GROUND WATER RECHARGE BEHAVIOUR OF LATERITIC AQUIFERS IN THE WESTERN GHAT REGION - INDIA

Thesis
Submitted in partial fulfillment of the requirements for the degree
of
DOCTOR OF PHILOSOPHY
by
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DECLARATION

I hereby *declare* that the Research Thesis entitled **“Ground water Recharge Behaviour of Lateritic Aquifers in the Western Ghat Region - India”** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy in Civil Engineering** is a *bonafide report of the research work carried out by me.* The material contained in this Research thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to *certify* that the Research Thesis entitled **"Ground water Recharge Behaviour of Lateritic Aquifers in the Western Ghat Region - India"** submitted by **S. K. Mahadeve Gowda** (Register Number: AM04F1) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy**.

Prof. M. K. Nagaraj
(Research Guide)

Prof. Subba Rao
(Chairman-DRPC)

Dedicated to

My gurus ….….

I always remain thankful to them…..

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ABSTRACT

For sustainable development of water resources, it is imperative to make quantitative estimation of the available water resources. It is necessary to maintain the ground water reservoir in a state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the monsoon and non-monsoon seasons. Ground water is a dynamic system. The total annual replenishable recharge is around 43 M ha m. In spite of the national scenario on the availability of ground water being favorable, there are many areas in the country facing scarcity of water. To assess the ground water potential, a suitable and accurate technique is required for a meaningful and objective analysis. A critical study has been carried out on the different methods of estimating the ground water recharge potential and compared to decide the most suitable technique for practical utility.

In the present study, infiltration tests were conducted at 10 well locations. For this purpose, double ring infiltrometer is used. Two infiltrometers are used, one with inner dia 25 cm, outer dia 35 cm and another with inner dia 15 cm, outer dia 30 cm. The infiltration tests were conducted at 2 locations in each site; one location being at the ground surface and the other one is 1 m below the ground surface. It has been observed that the rate of infiltration with respect to change in diameter of infiltrometer doesn't change much, but the rate of infiltration is more by 2.5 cm/hr on the surface compared to 1 metre below the ground surface level. It clearly indicates that, on the ground surface there will be a small amount of lateral flow in spite of using the double ring infiltrometer.

Electrical resistivity methods have been widely used for various hydro-geological applications. In ground water studies, it is used to find the aquifer type, thickness of aquifer and water table depth. Surface electrical resistivity methods have been applied to the shallow, unconfined, alluvial aquifer adjacent to the Haladi River, between Ullure and Kundapur to estimate aquifer thickness and hydraulic conductivity. From the above tests, it is found that in the study area, the aquifer thickness ranges from 12 m to 18 m. Additional testing of aquifer material for specific gravity, grain size analysis, mapping of aerial–aquifer extent and analysis of soil properties yielded estimates of hydraulic conductivity 150-250 m/day. The relative high pervious nature of the alluvial aquifer indicated by these analyses assures an adequate ground water-resource potential from well fields located in the alluvial adjoining a reservoir that impounds the Haladi River.

To estimate the annual dynamic ground water recharge of the river basin, the monthly average rainfall and the monthly average ground water level fluctuation data of 10 open wells during the period 1991-2005 is used (Dept. of Mines and Geology, Govt. of Karnataka). Zonation technique has been adopted considering the 10 open wells as the nodal point. The area of influence by the each open well has been calculated. Five methods adopted are, 1) Relationship between rainfall and recharge formula (Krishna Rao) 2) Ten year average water level fluctuation 3) Fluctuation between the lowest and highest water levels over ten years 4) Yearly water level fluctuation 5) Fluctuation in monsoon seasons.

A critical study is carried out on the different methods of estimating the ground water recharge and compared to decide the most suitable technique for practical utility. Among the five methods used in the above estimation, yearly water level fluctuation gives accurate estimate, which is on line with Central Water Commission (CWC-2006) estimate. By yearly water level fluctuation method the annual yield of Haladi River basin estimated as 288.22 Mm^3. The results of this study helps in accurate prediction of ground water potential of any hydrological unit. This in turn may avoid ground water over exploitation and help to restore the eco-systems.

