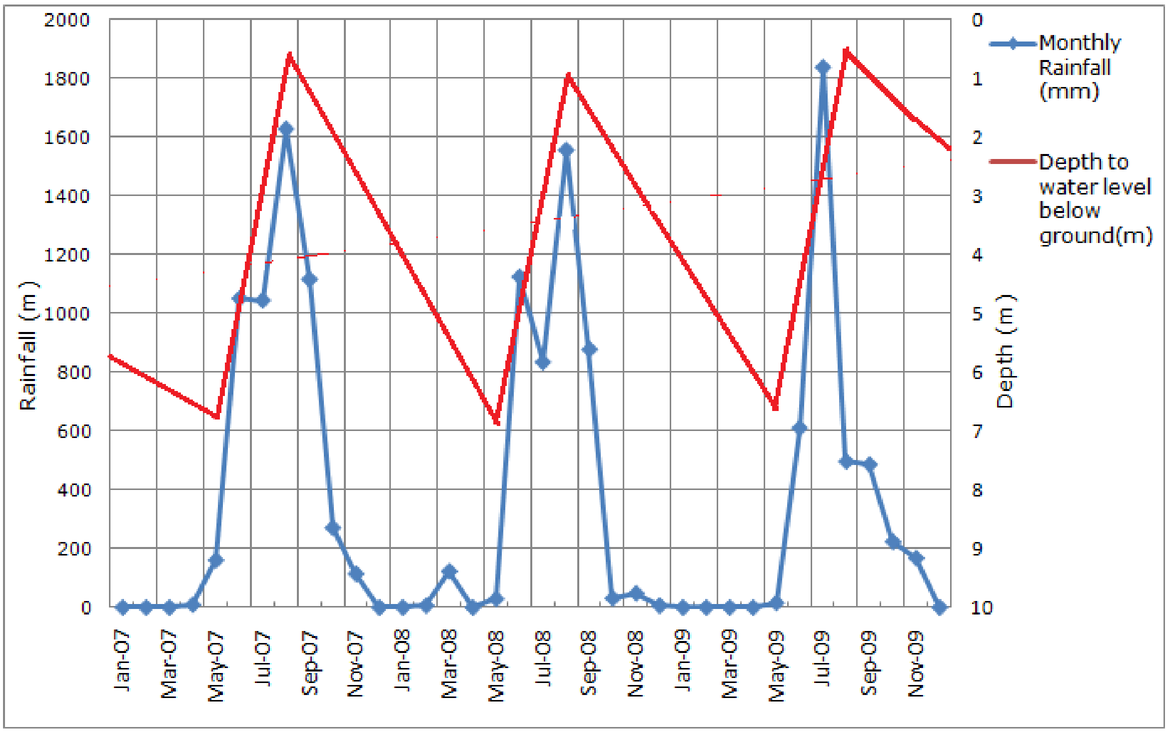


Figure 4.14 Well hydrograph and monthly rainfall for observation well no.104

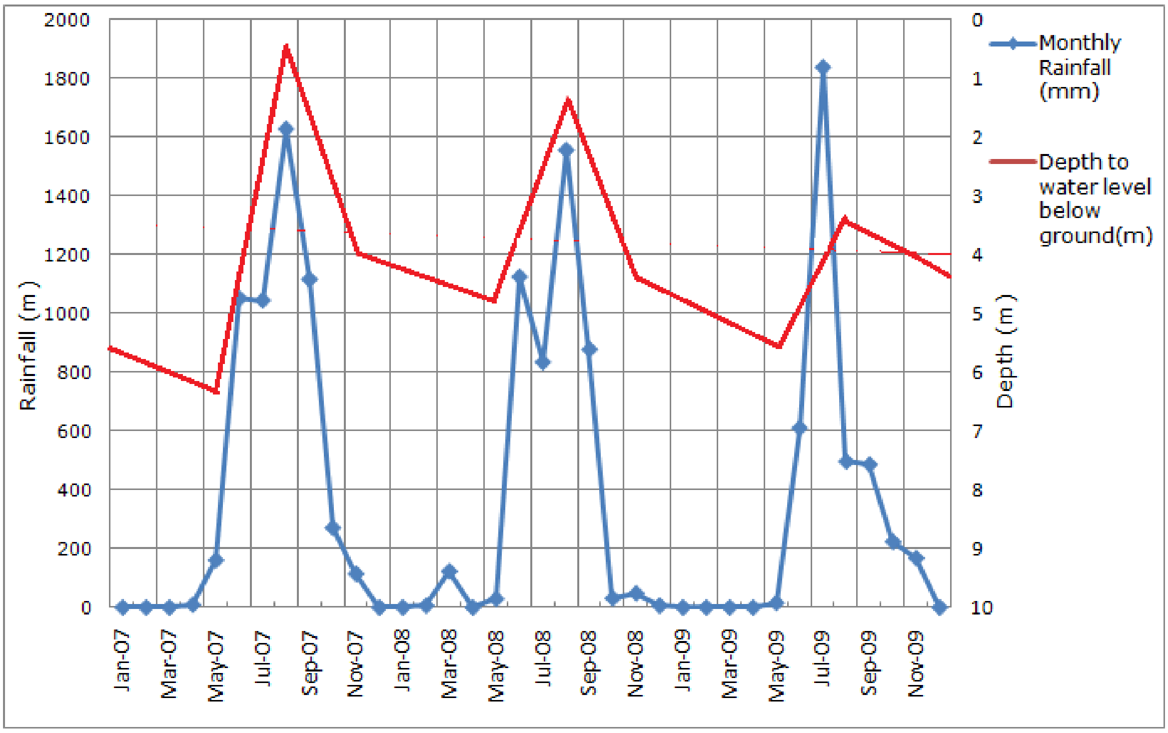


Figure 4.15 Well hydrograph and monthly rainfall for observation well no.116

The well hydrographs indicate that the water levels in the phreatic aquifers respond prominently to rainfall recharge. The steep slope of the rising limb of hydrograph indicate quick recharge to groundwater while the gentle slope of the falling limb of hydrograph indicate slow drainage of the aquifer which is considered good for the groundwater potential of the region.

4.6.1 Water Table Trend

The trend of water table for pre-monsoon and post-monsoon intervals has been computed using the procedure recommended by Groundwater Estimation Methodology Committee (GEC), 1997. The estimation of the trend of water table assumes that the variation of depth to water table below ground level over successive groundwater years is linear. The relation between years (x) and depth (y) is given as,

$y=ax+b$

where 'a' and 'b' are the regression constants

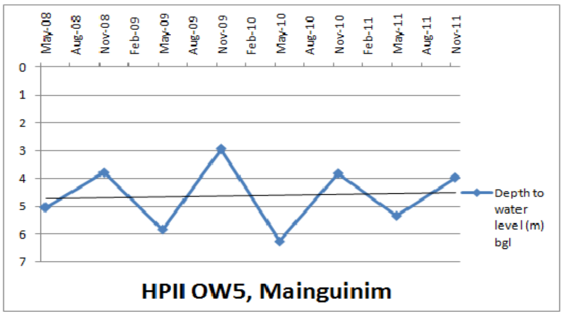
The value of 'a' obtained by linear regression analysis multiplied by 100 gives the trend (Z) of water table in cm/year. The water table shows a falling trend if 'Z' is positive and rising trend if 'Z' is negative. However, it is necessary to adopt a range of values for 'Z' within which the water table can be considered to show a neither rising nor falling trend. The GEM, 1997 has adopted a range from -5cm to +5cm for 'Z'. However, in the present study a range of -25cm to +25cm has been adopted in order to establish definite trends and avoid measurement errors that may occur in field.

The trend of water table during the study period has been established in each observation well located in the western low lying (Goa) region of the watershed for pre-monsoon and post-monsoon seasons. All the wells have been classified into three categories based on their water table trends during pre-monsoon and post-monsoon seasons (Table 4.7).

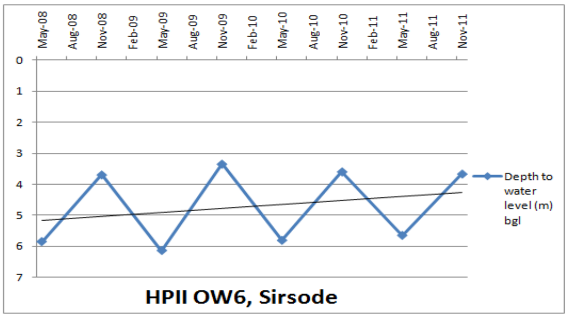
Table 4.7 Classification of wells using trend of hydrographs

Sr. No.	Water table trend	Pre-monsoon		Post-monsoon	
		No. of wells	Percentage of Total	No. of wells	Percentage of Total
1	Rising trend	7	10%	9	13%
2	Falling trend	23	33%	7	10%
3	No trend	39	57%	53	77%

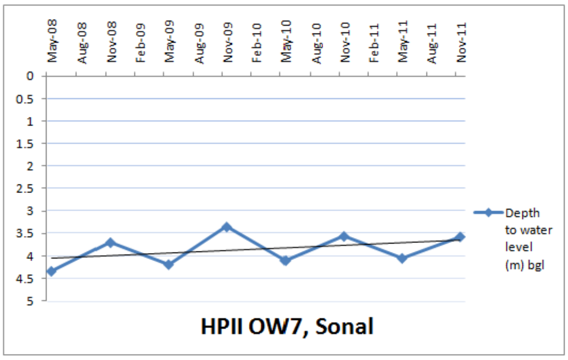
The classification of wells based on trend of water table has been shown in Figs. 4.16 and 4.17 for pre-monsoon and post-monsoon intervals respectively. It is observed that majority of the wells show no trend in water table during the study period though the amount of rainfall received during the period showed a falling trend from 2007 to 2009. Only four wells viz., Well No. 43, 44, 48 and 112 showed a falling trend both during the pre-monsoon and post-monsoon seasons while the remaining 19 wells showing falling trend during the pre-monsoon intervals do not show falling trend in the post-monsoon intervals. The seven wells showing falling trend in post-monsoon intervals could be due to the reduction in the total amount of rainfall from 2007 to 2009 as shown in Table 2.6. Only two wells viz., Well No. 19 and 113 showed rising trend in water table during both pre-monsoon and post-monsoon intervals.



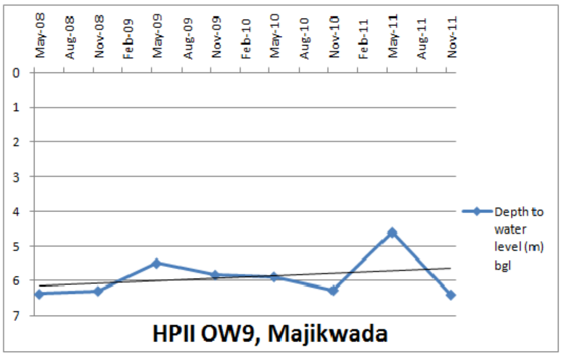
HPII OW5, Mainguinim



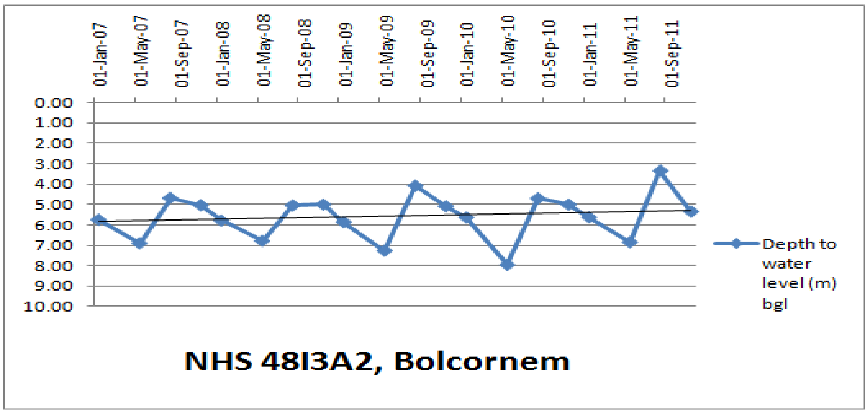
HPII OW6, Sirsode



HPII OW7, Sonal



HPII OW9, Majikwada



NHS 48I3A2, Bolcornem

The long term groundwater level data collected from the National Hydrograph Station (NHS) at Bolcornem and Hydrology Project II (HP II) Observation Wells located in the Mhadei watershed indicate normal to meagrely rising trend of groundwater levels.

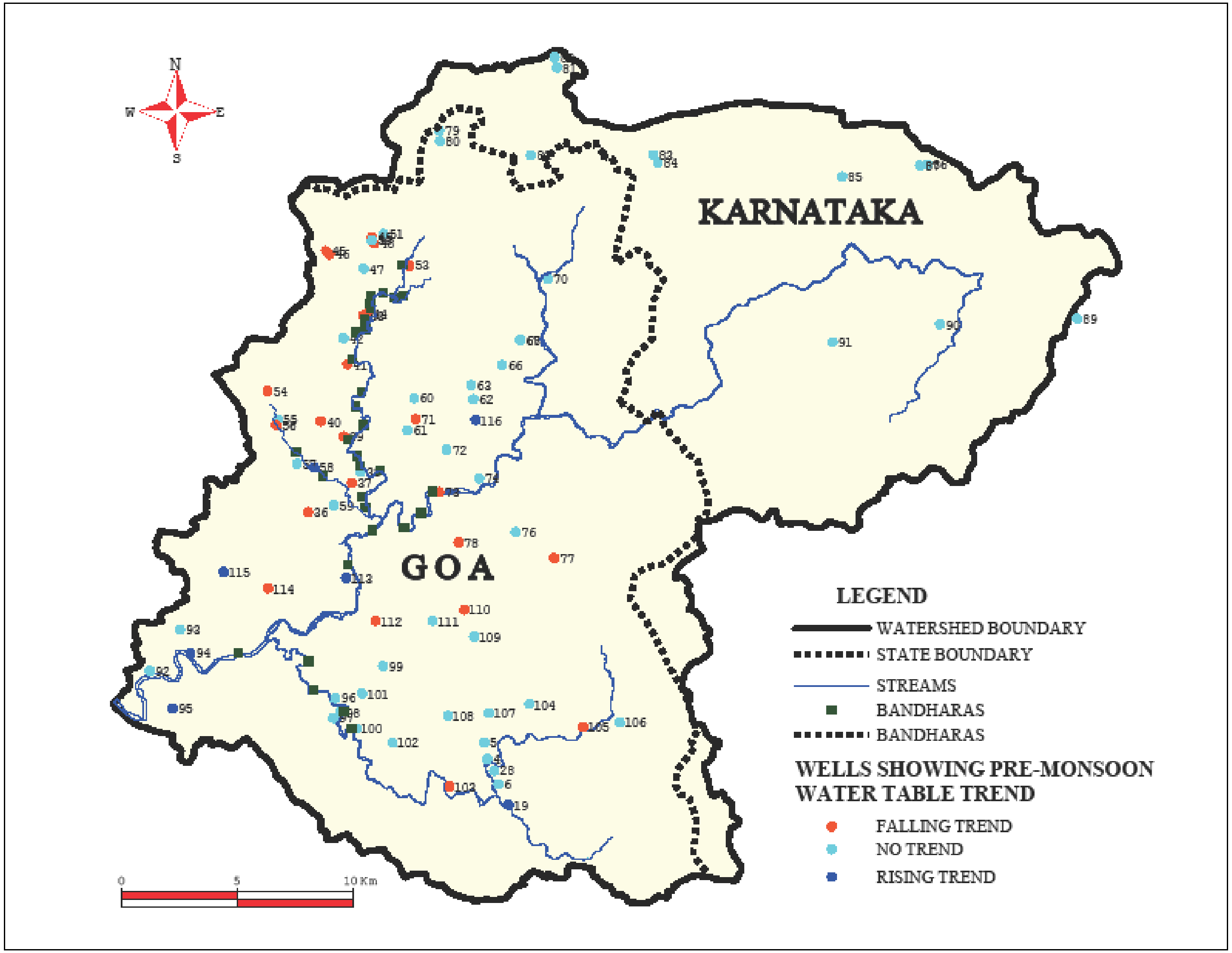


Figure 4.16 Classification of wells based on water table trend during the pre-monsoon intervals

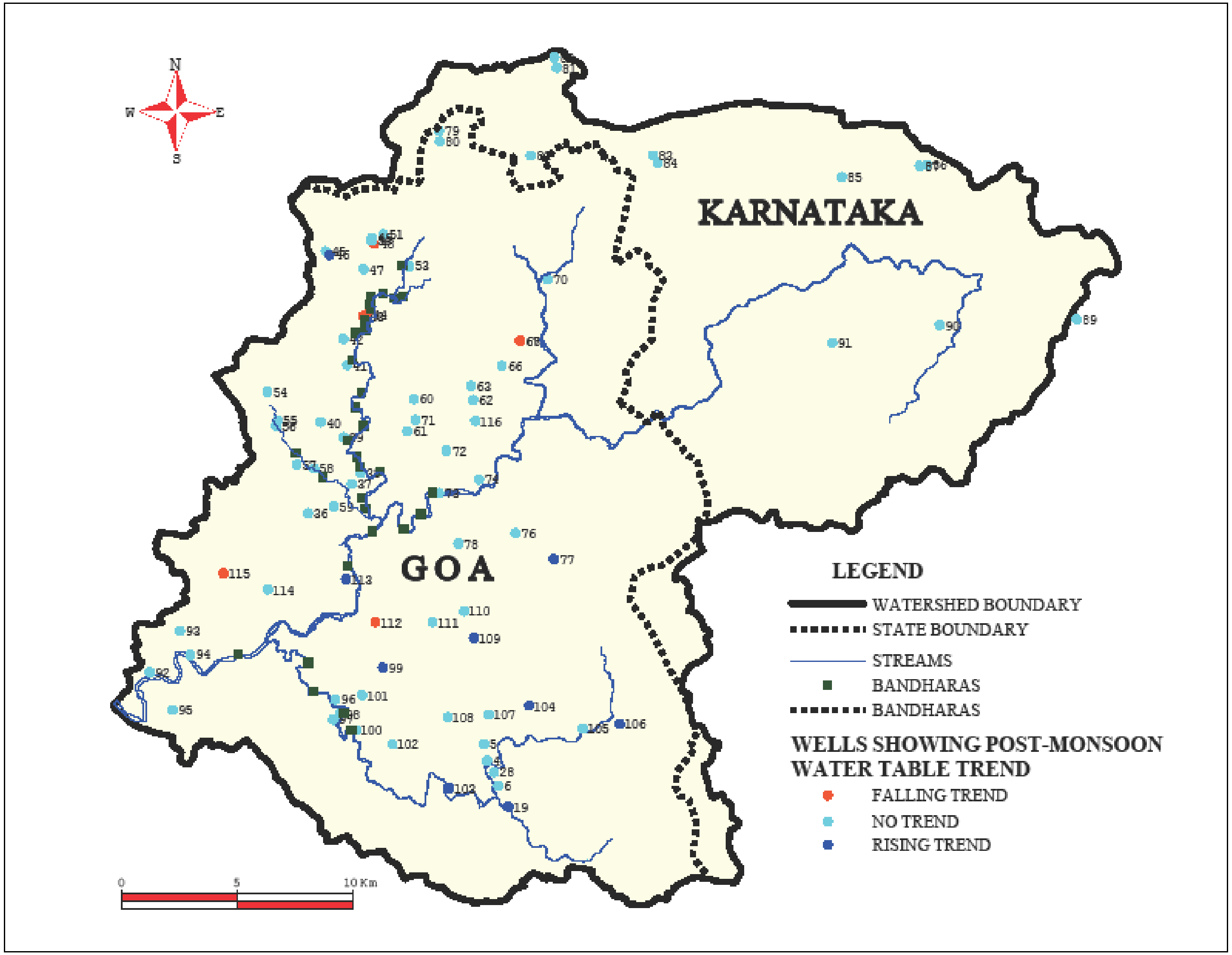


Figure 4.17 Classification of wells based on water table trend during the post-monsoon intervals

4.6.2 Specific Recharge using Well Hydrograph

The well hydrograph is made up of a rising limb during the monsoon season and a receding limb in the post-monsoon season. In the present study area, the groundwater levels reach to their maximum elevation during the month of August then they start falling. This happens despite the continuation of the monsoon rainfall during the subsequent months indicating that the rainfall during post-August is not sufficient to sustain the peak groundwater levels. The ratio of magnitude of water level rise during the monsoon to the corresponding rainfall provides a value of water level rise per unit of rainfall. This value in turn represents the potentiality of rainfall recharge at that point. In the present work, this is referred to as **Specific recharge**. Higher the specific recharge better is the groundwater recharge potential and vice-versa. Based on this concept of the magnitude variation in the specific recharge, the aquifer recharge potential has been categorised into three classes (Table 4.8).

Table 4.8 Classification of the aquifer recharge potential based on specific recharge

Sr. No.	Specific Recharge	Category of aquifer recharge potential	No. of wells	Percentage
1	>1	Good	42	51%
2	1 to 0.5	Moderate	22	27%
3	<0.5	Poor	18	22%

Based on above classification, the monitoring wells in the study area have been classified as shown in Fig. 4.18.

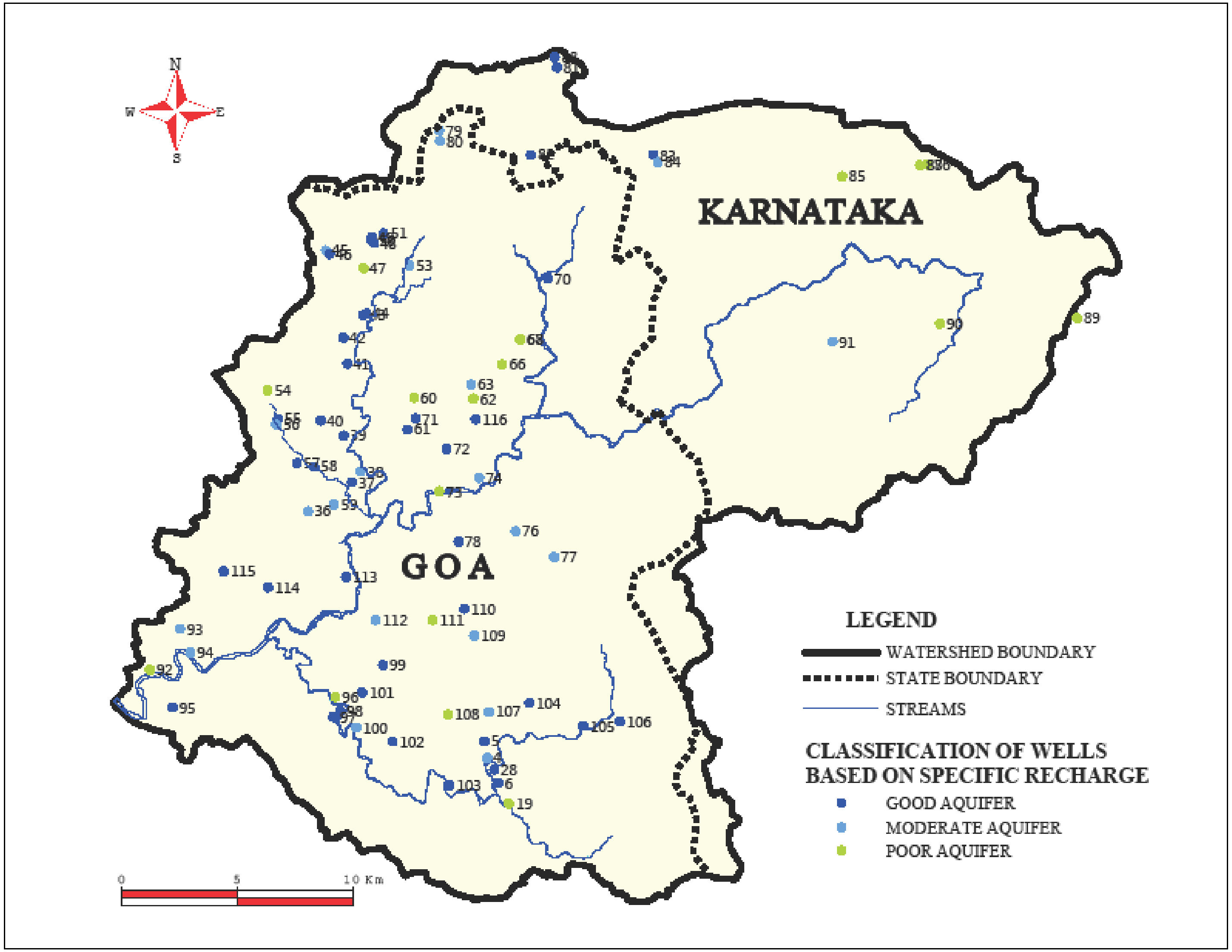


Figure 4.18 Classification of well aquifer recharge potential based on specific recharge

4.6.3 Relative Fall in Well Hydrograph

The magnitude of rate of fall in the groundwater level as depicted in the receding limb is influenced by withdrawals from aquifers and natural outflows besides rainfall recharge. The gradual and exponentially receding limb depicts sustainable availability of groundwater whereas the fast decay in the receding limb indicates the high drainability and poor retention of groundwater. Based on this concept a parameter called '**Relative fall**' in groundwater level has been computed for each of the hydrograph. This is computed as the ratio of magnitude fall in groundwater levels from August to November to magnitude rise in groundwater levels from May to August. Higher values of relative fall indicate poor aquifer potential and vice-versa. The relative fall values calculated for all the hydrographs have been classified into three categories as given in Table 4.9.

Table 4.9 Classification of aquifer potential based on relative fall in groundwater levels

Sr. No.	Relative fall in groundwater level (%)	Category of aquifer	No. of wells	Percentage
1	<50%	Good	29	35%
2	50 to 75%	Moderate	28	34%
3	>75%	Poor	25	31%

Based on above classification, the monitoring wells in the study area have been classified as shown in Figure 4.19.

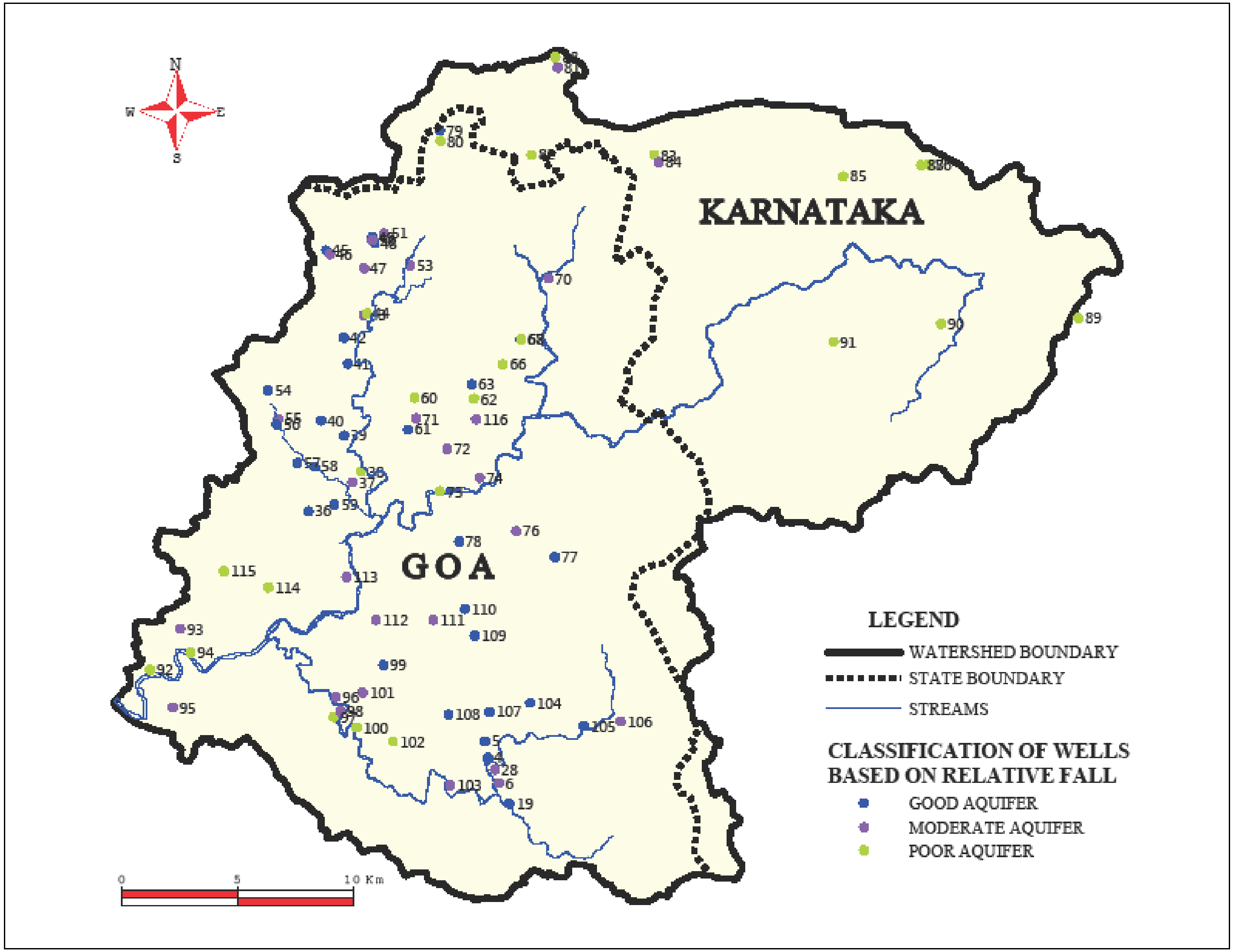


Figure 4.19 Classification of well aquifer potential based on relative fall in groundwater levels

4.7 Groundwater Flow-net Analysis

A flow-net is a sketched representation of the flow paths taken by water molecules through the sub-surface. Groundwater flow-nets covering pre-monsoon, monsoon and post-monsoon seasons have been prepared using elevation of groundwater levels with respect to mean sea level (Table 4.10) to understand the groundwater flow pattern. In the present study, the pre-monsoon, monsoon and post-monsoon water level contours drawn for the study area for the year 2007 are given in Figs. 4.20, 4.21 & 4.22 respectively.