Keywords: Ground water potential, ground water level fluctuation, unconfined aquifer, electrical resistivity, hydraulic conductivity, infiltration study, dynamic equilibrium.

TABLE OF CONTENTS

CHAPTER 2

CHAPTER 3

CHAPTER 6

CHAPTER 7

LIST OF FIGURES

LIST OF TABLES

LIST OF NOTATIONS

A	Area of the aquifer/ Area of watershed
C	Concentration in ground water
D	Diameter of well
Dd	Drainage density
dia.	Diameter
F	Formation factor
F_c	Final or equilibrium infiltration capacity
Fs	Stream frequency
f	Rainfall infiltration factor.
f_o	Initial infiltration capacity
f_{ir}	Infiltration that occurs at less than capacity rate
g	Acceleration due to gravity
h	Rise in water level
Δh	Change in water table elevation
K	Hydraulic conductivity
Ks	Saturated hydraulic conductivity
k	Constant
Ld	Lineament density
Lt	Lithology
Lu	Land use
m	Hydraulic mean radius
n_e	Effective porosity
P	Precipitation
Q	Total surface runoff
R	Net recharge due to precipitation
R_{gw}	Recharge due to ground water irrigation
R_f	Rain fall
R_m	Normal monsoon rainfall/non-monsoon rainfall
R_{rf}	Recharge due to rainfall
R_t	Recharge due to tanks, ponds and canals

R_{wc}	Recharge due to water conservation structures
S	Storage coefficient
S_l	longitudinal conductance
S_y	Specific Yield
t	Time
T	Transverse resistance
T'	Hydraulic transmissivity
Te	Topography elevation
W	Well
α	Porosity
μ	Dynamic viscosity of water
ρ	Density of fluid

ABBREVIATIONS

ARF	Annual Rain fall
Avg.	Average
BW	Bore Well
CGWB	Central Ground Water Board
cm	Centimetre
CWC	Central Water Commission
CWREC	Central Water Resource Estimation Committee
DMG	Department of Mines and Geology
DRI	Double Ring Infiltrometer
DWLR	Digital Water Level Recorder
ER	Electrical Resistivity
GEC	Ground water Estimation Resources Committee
GEM	Ground water Estimation Methodology
GIS	Geographic Information Systems
GPI	Ground water Potential Index
GPM	Ground water Potential Model
GW	Ground water
GWL	Ground water Level
GWT	Ground water Table
GWTF	Ground water Table Fluctuation
IHP	International Hydrological Program
INF/EXF	Infiltration/ Exfiltration
IPCC	Intergovernmental Panel on Climate Change
MCM	Million Cubic Metre
msl	Mean sea level
mm	Millimetre
Mm^3	Million Metre Cube
m	metre
Max.	Maximum
Min.	Minimum

NWP	National Water Policy
OW	Open Well
RGS	Rain Gauge Station
RI	Rainfall Infiltration
SGWD	State Ground water Department
SCS	Soil Conservation Service
St^n	Station
UNEP	United Nations Environmental Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDASCS	United States Department of Agriculture and Soil Conservation Service
VES	Vertical Electric Sounding
WMO	World Meteorological Organization
WTF	Water Table Fluctuation

CHAPTER -1

INTRODUCTION

1.1 GENERAL

Water is a precious, finite and scarce natural resource. It is a prime natural resource, a basic human need and a national asset. It is an essential natural resource for ecological sustenance, agricultural productivity, industrial growth, power production etc. All over the world, for an easy access to water, the human settlements occurred along the banks of the river and most of the civilizations flourished along the rivers. Water is the only natural resource which is available in nature in all its three physical forms viz. solid, liquid and vapors. This is the unique natural resource which gets replenished every year and can be used and reused. Water moves on, above, and below the earth's surface changing state from liquid to vapor to ice. This continuous movement is known as the water cycle or hydrologic cycle.

The endless circulation of water as it moves in its various phases through the atmosphere, to the earth, over and through the land, to the ocean, and back to the atmosphere is known as the hydrologic cycle. This cycle is powered by the sun and through phase changes of water (i.e., evaporation and condensation) involving storage and release of latent heat, it affects the global circulation of both the atmosphere and oceans and hence is instrumental in shaping weather and climate (Subramanya 1989) The efficiency of water as a solvent makes geochemistry an intimate part of the hydrologic cycle; all water-soluble elements follow this cycle at least partially. Thus, the hydrologic cycle is the integrating process for the fluxes of water, energy and the chemical elements. This cycle is the foundation of hydrologic science and occurs over a wide range of space and time scales.