Table 4.10 Elevations of groundwater levels (m) in the observation wells above mean sea level

Sr. No	Well No.	May 2007	Aug 2007	Nov 2007	May 2008	Aug 2008	Nov 2008	May 2009	Aug 2009	Nov 2009
1	4	42.68	45.49	44.71	43.25	44.91	44.15	43.15	44.8	44.00
2	5	61.67	67.62	64.77	63.17	66.8	64.57	61.98	62.7	64.80
3	6	43.85	49.34	45.42	43.88	46.19	44.95	43.98	45.8	45.50
4	19	40.43	42.73	41.61	40.68	41.61	41.01	41.41	42.07	42.40
5	28	49.82	53.86	50.54	49.88	51.52	50.52	49.82	53.86	50.54
6	36	24.20	27.16	26.03	24.93	26.53	26.14	23.55	26.61	26.19
7	37	23.95	27.37	25.62	24.21	27.18	25.08	22.89	27.20	25.94
8	38	18.18	21.38	18.61	18.41	19.99	18.55	18.08	20.14	18.64
9	39	20.93	25.23	24.40	22.61	24.65	24.35	19.84	24.77	24.49
10	40	43.35	46.78	46.28	44.26	46.55	46.20	41.51	46.70	46.38
11	41	45.28	49.55	48.04	46.00	48.11	47.31	44.52	48.28	47.66
12	42	56.32	60.00	59.43	57.36	59.77	59.23	55.65	59.90	59.70
13	43	54.38	57.85	55.75	53.72	57.25	55.53	53.32	57.70	54.68
14	44	49.35	53.05	49.72	48.79	51.74	49.40	46.84	52.09	48.90
15	45	102.2	104.2	103.9	101.7	104.1	103.4	100.1	103.9	103.8
16	46	105.0	108.6	106.4	105.1	107.9	106.1	103.7	107.3	109.0
17	47	76.30	77.78	77.18	76.03	76.76	75.97	77.40	78.67	78.00
18	48	100.3	103.6	101.7	99.93	101.9	100.9	98.75	102.3	101.2
19	49	113.6	120.4	117.3	113.9	120.0	117.3	113.1	120.4	117.5
20	50	112.2	117.0	114.2	113.0	116.3	114.3	112.0	116.6	114.7
21	51	113.8	117.1	114.8	113.6	115.5	114.2	113.9	116.5	114.6
22	53	126.8	130.9	127.4	126.6	128.4	127.4	126.2	128.5	127.5
23	54	118.4	119.0	119.0	118.4	119.0	119.0	117.6	117.9	119.1
24	55	43.30	49.10	45.43	43.30	49.10	45.43	43.56	47.97	45.80
25	56	42.10	43.98	43.43	42.10	43.98	43.43	41.42	43.98	43.44
26	57	40.40	44.58	42.60	40.40	44.58	42.60	40.15	44.30	42.87
27	58	22.42	28.16	27.22	22.42	28.16	27.22	24.58	27.78	27.31
28	59	27.82	29.89	29.63	28.45	29.89	29.36	28.24	29.88	29.83
29	60	48.68	48.72	48.70	48.31	48.31	48.29	48.26	48.27	48.65
30	61	36.45	40.18	37.55	35.88	38.95	37.44	35.58	39.18	37.73
31	62	139.3	141.6	139.5	139.3	140.2	139.4	139.0	139.8	139.5
32	63	119.9	121.8	120.9	120.0	121.6	120.9	120.1	121.7	121.0
33	66	91.37	92.00	91.50	92.00	92.00	92.00	91.27	91.75	91.40
34	67	88.17	90.00	90.00	88.11	88.78	88.76	88.17	90.00	90.00
35	68	81.60	83.00	82.78	81.66	81.77	81.58	81.60	83.00	82.78
36	70	114.1	118.1	115.4	114.2	120.2	115.6	114.1	118.1	115.4
37	71	58.54	64.61	60.91	57.70	64.38	60.38	57.15	64.42	61.25
38	72	107.8	115.8	111.0	109.0	115.5	110.9	107.9	114.8	111.1
39	73	28.11	28.80	25.97	27.28	26.94	25.73	27.00	27.20	25.82
40	74	38.03	40.38	38.23	37.70	39.73	38.25	37.78	39.8	38.52
41	76	51.90	53.66	52.25	51.99	53.30	52.59	51.62	53.26	52.60

Table 4.10 continued

Sr. No	Well No.	May 2007	Aug 2007	Nov 2007	May 2008	Aug 2008	Nov 2008	May 2009	Aug 2009	Nov 2009
42	77	81.44	84.28	82.88	81.44	84.15	83.61	80.00	82.81	83.81
43	78	84.20	87.80	87.44	84.84	87.86	87.15	83.01	87.86	87.81
44	79	722.8	724.7	724.0	NA	NA	NA	NA	NA	NA
45	80	749.5	751.8	749.7	NA	NA	NA	NA	NA	NA
46	81	736.9	745.0	739.0	NA	NA	NA	NA	NA	NA
47	82	783.3	789.4	784.2	NA	NA	NA	NA	NA	NA
48	83	798.4	802.2	799.3	NA	NA	NA	NA	NA	NA
49	84	796.5	800.0	797.6	NA	NA	NA	NA	NA	NA
50	85	780.6	783.1	781.1	NA	NA	NA	NA	NA	NA
51	86	846.1	846.9	846.1	NA	NA	NA	NA	NA	NA
52	87	837.8	838.3	837.9	NA	NA	NA	NA	NA	NA
53	88	740.2	744.7	740.4	NA	NA	NA	NA	NA	NA
54	89	669.1	670.9	668.8	NA	NA	NA	NA	NA	NA
55	90	646.0	646.0	646.0	NA	NA	NA	NA	NA	NA
56	91	740.2	743.0	742.0	NA	NA	NA	NA	NA	NA
57	92	11.30	11.28	11.30	11.32	11.33	11.30	11.25	11.28	11.30
58	93	47.93	50.44	48.84	48.85	50.23	48.92	48.01	50.44	48.91
59	94	16.07	18.64	16.25	17.24	18.42	17.49	16.64	18.64	16.64
60	95	8.41	12.64	10.04	8.82	11.29	10.21	9.07	12.64	10.40
61	96	18.13	18.87	18.38	18.22	18.92	18.36	18.21	18.87	18.51
62	97	57.88	61.23	58.29	57.93	61.18	58.18	57.94	61.23	58.23
63	98	57.60	60.77	58.43	58.02	60.84	58.22	57.36	60.77	58.84
64	99	39.10	44.82	42.46	39.54	44.88	42.14	38.75	44.82	43.04
65	100	23.38	26.12	23.41	23.58	26.24	25.13	23.28	26.12	23.48
66	101	25.18	35.65	29.66	27.71	34.77	30.46	25.35	35.65	29.63
67	102	33.33	37.03	34.14	33.46	37.07	37.33	33.28	37.03	34.06
68	103	37.42	42.58	38.72	37.84	42.68	40.13	36.33	42.58	40.96
69	104	83.21	89.39	87.34	83.11	89.03	87.18	83.46	89.39	88.27
70	105	82.10	87.53	84.64	83.31	85.79	84.64	81.45	87.53	85.03
71	106	106.4	111.3	108.5	106.9	112.7	109.4	106.1	111.4	109.0
72	107	82.65	85.58	84.52	82.95	85.45	83.29	82.23	85.58	84.71
73	108	54.93	55.30	55.22	54.93	55.3	55.22	55.19	55.3	55.24
74	109	57.28	59.98	58.67	57.56	59.95	57.75	57.07	59.98	59.87
75	110	60.36	63.71	62.47	60.90	63.83	61.41	59.43	63.71	62.62
76	111	29.58	30.68	29.90	30.17	30.96	30.28	29.58	30.68	29.90
77	112	19.18	21.55	21.53	20.13	21.57	20.51	18.64	21.55	20.04
78	113	10.32	17.59	11.59	11.59	17.24	13.58	12.25	17.59	13.59
79	114	10.64	15.71	10.81	10.64	15.71	10.81	9.69	15.71	10.94
80	115	23.77	36.86	30.35	27.40	37.54	27.79	27.52	36.86	27.91
81	116	136.6	142.4	138.9	138.2	141.6	138.6	137.4	139.6	139.0
82	117	83.49	85.49	83.82	83.49	85.49	83.82	83.49	85.49	83.82

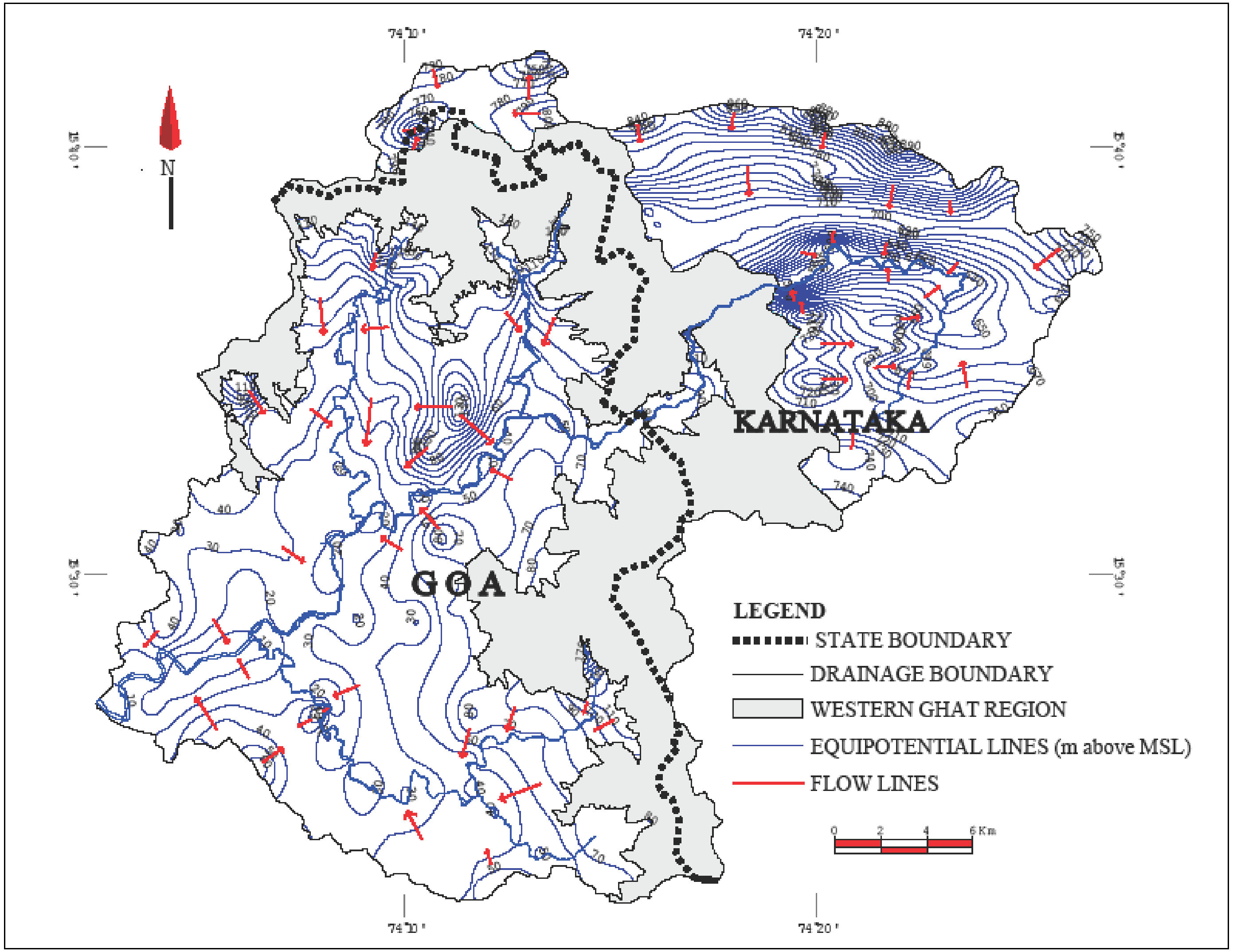


Figure 4.20 Groundwater flow-net in Mhadei River watershed for pre-monsoon 2007

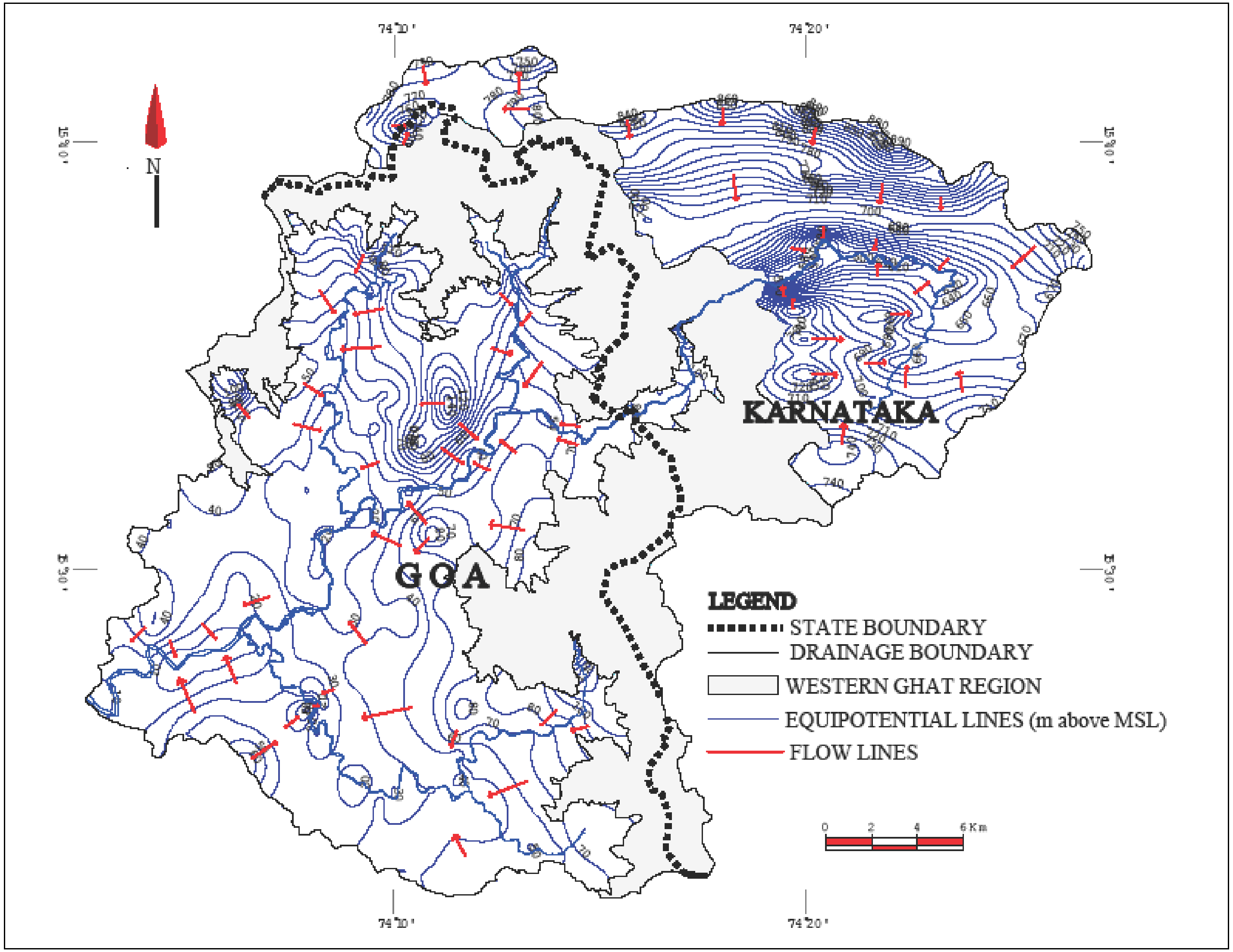


Figure 4.21 Groundwater flow net in Mhadei watershed for monsoon 2007

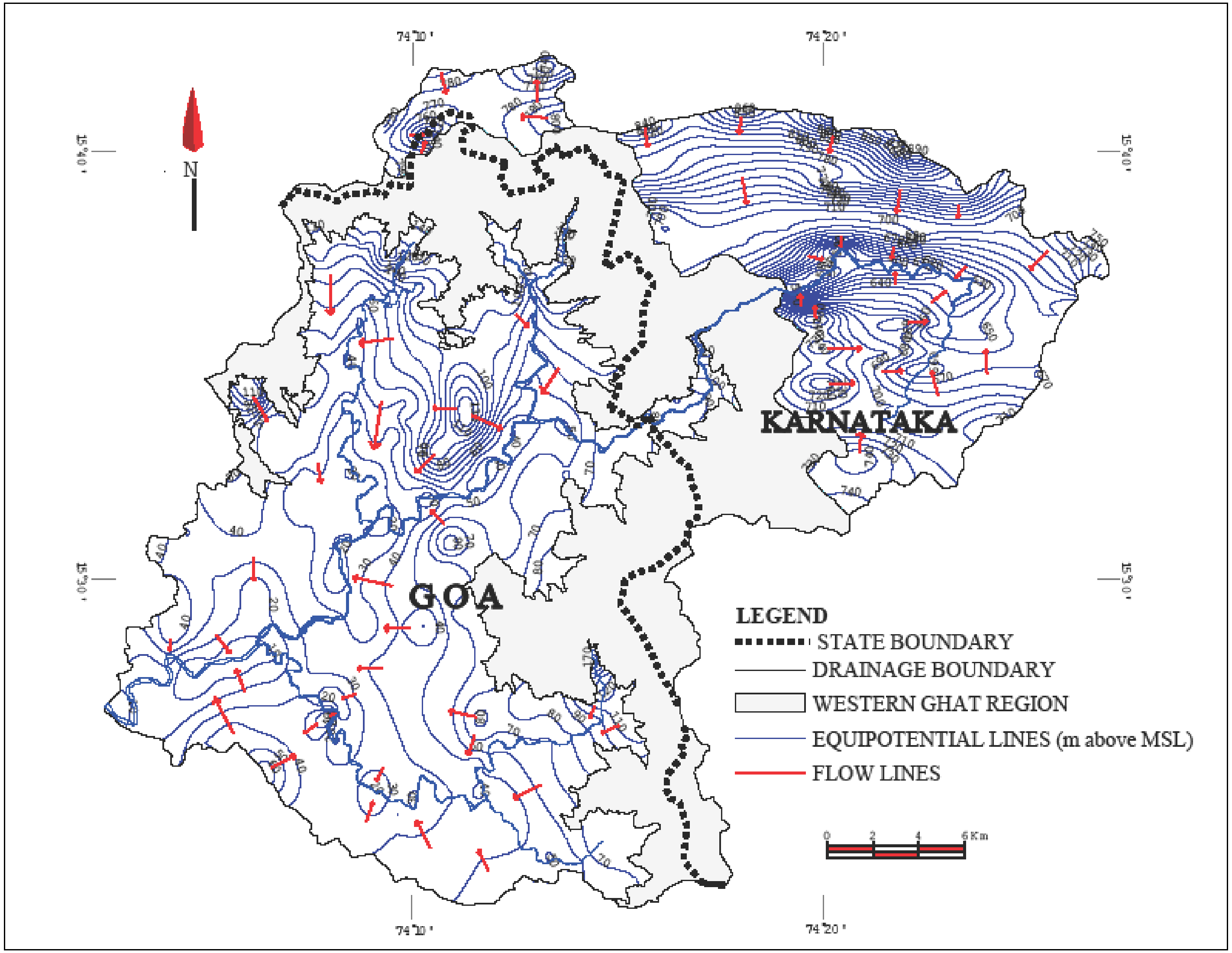


Figure 4.22 Groundwater flow net in Mhadei watershed for post-monsoon 2007

As seen from the above figures, two domains of groundwater occurrence have been identified using the flow nets- one in the western low lying region of the watershed which lies in the midland region of Goa and other in the eastern part of the watershed situated on the western fringe of the Karnataka plateau.

The two domains of groundwater are separated by the steep Western Ghats escarpment. The groundwater domain in the Goa region shows gentle hydraulic gradients indicating slow groundwater flow velocities. The study of the spacing of the equi-potential lines indicates relatively higher hydraulic conductivity of the aquifer. The eastern fringe and the northwestern fringe of the region in Goa form the major recharge areas for this domain. The area around village Dhave shows the presence of a groundwater mound indicating major recharge area. In majority of the locations the groundwater flow lines are directed towards the river reaches indicating effluent nature of the rivers. On the other hand, the ground water domain in Karnataka region, which is situated at higher topographic level has closely spaced equi-potential lines indicating steep hydraulic gradients and higher groundwater velocities. The southern and northern sectors on the plateau region form the major recharge areas for this groundwater domain. The flow of groundwater in this hydrogeological domain is also directed towards the river reaches. The pattern of groundwater flow regime in both the groundwater domains remains unchanged during monsoon and post-monsoon seasons except the magnitude of the mounds and troughs.

4.8 Pumping Test Studies and Analysis

Hydraulic properties of aquifers are very important as they govern the storage and transmitting characteristics of groundwater. The various aquifer properties include porosity, hydraulic conductivity, transmissivity, storativity (specific yield for unconfined aquifer), etc. Transmissivity and specific yield of an unconfined aquifer are the most important properties that control the groundwater flow behaviour and storage potential.

4.8.1 Transmissivity and Specific Yield of Unconfined Aquifers

Transmissivity (T) of an aquifer is the rate at which water is transmitted through its unit width under a unit hydraulic gradient. It is also called the coefficient of transmissivity. For an unconfined aquifer the transmissivity is not as well defined due to changing saturated thickness of the unconfined aquifer. However, transmissivity of an unconfined aquifer can be expressed with the help of expression T=Kb where 'K' is the hydraulic conductivity and 'b' representing the saturated thickness of the aquifer or the height of the water table above the top of the lower aquitard boundary. The transmissivity will vary both spatially and temporally if there are large seasonal fluctuations in the elevation of the water table or if the saturated thickness of the aquifer shows lateral variation.

The specific yield (Sy) of an unconfined aquifer is that volume of water that an unconfined aquifer releases from storage from unit surface area of aquifer per unit decline in the water table and is approximately equivalent to effective porosity of soil or rock. Specific yield is a dimensionless term.

4.8.2 Estimation of Aquifer Parameters

Estimation of aquifer parameters from large diameter dug wells in lateritic aquifer conditions has always been a matter of approximation. These parameters are determined by conducting pumping tests of wells located at various geomorphological locations. Pumping tests involves abstraction of water from a well at a controlled rate and observing the water level changes in the pumped well and/or in one or more observation wells with respect to time. Various analytical and numerical methods have been developed to analyse pumping test data by many researchers to estimate the aquifer parameters (Papadopulos and Cooper, 1967; Kumarswamy, 1973; Lai and Su, 1974; Zdankus, 1974; Boulton and Streltsova, 1976; Herbert and Kitching, 1981; Rushton and Holt, 1981; Rushton and Singh, 1983; Patel and Mishra, 1983; Mishra and Chachadi, 1985; Chachadi and Mishra, 1989; Singh and Gupta, 1986 etc). The assumptions, applicability and limitations of these methods for large diameter dug wells have been discussed by Kruseman and de Ridder (2000), Mishra and Chachadi (1984) and Naik and Awasthi (2007).

In the present study, short duration pumping tests were conducted on ten open dug wells to compute the aquifer parameters: Transmissivity

(T) and Specific yield (Sy). Type curve methods developed by Papadopulos and Cooper (1967) and Mishra and Chachadi (1985) have been used for analysis of the pumping test data. The details regarding the well locations, dimensions and pumping data are given in Tables 4.11 to 4.21.

Table 4.11 Details of the pumping tests conducted in the Mhadei River watershed

Sr. No.	Well No.	Well location	Well depth (m)	Well dia-meter (m)	Static water level (mbgl)	Discharge rate (m^3/day)	Pumping duration (min)	Draw-down (m)	Duration of observed recovery (min)	Reco-very (m)	Percent recovery
1	36	Valpoi	5.39	2.76	3.35	50.74	124	1.02	1426	0.98	95
2	42	Pali	5.76	1.50	4.33	45.60	110	1.09	110	1.09	100
3	47	HBudruk	3.61	3.50	2.86	245.00	27	0.75	470	0.68	90
4	48	HBudruk	6.50	2.06	4.09	49.95	127	0.79	225	0.15	19
5	95	Usgao	6.93	4.62	5.27	20.31	58	0.058	265	0.042	72
6	97	Paikul	4.79	2.44	4.08	13.32	58	0.064	260	0.036	56
7	99	Myangne	7.84	4.12	6.27	399.60	20	0.25	207	0.086	34
8	5	Bolcorne	9.40	3.16	7.59	25.00	15	0.052	185	0.014	27
9	103	Sancorde	8.50	3.32	4.09	136.00	40	0.13	40	0.105	81
10	107	Bothar	6.62	2.60	4.42	58.00	60	0.146	540	0.124	85

Table 4.12 Pumping test data at Well no. 36

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0.00	0	125.47	102.6
1.18	1.6	128.02	101.8
2.23	2.2	131.06	101.4
3.59	4.2	135.06	101.2
5.06	5.5	140.13	100.8
6.44	7.4	145.29	100.6
8.05	8.8	152.33	100.0
10.05	10.6	160.36	99.8
12.08	12.6	169.34	99.6
13.42	14.2	179.35	99.1
15.00	15.3	194.03	97.6
20.02	20.2	214.04	96.1
25.04	25.0	239.04	94.6
30.00	29.6	269.11	93.0
35.03	34.2	304.18	91.6
40.08	38.8	344.19	90.0
45.08	43.0	389.18	88.8
49.57	47.1	437.24	87.4
55.18	51.6	440.31	85.8
60.00	55.6	554.36	84.8
65.04	59.8	624.36	82.2
70.10	63.8	704.03	79.8
75.12	67.6	794.09	77.2
80.08	71.6	894.55	75.0
85.05	75.2	1005.19	73.2
90.06	78.8	1125.27	71.0
95.02	82.2	1940.35	12.0
100.02	85.8	3366.03	4.8
105.09	89.4		
110.03	92.8		
115.13	96.4		
119.59	99.6		
124.47 (pumping stopped)	102.6		

Table 4.13 Pumping test data at Well No. 42

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0	0	111.60	108.9
1.02	1.4	114.80	104.2
2.10	3.0	119.80	102.6
3.08	4.2	130.27	96.6
4.18	6.0	145.34	90.8
5.10	7.1	164.38	87.2
6.15	8.6	189.45	79.6
7.25	10.2	219.25	75.2
8.12	11.1	254.35	69.2
10.02	13.6	294.00	63.8
12.57	17.2	339.20	57.7
15.12	20.0	389.20	53.2
20.04	25.9	444.15	48.0
25.15	32.0	503.30	43.4
29.14	36.6	568.28	37.8
34.44	42.6	638.28	33.0
39.52	48.4	712.47	28.2
45.14	53.6	792.06	23.7
50.41	58.9	876.57	19.4
55.07	62.6	966.16	15.2
60.00	67.0	1061.40	10.8
65.57	72.6	1161.40	6.2
70.03	76.2	1266.45	3.6
75.34	80.6	1376.52	0.1
80.12	84.6		
85.07	88.8		
90.05	91.9		
95.24	96.2		
100.01	99.9		
104.41	103.4		
110.30 (Pumping stopped)	109.4		

Table 4.14 Pumping test data at Well No. 47

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0.00	0.0	28.34	67.8
1.00	2.2	30.48	67.0
2.10	5.0	33.62	66.4
2.59	6.4	37.68	66.1
4.04	8.6	42.96	66.0
5.06	10.8	53.07	64.4
6.02	13.0	68.17	62.2
8.20	17.8	88.32	60.0
10.10	22.6	113.37	59.0
12.07	28.2	143.50	57.2
14.10	32.2	183.58	54.8
16.06	36.4	233.61	51.2
18.40	42.6	293.61	49.0
20.01	46.8	363.67	47.0
22.03	52.1	445.83	44.2
24.12	58.8	535.39	42.8
26.04	66.2	635.40	41.0
27.14 (pumping stopped)	75.0	745.54	39.0
		865.59	37.4
		995.70	35.4
		1136.78	34.2
		1286.86	32.4
		1446.86	31.0
		1616.86	29.2
		1797.06	28.0
		1987.06	26.6
		2187.06	25.2
		2477.06	16.0
		2777.06	15.4
		3087.06	14.6
		3407.06	13.8
		3737.06	13.4
		4077.06	12.8
		4427.06	12.0
		4788.06	11.4
		5188.06	10.0
		5658.06	7.4

Table 4.15 Pumping test data at Well No. 48

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0.00	0.0	128.34	79.4
2.10	1.8	131.35	79.4
3.03	2.4	136.40	79.2
4.33	3.8	143.49	79.2
5.01	4.4	152.64	79.0
6.04	5.0	163.66	79.0
6.30	5.4	176.66	78.8
7.03	6.0	191.86	78.6
8.06	7.2	212.11	78.2
9.12	9.4	237.26	78.0
10.03	10.6	267.27	77.7
11.02	11.6	302.56	77.3
12.18	12.4	342.69	77.0
15.39	14.2	387.84	76.5
20.03	16.0	437.94	76.0
25.06	20.0	492.94	75.5
30.08	23.6	553.03	75.0
38.34	28.0	628.03	74.0
39.47	31.0	733.03	72.0
45.08	35.6	868.03	70.2
51.19	39.4	1033.03	68.0
55.10	42.0	1218.03	67.0
60.00	45.4	1423.03	65.8
65.05	49.0	1648.03	64.4
70.00	52.0		
75.08	54.8		
80.05	57.6		
85.40	60.4		
90.04	62.5		
95.07	65.0		
100.06	67.2		
111.10	72.4		
120.19	76.2		
127.07 (pumping stopped)	79.4		

Table 4.16 Pumping test data at Well No. 95

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0.00	0.0	58.20	5.8
1.06	1.2	63.54	5.6
2.10	1.4	73.54	5.4
3.03	1.6	88.57	5.4
4.09	1.8	108.63	5.2
5.05	2.0	133.84	5.0
6.07	2.2	163.93	5.0
7.30	2.4	204.03	5.0
8.10	2.4	259.11	4.6
9.27	2.4	329.21	4.4
14.25	2.6	414.41	4.2
19.90	2.8	529.51	3.6
25.06	3.2	674.72	3.2
30.22	3.6	849.81	2.8
34.44	4.0	1054.96	2.4
40.11	4.2	1280.17	2.0
45.20	5.0	1545.28	1.6
49.53	5.2		
55.12	5.6		
58.20 (pumping stopped)	5.8		

Table 4.17 Pumping test data at Well No. 97

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0.00	0.0	58.56	6.5
1.12	0.3	63.56	6.5
2.14	0.5	73.63	6.3
3.03	0.5	88.73	6.3
4.03	0.7	108.83	6.1
5.07	0.9	138.87	5.9
6.07	0.9	178.87	5.7
7.00	1.1	228.87	5.5
8.02	1.1	288.9	5.3
9.00	1.3	358.91	5.1
10.04	1.3	438.93	4.9
15.00	2.1	529.02	4.7
20.00	2.5	629.02	4.5
24.55	2.9	749.02	4.1
30.10	3.7	889.06	3.9
35.10	4.1	1049.06	3.7
39.48	4.7	1229.16	3.5
45.04	5.1	1429.26	3.3
49.51	5.7	1649.31	3.1
55.00	6.3	1889.31	2.9
58.56 (pumping stopped)	6.5	2149.31	2.9

Table 4.18 Pumping test data at Well No. 99

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0.00	0.0	25.18	25.0
2.20	1.2	35.31	24.6
3.03	2.8	50.38	24.2
3.57	3.8	70.46	24.0
5.04	5.2	100.5	23.4
5.52	6.4	140.04	23.0
6.50	7.8	190.07	22.2
8.00	9.8	250.13	22.0
8.53	10.4	320.14	21.6
9.55	11.8	400.42	21.2
14.55	18.4	495.75	20.8
20.10 (pumping stopped)	25.2	625.11	19.4
		780.15	18.4
		964.19	17.6
		1171.58	16.6

Table 4.19 Pumping test data at Well No. 5

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
1	10	20	49
2	15	25	46
2.5	18	30	44
3	20	35	43
4	26	40	42
5	30	50	41
6	34	60	40
7	38	70	39
8	42	80	38.5
9	47	90	38.5
10	50	100	38
12	52	150	38
15 (pumping stopped)	52	200	38

Table 4.20 Pumping test data at Well No. 103

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
0.5	1	42.52	12
2.48	2	43.27	11
4.42	3	44.09	10
6.28	4	46.24	9
7.08	4	48.58	8
9.09	5	51.31	7
11.32	6	55.4.0	6
13.39	7	59.47	5
16.44	8	64.41	4
18.38	9	67.00	3.5
19.40	9	76.48	3
22.30	10	80.51	2.5
24.43	11		
25.22	12		
28.02	13		
40.04 (p.s.)	13		

Table 4.21 Pumping test data at Well No. 107

Time (min)	Drawdown (cm)	Time (min)	Recovery (cm)
1	20	61	137
3	30	63	137
5	40	65	120
10	60	70	112
15	70	75	100
20	80	80	95
25	90	85	80
30	100	90	70
35	110	95	62
40	121	100	60
45	130	120	51
50	140	150	42.5
55	146	200	36
60 (pumping stopped)	146	210	35
		250	31
		300	29
		600	21.5

4.8.3 Papadopulos- Cooper Method (1967)

This method is an extension of non-equilibrium formula developed by Theis (1935) for a pumped well of an infinitesimal diameter with a negligible storage inside the well at beginning of pumping or afterwards. The method presented by Papadopulos and Cooper (1967) analyses the pumping test data from wells of large diameter, taking into account the storage capacity of the well itself. The assumptions are:

(1) The aquifer under test has an infinite areal extent.