The importance of understanding recharge and discharge processes within the hydrologic cycle has led the National Research Council (NRC), Govt. of India to characterize research on these topics as one of the critical national research activities which should be given top priority. Community leaders and engineers must understand where the water is and how it moves through the hydrologic cycle. Among the least understood pathways are ground water recharge and discharge, whose rates and spatial distributions define the relationships between ground water and the other components of the hydrologic cycle such as precipitation, evapotranspiration and surface water. Unfortunately, recharge and discharge rates and patterns are difficult to characterize and cannot be estimated using a single method for all practical applications. This adds uncertainty to the management of water resources. For example, recharge and discharge are known to relate to surface water features, soil types, land use and topography. However, there is no deterministic function to delineate these relationships.

In spite of undertaking many water resources development programs by different agencies at various levels about one third of the world's population lacks access to safe drinking water (UNESCO 2006). The growing population in many developing countries and their race towards industrialization and extensive irrigation is placing an enormous stress on the available water resources. Reasons for the shortages could be natural forces like scarce rainfall, hot weather, low infiltration, high runoff or due to human interventions like over-exploitation of water, poor water management, wrong policies, Kurup et al. (1998). Global climate change may also play an important role as a result of which water scarce regions in the subtropics are likely to have reduced water availability and others are likely to have greater precipitation. In both the cases, climate change is likely to increase the stress on the water resources systems (UNEP 2006).

Demand for water is continuously increasing and it is now important to manage the available resources in an efficient way. A complexity of factors like hydro geological, hydrological and climatologically controls the ground water occurrence and movement. The precise assessment of recharge and discharge is rather difficult, as no techniques are currently available for their direct measurements. Hence, the methods employed for ground water resource estimation are all indirect. Ground water being a dynamic and replenishable resource is generally estimated based on the component of annual recharge, which could be subjected to development by means of suitable ground water structures. For quantification of ground water resources, proper understanding of the behavior and characteristics of the water bearing rock formation, known as aquifer, is essential. An aquifer has two main functions - (i) to transmit water (conduct function) and (ii) to store it (storage function). The ground water resources in unconfined aquifers can be classified as static and dynamic. The static resources can be defined as the amount of ground water available in the permeable portion of the aquifer below the zone of water level fluctuation. The dynamic resources can be defined as the amount of ground water available in the zone of water level fluctuation. The replenishable ground water resource is essentially a dynamic resource which is replenished annually or periodically by precipitation, irrigation return flow, canal seepage, tank seepage, influent seepage, etc. Mohan and Ramani (2000) stated that ground water was the major source for irrigation prior to the introduction of canal irrigation system in India up to the 19th century. Water contained in the voids of the geologic materials that comprise the crust of the earth is the ground water. It exists at a pressure greater than or equal to atmospheric pressure. The experimental and mathematical methods required for analysis are distinctly different as it is exploited and used in human affairs in different ways.

The important hydrogeological parameters such as porosity and hydraulic conductivity of the geologic stratum determine the performance of the aquifer. Added to this, an important factor is the length of data considered for predicting the ground water potential. Thus, with adequate length of the database, the prediction of any derived model will reproduce the statistical properties. Otherwise, it is difficult to predict the regional ground water flow conditions, subject to measurable hydrological, hydrogeological and meteorological variables in nature. As it is largely uncertain in nature, this cannot be left in isolation. Hence, it prompts the importance of understanding and estimating the regional ground water flow regime.

1.2 WATER RESOURCES

1.2.1 Water resources of the country

India, which has 2.45 percent of the world's land resources, has 4.00 percent of the world's fresh water, whereas the country's population is 16.00 percent of the world's population. Most of the rainfall in India occurs as a result of the south-west monsoon during the period from June to September. In macro terms, India receives an average annual precipitation of about 4,000 km^3. The monsoon rainfall (June to September) is of the order of 3,000 km^3, out of this, average annual flow available in rivers is 1953 km^3 (Subramanya 1989).