(2) The aquifer is homogenous, isotropic and of uniform thickness over the area influenced by the pumping tests.

(3) Prior to pumping the piezometric surface or phreatic surface is (nearly) horizontal over the area influenced by the pumping tests.

(4) The aquifer is pumped at a constant discharge rate.

(5) The pumped well penetrates the entire aquifer and thus receives water from the entire thickness of the aquifer by horizontal flow.

(6) The well diameter cannot be considered very small. Hence storage in the well cannot be neglected.

(7) The aquifer is confined.

(8) Flow to the well is in unsteady state.

(9) The well losses are negligible, i.e., the entrance resistance in the well is zero.

The general flow equation describing the drawdown 's_w' in the vicinity of a large diameter well is given by

$$s_w = \frac{Q}{4\pi T} F(u_w, \beta) \quad \text{------ (1)}$$

where, Q is the discharge rate (m^3/day), T is the transmissivity (m^2/day), s_w is the drawdown (m) at the pumped well and F (u_w, β) is a well function for which numerical values are

$$u_w = r_w^2 S/4Tt \quad \text{------ (2)}$$

$$\beta = r_w^2 S/r_c^2 \quad \text{------ (3)}$$

where, t is the time since pumping started, S is the storage coefficient, u_w is the non-dimensional time factor, r_w is the radius of screened part of the well and r_c is the radius of unscreened part of the well.

Thus, transmissivity (T) in the large diameter well is obtained by rearranging equation (1) and storage coefficient (S) by rearranging equation (2) as

$$T = \frac{Q}{4\pi s_w} F(u_w, \beta) \quad \text{------ (4)}$$

$$S = 4Ttu_w / r_w^2 \quad \text{------ (5)}$$

Papadopulos and Cooper presented tables for the function F (u_w,β) from which the appropriate type curves were prepared. This involves plotting of F (u_w, β) verses 1/u_w for different values of β. For estimation of T and

S, the field data of drawdown (s_w) versus time (t) was plotted on a log-log paper of the same scale as that of the type curves. The field data curve thus obtained for a single test was matched with one of the type curves and the match point was selected (Figs. 4.23 to 4.32). An arbitrary point (A) was chosen for which the values of F (u_w, β), $1/u_w$, s_w and t were obtained from the type curve plot and the time-drawdown plot (Table 4.11) along with β values. Q and r_w were known from field measurements. Substituting these values in equation (4) and (5), the T and Sy values were computed (Table 4.12).

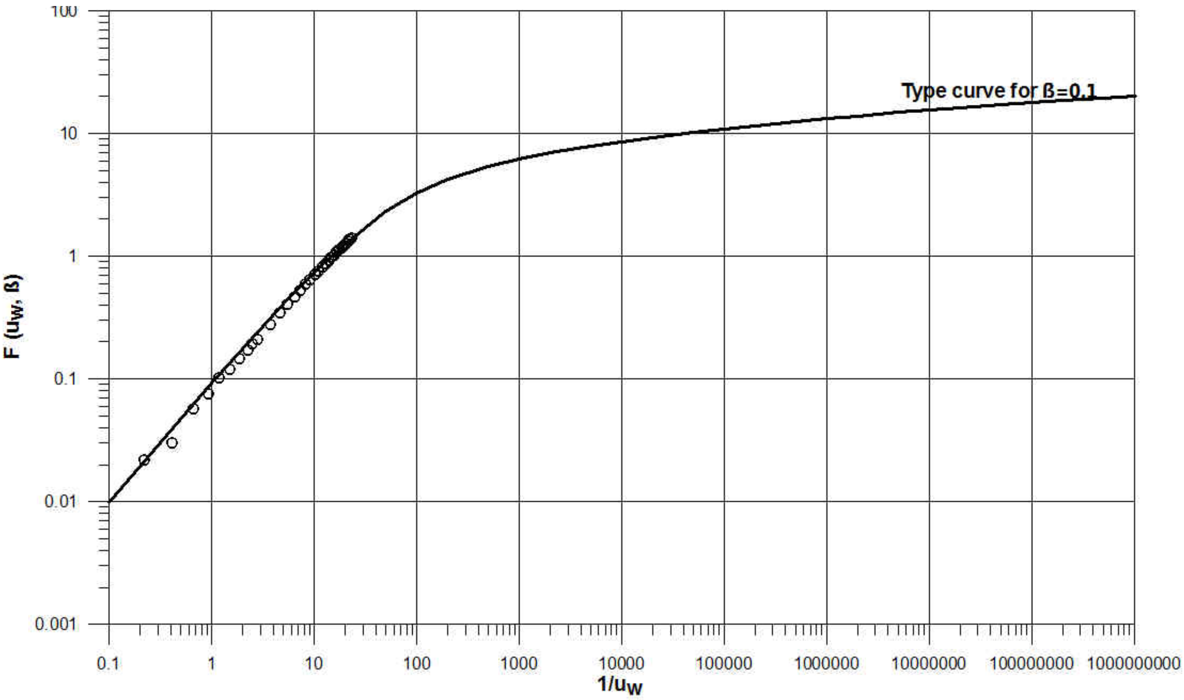


Figure 4.23 Field data match with type curve (β=0.1) of Papadopulos - Cooper method for pumping test at Well No. 36

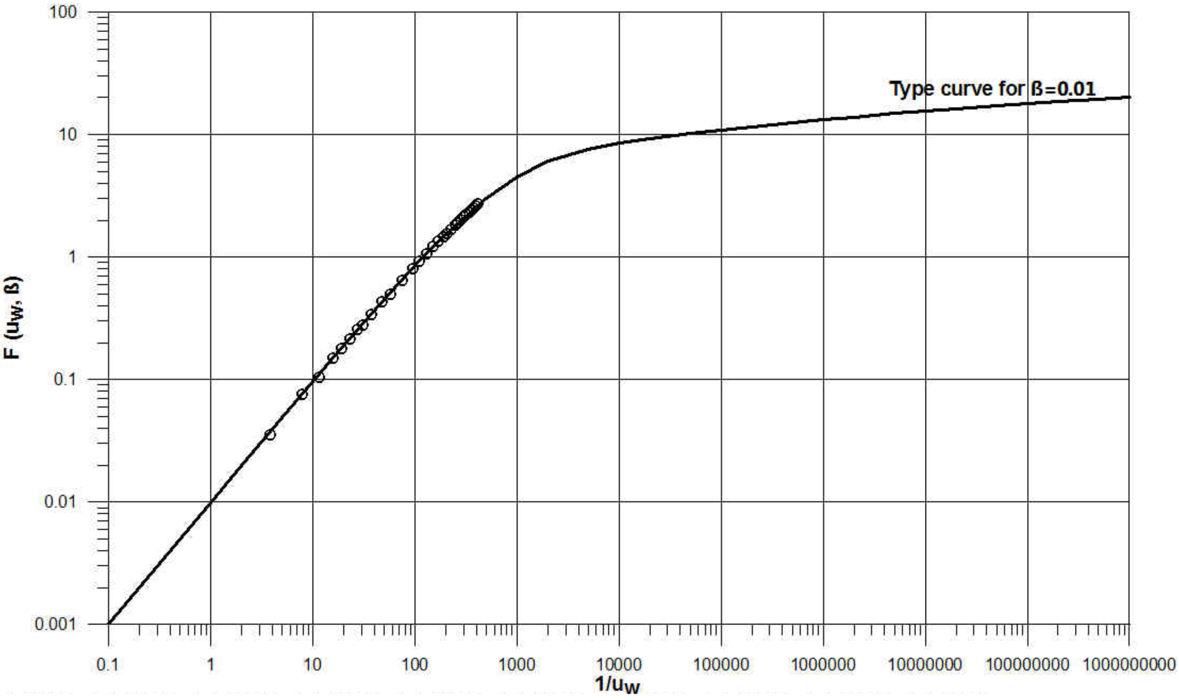


Figure 4.24 Field data match with Type curve (β=0.01) of Papadopulos - Cooper method for pumping test at Well No. 42

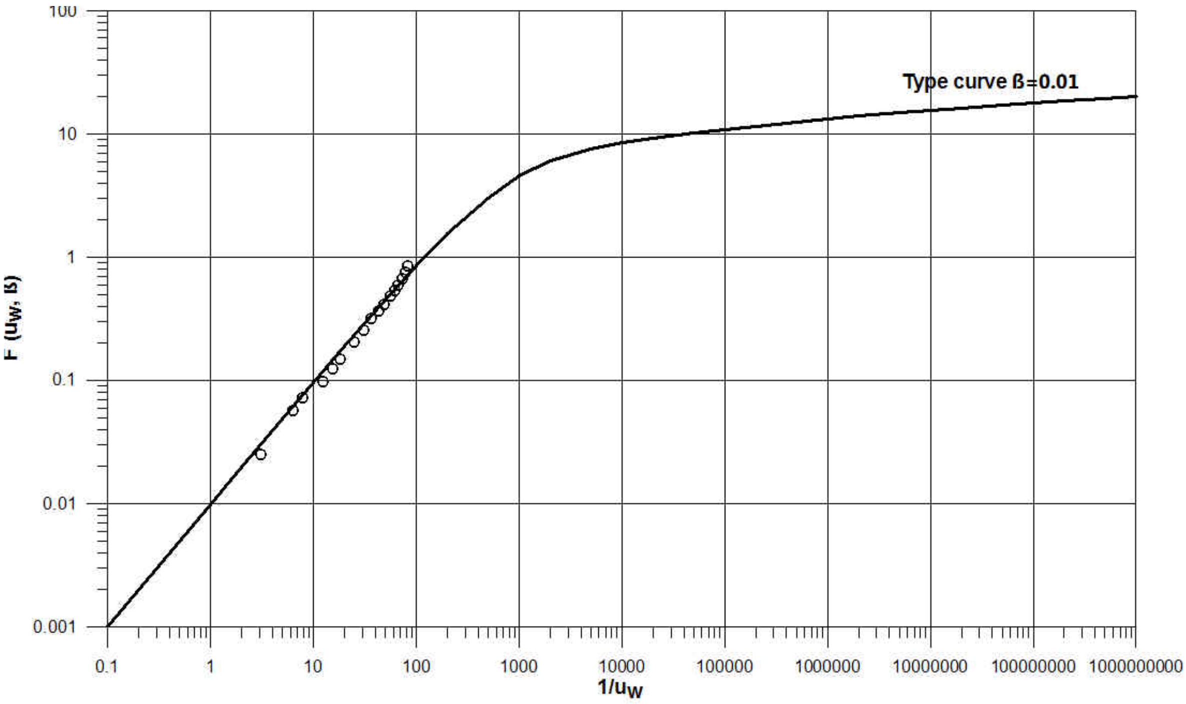


Figure 4.25 Field data match with Type curve (β=0.01) of Papadopulos - Cooper method for pumping test at Well No. 47

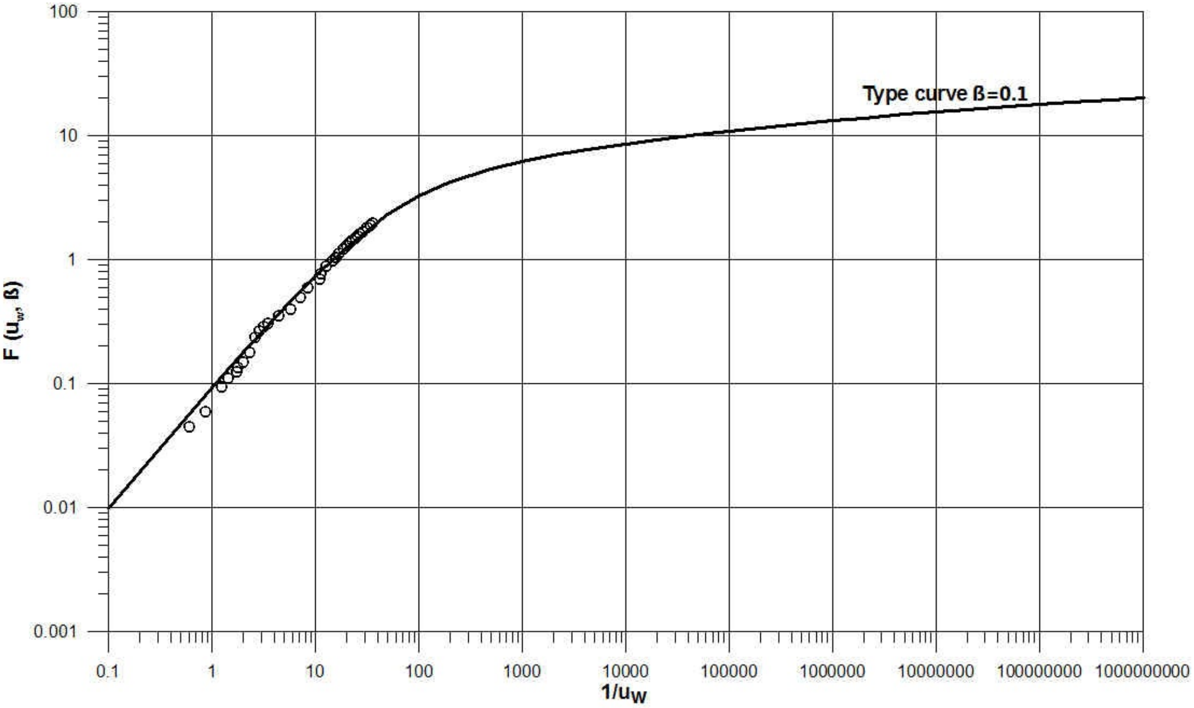


Figure 4.26 Field data match with Type curve (β=0.1) of Papadopulos - Cooper method for pumping test at Well No. 48

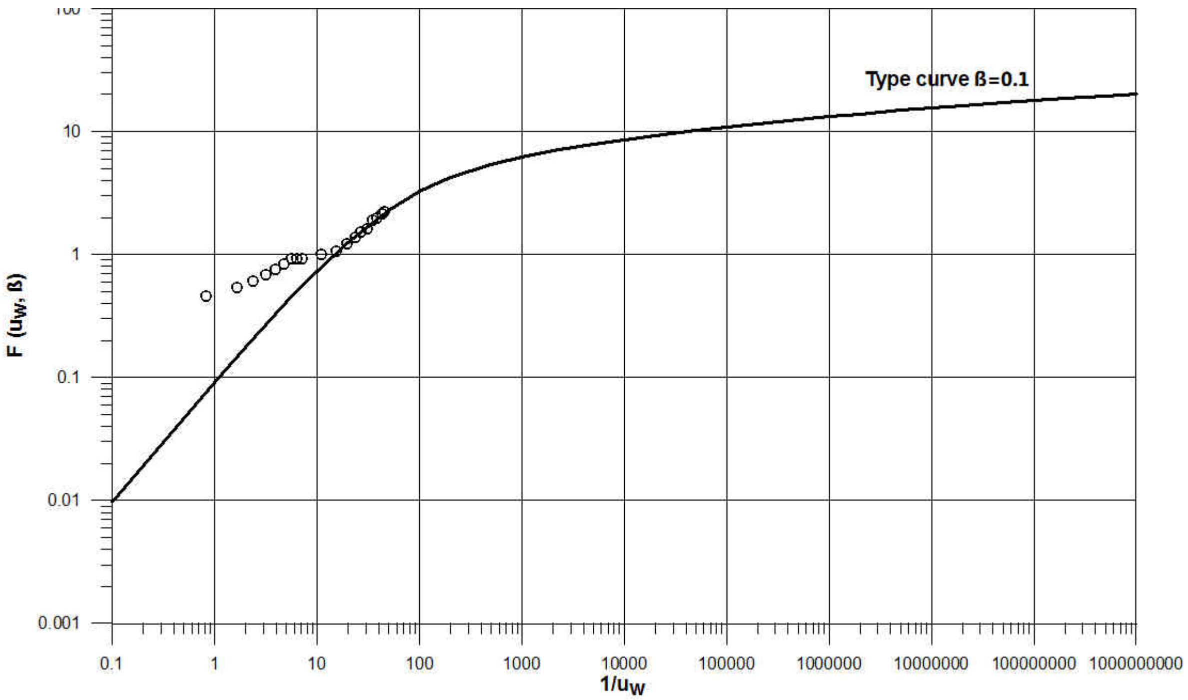


Figure 4.27 Field data match with Type curve (β=0.1) of Papadopulos - Cooper method for pumping test at Well No. 95

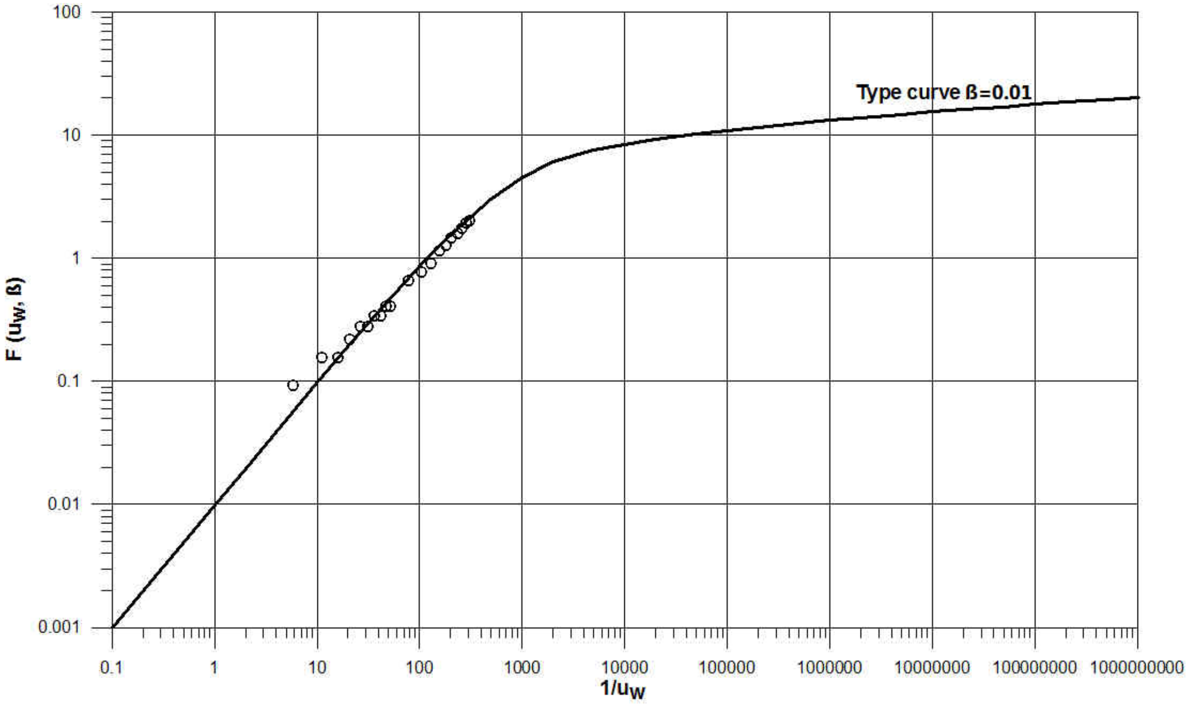


Figure 4.28 Field data match with Type curve (β=0.01) of Papadopulos - Cooper method for pumping test at Well No. 97

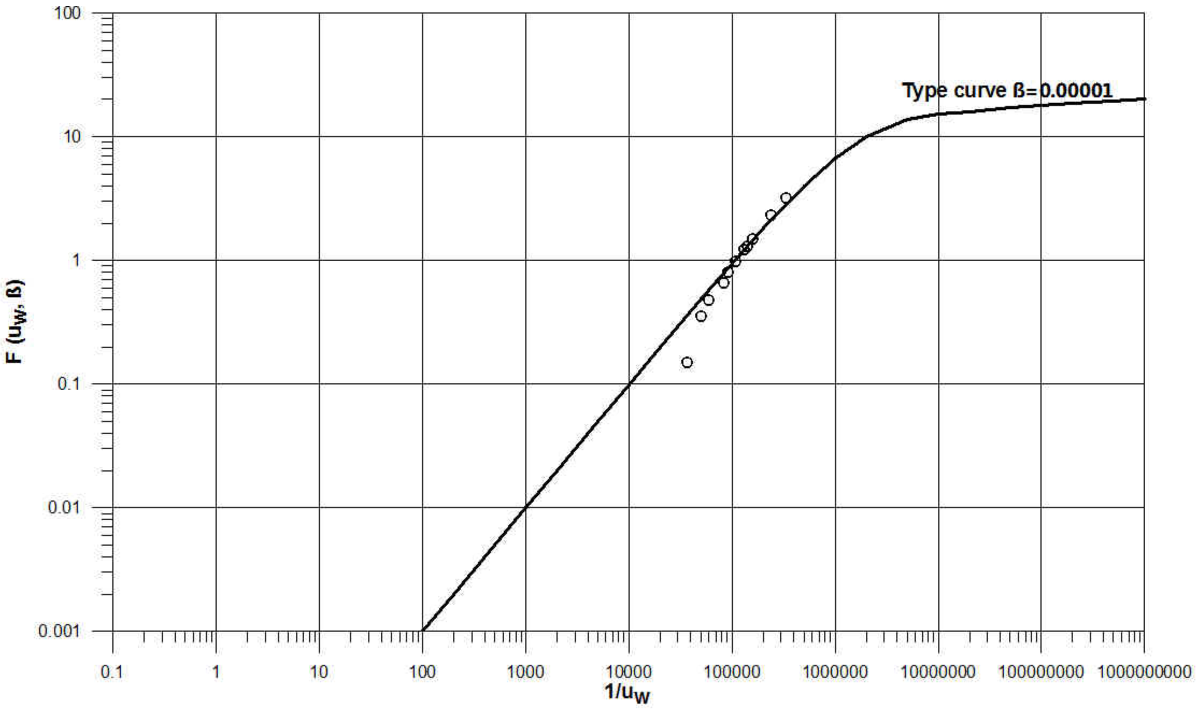


Figure 4.29 Field data match with Type curve (β=0.00001) of Papadopulos - Cooper method for pumping test at Well No. 99

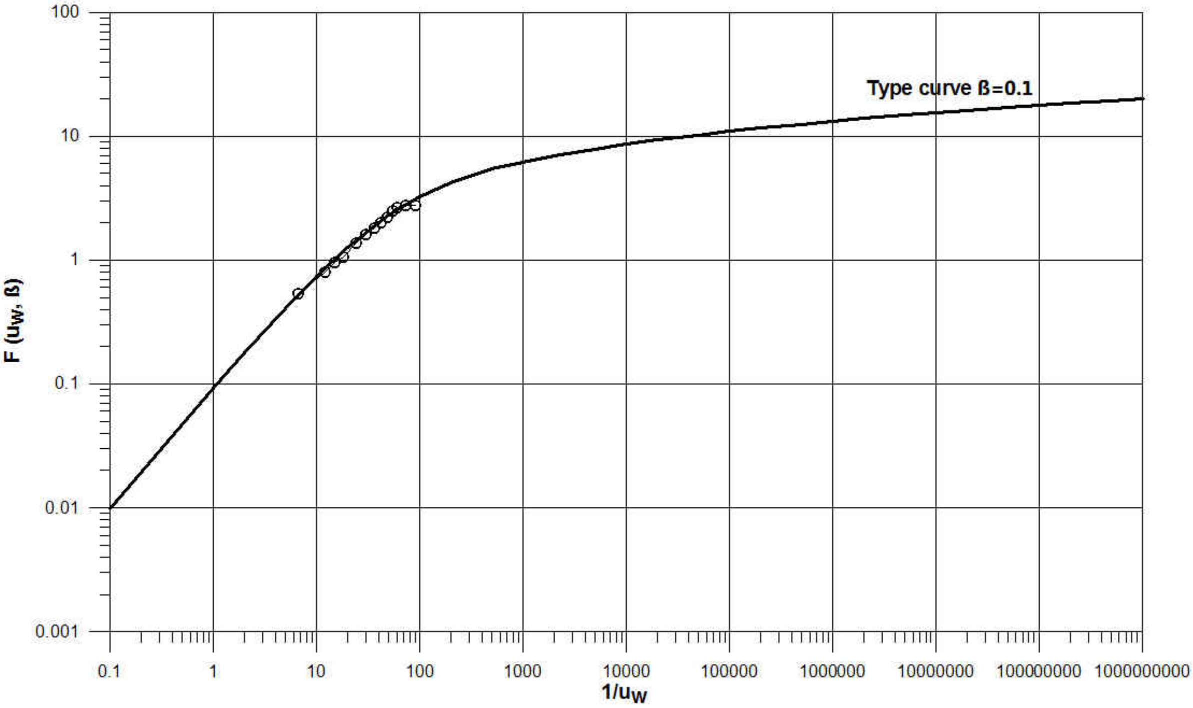


Figure 4.30 Field data match with Type curve (β=0.1) of Papadopulos - Cooper method for pumping test at Well No. 5

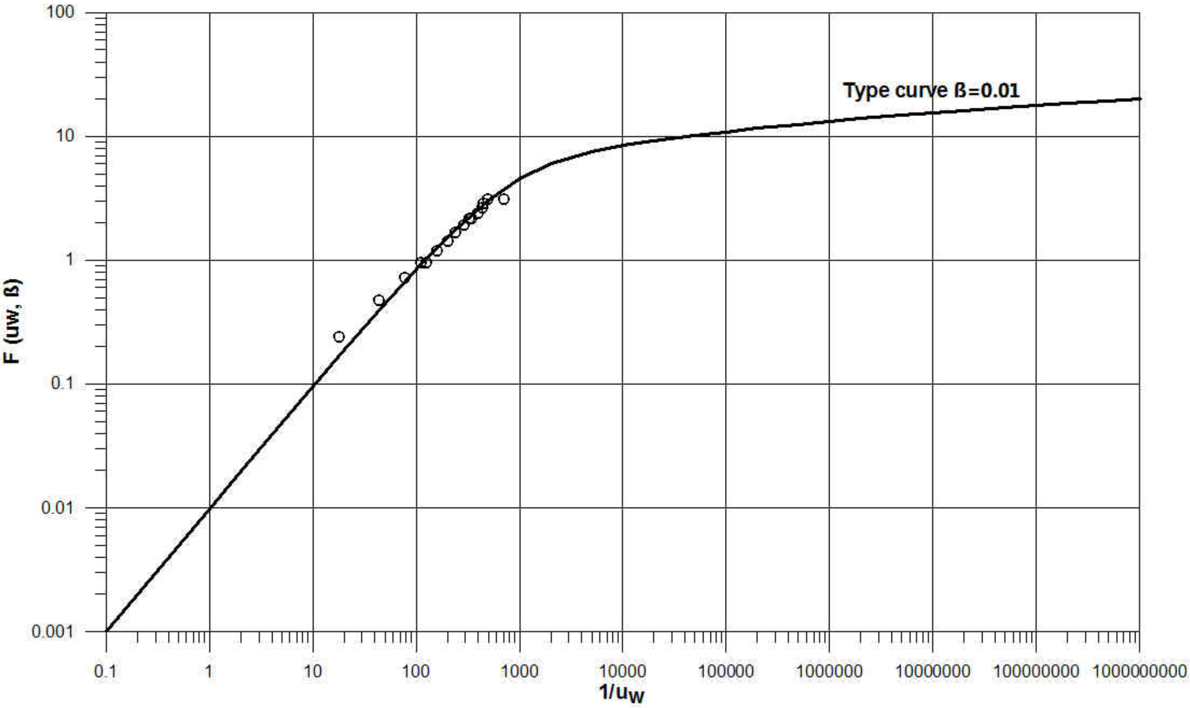


Figure 4.31 Field data match with Type curve (β=0.01) of Papadopulos - Cooper method for pumping test at Well No. 103

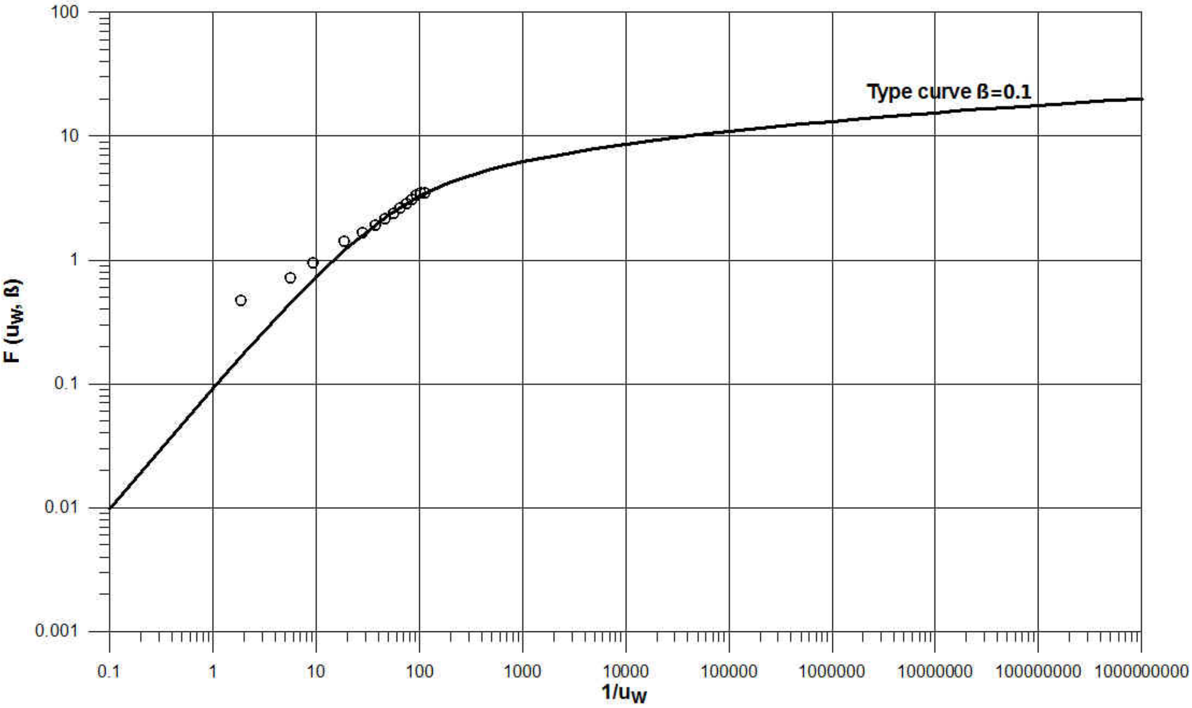


Figure 4.32 Field data match with Type curve (β=0.1) of Papadopulos - Cooper method for pumping test at Well No. 107

4.8.4 Mishra - Chachadi Method (1985)

Mishra and Chachadi (1985) have analysed flow to large diameter well using discrete kernel approach to calculate flow to large diameter well during abstraction as well as recovery phase. A solution is found to determine drawdown and recovery in and around large diameter well in a confined aquifer taking the well storage into consideration. The assumptions made in the analysis are:

1) At any time, the drawdown in the aquifer at the well face is equal to the drawdown in the well.

2) The time parameter is discrete; within each time step, the abstraction rate of water derived from well storage and that from the aquifer storage are separate constants.

Mishra and Chachadi (1985) have derived a family of type curves which include the response of a homogenous isotropic and confined aquifer both during abstraction and recovery phases for various values of α, where α is equal to $(r_w^2/r_c^2)*S$, r_w and r_c being the radius of the well screen and the well casing respectively and S being the aquifer storativity. Each of the recovery curves are characterised by a non-dimensional time factor, $4Tt_p/Sr_w^2$ (in which T is the transmissivity of the aquifer and t_p is the time of pumping) at which it deflects from the time-drawdown curve of the abstraction phase. This non-dimensional time factor can be used to check the accuracy of the aquifer parameters determined by curve matching.

In order to determine the aquifer parameters, the time-drawdown and the time-recovery data of each well was plotted on a double logarithmic paper of the same scale as that of the type curves for obtaining the best match, particularly for the recovery part of the plot (Figs. 4.33 to 4.42). An arbitrary point (B) was selected and relevant values of $F(u_w, \alpha)$, $1/u_w$, $4Tt_p/Sr_w^2$, α, s_w and t were noted from the type curves and field data curves (Table 4.22). Using these values, the value of T and Sy for each test site was calculated through equation (4) and (5). The results are tabulated in Table 4.23.

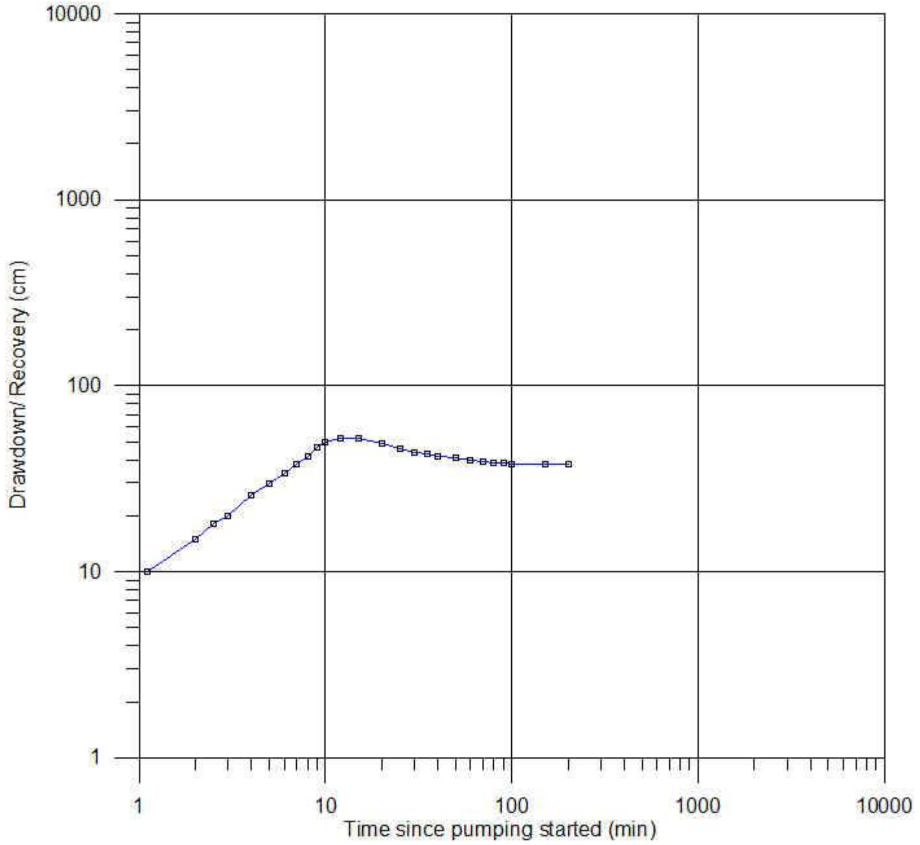


Figure 4.33 Field curve of pumping test at Well No. 5

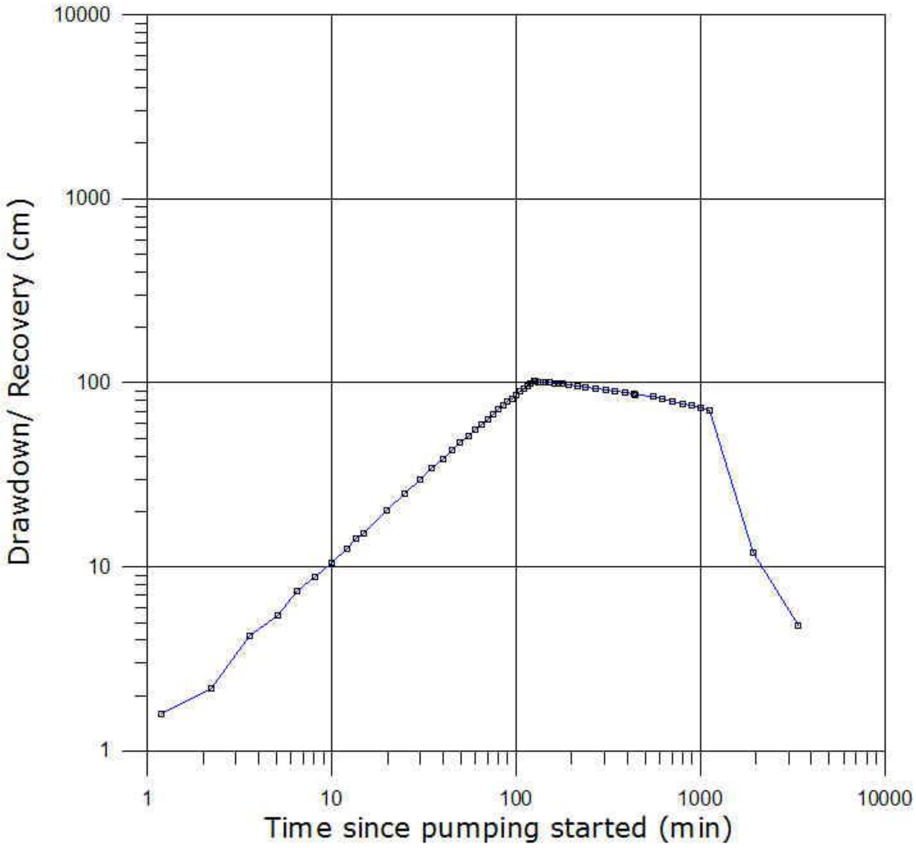


Figure 4.34 Field curve of pumping test at Well No. 36

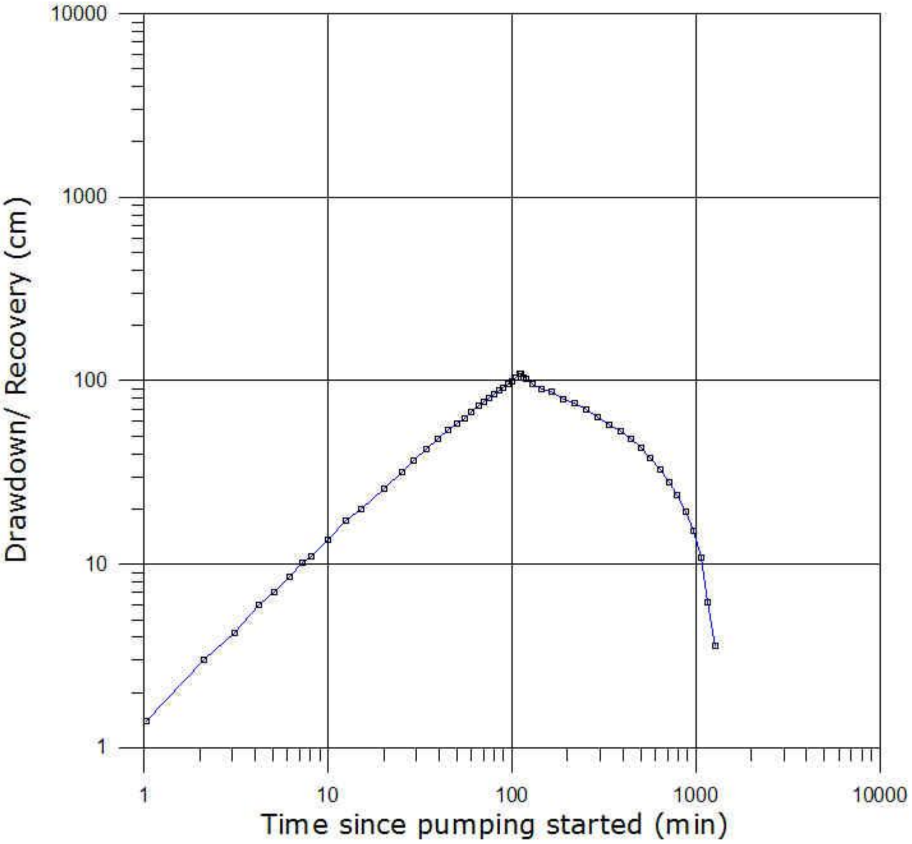


Figure 4.35 Field curve of pumping test at Well No. 42

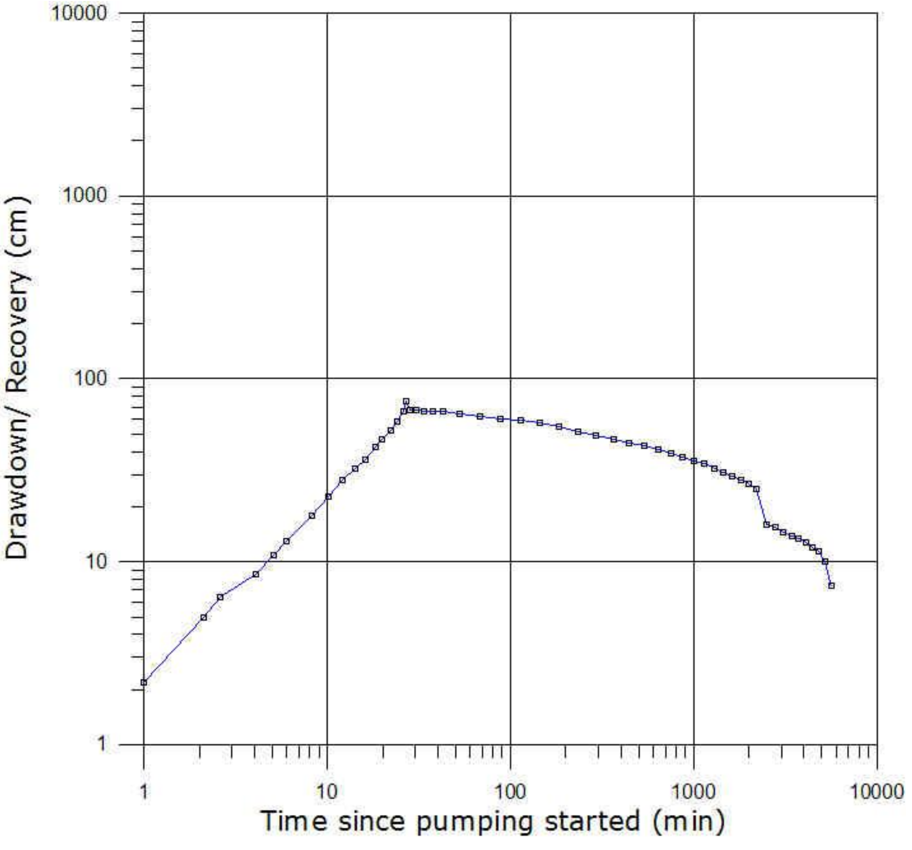


Figure 4.36 Field curve of pumping test at Well No. 47

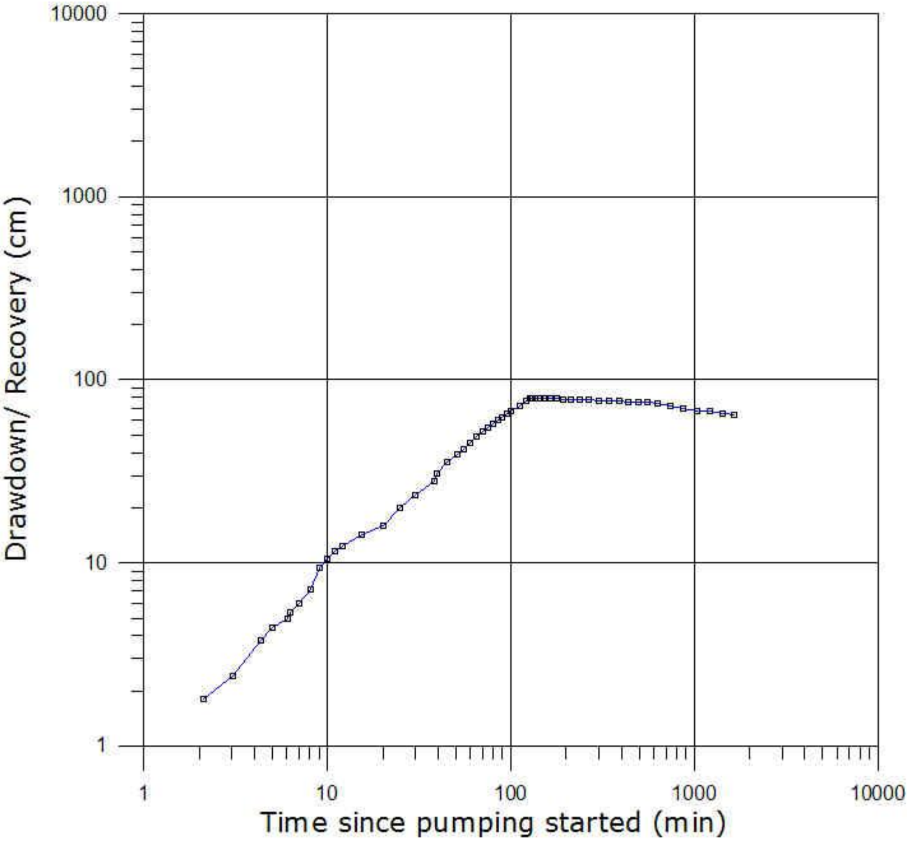


Figure 4.37 Field curve of pumping test at Well No. 48

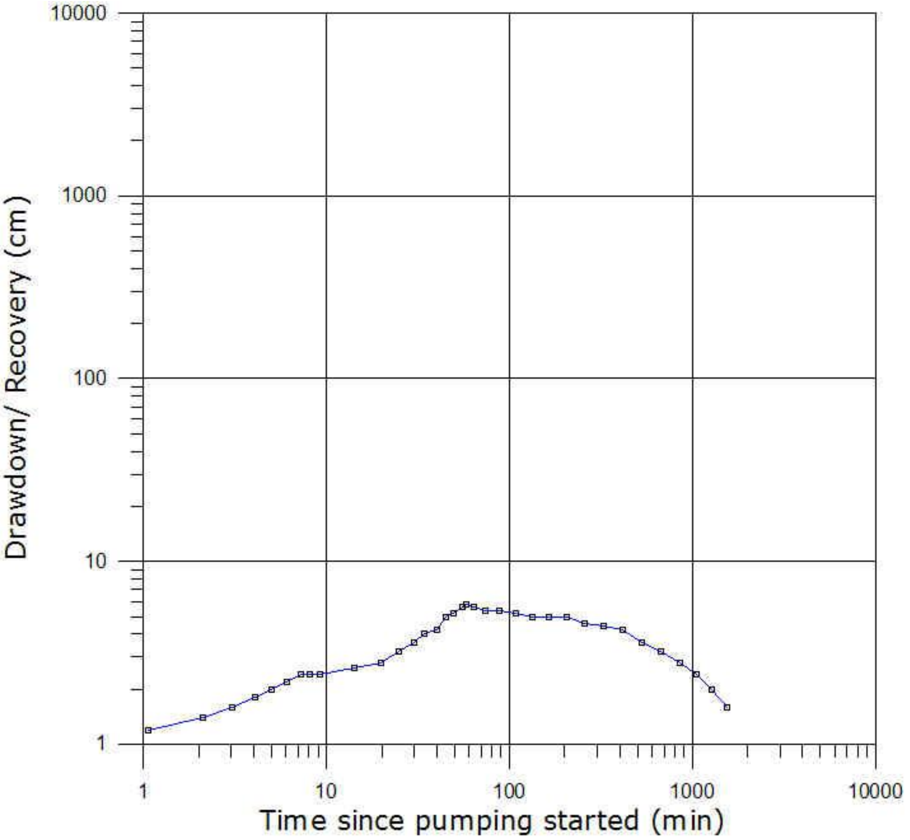


Figure 4.38 Field curve of pumping test at Well No. 95

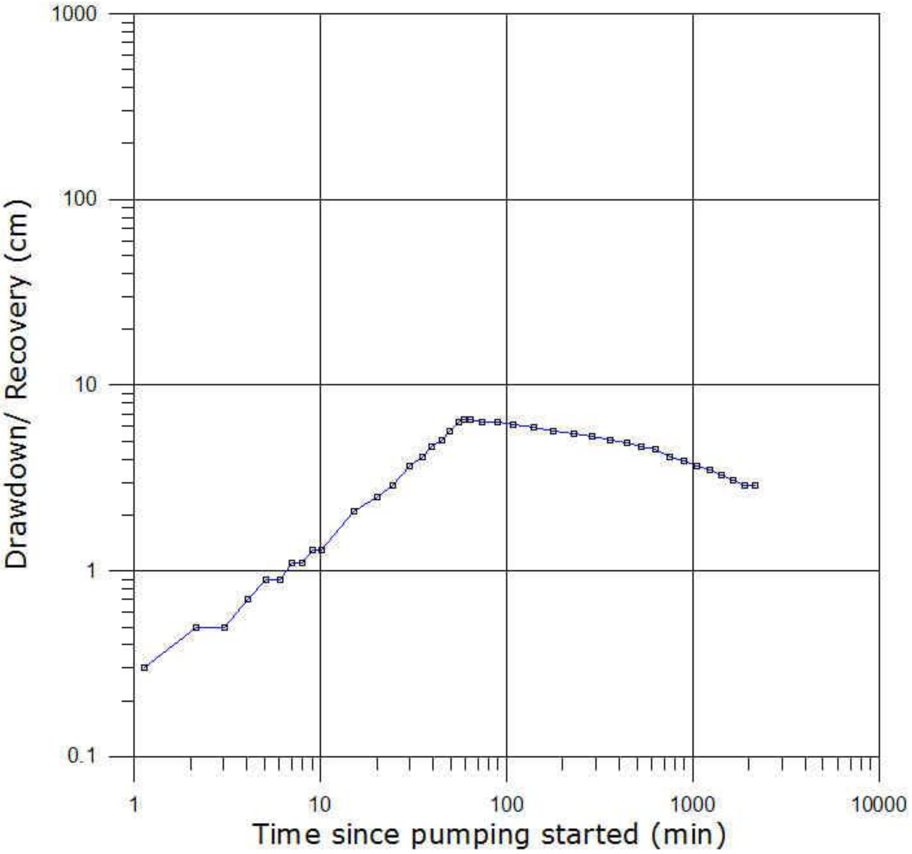


Figure 4.39 Field curve of pumping test at Well No. 97

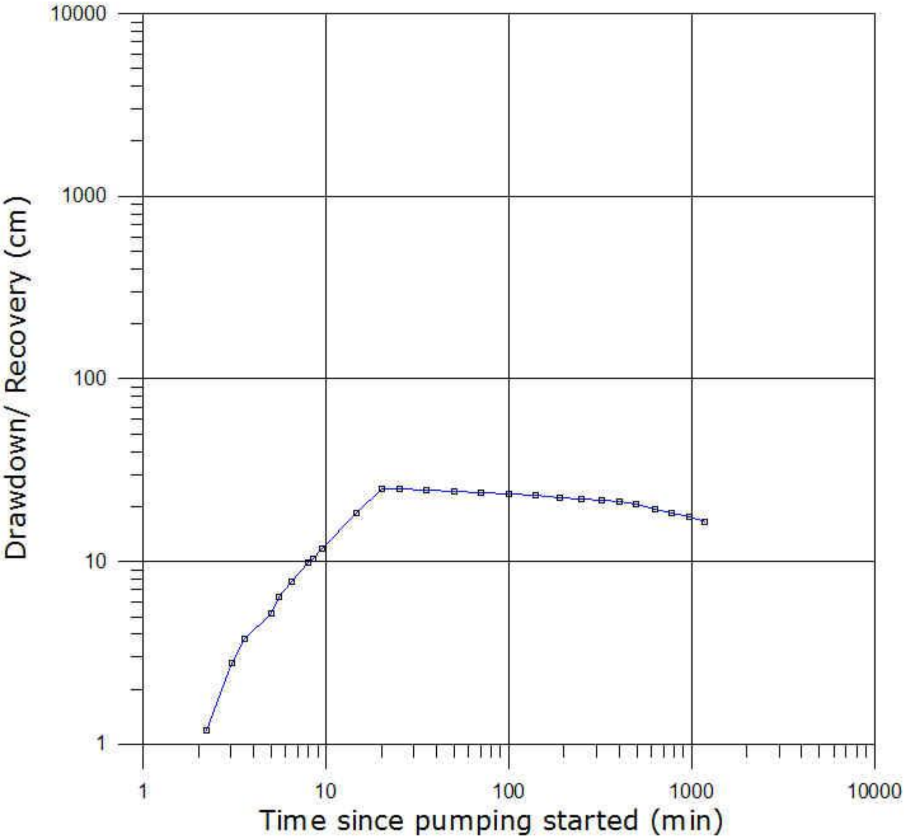


Figure 4.40 Field curve of pumping test at Well No. 99

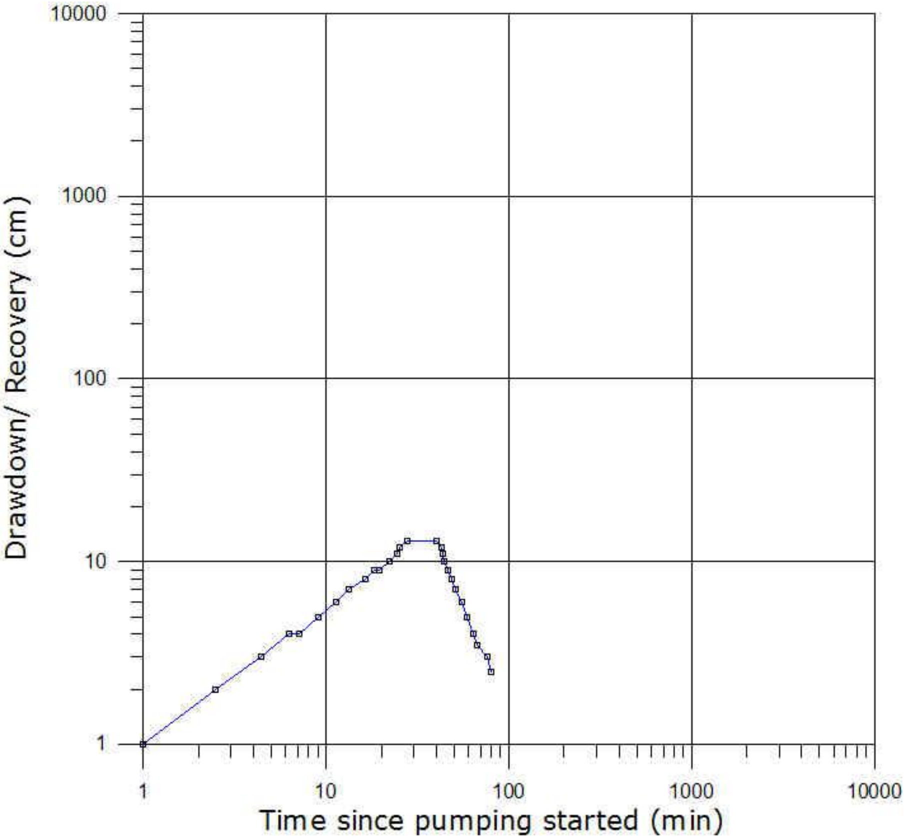


Figure 4.41 Field curve of pumping test at Well No. 103

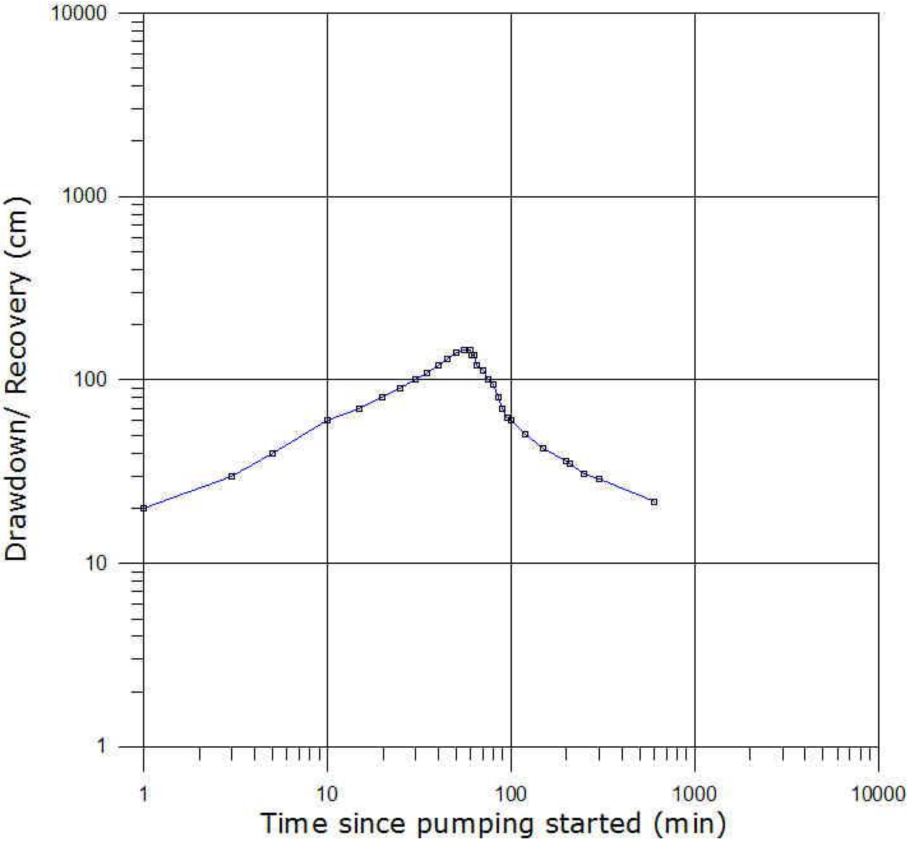


Figure 4.42 Field curve of pumping test at Well No. 107

Table 4.22 Match point details of Papadopulos - Cooper Method and Mishra - Chachadi Method

Sr. No.	Well No.	Papadopulos and Cooper Method (1967)					Mishra and Chachadi Method (1985)				
		From type curves			From field curves		From type curves			From field curves	
		β	$F((u_w,\beta)$	$1/u_w$	s (cm)	t (min)	α	$F((u_w,\beta)$	$1/u_w$	s (cm)	t (min)
1	36	$1x10^{-1}$	1	10	1.0	84	$1x10^{-4}$	1	10^5	33	320
2	42	$1x10^{-2}$	1	10^2	39.0	26	$1x10^{-3}$	1	10^4	20	135
3	47	$1x10^{-2}$	1	10	240.0	10	$1x10^{-4}$	1	10^5	47	190
4	48	$1x10^{-1}$	1	10	60.0	62	$1x10^{-1}$	1	10^2	90	970
5	95	$1x10^{-1}$	1	10	6.4	42	$1x10^{-1}$	1	10	6.7	390
6	97	$1x10^{-2}$	1	10^2	4.8	36	$1x10^{-2}$	1	10^2	4.7	365
7	99	$1x10^{-5}$	1	10^5	17.0	13	$1x10^{-6}$	1	10^7	17	130
8	5	$1x10^{-1}$	1	10	3.6	4.2	$1x10^{-1}$	1	10^2	6.1	77
9	107	$1x10^{-1}$	1	10	5.1	7.3	$1x10^{-1}$	1	10^2	5.2	72
10	103	$1x10^{-2}$	1	10^3	5.0	71	$1x10^{-2}$	1	10^3	7.5	20

Table 4.23 Transmissivity (T), Specific yield (Sy) and Specific Capacity of aquifers

Sr. No.	Well No.	Aquifer thickness b (m)	T (m^2/d) P & C* Method	T (m^2/d) M & C# Method	K (m/d) P & C Method	K (m/d) M & C Method	'Sy' P & C Method	'Sy' M & C Method	'C' Specific Capacity (m^2/d)	Aquifer
1	36	2.04	4	12	1.96	5.88	0.05	0.0001	26	Laterite
2	42	1.43	12	18	8.39	12.58	0.016	0.0012	39	Argillite
3	47	0.75	8	41	10.66	54.66	0.01	0.0001	115	Metagreywacke
4	48	2.41	7	4	2.90	1.66	0.19	0.11	4	Valley fill
5	95	1.66	25	24	15.00	14.45	0.06	0.1	102	Laterite
6	97	0.71	22	22	30.98	30.98	0.015	0.0015	23	Laterite
7	99	1.57	187	187	119.10	119.10	0.000015	0.000001	43	Schist
8	5	1.81	55	33	30.38	18.23	0.026	0.028	49	Laterite
9	107	4.41	91	92	20.63	20.86	0.11	0.11	133	Laterite
10	103	2.20	216	144	98.18	65.45	0.015	0.0003	513	Laterite

*P & C – Papadopulos and Cooper Method
#M & C – Mishra and Chachadi Method

It is seen from Table 4.23 that there is a large variation in the transmissivity and specific yield values indicating inhomogeneous nature of shallow aquifers in the study area. The transmissivity values varies from 4 m^2/day to 216 m^2/day with an average of 62 m^2/day by Papadopulos and Cooper method and 58 m^2/day by Mishra and Chachadi method. The specific yield values are within the range of values for unconfined aquifers (except for well no. 99 which is tapping a confined aquifer). The average transmissivity and specific yield are computed as 60 m^2/day and 0.05 (5%) respectively.

4.8.5 Slitcher’s Method to Estimate Specific Capacity

The production capacity of a well is expressed by its specific capacity. Specific capacity is defined as the discharge per unit time per unit length of drawdown. Specific capacity of a well depends on various factors including the aquifer properties, well dimensions and pumping duration.

Slitcher (1906) gave an expression for determination of specific capacity of large diameter wells with the help of recovery data. The formula as given by Slitcher is,

$$\mathbf{C = 2.303(A/t') \log_{10}(s_1/s_2)}$$

where, C is the specific capacity (m^2/day), A is the cross-sectional area of the well (m^2), t′ is the duration of observed recovery after stoppage of pumping (day), s_1 is the drawdown at stoppage of pumping (m) and s_2 is the residual drawdown at time t' (m).

Despite various limitations as mentioned in Mishra and Chachadi (1984), the Slitcher's formula provides a useful basis for comparison of the yield of the wells of similar types (identical area of cross-section) in similar geological conditions provided same discharge rates and same durations of pumping time are maintained during abstraction phase. The specific capacity (C) has been computed using Slitcher's method at 1 hour recovery (Table 4.23).

4.9 Groundwater Recharge Estimation

The groundwater recharge in the Mhadei River watershed has been assessed as per methodology recommended by Groundwater Estimation Methodology Committee (GEC, 1997). The recharge has been calculated using both Rainfall infiltration method and Water table fluctuation method (Table 4.24). The recharge has been calculated separately for each domain of groundwater in Goa and Karnataka.