The total geographical area of land in India is 328.762 Mha. The per capita water availability in the country is 1,703.60 m^3 per year. The average annual yield of the rivers of the country has been estimated to be 1869 km^3. But the amount of water that can be actually put to beneficial use is much less due to severe limitations imposed by topography and other issues. The recent estimates made by the Central Water Commission indicate that the water resources utilizable through surface structures are about 690 km^3. The estimates made by the central ground water board indicate that the utilizable ground water is about 432 km^3. Thus, total utilizable water resources are estimated to be 1122 km^3 (CWC 2006).

Use of ground water is likely to grow in the years ahead because of the uncertainty associated with availability of surface water against reliability of ground water, untapped potential in various regions of the country, as well as the ease and simplicity with which it can be extracted. For the projected population in 2025, per capita availability of water in the country will be 1403m^3 per year (Fig.1.1). The total quantum of available water may be sufficient today but the country will be water stressed due to rapidly rising population and increasing agricultural, industrial, and other requirements (Rakes et al., 2005). In a country if the available water resource is between 1000 - 2000 m^3 /year/capita, then the country is termed as “water scarce”, while if the available water is less than 500 m^3 /year/capita, then it is termed as water stress (CWC 2006).

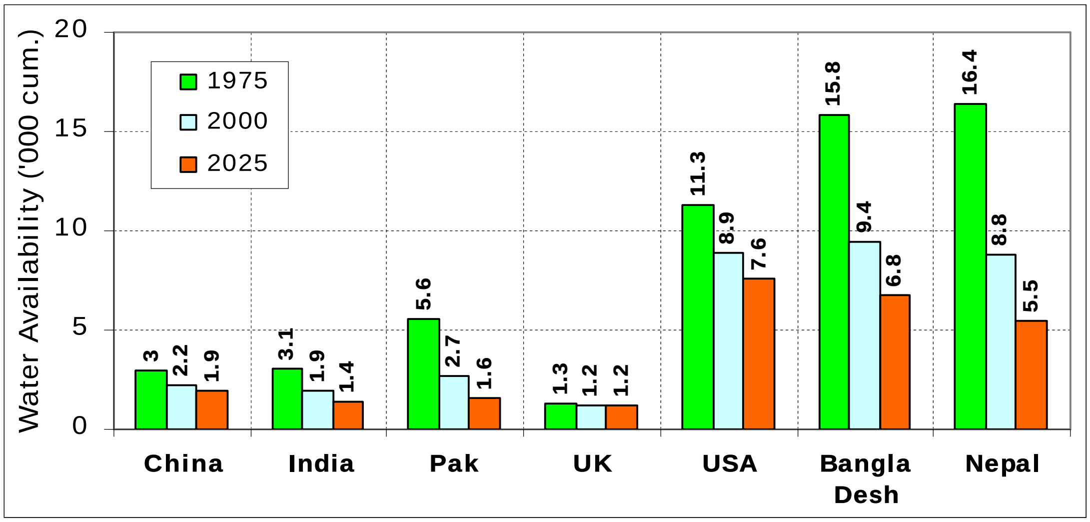


Fig. 1.1 Water availability in the past, present and future/capita (CWC, 2006)

Over the past several years, there has been a continuous growth in the demand of water throughout the world. The economic, social and environmental effects of water management and development have come under intense economic, social and political scrutiny due to the importance that they have. There are two major sources to meet these demands, surface water and ground water (Draper et al., 2003).

Ground water is a limited natural fresh water resource which plays a vital role in meeting the fresh water demand for various purposes. The quality of ground water is generally considered to be superior to that of surface water since the soil column purifies the infiltrating water and removes the contaminants. However it should be noted that in many sites the ground water is contaminated due to the natural geological process and due to manmade activities. In view of the vital importance of water in maintaining ecological balance, developmental activities, economical and equitable use has become a matter of utmost urgency. For sustainable water resources development and management, a hydrology project is under consideration with the World bank assistance. This massive plan of inter-basin water transfer involves about 30 links between different river basins (CWC 2006).

1.2.2 Water resources of the Karnataka state

The rainfall variation across Karnataka state is from 569 mm to 4762 mm. The mean annual rainfall in the state is 1138 mm with more than 73% of it being due to south-west monsoon. Two thirds of geographical area receives less than 750 mm rain (GoI 2002). During the period from 1970 to 2003, deficit rainfall was recorded on 22 occasions and the highest deficit of 55% was observed in 1983. The major source of drinking water in the state is ground water. The ground water table is fast declining in the state and 34 taluks are considered as critical due to over - exploitation. The state has recorded ground water fluctuations in 500 places across the state and has found 380 stations indicating declining ground water table up to the depth of 4 m in one year. Availability of safe drinking water is the major concern with 36% of the habitants getting inadequate drinking water (GoI 2002).

Due to excessive mining of ground water, the number of villages where drinking water quality is affected is also increasing. The direct cause of ground water depletion has their origin in the pricing policies of electricity and subsidies of diesel. The subsidies should be very specifically targeted to the poor (GoI 2002). At the state level, one of the most ambitious programs of the government in the recent years is harnessing west flowing rivers in the coastal districts of Uttar

Kannada, Udupi and Dakshina Kannada for improving the availability of water for drinking and irrigation. It is proposed to have 907 vented dams in these three districts across 19 minor and major rivers so as to supply water to 17 taluks. The state government is on a course to hold the flow of water in the rivers bound to Arabian Sea in order to increase the ground water level in the coastal districts of Karnataka. A project to construct 2,473 check dams to irrigate about 47,837 acres of barren land is under consideration.

1.2.3 Water status in the Udupi district

The Udupi district is one of the rapidly growing districts of Karnataka State. Water status in the district is not very good; with 48 % habitant getting less than 55 liter of water per capita per day which is the norm prescribed by state government. Due to increasing demand, water is being over-exploited in the district at many places. Out of 56 stations, 43 stations have shown the declining trend of ground water table. The district receives an average annual rainfall of 4730 mm and still experiences acute shortage of fresh water in the non-monsoon periods. This is due to the steep slopes and the hydro-geological characteristics of the basin. Laterite occupies a larger portion of the basin. The district is part of the western coast which is almost continuously covered by a sheet of laterite rock. This rock has very high permeability and hence the rainwater either flows as surface flow due to steep slope, or as a subsurface flow due to high permeability of laterite (Newbold 2001).

1.3 DESCRIPTION OF THE STUDY AREA

1.3.1 Study area

Udupi district encompasses 3094.6 Sq. km. The total population is around 12 lakhs. Of this about 82% live in the rural area. The density of population per sq. km. is around 390. It is situated between the Longitude 74.58° to 75.21° and Latitude 12.98° to 13.98°. Several ridges and spurs of the Western Ghats traverse this region. The terrain has number of rivers, creeks, waterfalls, peaks and ranges of hills. The coastal region consists of two broad physical units, the plains and the Western Ghats. The coastal plains represent a narrow stretch of estuarine and marine plains. The abrupt rise at the eastern flank forms the Western Ghats. The coastal belt has an average width of 50 to 80 km. The general topography consists of a narrow but continuous coastal track. A strip of sandy marine alluvium of about one to two kilometer wide, initiating at the interface of land and sea margin. The coastal region gradually rises in steps and suddenly there is a drastic change in its altitude that is called as *Sahyadri*, the magnificent mountain range along western India (Subramanya 2001).

The study area for investigation is Haladi river basin in Udupi district of Karnataka (Fig.1.2). The Haladi River lies between the latitude 13.30° to 13.50° N and longitude 74.40° to 75.06° E, and originates at an altitude of 965 m above the mean sea level (msl) in the Western Ghats of Udupi district, Karnataka state. Total length of the river is about 103 km, which drains an area of about 614.87 km^2 (CWC 2006). Within a run of 6.5 km, the river loses its elevation by about 650 m (1 in 10). After this, it becomes gentle i.e. 3.5 m in 2.5 km. (1 in 714) (Murthy 1977).