Table 4.24 Computation of groundwater recharge in the Mhadei River watershed

1	Total geographic area of Mhadei watershed (A)	89900 ha
2	Total area of the watershed in Goa (A_G)	57300 ha
3	Total area of the watershed in Karnataka (A_K)	32600 ha
4	Area not suitable for groundwater recharge in the watershed	23000 ha
5	Area suitable for groundwater recharge in Goa (A_{SG})	38100 ha
6	Area suitable for groundwater recharge in Karnataka (A_{SK})	28800 ha
7	Normal annual rainfall in watershed in Goa (NAR_G)	4.160 m
8	Normal annual rainfall in watershed in Karnataka (NAR_K)	3.539 m
9	Rainfall infiltration factor (RIF) adopted from GEMC,1997	0.06
10	Average water table fluctuation in Goa (ΔWTF_G)	1.57 m
11	Average water table fluctuation in Karnataka (ΔWTF_K)	0.83 m
12	Average Specific yield of aquifers (Sy)	0.05
13	**Groundwater recharge by rainfall infiltration method**	
a	Recharge from rainfall in Goa (R_{RG}) = NAR_G x A_{SG} x RIF	9510 ham
b	Recharge from rainfall in Karnataka (R_{RK}) = NAR_K x A_{SK} x RIF	6115 ham
c	Total recharge from rainfall in the watershed= a+b	15625 ham
14	**Groundwater recharge by water table fluctuation method**	
a	Total Recharge in Goa (R_G) = A_{SG} x ΔWTF_G x Sy	2991 ham
b	Total Recharge in Karnataka (R_K) = A_{SK} x ΔWTF_K x Sy	1195 ham
c	Total Recharge in the watershed = a+b	4186 ham

Since the agricultural area in the Mhadei River watershed is merely 3.5% of the total watershed area and only about 25% of it is irrigated during non-monsoon season, the return seepage from irrigation during the non-monsoon season may be considered as negligible. Similarly, there are no tanks, ponds or canals in the watershed. Therefore, recharge from all other sources may be considered as negligible.

The total groundwater recharge in the watershed computed using water table fluctuation method is 4186 hectare meter (ham) (41.86 MCM) while that computed by rainfall infiltration factor method is 15625 ham (156.25 MCM). The large discrepancy between the two values of groundwater recharge is due to the use of high rainfall infiltration factor of 6% as recommended by GEC, 1997 norms for this lithology. As brought out in Chapter 2, the estimated difference between the volume of the rainfall and the measured run-off is 3% for the entire watershed. Allowing 1.5% for evapo-transpiration the rainfall recharge to groundwater should only be 1.5%. The groundwater recharge estimation using water table fluctuation method has provided the quantum of rainfall recharge as 1.9% for Goa region and 1.2% for Karnataka region which supplements the above computation. Therefore, the groundwater recharge by rainfall infiltration method estimated separately for Goa and Karnataka regions using the estimated recharge rate of 1.9% and 1.2% respectively for Goa and Karnataka regions works out to be 3011 ham and 1223 ham respectively. Therefore, the rainfall infiltration factor for the Mhadei River watershed should be taken as 0.015 (1.5%) or maximum as 0.02 (2%).

4.10 Infiltration Tests

Infiltration is defined as the process by which water enters the surface strata of the earth under the influence of gravity. It is an important process by which soil is saturated and ground water body is replenished. The maximum rate at which the ground is capable of absorbing water under given conditions is defined as ‘infiltration capacity’.

Infiltration capacity is influenced by many factors. These factors are not constant throughout the year. The factors include antecedent soil moisture, compaction, surface cover conditions, duration of rainfall, slope, drainage texture, temperature, etc. Infiltration is less if the soil is moist and high if it is dry. Compaction reduces porosity of the soil and hence decreases the infiltration. Presence of vegetative cover on the surface of the ground increases infiltration capacity as it retards the movement of overland flow. However, covering of soil surface with vegetal matter may inhibit infiltration. Rainfall of modest intensity spread over longer period may cause satisfactory infiltration. However, high intensity rainfall of short duration may not result in good infiltration. Since movement of water is controlled by gravity it flows on sloping surfaces and hence reducing the infiltration. Similarly, fine drainage texture results in faster run-off and hence promotes faster overland flow and consequently less infiltration. Finally, infiltration is higher at higher temperature since the viscosity of water is low in such conditions.

The infiltration process can be described in terms of accumulated infiltration, instantaneous infiltration and average infiltration. Accumulated infiltration is the total volume of water that has infiltrated through a unit area of soil surface over a given period of time. Instantaneous infiltration is the rate of volume of water passing through a unit area of soil surface at any given instant. The average infiltration equals cumulative infiltration divided by time since infiltration started.

Infiltration study is useful in hydrogeological investigations to find the quantum of various recharge components to the ground water regime. Infiltration rates are required in many hydrologic studies such as runoff estimation and soil moisture budgeting. The knowledge of infiltration also helps in adopting proper irrigation methods, scheduling of water to the fields, design of sprinkler irrigation system etc.

In the present study, nine infiltration tests were carried out to estimate infiltration capacity of soils covering various land-use/ land-cover types in the Mhadei River watershed. The infiltration tests were carried out with the help of Double-ring Infiltrometer. Double-ring Infiltrometer is a flooding type infiltrometer wherein water is applied in the form of a sheet usually with a constant depth of flooding. The double-ring infiltrometer consisted of an inner ring having a diameter of 30 cm and area (A) of 706.5 cm^2 and an outer ring with a diameter of 45 cm. They are hammered into the ground up to a depth of 5-10 cm. Water is added to the inner ring up to a particular marked level. Water is also added in the outer ring to maintain the vertical flow in the inner ring. After a specific time interval the lowered level of water due to infiltration in the inner ring is measured. With the help of calibrated apparatus water is added to the inner ring to bring the level of water to original level. The amount of water added and the time interval is noted down.

Of the nine infiltration tests carried out in the Mhadei river watershed, four were carried out in forest land, two in agricultural land, one in plantation zone, one in mining zone and one in settlement zone. The field data and computed infiltration parameters are given in Table 4.25 to Table 4.33. The variation of infiltration rate with time at each test site is shown in Figs. 4.43 to 4.51.

Table 4.25 Field data and computed parameters of Infiltration Test No: 1

Location: Valpoi; near Well No. 36; Latitude: N15° 31′ 32″; Longitude: E74° 07′ 10.4″; Land type: Plantation

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumulative infiltration depth F=V/A (cm)	Incremental infiltration ΔF (cm)	Infiltration rate f=ΔF/Δt (cm/hr)	Accumulated infiltration $fa=at^b$ (cm) a=3 b=0.5	Average infiltration fav=fa/t (cm/min)	Instantaneous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	1200	1200	1.70	1.70	20.38	6.71	1.34	0.67	0.067
10	0.083	350	1550	2.19	0.50	5.94	9.49	0.95	0.47	0.047
15	0.083	100	1650	2.34	0.14	1.70	11.62	0.77	0.39	0.039
20	0.083	155	1805	2.55	0.22	2.63	13.42	0.67	0.34	0.034
30	0.167	400	2205	3.12	0.57	3.40	16.43	0.55	0.27	0.027
40	0.167	315	2520	3.57	0.45	2.68	18.97	0.47	0.24	0.024
50	0.167	250	2770	3.92	0.35	2.12	21.21	0.42	0.21	0.021
60	0.167	250	3020	4.27	0.35	2.12	23.24	0.39	0.19	0.019
75	0.250	350	3370	4.77	0.50	1.98	25.98	0.35	0.17	0.017
90	0.250	350	3720	5.27	0.50	1.98	28.46	0.32	0.16	0.016
120	0.500	700	4420	6.26	0.99	1.98	32.86	0.27	0.14	0.014
150	0.500	850	5270	7.46	1.20	2.41	36.74	0.24	0.12	0.012

Table 4.26 Field data and computed parameters of Infiltration Test No: 2

Location: Nanoda; near Well No. 117; Latitude: N15° 35′ 17.6″; Longitude: E74° 11′ 28.7″; Land type: Forest

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumu-lative infiltration depth F=V/A (cm)	Increm-ental infiltration ΔF (cm)	Infiltra-tion rate f=ΔF/Δt (cm/hr)	Accumu-lated infiltration $fa=at^b$ (cm) a=1.3 b=0.81	Average infiltration fav=fa/t (cm/min)	Instanta-neous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	1700	1700	2.41	2.41	28.87	4.79	0.96	0.78	0.078
10	0.083	1740	3440	4.87	2.46	29.55	8.39	0.84	0.68	0.068
15	0.083	1650	5090	7.20	2.34	28.03	11.66	0.78	0.63	0.063
20	0.083	1580	6670	9.44	2.24	26.84	14.72	0.74	0.60	0.060
25	0.083	1250	7920	11.21	1.77	21.23	17.63	0.71	0.57	0.057
30	0.083	1135	9055	12.82	1.61	19.28	20.44	0.68	0.55	0.055
35	0.083	1160	10215	14.46	1.64	19.70	23.15	0.66	0.54	0.054
40	0.083	1180	11395	16.13	1.67	20.04	25.80	0.64	0.52	0.052
45	0.083	1000	12395	17.54	1.42	16.99	28.38	0.63	0.51	0.051
50	0.083	1125	13520	19.14	1.59	19.11	30.91	0.62	0.50	0.050
55	0.083	1050	14570	20.62	1.49	17.83	33.39	0.61	0.49	0.049
60	0.083	1000	15570	22.04	1.42	16.99	35.83	0.60	0.48	0.048

65	0.083	925	16495	23.35	1.31	15.71	38.23	0.59	0.48	0.048
70	0.083	1080	17575	24.88	1.53	18.34	40.60	0.58	0.47	0.047
75	0.083	1000	18575	26.29	1.42	16.99	42.93	0.57	0.46	0.046
80	0.083	1000	19575	27.71	1.42	16.99	45.23	0.57	0.46	0.046
85	0.083	925	20500	29.02	1.31	15.71	47.51	0.56	0.45	0.045
90	0.083	1120	21620	30.60	1.59	19.02	49.76	0.55	0.45	0.045
95	0.083	760	22380	31.68	1.08	12.91	51.99	0.55	0.44	0.044
100	0.083	1205	23585	33.38	1.71	20.47	54.19	0.54	0.44	0.044
105	0.083	820	24405	34.54	1.16	13.93	56.38	0.54	0.43	0.043
110	0.083	1000	25405	35.96	1.42	16.99	58.54	0.53	0.43	0.043
115	0.083	930	26335	37.28	1.32	15.80	60.69	0.53	0.43	0.043
120	0.083	1000	27335	38.69	1.42	16.99	62.82	0.52	0.42	0.042
125	0.083	1000	28335	40.11	1.42	16.99	64.93	0.52	0.42	0.042
130	0.083	1000	29335	41.52	1.42	16.99	67.03	0.52	0.42	0.042
135	0.083	1000	30335	42.94	1.42	16.99	69.11	0.51	0.41	0.041
140	0.083	1000	31335	44.35	1.42	16.99	71.17	0.51	0.41	0.041
145	0.083	1165	32500	46.00	1.65	19.79	73.22	0.50	0.41	0.041
150	0.083	975	33475	47.38	1.38	16.56	75.26	0.50	0.41	0.041

Table 4.27 Field data and computed parameters of Infiltration Test No: 3
Location: Kumbharwada; Sancordem, near Well No. 102; Latitude: N15° 31’ 32”; Longitude: E74° 07’ 10.4”; Land type: Agricultural land

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumulative infiltration depth F=V/A (cm)	Incremental infiltration ΔF (cm)	Infiltration rate f=ΔF/Δt (cm/hr)	Accumulated infiltration $fa=at^b$ (cm) a=6 b=0.71	Average infiltration fav=fa/t (cm/min)	Instantaneous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	1065	1065	1.51	1.51	18.09	18.81	3.76	2.67	0.27
10	0.083	350	1415	2.00	0.50	5.94	30.77	3.08	2.18	0.22
15	0.083	250	1665	2.36	0.35	4.25	41.04	2.74	1.94	0.19
25	0.167	500	2165	3.06	0.71	4.25	58.98	2.36	1.67	0.17
35	0.167	400	2565	3.63	0.57	3.40	74.89	2.14	1.52	0.15
45	0.167	420	2985	4.23	0.59	3.57	89.52	1.99	1.41	0.14
60	0.250	590	3575	5.06	0.84	3.34	109.81	1.83	1.30	0.13
75	0.250	610	4185	5.92	0.86	3.45	128.66	1.72	1.22	0.12
90	0.250	580	4765	6.74	0.82	3.28	146.44	1.63	1.16	0.12
105	0.250	650	5415	7.66	0.92	3.68	163.38	1.56	1.10	0.11
120	0.250	560	5975	8.46	0.79	3.17	179.63	1.50	1.06	0.11
135	0.250	630	6605	9.35	0.89	3.57	195.29	1.45	1.03	0.10

Table 4.28 Field data and computed parameters of Infiltration Test No: 4

Location: Tambdi Surla; near Shiva temple; Latitude: N15° 26′ 27.6″; Longitude: E74° 15′ 07″; Land type: Forest

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumulative infiltration depth F=V/A (cm)	Incremental infiltration ΔF (cm)	Infiltration rate f=ΔF/Δt (cm/hr)	Accumulated infiltration fa=at^b (cm) a=0.9 b=0.92	Average infiltration fav=fa/t (cm/min)	Instantaneous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	3250	3250	4.60	4.60	55.20	3.96	0.79	0.73	0.073
10	0.083	3000	6250	8.85	4.25	50.96	7.49	0.75	0.69	0.069
15	0.083	3000	9250	13.09	4.25	50.96	10.87	0.72	0.67	0.067
20	0.083	2860	12110	17.14	4.05	48.58	14.16	0.71	0.65	0.065
25	0.083	2770	14880	21.06	3.92	47.05	17.39	0.70	0.64	0.064
30	0.083	2830	17710	25.07	4.01	48.07	20.57	0.69	0.63	0.063
35	0.083	2600	20310	28.75	3.68	44.16	23.70	0.68	0.62	0.062
40	0.083	2100	22410	31.72	2.97	35.67	26.80	0.67	0.62	0.062
45	0.083	3100	25510	36.11	4.39	52.65	29.87	0.66	0.61	0.061
50	0.083	2450	27960	39.58	3.47	41.61	32.91	0.66	0.61	0.061
55	0.083	2640	30600	43.31	3.74	44.84	35.92	0.65	0.60	0.060
60	0.083	2350	32950	46.64	3.33	39.92	38.92	0.65	0.60	0.060

Table 4.28 continued

65	0.083	2328	35278	49.93	3.30	39.54	41.89	0.64	0.59	0.059
70	0.083	2264	37542	53.14	3.20	38.45	44.85	0.64	0.59	0.059
75	0.083	2340	39882	56.45	3.31	39.75	47.79	0.64	0.59	0.059
80	0.083	2350	42232	59.78	3.33	39.92	50.71	0.63	0.58	0.058
85	0.083	2100	44332	62.75	2.97	35.67	53.62	0.63	0.58	0.058
90	0.083	2100	46432	65.72	2.97	35.67	56.51	0.63	0.58	0.058
95	0.083	2250	48682	68.91	3.18	38.22	59.39	0.63	0.58	0.058
100	0.083	2100	50782	71.88	2.97	35.67	62.26	0.62	0.57	0.057
105	0.083	2250	53032	75.06	3.18	38.22	65.12	0.62	0.57	0.057
110	0.083	1971	55003	77.85	2.79	33.48	67.97	0.62	0.57	0.057
115	0.083	2100	57103	80.83	2.97	35.67	70.81	0.62	0.57	0.057
120	0.083	2250	59353	84.01	3.18	38.22	73.64	0.61	0.56	0.056

Table 4.29 Field data and computed parameters of Infiltration Test No: 5

Location: Surla; near Kalsa Nala; Latitude: N15° 40′ 52.4″; Longitude: E74° 10′ 45.5″; Land type: Forest

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumulative infiltration depth F=V/A (cm)	Incremental infiltration ΔF (cm)	Infiltration rate f=ΔF/Δt (cm/hr)	Accumulated infiltration $fa=at^b$ (cm) a=2.3 b=0.93	Average infiltration fav=fa/t (cm/min)	Instantaneous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	1350	1350	1.91	1.91	22.93	10.27	2.05	1.91	0.19
10	0.083	1350	2700	3.82	1.91	22.93	19.58	1.96	1.82	0.18
15	0.083	1200	3900	5.52	1.70	20.38	28.54	1.90	1.77	0.18
20	0.083	1077	4977	7.04	1.52	18.29	37.30	1.86	1.73	0.17
25	0.083	1193	6170	8.73	1.69	20.26	45.90	1.84	1.71	0.17
30	0.083	1200	7370	10.43	1.70	20.38	54.38	1.81	1.69	0.17
35	0.083	1100	8470	11.99	1.56	18.68	62.76	1.79	1.67	0.17
40	0.083	1178	9648	13.66	1.67	20.01	71.06	1.78	1.65	0.17
45	0.083	1051	10699	15.14	1.49	17.85	79.29	1.76	1.64	0.16
50	0.083	1200	11899	16.84	1.70	20.38	87.45	1.75	1.63	0.16
55	0.083	935	12834	18.17	1.32	15.88	95.56	1.74	1.62	0.16
60	0.083	1200	14034	19.86	1.70	20.38	103.61	1.73	1.61	0.16

Table 4.29 continued

65	0.083	1250	15284	21.63	1.77	21.23	111.62	1.72	1.60	0.16
70	0.083	850	16134	22.84	1.20	14.44	119.58	1.71	1.59	0.16
75	0.083	1200	17334	24.54	1.70	20.38	127.51	1.70	1.58	0.16
80	0.083	887	18221	25.79	1.26	15.07	135.39	1.69	1.57	0.16
85	0.083	1000	19221	27.21	1.42	16.99	143.25	1.69	1.57	0.16
90	0.083	1000	20221	28.62	1.42	16.99	151.07	1.68	1.56	0.16
95	0.083	943	21164	29.96	1.33	16.02	158.86	1.67	1.56	0.16
100	0.083	1000	22164	31.37	1.42	16.99	166.62	1.67	1.55	0.15
105	0.083	1000	23164	32.79	1.42	16.99	174.35	1.66	1.54	0.15
110	0.083	1100	24264	34.34	1.56	18.68	182.06	1.66	1.54	0.15
115	0.083	1000	25264	35.76	1.42	16.99	189.75	1.65	1.53	0.15
120	0.083	1000	26264	37.17	1.42	16.99	197.41	1.65	1.53	0.15

Table 4.30 Field data and computed parameters of Infiltration Test No: 6

Location: Hivre Budruk; near Well No. 48; Latitude: N15° 37′ 44.5″; Longitude: E74° 08′ 50″

Land type: Agricultural land

Time 't' (min)	Time 'Δt' (hr)	Vol. of water added at each 't' (cm^3)	Vol. of water added since start 'V' (cm^3)	Cumu-lative infiltration depth F=V/A (cm)	Increm-ental infiltration ΔF (cm)	Infiltra-tion rate f=ΔF/Δt (cm/hr)	Accumu-lated infiltration $fa=at^b$ (cm) a=0.01 b=0.35	Average infiltration fav=fa/t (cm/min)	Instanta-neous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	525	525	0.74	0.74	8.92	0.018	0.0035	0.0012	0.00012
10	0.083	150	675	0.96	0.21	2.55	0.022	0.0022	0.0008	0.00008
15	0.083	200	875	1.24	0.28	3.40	0.026	0.0017	0.0006	0.00006
25	0.167	150	1025	1.45	0.21	1.27	0.031	0.0012	0.0004	0.00004
35	0.167	125	1150	1.63	0.18	1.06	0.035	0.0010	0.0003	0.00003
55	0.333	200	1350	1.91	0.28	0.85	0.041	0.0007	0.0003	0.00003
75	0.333	125	1475	2.09	0.18	0.53	0.045	0.0006	0.0002	0.00002
95	0.333	75	1550	2.19	0.11	0.32	0.049	0.0005	0.0002	0.00002
115	0.333	125	1675	2.37	0.18	0.53	0.053	0.0005	0.0002	0.00002
135	0.333	75	1750	2.48	0.11	0.32	0.056	0.0004	0.0001	0.00001
155	0.333	75	1825	2.58	0.11	0.32	0.058	0.0004	0.0001	0.00001

Table 4.31 Field data and computed parameters of Infiltration Test No: 7

Location: Valpoi; near Well No. 36; Latitude: N15° 31′ 27.7″; Longitude: E74° 07′ 13.3″; Land type: Forest

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumulative infiltration depth F=V/A (cm)	Incremental infiltration ΔF (cm)	Infiltration rate f=ΔF/Δt (cm/hr)	Accumulated infiltration fa=at^b (cm) a=1.4 b=0.81	Average infiltration fav=fa/t (cm/min)	Instantaneous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	2000	2000	2.83	2.83	33.97	5.16	1.03	0.84	0.084
10	0.083	1300	3300	4.67	1.84	22.08	9.04	0.90	0.73	0.073
15	0.083	1540	4840	6.85	2.18	26.16	12.55	0.84	0.68	0.068
20	0.083	1150	5990	8.48	1.63	19.53	15.85	0.79	0.64	0.064
25	0.083	1125	7115	10.07	1.59	19.11	18.99	0.76	0.62	0.062
30	0.083	1250	8365	11.84	1.77	21.23	22.01	0.73	0.59	0.059
35	0.083	1000	9365	13.26	1.42	16.99	24.94	0.71	0.58	0.058
40	0.083	1000	10365	14.67	1.42	16.99	27.78	0.69	0.56	0.056
45	0.083	1100	11465	16.23	1.56	18.68	30.57	0.68	0.55	0.055
55	0.167	2000	13465	19.06	2.83	16.99	35.96	0.65	0.53	0.053
65	0.167	1600	15065	21.32	2.26	13.59	41.17	0.63	0.51	0.051
75	0.167	1800	16865	23.87	2.55	15.29	46.23	0.62	0.50	0.050
85	0.167	1480	18345	25.97	2.09	12.57	51.16	0.60	0.49	0.049
95	0.167	1450	19795	28.02	2.05	12.31	55.99	0.59	0.48	0.048
105	0.167	1500	21295	30.14	2.12	12.74	60.71	0.58	0.47	0.047
115	0.167	1350	22645	32.05	1.91	11.46	65.36	0.57	0.46	0.046
135	0.333	2800	25445	36.02	3.96	11.89	74.42	0.55	0.45	0.045
155	0.333	2800	28245	39.98	3.96	11.89	83.23	0.54	0.43	0.043

Table 4.32 Field data and computed parameters of Infiltration Test No: 8

Location: Gaonkarwada, Usgao; Latitude: N15° 26’ 54.6”; Longitude: E74° 03’ 52.9”; Land type: Settlement zone

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumu-lative infiltration depth F=V/A (cm)	Increm-ental infiltration ΔF (cm)	Infiltra-tion rate f=ΔF/Δt (cm/hr)	Accumu-lated infiltration fa=at^b (cm) a=1.6 b=0.57	Average infiltration fav=fa/t (cm/min)	Instanta-neous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	55	55	0.08	0.08	0.93	4.00	0.80	0.46	0.046
10	0.083	90	145	0.21	0.13	1.53	5.94	0.59	0.34	0.034
15	0.083	51	196	0.28	0.07	0.87	7.49	0.50	0.28	0.028
25	0.167	100	296	0.42	0.14	0.85	10.02	0.40	0.23	0.023
30	0.083	62	358	0.51	0.09	1.05	11.12	0.37	0.21	0.021
40	0.167	19	377	0.53	0.03	0.16	13.10	0.33	0.19	0.019
50	0.167	46	423	0.60	0.07	0.39	14.88	0.30	0.17	0.017
60	0.167	53	476	0.67	0.08	0.45	16.51	0.28	0.16	0.016
70	0.167	44	520	0.74	0.06	0.37	18.02	0.26	0.15	0.015
80	0.167	52	572	0.81	0.07	0.44	19.45	0.24	0.14	0.014
90	0.167	35	607	0.86	0.05	0.30	20.80	0.23	0.13	0.013
100	0.167	23	630	0.89	0.03	0.20	22.09	0.22	0.13	0.013
120	0.333	84	714	1.01	0.12	0.36	24.50	0.20	0.12	0.012
140	0.333	86	800	1.13	0.12	0.37	26.76	0.19	0.11	0.011
170	0.500	100	900	1.27	0.14	0.28	29.89	0.18	0.10	0.010

Table 4.33 Field data and computed parameters of Infiltration Test No: 9

Location: Kasrwada, Usgao; Latitude: N15° 27′ 46.2″; Longitude: E74° 04′ 26.6″; Land type: Mining zone

Time ‘t’ (min)	Time ‘Δt’ (hr)	Vol. of water added at each ‘t’ (cm^3)	Vol. of water added since start ‘V’ (cm^3)	Cumulative infiltration depth F=V/A (cm)	Incremental infiltration ΔF (cm)	Infiltration rate f=ΔF/Δt (cm/hr)	Accumulated infiltration $fa=at^b$ (cm) a=0.9 b=0.85	Average infiltration fav=fa/t (cm/min)	Instantaneous infiltration fi=fav x b (cm/min)	Field Capacity fc=0.1 x fi (cm/min)
5	0.083	415	415	0.59	0.59	7.05	3.53	0.71	0.60	0.060
10	0.083	128	543	0.77	0.18	2.17	6.37	0.64	0.54	0.054
15	0.083	72	615	0.87	0.10	1.22	8.99	0.60	0.51	0.051
20	0.083	250	865	1.22	0.35	4.25	11.48	0.57	0.49	0.049
30	0.167	250	1115	1.58	0.35	2.12	16.21	0.54	0.46	0.046
40	0.167	140	1255	1.78	0.20	1.19	20.70	0.52	0.44	0.044
50	0.167	245	1500	2.12	0.35	2.08	25.02	0.50	0.43	0.043
60	0.167	101	1601	2.27	0.14	0.86	29.22	0.49	0.41	0.041
70	0.167	250	1851	2.62	0.35	2.12	33.31	0.48	0.40	0.040
80	0.167	95	1946	2.75	0.13	0.81	37.31	0.47	0.40	0.040
90	0.167	205	2151	3.04	0.29	1.74	41.24	0.46	0.39	0.039
110	0.333	400	2551	3.61	0.57	1.70	48.91	0.44	0.38	0.038
130	0.333	315	2866	4.06	0.45	1.34	56.38	0.43	0.37	0.037
150	0.333	325	3191	4.52	0.46	1.38	63.67	0.42	0.36	0.036
170	0.333	175	3366	4.76	0.25	0.74	70.81	0.42	0.35	0.035
190	0.333	250	3616	5.12	0.35	1.06	77.84	0.41	0.35	0.035
210	0.333	300	3916	5.54	0.42	1.27	84.75	0.40	0.34	0.034

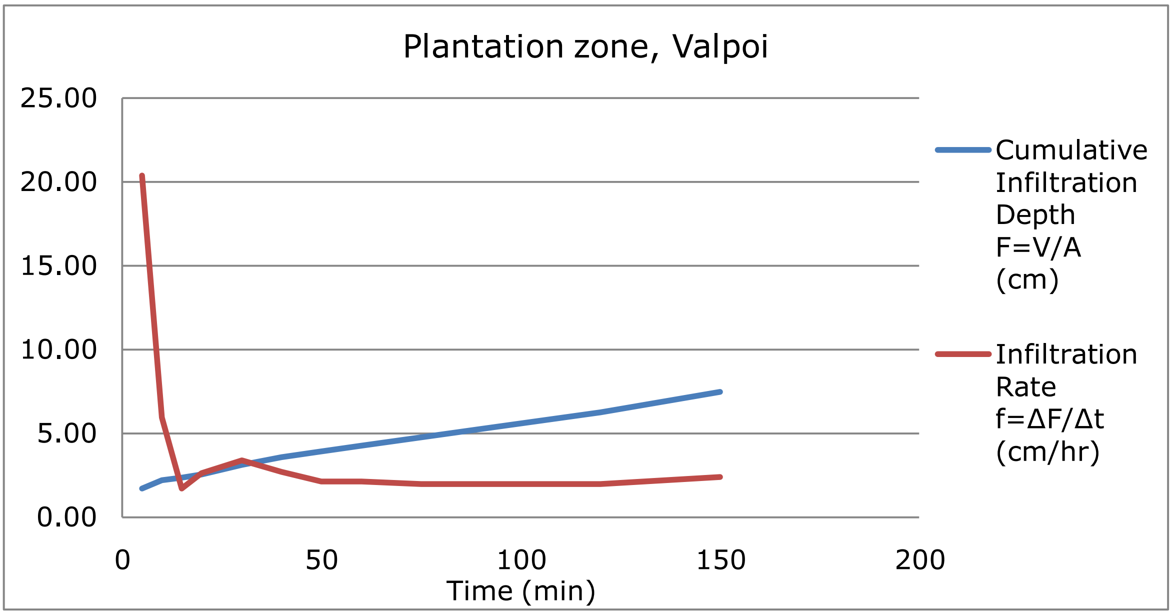


Figure 4.43 Variation of infiltration rate with time at infiltration test No.1

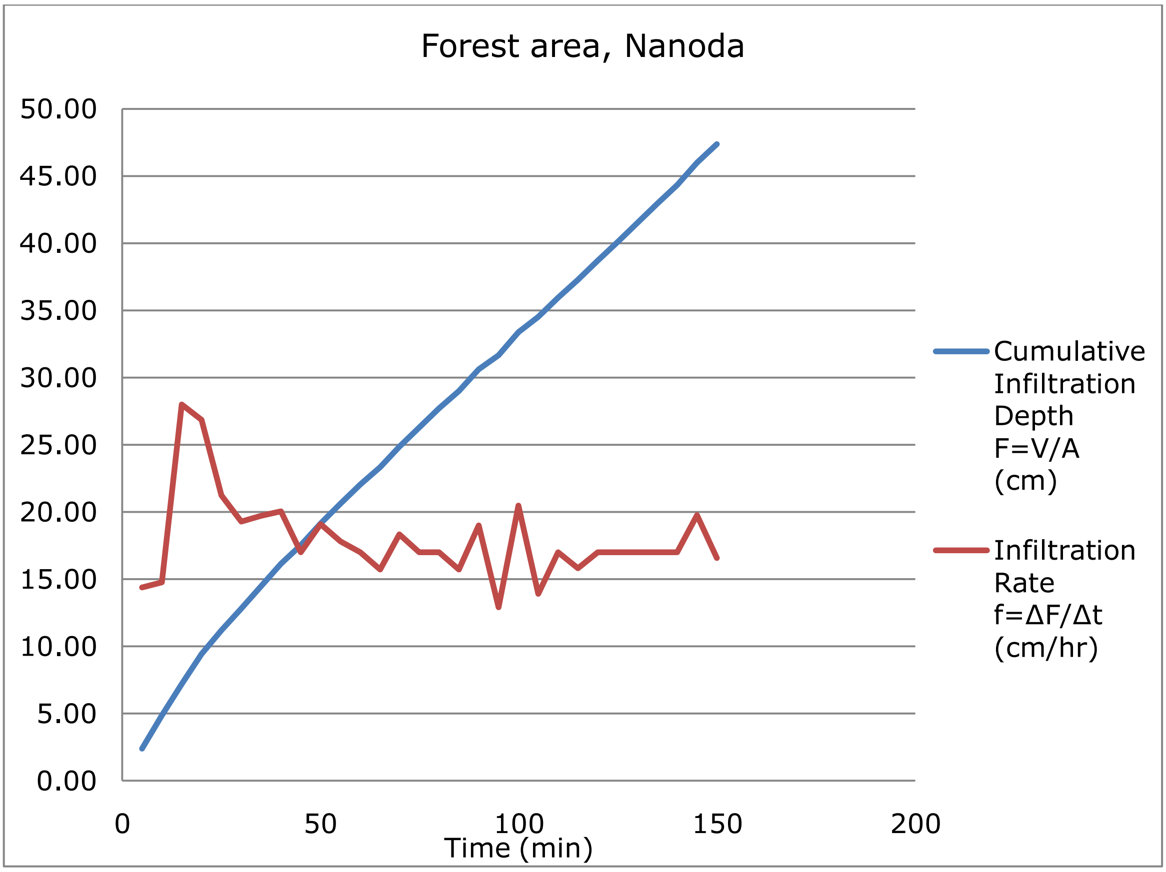


Figure 4.44 Variation of infiltration rate with time at infiltration test No.2

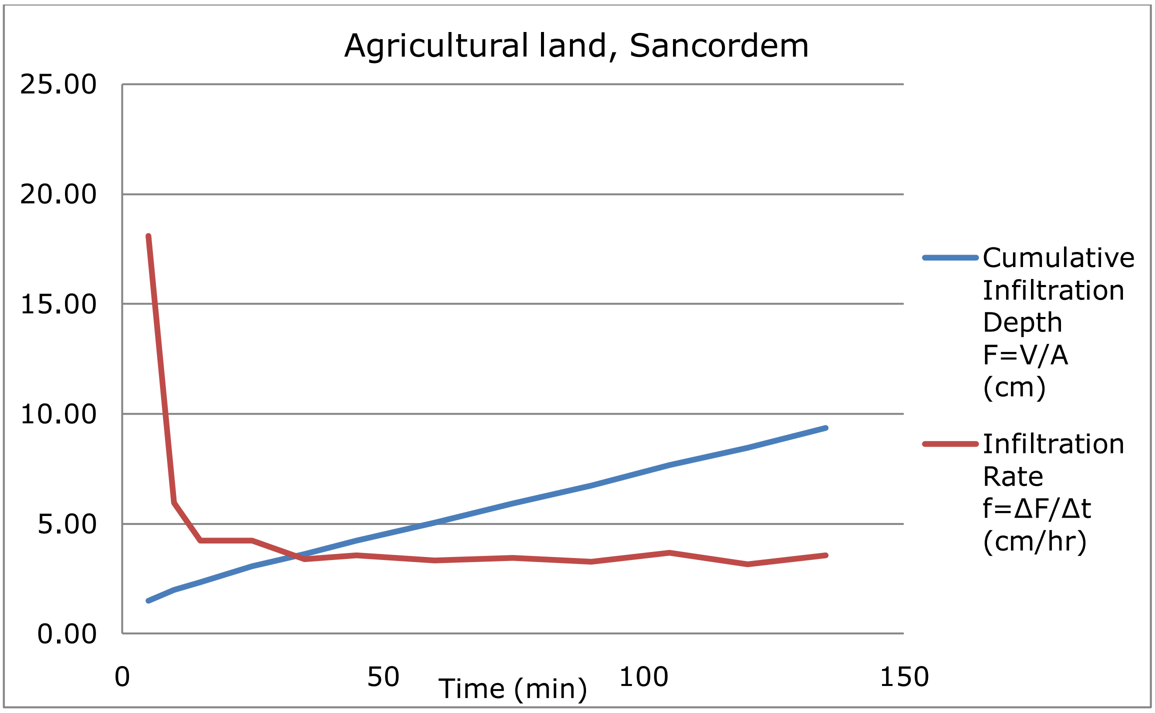


Figure 4.45 Variation of infiltration rate with time at infiltration test No.3

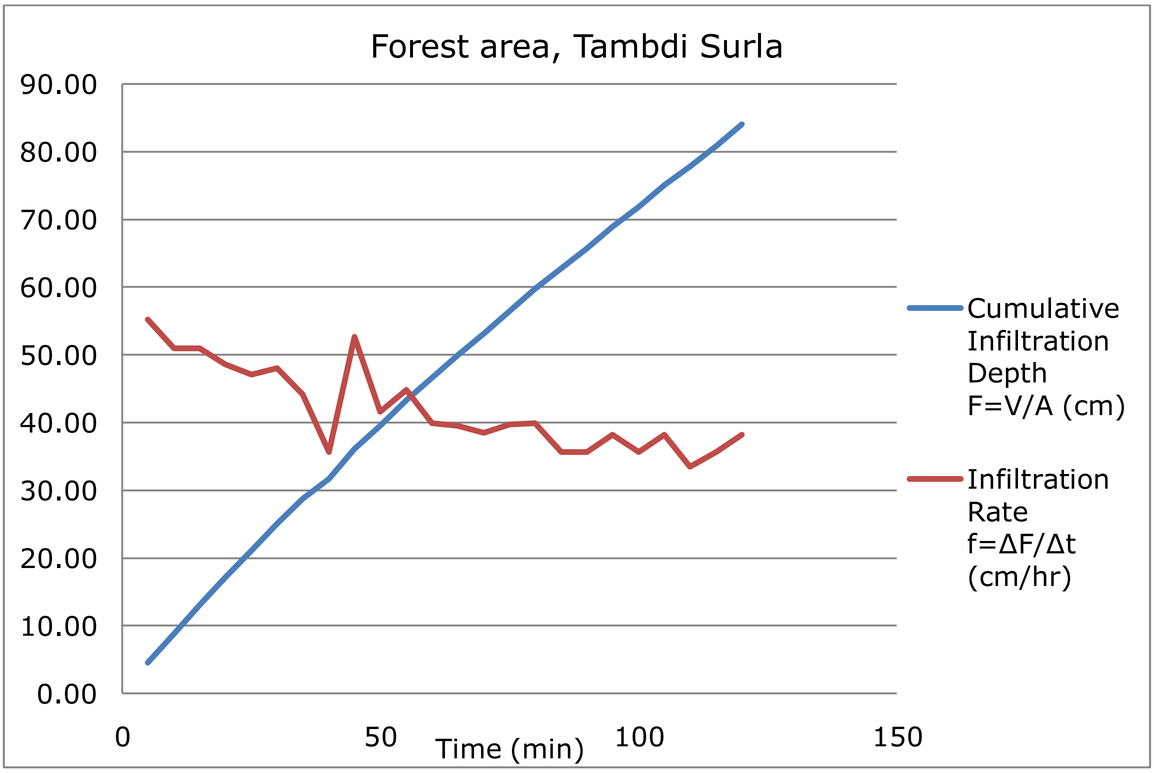


Figure 4.46 Variation of infiltration rate with time at infiltration test No.4

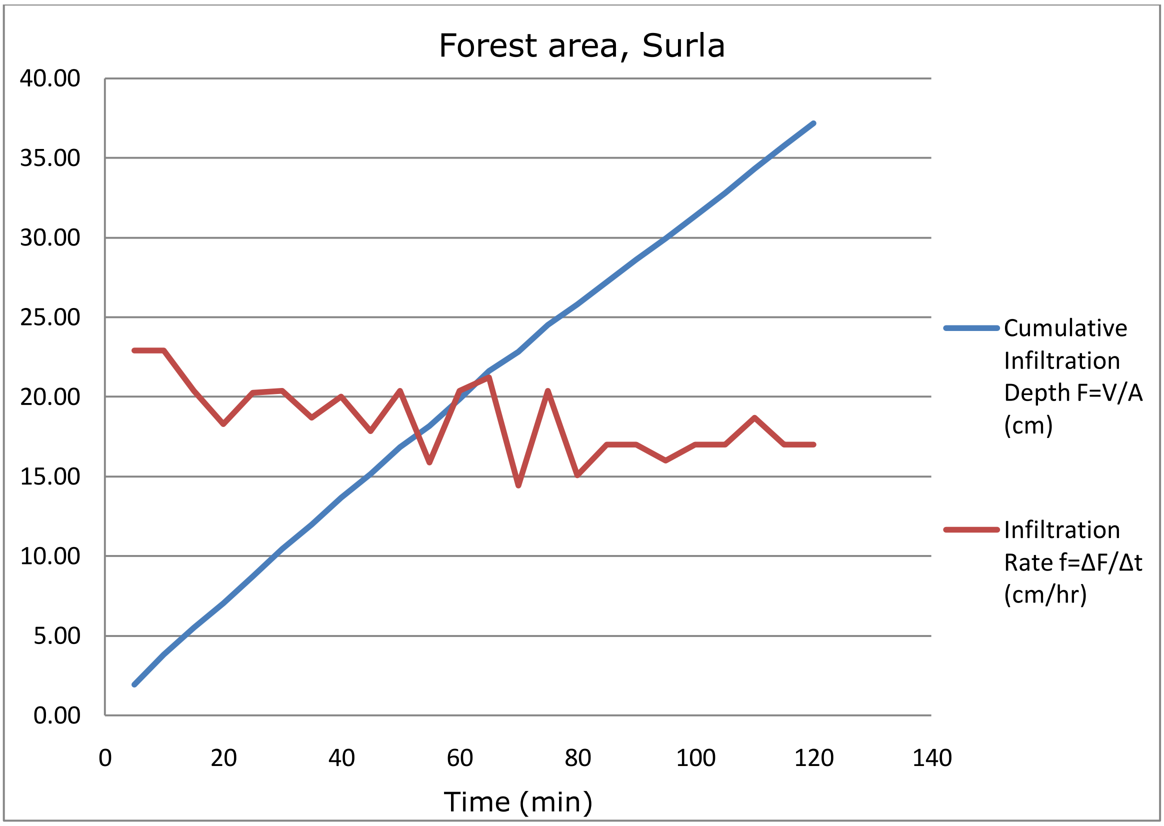


Figure 4.47 Variation of infiltration rate with time at infiltration test No.5

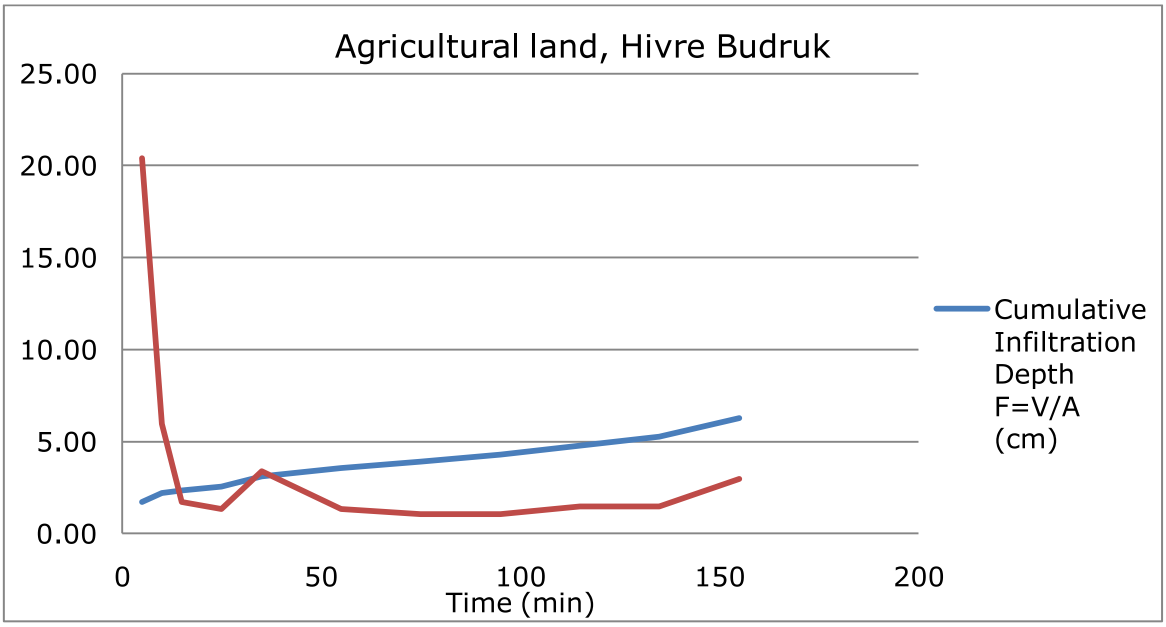


Figure 4.48 Variation of infiltration rate with time at infiltration test No.6

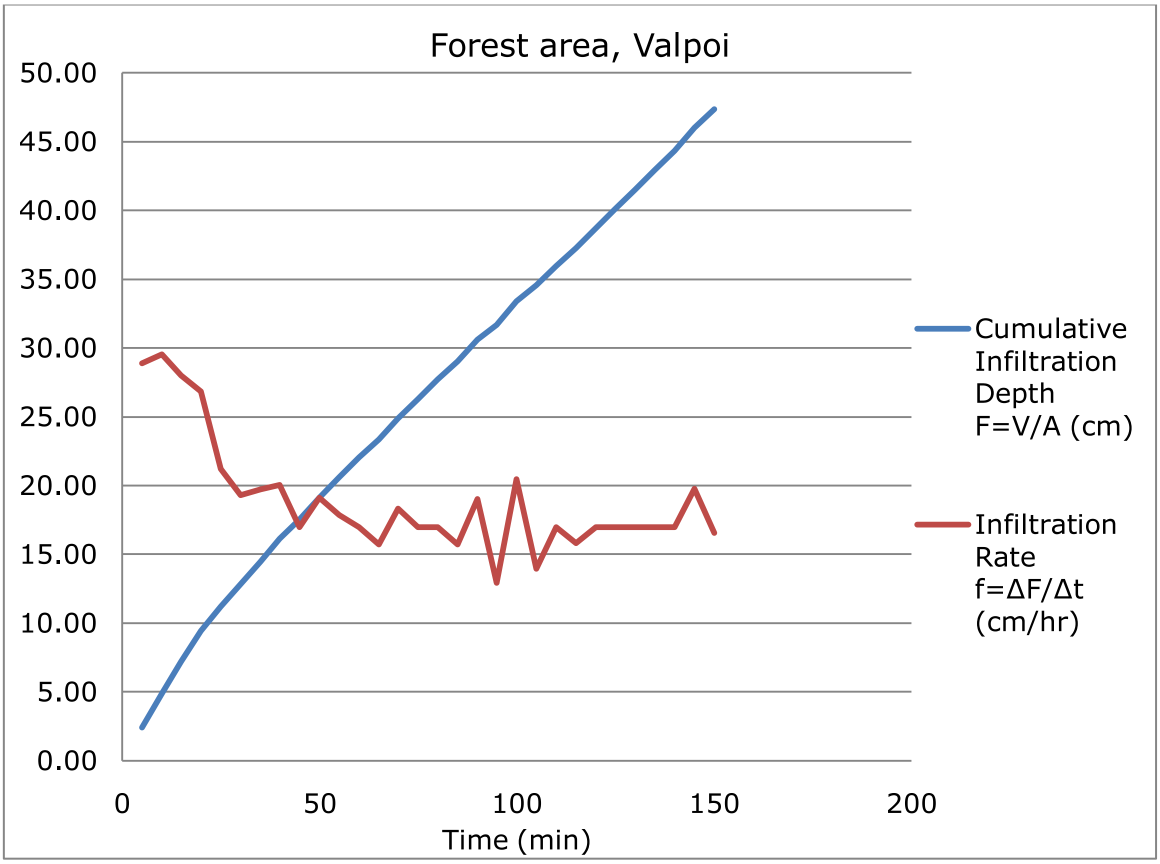


Figure 4.49 Variation of infiltration rate with time at infiltration test No.7

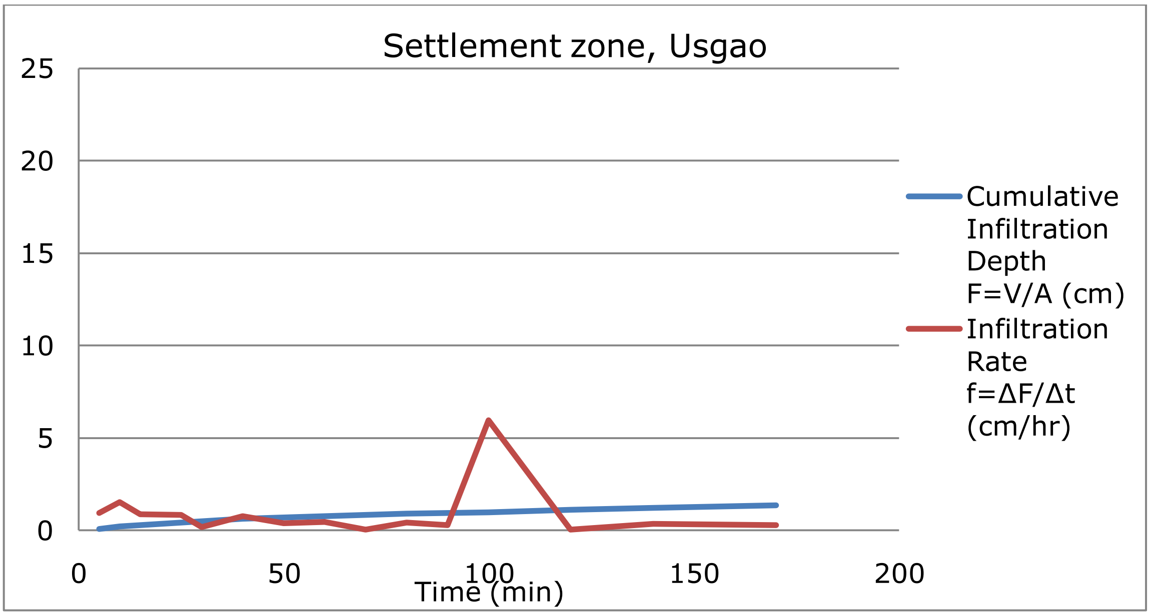


Figure 4.50 Variation of infiltration rate with time at infiltration test No.8

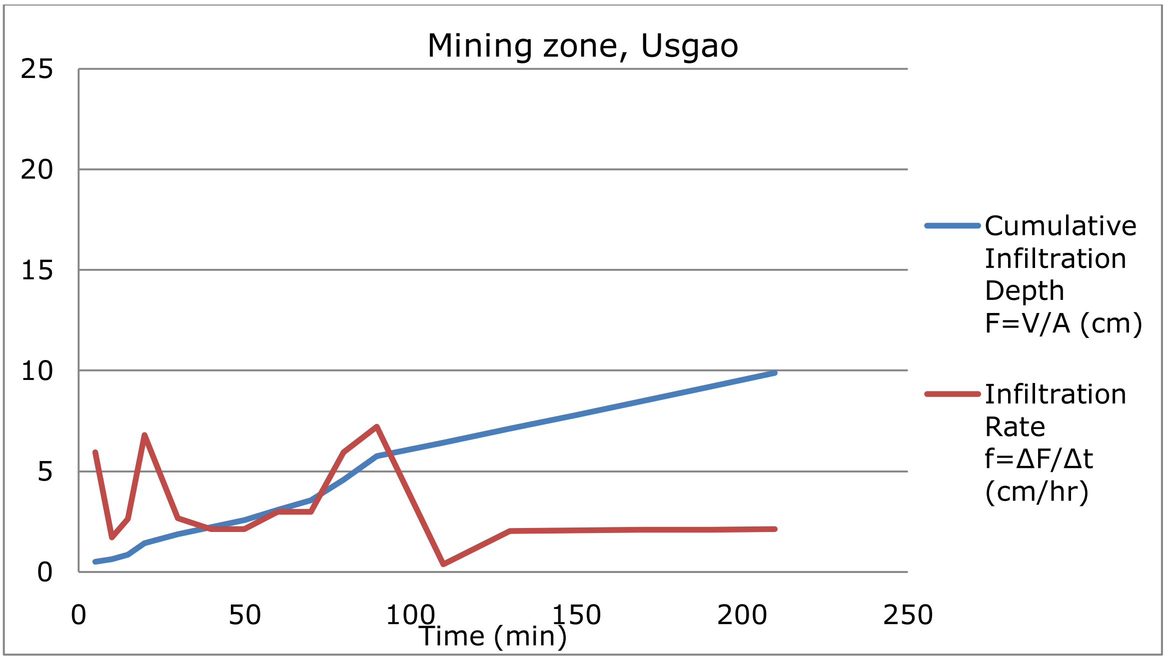


Figure 4.51 Variation of infiltration rate with time at infiltration test No.9

The plots of infiltration rates at all the test sites indicate that the infiltration rate is high at the beginning of the process however it stabilises as soon as the infiltration passes through the top root zone of the soil. It is also observed that the infiltration rate in the forest areas fluctuates highly compared to the more uniform infiltration rates in other areas. The spiked nature of the infiltration curves in forest sites is usually attributed to the escape of the entrapped air in the porous soils.

The steady state infiltration rates along with cumulative infiltration depths and accumulated infiltrations of all the test sites are summarised in Table 4.34.

Table 4.34 Summary of infiltration rates in various land-use types in Mhadei River watershed

Infiltra-tion test No.	Land-use type	Duration of test (min)	Cumulative Infiltration Depth (cm/hr)	Final Infiltration Rate (cm/hr)	Accumu-lated Infiltration (cm)
1	Plantation	150	7.46	2.41	36.74
2	Forest	150	47.38	16.56	75.26
3	Agriculture	135	9.35	3.57	195.29
4	Forest	120	84.01	38.22	73.64
5	Forest	120	37.17	16.99	197.41
6	Agriculture	155	2.58	0.32	0.053
7	Forest	155	39.98	11.89	83.23
8	Settlement	170	1.27	0.28	29.89
9	Mining	210	5.54	1.27	84.75

As seen from the table, the forest land shows high but variable steady state infiltration rates ranging from 11 cm/hr to 38 cm/hr as compared to other land-use types such as agricultural land, settlement, plantation and mining zones which show infiltration rates between 0.28 cm/hr to 3.57 cm/hr.

4.11 Groundwater Availability

The thickness of the water column during the dry season (pre-monsoon) in a dug well is a good indicator of groundwater availability in a region provided the well has been dug through the entire thickness of the unconfined aquifer. Assuming that the dug wells in the Mhadei River watershed have been dug through the entire thickness of the unconfined aquifer, the wells have been classified based on the thickness of the water column.

In order to achieve this ad-hoc classification, the thickness of the water column in each observation well has been computed by subtracting the depth to groundwater level below ground from total depth of the well below ground. This has been done for post-monsoon (November) and pre-monsoon (May) seasons of the three consecutive years of water level observations and an average value has been computed (Table 4.35). The percentage water column in the month of May compared to the post-monsoon (November) water column is considered as a deciding criterion. If the water column in a well in May remain 50% and above of the post-monsoon water level then the water availability is considered as good, if between 25% and 50% is considered moderate and less than 25% is considered poor.

Table 4.35 Average thickness of water column (m) in each observation well for three consecutive years

Sr. No.	Well No.	Average pre-monsoon (May)	Average post-monsoon (November)	Percentage water column during May	Water availability
1	4	0.32	1.78	18	Poor
2	5	1.05	3.30	32	Moderate
3	6	0.66	1.98	33	Moderate
4	19	0.69	1.44	48	Moderate
5	28	0.50	1.18	42	Moderate
6	36	1.62	3.51	46	Moderate
7	37	1.68	3.55	47	Moderate
8	38	0.51	0.89	57	Good
9	39	2.63	5.91	45	Moderate
10	40	1.87	5.21	36	Moderate
11	41	1.16	3.56	33	Moderate
12	42	1.20	4.21	28	Moderate
13	43	1.21	2.72	45	Moderate
14	44	2.33	3.34	70	Good
15	45	1.05	3.30	28	Moderate
16	46	1.06	3.66	29	Moderate
17	47	1.48	1.95	76	Good
18	48	1.19	2.79	43	Moderate
19	49	0.50	4.31	12	Poor
20	50	0.39	2.35	15	Poor
21	51	0.44	1.22	36	Moderate
22	53	0.55	1.43	38	Moderate
23	54	2.16	3.13	69	Good
24	55	0.42	1.87	22	Poor
25	56	1.25	2.89	43	Moderate
26	57	1.38	3.07	45	Moderate
27	58	0.86	3.67	23	Poor
28	59	3.24	4.68	69	Good
29	60	0.16	0.29	55	Good
30	61	0.94	2.54	37	Moderate
31	62	0.38	0.68	56	Good
32	63	0.42	1.33	32	Moderate
33	66	1.43	1.51	95	Good
34	67	0.37	1.61	23	Poor
35	68	0.25	0.80	31	Moderate
36	70	0.24	1.54	16	Poor
37	71	0.70	3.62	19	Poor
38	72	2.33	5.03	46	Moderate
39	73	1.87	0.76	246	Good

Table 4.35 continued

40	74	1.54	1.88	82	Good
41	76	1.11	1.64	68	Good
42	77	0.91	3.12	29	Moderate
43	78	1.56	4.29	36	Moderate
44	79	3.73	5.61	66	Good
45	80	3.17	3.44	92	Good
46	81	2.07	4.09	51	Good
47	82	0.99	2.04	49	Moderate
48	83	1.66	2.17	77	Good
49	84	1.05	2.14	49	Moderate
50	85	1.24	1.75	71	Good
51	86	0.59	0.68	87	Good
52	87	0.93	1.02	91	Good
53	88	1.54	2.19	70	Good
54	89	2.20	1.84	119	Good
55	90	NA	NA	-	Moderate
56	91	1.20	1.20	100	Good
57	92	0.54	0.56	96	Good
58	93	1.30	2.21	59	Good
59	94	1.89	1.98	95	Good
60	95	0.67	2.15	31	Moderate
61	96	0.60	0.88	68	Good
62	97	0.70	1.05	67	Good
63	98	1.17	2.02	58	Good
64	99	1.15	3.77	30	Moderate
65	100	1.16	2.10	55	Good
66	101	0.74	4.17	18	Poor
67	102	1.39	2.84	49	Moderate
68	103	3.01	6.28	48	Moderate
69	104	2.72	6.46	42	Moderate
70	105	0.69	4.08	17	Poor
71	106	0.97	3.05	32	Moderate
72	107	0.53	2.79	19	Poor
73	108	1.08	1.25	86	Good
74	109	0.83	2.29	36	Moderate
75	110	1.21	3.15	38	Moderate
76	111	0.37	0.62	60	Good
77	112	0.92	2.29	40	Moderate
78	113	3.10	4.63	67	Good
79	114	0.85	1.56	54	Good
80	115	3.43	5.90	58	Good
81	116	0.93	2.20	42	Moderate
82	117	1.50	1.90	79	Good

The classification of well-aquifer potential based on percentage thickness of the water column during the pre-monsoon season has been shown in Table 4.36 and Figure 4.52.

Table 4.36 Classification of the percentage thickness of water column during pre-monsoon season

Sr. No.	Percentage thickness of pre-monsoon water column	Category of well-aquifer potential	No. of wells	Percentage
1	>50%	Good	34	42%
2	50 to 25%	Moderate	37	45%
3	<25%	Poor	11	13%

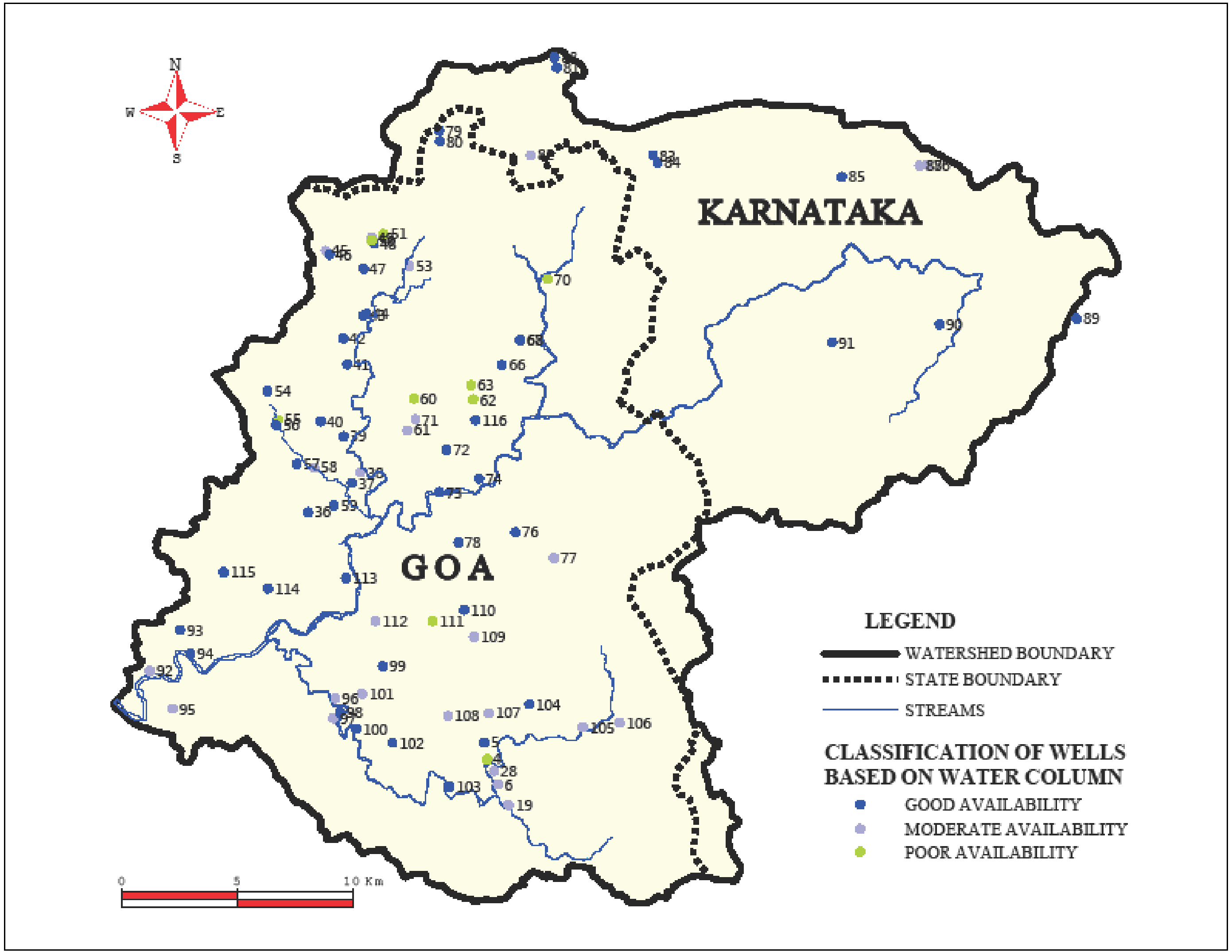


Figure 4.52 Classification of wells based on height of water column in the wells during pre-monsoon season

4.12 Identification of Groundwater Potential Zones

Conventionally, the groundwater potential zones are identified using indirect indicators such as geology, geomorphology, ground slope, land use pattern, soil cover, drainage density, lineament density, aquifer types, etc. These indicators are combined using GIS modelling technique of Weighted Index Overlay Analysis. In the present study, a new approach has been derived and adopted for mapping of the groundwater potential zones. Two new parameters, termed, ‘specific recharge’ and ‘relative fall’ of groundwater level derived from well hydrographs in conjunction with ‘percentage thickness of water column’ in wells during pre-monsoon season have been used to identify groundwater potential zones in the watershed.

In order to achieve this, each class of every parameter has been assigned decreasing rating from 3 to 1. Higher rating indicates good groundwater potential and vice-versa. Each parameter is considered to have equal weight (Table 4.37). Using these ratings and weights, groundwater potential index values have been computed for each well.

Table 4.37 Assigned ratings and weights to integrate parameters indicative of groundwater potential

Parameter	Class	Category	Rating	Parameter Weight	Index
Specific Recharge	>1	Good	3	1	3
	1-0.5	Moderate	2		2
	<0.5	Poor	1		1
Relative Fall	<50%	Good	3	1	3
	50-75%	Moderate	2		2
	>75%	Poor	1		1
Percentage thickness of water column	>50%	Good	3	1	3
	50-25%	Moderate	2		2
	<25%	Poor	1		1

Thus, each well can have a Groundwater Potential Index Value (GPIV) of minimum 3 and maximum 9. Using this index value for each well, contour map has been prepared for the entire watershed. Based on the index value of these contours, the watershed has been divided into three categories of aquifer potential as shown in Table 4.38 and Fig. 4.53.