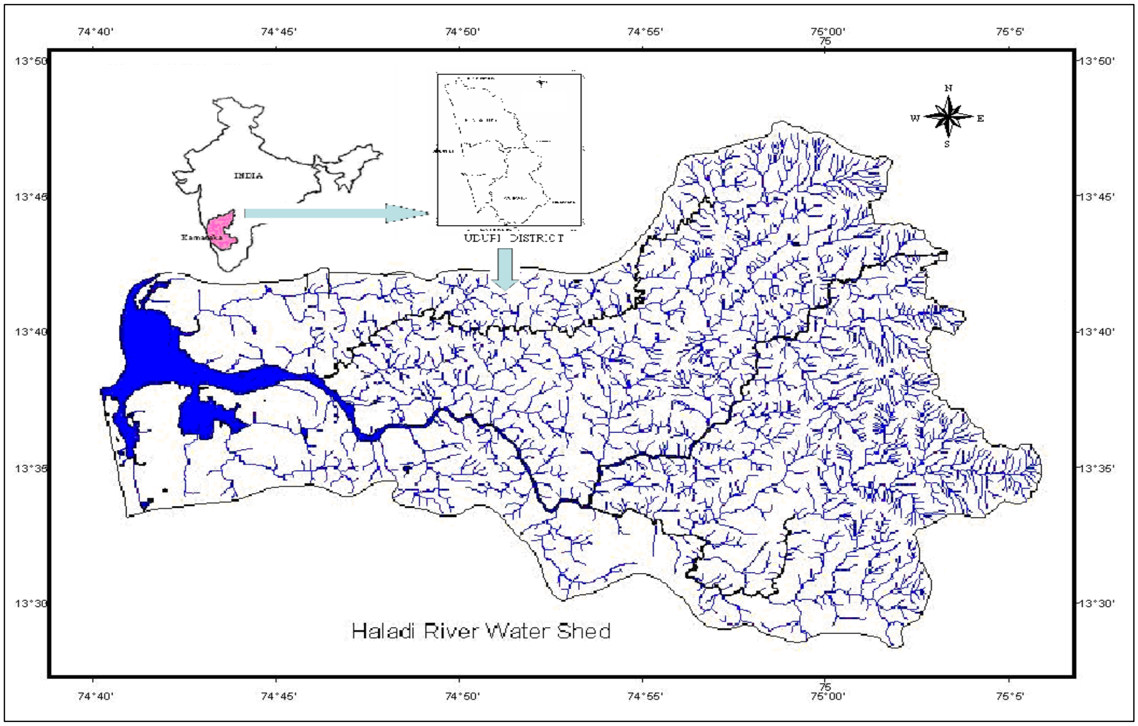


Fig.1.2 Study area- Haladi River basin

1.3.2 Climate

Based on the climate, the year can be classified into four seasons

A) March to May: This season is generally hot with high humidity throughout the day. The maximum temperature would generally be experienced around 2 p.m. in the afternoon except in the coast close to the sea and minimum at around 3 a.m. During this period the difference between the maximum and minimum temperature is generally not very large ($<10^0$c).

B) June to September: The southwest monsoon generally sets in the month of June due to depression in the Arabian Sea. The districts experienced heavy downpour during this season with the heaviest precipitation between July and august. The rivers during this season flow to their brim, flooding the vast plants finally discharging in to the sea.

C) October to December: As the southwest monsoon starts retreating during the month of October, northeasterly monsoon sets in the little rain during this period. The temperature during this period is cool to moderate and enjoyable.

D) January and February: Dry season starts during this period and during these months, little or no showers are experienced. The climate will still be moderate and pleasant.

1.3.3 Topography

Western India has a long coastline. The coastline is bordered by coastal plain of low elevation and of width varying from 30 to 50 km. A large part of the terrain is uneven and the elevated portions are flat topped and covered by laterite. The eastern edge of the Western Ghats is the water divide between the east and west flowing rivers. The basins of west flowing rivers consist of all small independent river basins of the peninsular India lying to the south of Krishna basin, except the Cauvery basin. There are about 22 river basins and they are located within 8^0 43' to 19^0 10' N latitude and 73^0 15' to 76^0 51' E longitude. These rivers are draining into the Arabian Sea. The basins of the west flowing rivers cover areas of Maharashtra, Karnataka, Tamilnadu and Kerala. All the rivers originate from the Western Ghats and exhibit similar characteristics. They have steep high banks near the Western Ghats, which rarely overflow or cause floods (CWC 2006).