Table 4.38 Categorization of Groundwater Potential Index Values

Sr. No.	Groundwater Potential Index Value	Aquifer potential zone
1	>7	Good
2	7 – 6	Moderate
3	<6	Scarcity

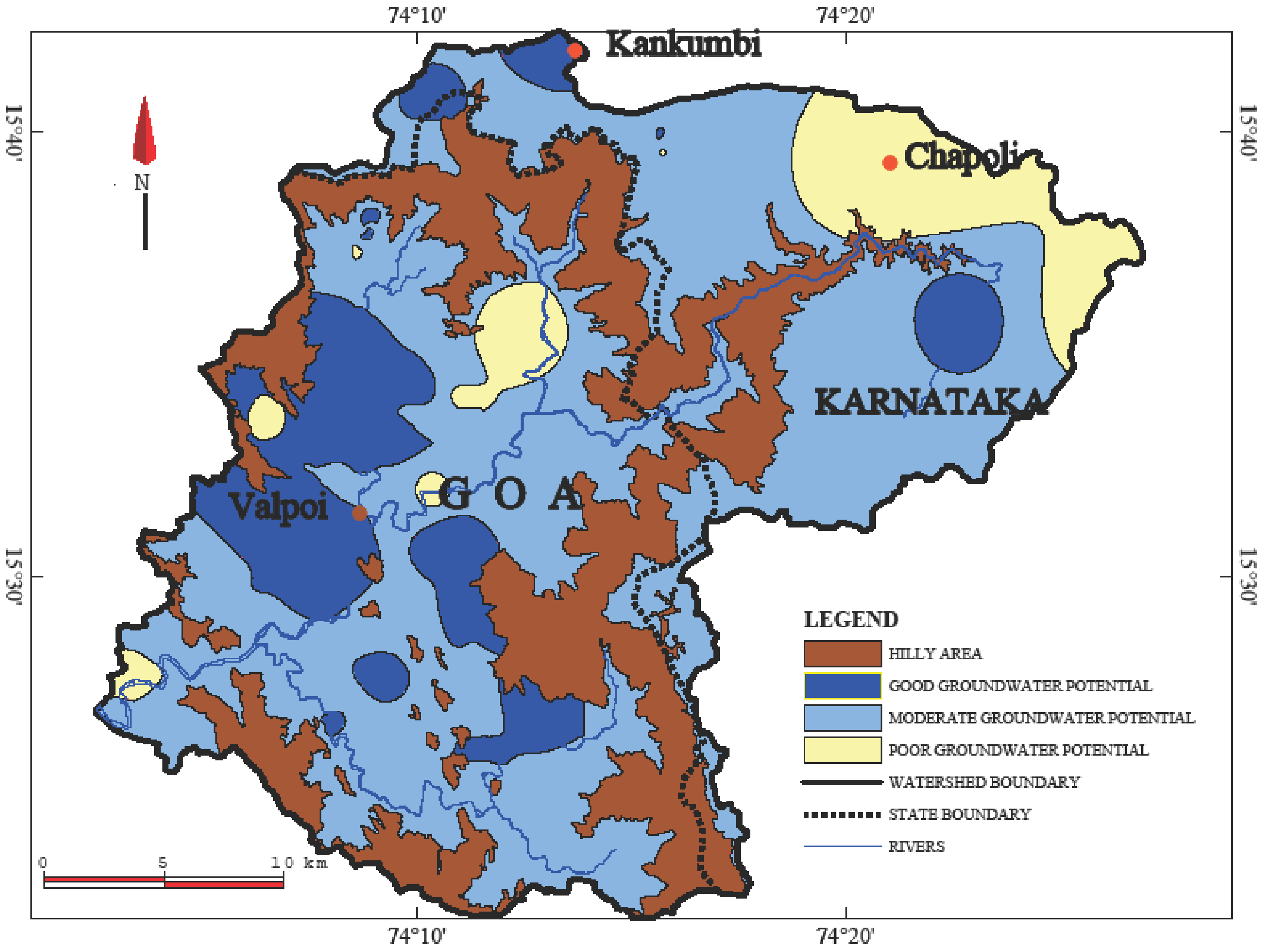


Figure 4.53 Map showing groundwater potential zones in the Mhadei River watershed

As seen from the figure of groundwater potential zones, the area around Valpoi-Mauxi-Koparde-Pali and Bolcornem in Goa region shows good groundwater potential. Similarly the area around Surla, Kankumbi and Kongle in Karnataka plateau region shows good groundwater potential. However, area around Kodal and Dabem in Goa region and Chapoli-Kapoli-Nerse in Karnataka region shows poor groundwater potential zones. The rest of the areas in the Mhadei watershed show moderate groundwater potential. An overlay of the groundwater potential map on the geological map of the watershed indicate that the laterites formed on metabasalts and metagreywackes of the Vageri Formation give better yield followed by laterites developed on phyllites. On the other hand, the groundwater potential on the Karnataka plateau is mainly governed by the intensity of fracturing and weathering of the rocks.

4.13 Discussion

Laterite is the most widespread aquifer in the Mhadei River watershed. Groundwater occurs in water table condition in this aquifer and is extensively used for domestic and irrigation purposes. Valley fill deposits and weathered basalts also constitute important unconfined aquifers locally. However, the confined aquifers of iron ore bodies and fractured schistose rocks are rarely utilised. The groundwater level in the unconfined aquifers is less than 6 m bgl even during the dry season indicating occurrence of groundwater at shallow depth in the watershed. Though there is a considerable rise in water table due to rainfall recharge during the monsoon season, the water levels fall rapidly as soon as the withdrawal of monsoon indicating fairly drainable nature of the unconfined aquifers along with topographical slopes. The water table fluctuation is less than 2m over a large area of the watershed resulting in a small quantity of the dynamic groundwater resource in the watershed. Two domains of groundwater occur in the watershed at two different topographic levels separated by the Western Ghats escarpment. The Mhadei River and its tributaries are effluent in nature and receive baseflow from the two domains of groundwater throughout the year. The area around Dhave village is a major recharge zone in the watershed. The transmissivity values of the unconfined aquifers in the watershed vary from 4 m^2/day to 216 m^2/day indicating inhomogeneous nature of shallow aquifers. The average transmissivity and the average specific yield are computed as 60 m^2/day and 0.05

(5%) respectively. The groundwater recharge computed by water table fluctuation method is 4186 ham and therefore the rainfall infiltration factor should be taken as 0.02 for the Mhadei River watershed. The area around Valpoi-Mauxi-Koparde-Pali and Bolcornem in Goa region and the area around Surla, Kankumbi and Kongle in Karnataka region show good groundwater potential and therefore, may be considered for future groundwater development programs in the watershed. However, the area around Kodal and Dabem in Goa region and Chapoli-Kapoli-Nerse in Karnataka region have been identified as groundwater scarcity zones and therefore groundwater augmentation measures should be initiated on priority basis in these regions.

CHAPTER 5

IMPACT ASSESSMENT OF SURFACE WATER DEVELOPMENT PROJECTS ON THE DOWNSTREAM HYDROLOGICAL REGIME OF MHADEI RIVER WATERSHED

5.1 Introduction

When a river system drains more than one State the task of equitable distribution of its water resources becomes difficult and questionable. Harnessing of the river water by the riparian states in the upper reaches of the watershed often leads to interstate conflicts. Several interstate river water disputes have arose in parts of India. The present study area i.e. the watershed of Mhadei River is partly located in Goa and partly in Karnataka making it an interstate river. Mhadei River has been under scrutiny for such an activity of water harnessing by the neighboring state of Karnataka. The government of Karnataka has proposed to build river water retention (dams/bandharas) and diversion structures (channels/water conduits) in the upper reaches of Mhadei River that lies in Karnataka state. The State of Goa has expressed concern about the likely effects of such river water retention and diversion structures on the hydrological regime, ecological balance and economic development in the lower reaches of the Mhadei River watershed.

However, on the other hand, the Karnataka Government intends to supply drinking water from the proposed projects to its developing towns like Dharwad and Hubli, which otherwise face acute shortage of drinking water.

The proposed construction of dams across some upstream tributaries of Mhadei River has raised an alarm in the State of Goa so much so that the Government of Goa approached the Supreme Court in 2006 in order to restrain the Government of Karnataka from proceeding with the planning, construction and water regulation of any project in the Mhadei river basin involving trans-basin diversion of water. The Government of Goa had also requested the Central Government in 2002 to constitute Mandovi/Mhadei Interstate River Water Dispute Tribunal to adjudicate and resolve the interstate dispute.

The Karnataka Government has been quite aggressive in its approach and went on with the construction work unwilling to give consideration to the issues raised by Goa. Subsequently, the Central Government approved the proposal for constitution of Mhadei Water Disputes Tribunal in 2009.

5.2 Proposed River Water Retention and Diversion Structures

The Karnataka Government has proposed six water retention structures (dams/bandharas) in part of the watershed of Mhadei River lying in Karnataka State (Figs. 5.1 to 5.5). The reservoirs of these water retention structures will be connected to the streams of Malaprabha River through channels / water conduits (based on data provided by Irrigation Department of Government of Karnataka to the Water

Resources Department of Government of Goa as on 2007). The main aim of this diversion is to augment drinking water supplies to major cities like Dharwad and Hubli through Malaprabha dam at Saundatti built on Malprabha River. Karnataka proposes to divert 7.56 TMC ft (214 MCM) of water per year from these projects. The projects will be implemented in two stages. Stage-I consists of three phases, of which Phase-1 involves construction of Kalsa dam on Kalsa nala, a fourth order stream of Mhadei river and diversion of water to Malaprabha valley through a channel having a length of 4.65 km. Phase-2 and Phase -3 consists of construction of dams and channels on streams outside the Mhadei River watershed. Stage-II involves construction of Kotni dam at the confluence of Kotni nadi with Mahadayi stream. The water will be diverted from this reservoir to the Malaprabha River through Singar Nala and a channel / tunnel of 5.7 km length having a discharge capacity of 14.57 cubic meters per second (cumec). The details regarding the catchment area of these structures have been procured from the Water Resources Department, Govt. of Goa as provided by the Karnataka Government and are also estimated during the present study. The data is given in Table 5.1.

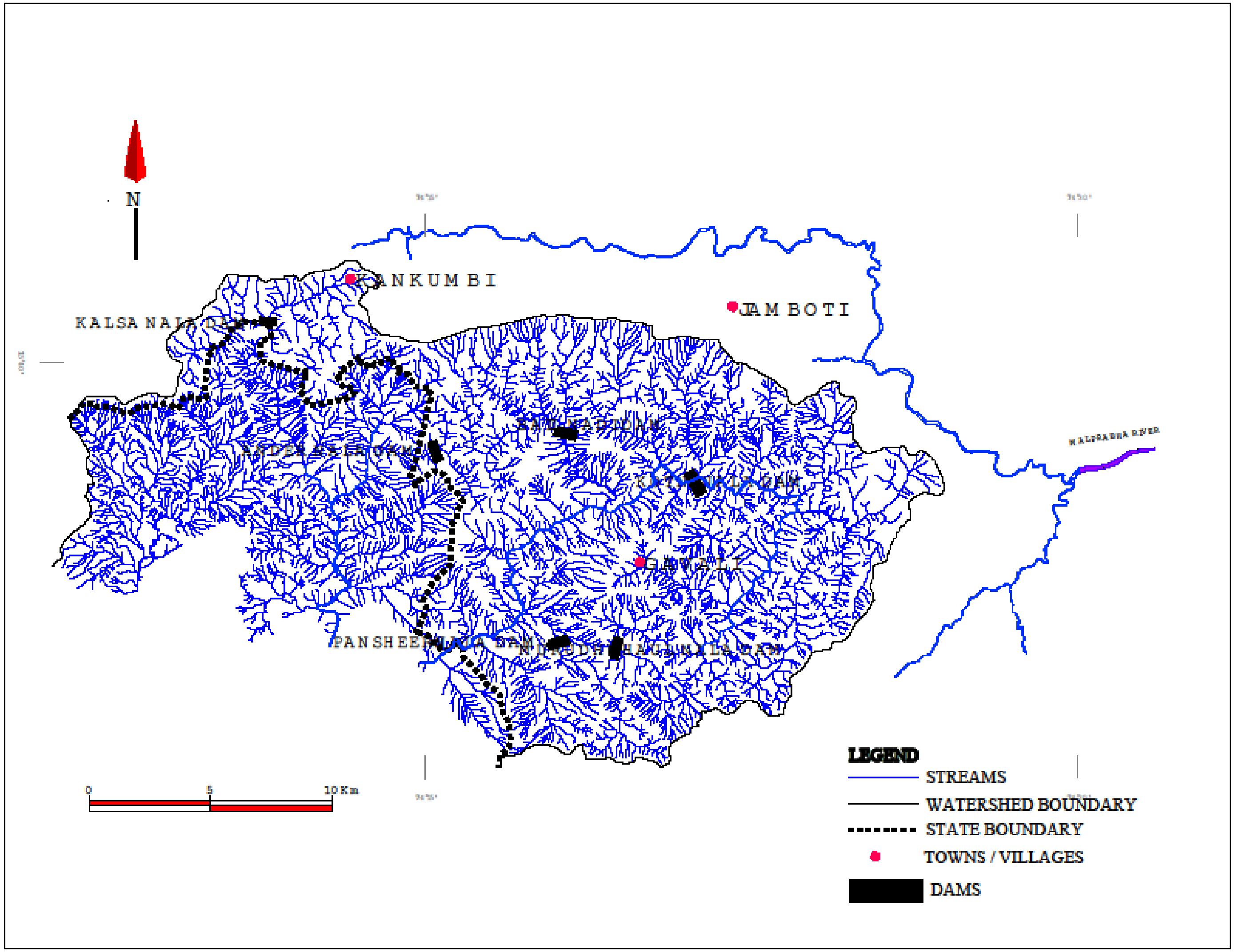


Figure 5.1 Location of proposed river water development structures in the Karnataka region of the Mhadei River watershed

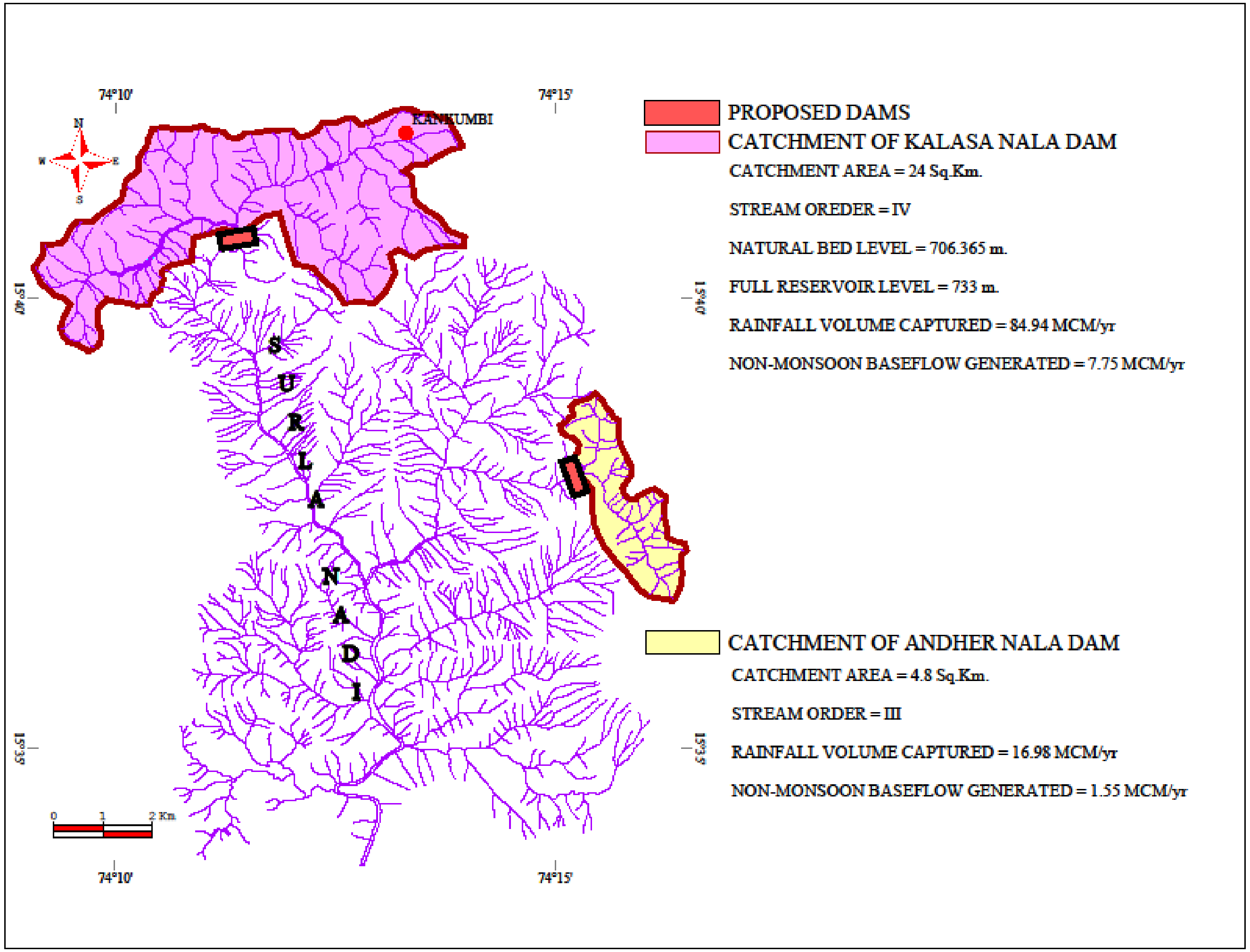
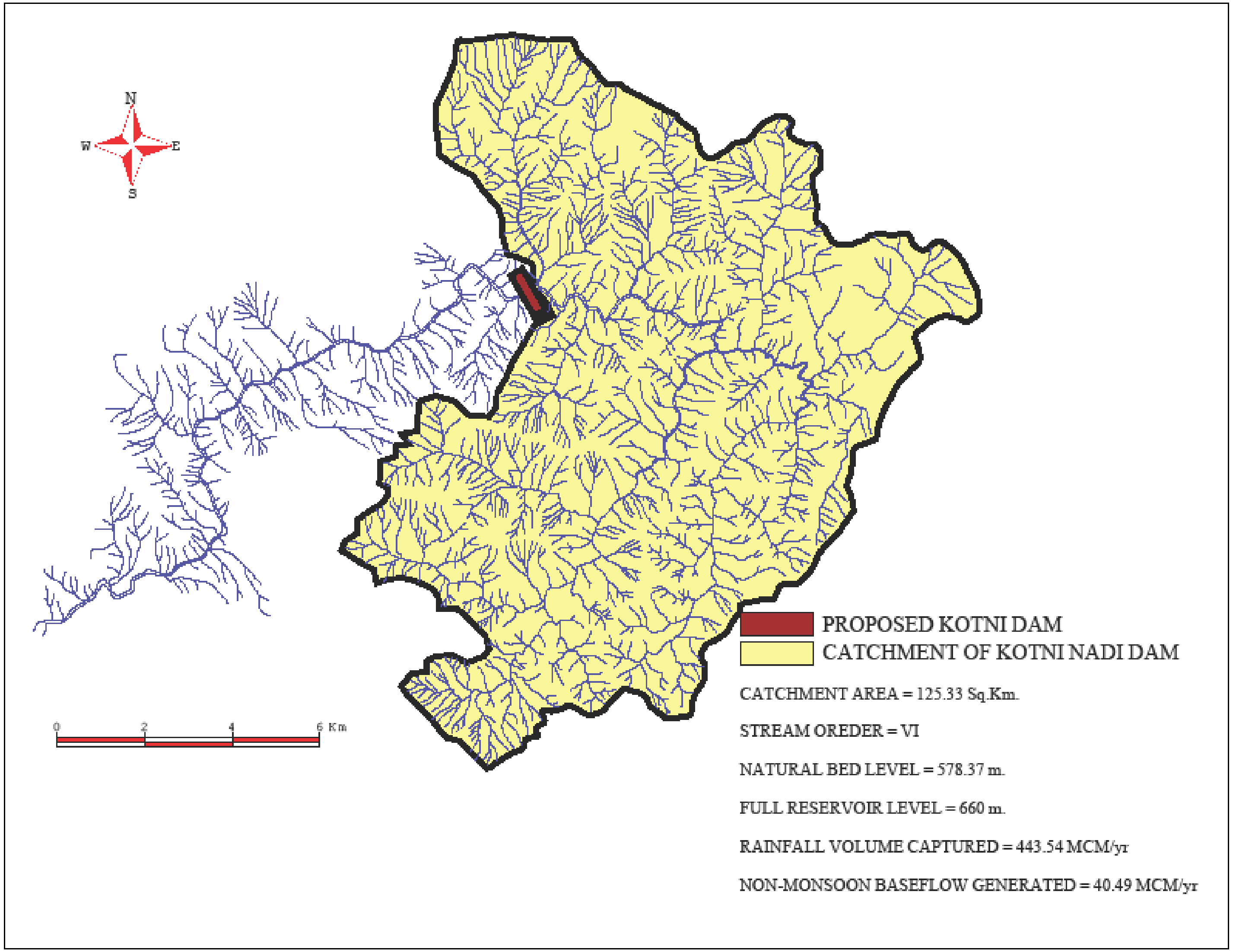


Figure 5.2 Catchment areas of the proposed Kalasa Nala dam and Andher Nala dam in the Mhadei River watershed



CATCHMENT AREA = 125.33 Sq.Km.

STREAM OREDER = VI

NATURAL BED LEVEL = 578.37 m.

FULL RESERVOIR LEVEL = 660 m.

RAINFALL VOLUME CAPTURED = 443.54 MCM/yr

NON-MONSOON BASEFLOW GENERATED = 40.49 MCM/yr

Figure 5.3 Catchment area of the proposed Kotni Nala dam in the Mhadei River watershed

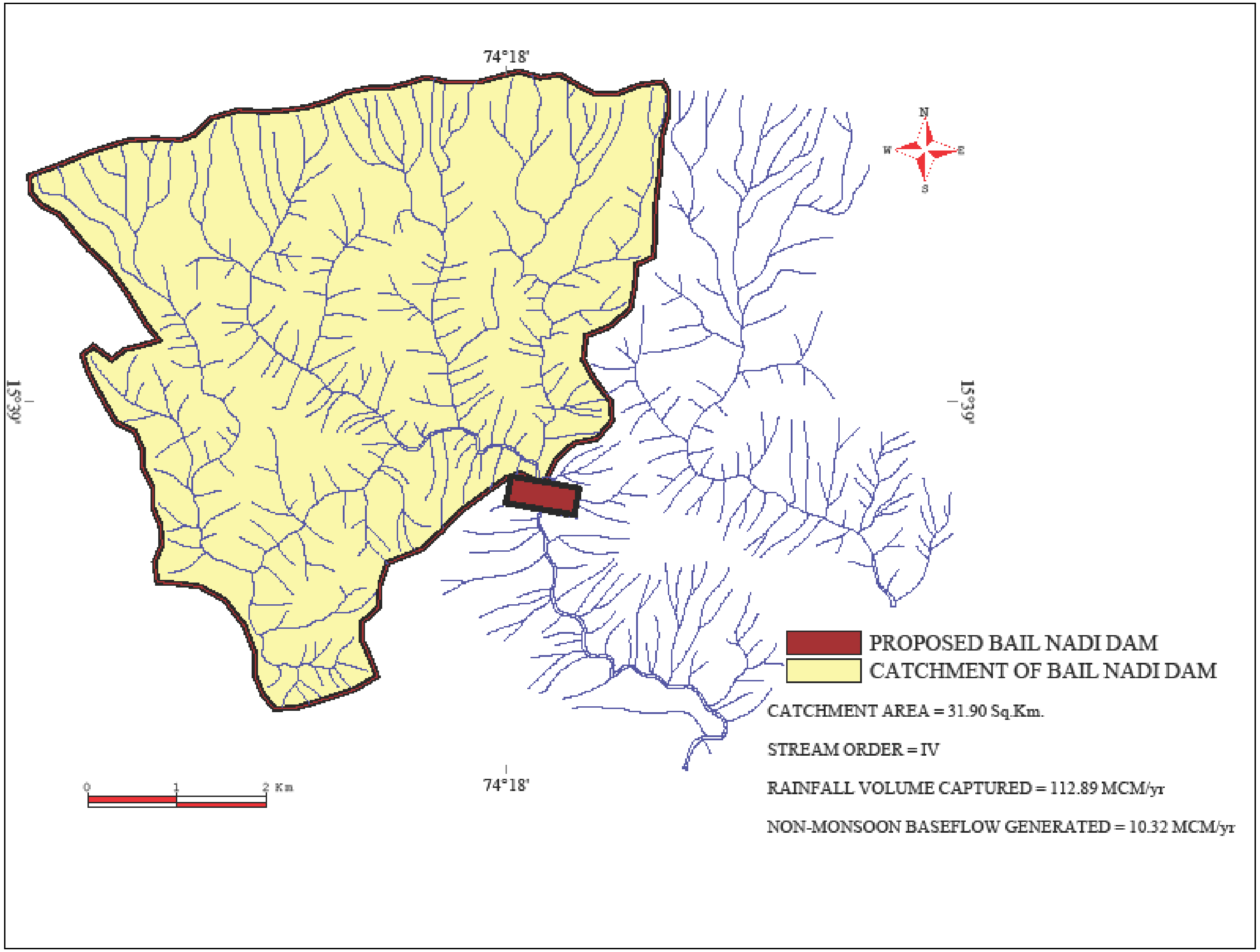


Figure 5.4 Catchment area of the proposed Bail Nala dam in the Mhadei River watershed

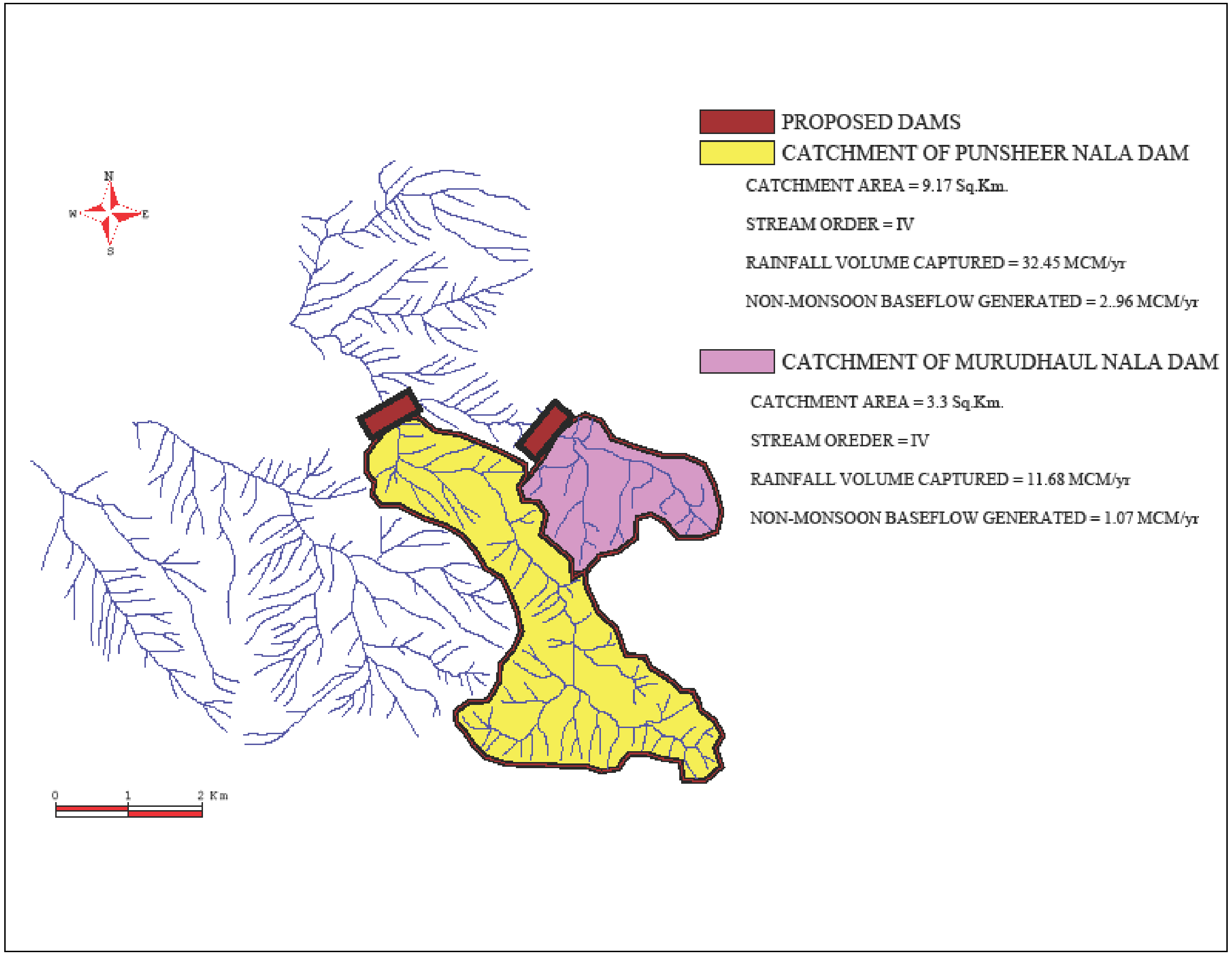


Figure 5.5 Catchment areas of the proposed Punsheer Nala dam and Murudhaul Nala dam in the Mhadei River watershed

Table 5.1 Catchment areas of each proposed water retention structure in the Mhadei River watershed lying in Karnataka.

Sr. No.	Name of the proposed structure	Stream Order	Catchment area (km^2)		
			As per Karnataka govt. data	Estimated during present study	Area adopted for run-off computation
1	Kalsa Nala	IV	24.00	20.25	24.00
2	Kotni Nala	VI	124.43	125.33	125.33
3	Andher Nala	III	4.80	4.80	4.80
4	Bail Nala	IV	31.90	31.80	31.90
5	Punsheer Nala	IV	4.50	9.17	9.17
6	MurudhaulNala	IV	3.30	3.05	3.30
	TOTAL		192.93	194.40	198.50

All the catchment areas reported by the Karnataka Government are in close agreement with the computed values except at Punsheer Nala structure. This possible discrepancy could be due to inaccurate location of the proposed structure in the watershed map. For the computation of the run-off, the higher values of the catchment area are considered to be on a safer side.

5.3 Environmental Impact Analysis

Under natural conditions, various fluxes of matter and energy are in dynamic equilibrium. These fluxes could involve energy flux, material flux and biological flux. The dynamic equilibrium of fluxes gets disturbed when a stress is imposed on these fluxes either by natural processes or man-made activities. The changed regime of fluxes can render influence on various environmental and ecological parameters with which these fluxes were interacting before the stresses are imposed.

In the Mhadei River watershed, it has been proposed to build as many as six water retention and diversion structures in the area lying in Karnataka. Under the present circumstances, the fluxes are towards Arabian Sea in south-west direction; however post-retention fluxes are going to be reoriented towards east for augmenting river flows of Malaprabha River. Therefore, there is a total reversal in the direction of fluxes. The various fluxes that are likely to be involved are being discussed here include:

1. Volume of water flux
2. Sediment flux
3. Biological flux
4. Energy flux
5. Water quality flux

Therefore, it involves a complex interaction of energy with material and biological matters.

In order to assess the environmental impacts arising out of these water retention and diversion projects, the catchment areas of the water retention structures have been computed as shown in Figs. 5.1 to 5.5. The volume of surface run-off generated from the catchments of each dam has been computed by considering the average rainfall in the Karnataka area (as computed in Chapter 2). The baseflow generated from watershed of each dam has also been estimated by adopting the values of unit area baseflow (as computed in Chapter 2) for the Karnataka region. The details are given in Table 5.2.

Table 5.2 Surface run-off and baseflow components of the proposed water retention structures.

Name of the water retention structure	Catch-ment area (km²)	Surface Run-off volume (MCM/yr)	% of total monsoon rainfall received in the watershed	Computed base flow for non-monsoon months (MCM/yr)	% of baseflow measured at Ganjem station
Kalsa nala	24.0	84.94	2.73	7.75	2.7
Kotni nala	125.33	443.54	13.46	40.49	14.21
Andher nala	4.8	16.98	0.51	1.55	0.54
Bail nala	31.9	112.89	3.42	10.31	3.62
Punsheer nala	9.17	32.45	0.98	2.96	1.04
Murudhahaul	3.3	11.68	0.35	1.07	0.38
TOTAL	**198.5**	**702.48**	**21.45**	**64.13**	**22.49**

It is seen from Table 5.2, that the total area of catchments of all the proposed water retention structures is 198.5 km^2 which is 61% of the area of the Mhadei River watershed that lies in Karnataka and 22% of the total area of the Mhadei River watershed. The average annual discharge measured at the Ganje river-gauging station located on the Mhadei River outlet is 3447 MCM/yr. The total volume of rainwater that will be captured in the catchments of all the proposed water retention structures is 702.48 MCM/yr which is 21% of the total volume of monsoon rainfall received in the Mhadei River watershed.

The average baseflow measured for the Mhadei River at Ganje river-gauging station for non-monsoon season is 285 MCM/yr. The base flow contribution from Karnataka region for non-monsoon season is 109 MCM/yr which is 38% of the total base flow. The total base flow generated from catchments of all the six water retention structures for non-monsoon season is 64 MCM/yr. The above computed base flow contribution from catchments of all the structures is 61% of the base flow of the Karnataka region and 22% of the total base flow measured at Ganje station in Goa. The maximum baseflow comes from Kotni nala area which is 38% of all the base flow from Karnataka and 14% of the entire Mhadei River watershed. Thus, the cumulative proposed retention volume of water behind these proposed structures is about 702 MCM/yr which amounts to about 21% of the total volume of monsoon rainfall (3294 MCM) received in the Mhadei River watershed. Karnataka has proposed to divert 7.56 TMC ft (214 MCM) of water from these projects to its Malaprabha River. Besides the surface run-off, about 64 MCM/yr of the baseflow volume which amounts to 22% of the total non-monsoon baseflow of the entire watershed is going to be arrested by these structures.

The following are the probable regimes which are likely to be influenced by the proposed water retention and diversion structures which will approximately retain 21% of the annual monsoon rainfall and 22% of the baseflow during non-monsoon season.

1. **Volume of water flux:**

The surface run-off arising from the monsoon rainfall from June to September flows rapidly with higher velocities, thereby cleansing the river bed downstream of the silt, sediment and other matrix. Once the water is impounded in the structures upstream, the flow volume and hence the velocity of flow would be reduced by about 21% of the pre-retention structures. This may enhance silt accumulation on the river beds downstream due to lack of sufficient flow velocities leading to reduction in river bed percolation rates. This can have adverse impact on groundwater recharge if the river bed is influent in nature. However, the analysis of groundwater flow nets of the study area has revealed that the entire stretch of the Mhadei River watershed is effluent in nature and therefore even if the silt accumulates on the river bed it may not adversely affect groundwater regime. However, continued stream bed siltation would reduce the carrying capacity of the stream which may lead to flooding at selected stream stretches under extreme rainfall events. Further, when the flow volume in the river is reduced the water level stage in the river also gets reduced. As the groundwater table generally intersect the river water level, reduced river level may lead to increased groundwater level gradients adjacent to river banks leading to rapid groundwater drainage and dewatering of the aquifer. This may affect groundwater availability in the immediate vicinity of the river banks (Fig. 5.6).

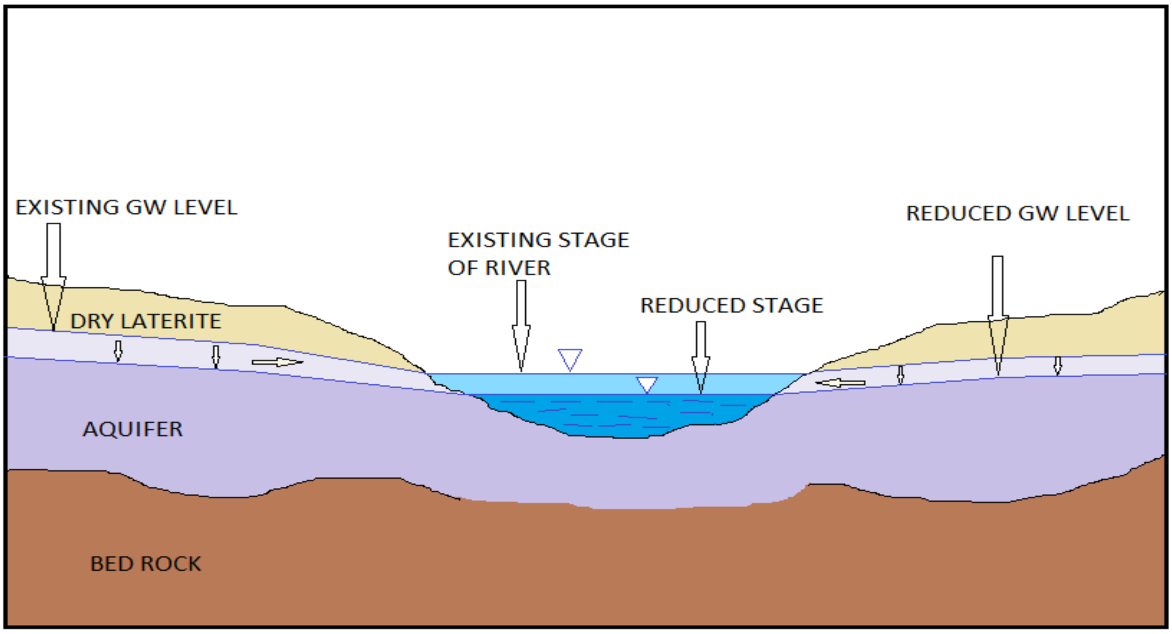


Figure 5.6 Schematic diagram showing the position of water table in response to change in river water level.

The groundwater levels in the Mhadei River watershed rise by almost 3 m during the monsoon season due to highly permeable nature of the unsaturated vadose zone. However, the excess groundwater recharge during the monsoon period is lost immediately after the withdrawal of the monsoon. The rivers in the Mhadei River watershed are effluent in nature and therefore receive baseflow from the groundwater. Therefore, the groundwater levels in the watershed are in equilibrium with the river water levels. Under continued river bed siltation due to reduced stream-flow velocity and volume, the siltation may choke the groundwater inflows into the river. It may also happen that the choking of river bed inhibits the groundwater flow into the river leading to local rise in water table adjacent to river banks which may under situation give rise to shallow water table or water logging conditions (Figs. 5.7A and 5.7B).

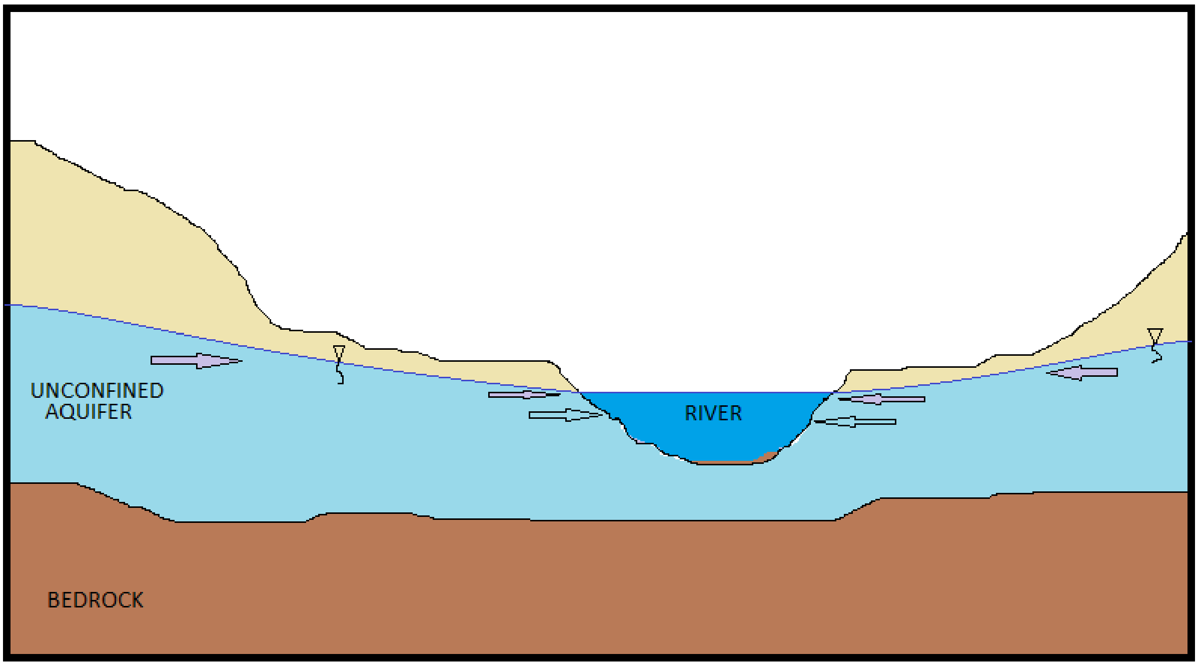


Figure 5.7A Schematic cross-section showing the effluent nature of the Mhadei River (groundwater flowing into the river)

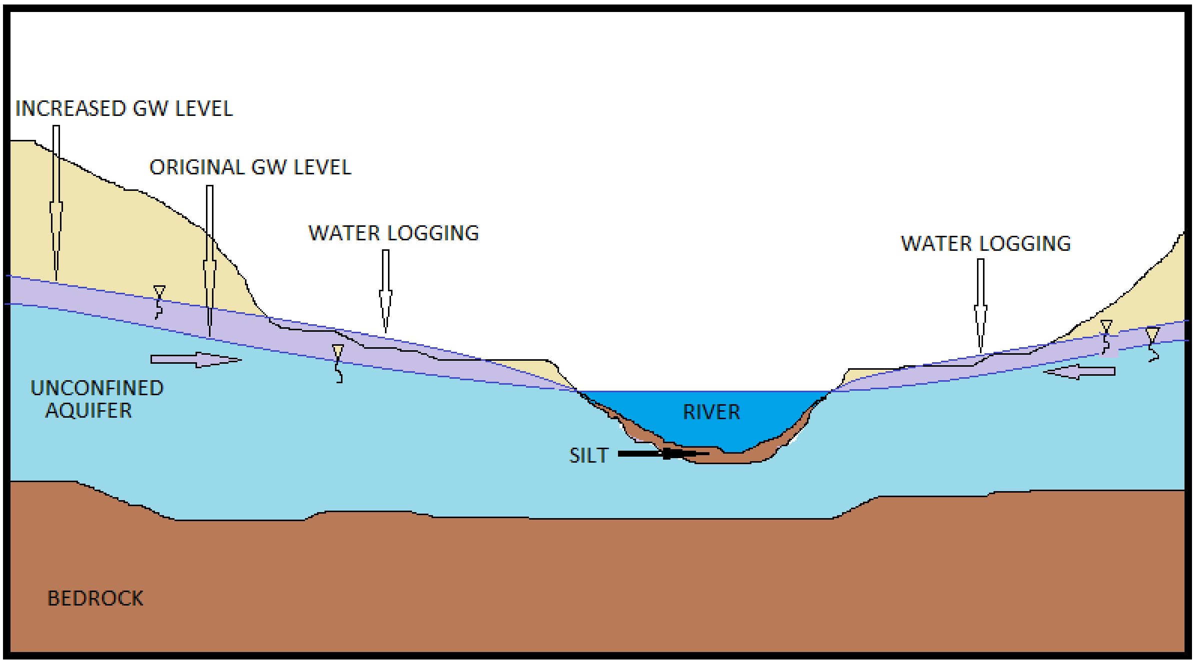


Figure 5.7B Schematic cross-section showing the expected increase in groundwater level thereby causing water logging along the banks of the river as a result of silt accumulation on the river bed due to reduction in surface flow velocity.

There are 32 *bandharas* (temporary water storage structures in the river banks- Plate 5.1) built across the streams of Mhadei and its tributaries to harvest dry weather flow for agricultural and domestic use (Fig. 5.8). Of these, six major bandharas are built across the main Mhadei River channel and have a storage capacity of about 6.8 MCM of water (WRD, 2010). The bandharas store water from October onwards after the cessation of monsoon rainfall and therefore essentially accumulate baseflow coming from the upstream side. A large population depend on this stored water for their domestic and agricultural requirements during the non-monsoon period. Impoundment of baseflow in the proposed water retention structures may deprive these bandharas of the dry weather flows to the tune of 22%.

Plate 5.1 Pictures of bandharas built across the Mhadei River channel at Sonal and Ganje

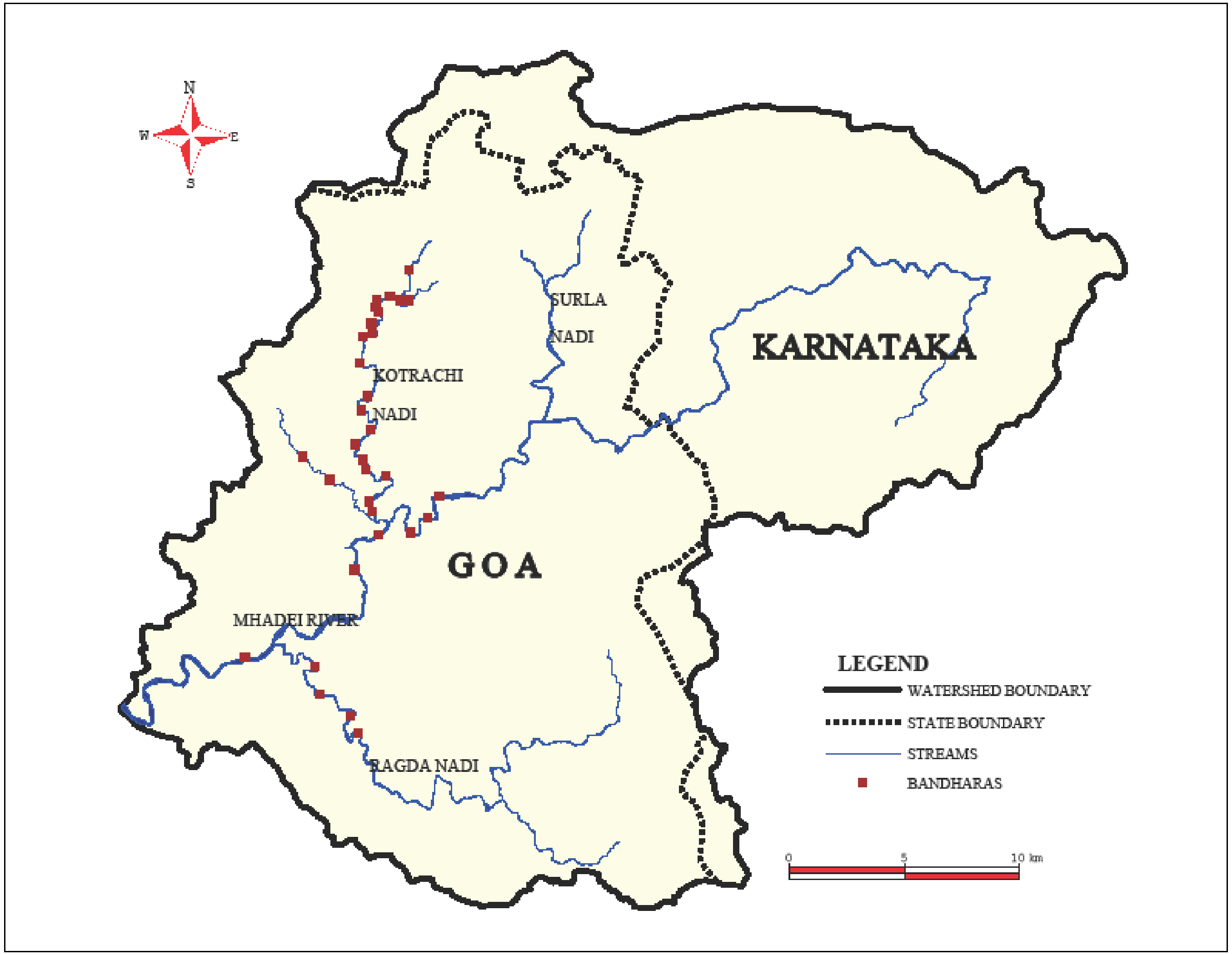


Figure 5.8 Locations of bandharas built across the Mhadei River and its tributaries.

2. **Sediment flux:**

During the monsoon season lot of suspended sediment load is generally carried downstream by the river. The sediment load in the rapidly flowing streams influence the river bank erosion because higher the sediment load, more is the erosion of the river banks. Construction of dams usually inhibits the downstream transport of the suspended sediments as they get accumulated in the reservoir. Therefore, the erodibility of the river bed and banks could be reduced by about 21% as there is a reduction of flows and sediment load to the tune of 21%. Further, the suspended sediments play a crucial role in control of nutrient level in water as the nutrients get adsorbed onto the fine particles.

3. **Biological flux:**

The Mhadei River watershed encompasses wide variety of flora, fauna, microbes and other inorganic nutrients. Western Ghats, which is regarded as one of the hotspots of biodiversity in India with about 1500-1600 endemic species (World Conservation Monitoring Centre, 1992), runs through the centre of the Mhadei River watershed. There are two micro-climatic zones in this watershed- one representing the Karnataka plateau and other downstream of the Western Ghats separated by an elevation of nearly 700-800m. This difference in elevation has a greater influence on the magnitude of rainfall distribution and hence micro-climatic change. There could be some degree of change in the fauna, flora, microbes and nutrient levels in the two micro-climatic zones. Under the natural system of uninterrupted fluxes, the biological flux remains in dynamic equilibrium with the natural exchanges and adaptations of fauna, flora and nutrient levels. The proposed retention of the flows would influence this biological equilibrium and may also affect possible bio-diversity commensurate with the changes.

The biological matrix also constitutes large amounts of nutrients which are essential components for the growth and diversification of flora and fauna downstream. The most important nutrients in surface water are nitrogen, phosphorus and silica. Nitrogen and phosphorus primarily occur in the oxidized forms as nitrate (NO_3^-), nitrite (NO_2^-) and phosphate (PO_4^{-3}). These nutrients are used by the algae and other primary food producers in the food web of the water bodies. Silica (SiO_2) is a key nutrient in diatom production, a very common algal group on which the micro-organisms feed. SiO_2 concentrations can limit diatom production if the surface water is depleted of silica. In rivers, concentrations of all these nutrients primarily depend on the native rock types within the river basin and are closely associated with hydrological variations. Nutrient concentration in non-polluted water bodies vary seasonally with maximum during rainy season. Reduction in the supply of all these nutrients from the upstream of the Mhadei River watershed due to reduction in the flows could influence the intricate balance in the ecosystem of the river downstream.

Reduction in the volume of flow of Mhadei River due to the proposed impoundments will increase the possibility of anthropogenic pollution from agricultural land and settlement areas in the watershed as most of them are located in the downstream side.

4. **Energy flux:**

The Mandovi River stretch constitutes a tidal influx up to Ganjem to a distance of about 40 km inland (about 8 km upstream from the outlet of Mhadei River). Once the energy flux is reduced due to water retention in the upstream side the tidal influence may shift further upstream. This may locally influence the typical biodiversity that is common in the tidal zones. However, under prevailing conditions the interface is largely governed by the topography rather than the freshwater flow mixing (Fig. 5.9). The tidal effect is observed up to a point where the channel elevation is below the sea level. The tide reaches Ganje only when the tide is high enough to overcome the effect of increased channel elevation (Shetye et al, 2007). Therefore, there may not be any significant shift in the interface due to reduction in the flow volume or flow velocity of the river. However, Shetye et al (2007) have shown that the runoff in the Mhadei River is much greater than the volume of the Mandovi River channel and hence, in an average year, the volume of fresh water flowing through the Mhadei River exceeds the volume of the Mandovi estuary by a factor of about 20. Most of this fresh water flux occurs during June-October, implying that the water in the river channel is flushed out and renewed several times during the monsoon season. Such episodes are expected to turn the estuarine water fresh from head to mouth. However, such flushing does not occur during the non-monsoon period because the run-off decreases rapidly. However, even this meagre run-off tend to freshen the channel for some distance (5-10 Km) from the head of the estuary, implying that the salinity should decrease towards the head of the river even during the lean months (Shetye et al, 2007). Thus, reduction in freshwater surface flow by about 21% due to the proposed impoundments and further reduction of the baseflow would tend to increase the salinity in the zone of mixing.

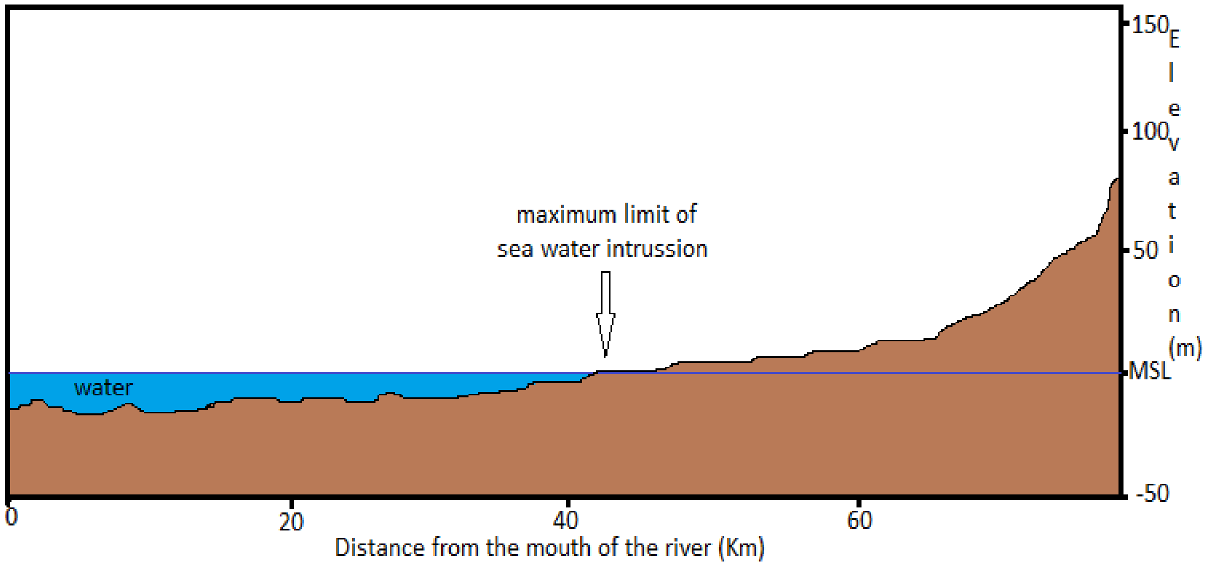


Figure 5.9 A hypothetical section along a line drawn through the Mandovi River channel showing tidal influx up to 40 km inland

5. **Water quality flux:**

When the rainwater falls on the surface of the earth its chemical and biological quality changes due to interaction with the rocks, soils and other matrix. Under natural flow system water gets enriched with minerals depending on the contact time, type of rock, soil and other physico-chemical conditions. The resultant water quality in the downstream of the river system is a cumulative of all the water qualities derived from different geological and agro-climatic domains. The retention of the flows in the upstream of the present watershed is expected to produce some changes in the resultant water quality in the downstream.

Chapter 6

CONCLUSIONS

Hydrological and hydrogeological evaluation of surface water and groundwater resources with watershed as a unit is a prime requirement for sustainable development and management of water resources. The interstate Mhadei River watershed is at the peak of its water resource development strategy. Therefore, a scientific quantitative analysis of its water resources has been carried out during the present study by generating the primary data regarding occurrence, distribution and availability of surface and groundwater resources.

The Mhadei River watershed is located in three distinct physiographic units of the West coast of India, namely, the Coastal low lying region, the Western Ghats and the Karnataka plateau. It receives abundant rainfall generating 3538 MCM of water per year out of which 2383 MCM i.e., 67% is received by Goa and 1155 MCM i.e., 33% is received by Karnataka watershed. However, 97% of the total volume of rainfall is lost as river discharge allowing only about 3% to be distributed between groundwater recharge and evapo-transpiration. The total volume of monsoon rainfall received in the Mhadei River watershed is 3294 MCM while the total volume of non-monsoon rainfall is 244 MCM. The histogram of monthly rainfall versus discharge indicates that the soil moisture retention and groundwater recharge takes place predominantly in the first three months of the rainy season. Stream hydrograph analysis using Constant slope method has been adopted for separation of the baseflow. It is estimated that 638 MCM (19%) of the total annual discharge measured at Ganjem river-gauging station is baseflow component. The baseflow component sustains till January indicating higher groundwater levels during this period. However, it diminishes rapidly then onwards during the summer season. The baseflow contribution from Karnataka region of the watershed has been estimated by computing *unit area baseflow* using stream-flow measurements at the Goa-Karnataka boundary. The Karnataka watershed contributes about 109 MCM (38%) of the total non-monsoon baseflow (285 MCM) of the entire Mhadei River watershed. The dry weather flow is extensively utilized in the downstream region of the watershed by storing the water within river banks by constructing *bandharas* across the streams.

The watershed of the Mhadei River is an integral part of the Mandovi River basin. Therefore, morphometric analysis of both, the Mhadei River watershed and the entire Mandovi River basin has been carried out. About 64% of the Mhadei River watershed lies in Goa and 36% lies in Karnataka. The watershed extends in three distinct physiographic zones namely, the Midland region of Goa, the Western Ghats and the Karnataka Plateau. The Mhadei River attains VIIth order of stream. The stream numbers of all the lower orders follow Horton's law of stream number while the stream lengths follow Horton's law of stream length except the higher order streams which show deviation from the straight line indicating a structural control on their development. The overall drainage pattern in the Mhadei River watershed is dendritic to sub-dendritic. However, IV and V order streams show a common NW-SE to NNW-SSE trend resulting in trellis drainage pattern and high bifurcation ratio along these streams, confirming the structural control on their development along regional Dharwarian NW-SE trend. The shape factors indicate that the watershed is moderately elongated. The drainage texture is medium and the ground is moderately permeable. Thus, the drainage development in the Mhadei River watershed is partially controlled by the underlying rock structure and allows moderate infiltration conditions. Although the infiltration conditions are fairly good, the rainfall recharge rates are moderate. This has been attributed to the widespread forest cover with thick leaf foliage which inhibits rainwater to come in contact with ground. The morphometric parameters indicate an extended but flat peak flow due to semi-elongated shape of the drainage basin.

Laterite, valley fill deposits and weathered and fractured basalts form unconfined aquifers in the Mhadei River watershed. However, the aquifers of weathered and fractured basement rocks and the iron ore deposits are of semi-confined to confined nature. Laterite constitutes the most widespread aquifer containing groundwater at very shallow depths. The average depth to groundwater level below ground in the pre-monsoon season (May) is 5.53 m, in the monsoon season (August) is 2.37 m while that in the post-monsoon season (November) is 4.10

m. It is observed that about 72% of the wells show water table fluctuation of less than 2 m. The average groundwater fluctuation in the low lying region of Goa is 1.57 m while that in Karnataka region is 0.83 m. The study of the temporal variation of the groundwater levels indicates that the water levels remain within the limits of seasonal fluctuation. However, during pre-monsoon season few wells shows declining trend. This has been attributed to the minor declining trend in rainfall during the corresponding period.

There are two groundwater domains in the watershed separated by the Western Ghats escarpment. The two domains show distinct difference in their hydraulic properties as indicated by the spacing of the equi-potential lines in the flow-nets. The groundwater flow lines are directed towards the river reaches indicating effluent nature of the rivers. The region around village Dhave shows presence of a groundwater mound indicating major recharge area. There is a large variation in the transmissivity and specific yield values computed by pumping tests indicating inhomogeneous nature of shallow aquifers in the study area. The average transmissivity and specific yield are computed as 60 m^2/day and 0.05 (5%) respectively. The groundwater recharge estimated using water table fluctuation method separately for Goa and Karnataka regions of the Mhadei River watershed works out to be 2991 ham and 1195 ham respectively. The rainfall infiltration factor worked out in the present study is 2% for the Mhadei River watershed. Infiltration studies carried out in various land-use types in the watershed shows that the forest region has high but variable steady state infiltration rates ranging from 11 cm/hr to 38 cm/hr as compared to other land-use types such as agricultural land, settlement, plantation and mining zones which show infiltration rates between 0.28 cm/hr to 3.57 cm/hr. However, thick foliage in the forest inhibits infiltration resulting in faster run-off.

The groundwater potential zones identified using new approach viz., *specific recharge*, *relative fall* and *percentage thickness of water column* derived from well hydrograph analysis indicates that the area around Valpoi-Mauxi-Koparde-Pali and Bolcornem in Goa region has good groundwater potential. Similarly the area around Surla, Kankumbi and Kongle in Karnataka region shows good groundwater potential. However, area around Kodal and Dabem in Goa region and Chapoli-Kapoli-Nerse in Karnataka region shows poor groundwater potential zones. The rest of the areas in the Mhadei River watershed show moderate groundwater potential.

The Karnataka region of the Mhadei River watershed contributes 33% of the surface run-off and 38% of the non-monsoon baseflow of the entire watershed. The total area of catchments of all the six proposed water retention structures in the Karnataka region of the Mhadei River watershed is 198.5 km^2 which is 61% of the area of the Mhadei River watershed that lies in Karnataka and 22% of the total area of the Mhadei River watershed. It is estimated that the proposed water retention and diversion structures will impound 702 MCM (21%) of the total volume of monsoon rainfall and 64 MCM (22%) of the non-monsoon baseflow of the Mhadei River. Reduction in the flow volume of the Mhadei River due to the proposed impoundments can have diverse impacts on the dynamic equilibrium between the various natural fluxes of matter and energy existing in the watershed. The reduced flow volume may reduce the flow velocity and hence the sediment load carrying capacity of the river. This can result in excessive silt accumulation on the river bed in the downstream region. Silt accumulation reduces the channel volume and therefore can induce flooding in some reaches of the river during extreme rainfall events. Further, reduced flow volume may result in reduced stage of river, especially during the non-monsoon season. Since the river is effluent in nature and receives groundwater, reduced level of water in river may cause steeper groundwater gradients along the river banks leading to reduction in groundwater levels in the vicinity. On the other hand, accumulated silt can inhibit flow of groundwater to the river resulting in increased groundwater levels occasionally leading to water logging along the river banks. One of the major anticipated effects on the water regime is the reduction in water storage in the *bandharas* built across the Mhadei River. The *bandharas* store dry weather flow which is dominantly contributed by the baseflow from upstream region of the watershed. A large population in the downstream region depends on this water for domestic and agricultural use.

Further, accumulation of silt in the reservoirs of the proposed water retention structures may result in decrease in the suspended load in the river. This may result in less erosion on the river bed and banks.

The Western Ghats which is recognised as one of the hot spots of biodiversity runs through the middle of the Mhadei River watershed. This region is known for its wide variety of flora and fauna. A large number of these are endemic to the region implying that the micro-climatic factors of the region are essential for their survival. Construction of dams tends to fragment the river ecosystems thereby disturbing the natural equilibrium between the organisms and their environment. The nutrients present in the river water also play an important function in the web of life in the river and its watershed. Reduction in the supply of these nutrients from the upstream region due to the proposed impoundments may influence the ecosystem in the immediate vicinity of the river.

It is observed that the freshwater-sea water interface in the Mhadei River is governed by the elevation of the river bed with respect to the mean sea level. Therefore, reduction in the flow volume and velocity may not substantially affect this interface. However, minor increase in the salinity of the mixing zone cannot be ruled out. Finally, the quality of water in a watershed is a result of sum total of the interactions of rainwater with all the rock types present in the basin. The retention of the flows in the upstream of the present watershed may lead to some changes in the resultant water quality in the downstream.

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