The topography of the coastal region is from plain to undulating with hilly regions and natural valleys. The ambient temperature varies from a minimum of 17°C in December-January to a maximum of 37°C during April- May. The relative humidity is generally very high reaching saturation levels during the monsoon months. The geology of the river basin has been characterized by hard laterite in hilly tracts and sandy soil near seashore (CWC 2006).

1.3.4 Humidity

The weather is highly humid all through the year and particularly so during the southwest monsoon period. A maximum of 100% humidity recorded in June and July almost every year and a minimum of 14% was recorded on 27th February 1984 (Udupi Brochure 2008).

1.3.5 Winds

Winds are strong and are mainly westerly or southwesterly during the southwest monsoon period that is in June and July. During the rest of the year, winds are northeasterly. The maximum wind velocity has been recorded as 72 km/hr on 21st July 1983 (Udupi Brochure 2008).

1.3.6 Rainfall

The rainfall is mainly due to cyclonic and orographic effects. Though a convention effect exists, the contribution of convention rainfall compared to total annual rainfall is negligible. During the south-west monsoons, the moist air is lifted due to depressions over the Arabian Sea and is carried by the sea breeze towards the canopy of the Western Ghats resulting in the orographic precipitation. The high lands closer to the Western Ghats experience heavy rainfall compared to the narrow belt near the coast.

The Haladi river basin is marked by oppressive weather in the hot season during March to May. This is followed by the southwest monsoon season from June to September. October and November constitute the retreating monsoon. December to February is usually the dry season with mild temperature. The river basin being part of the west coast enjoys a tropical climate of high humidity evinced by a sultry weather during most part of the year, with an average day temperature ranging from 30 to 33°C and night temperatures ranging from 24 to 28°C. The southwest monsoon is the principal rainy season during which the river basin receives 80% of rainfall. Southwest monsoon normally sets in by about first week of June. The rainy months June, July and August account to about 80% of annual rainfall. The average annual rainfall in the region is 5167 mm (Appendix III).

1.3.7 Vegetation

Vegetation explains the environment under which it is grown. Good water, soil and climate favor luxurious growth of vegetation. Entire district enjoy favorable conditions for vegetation from seashore to the Western Ghats along the low lines, mid lands and forest region of the high land. The mid land region of the district has thick vegetation, cultivated coconut and areca nut palms on the shoulders of the valley. The higher elevated areas are mostly covered by lateritic soils with sparse vegetation. The topography and climatic conditions of the Western Ghats in the lands of the district have led to the growth of a variety of plants and grasses. The evergreen forests occupy the steep Western Ghat slopes and narrow valleys. In some parts of the forest there are gigantic timber yielding trees. These trees cause the formation of the macro pores in the soils, when their decay, thus causing faster of the water percolating in to the soil.

The earliest and most widespread modification of the climate was by conversion of natural vegetation into cultivable lands and pastures. The removal of forests, where there is considerable rainfall, results in drastic reduction in rainfall. The natural cycle of precipitation, percolation, evaporation and transpirations are disturbed due to denudation of the forests. It is important, therefore to project the vegetative life in order to avoid ecological imbalance and to prevent erosion and natural calamities (CGWB 2008).

1.3.8 Drainage

Several west flowing rivers transverse the Udupi district and flow into the Arabian Sea. The rivers have a characteristic coast parallel bend near the seashore. The river discharges gradually decrease after the cessation of rainfall ending up in almost dry or base flow discharging to streams during the summer. Important rivers in the district are Udyavara, Sita, Swarna, Halady, Kollur, Chakra, Baindoor, Shiroor and Mulki. The rivers during heavy monsoon result in flash floods, carrying away lot of sediment resulting in heavy erosion and loss of soil fertility (CGWB 2008). The combined drainage map of river basins of Haladi, Sita, Swarna and Udyavara are as shown in Fig.1.3. Ground water resources are estimated with watershed as unit of assessment. The watersheds as per “Watershed Atlas of India (1990)” has been digitized and used for the purpose.

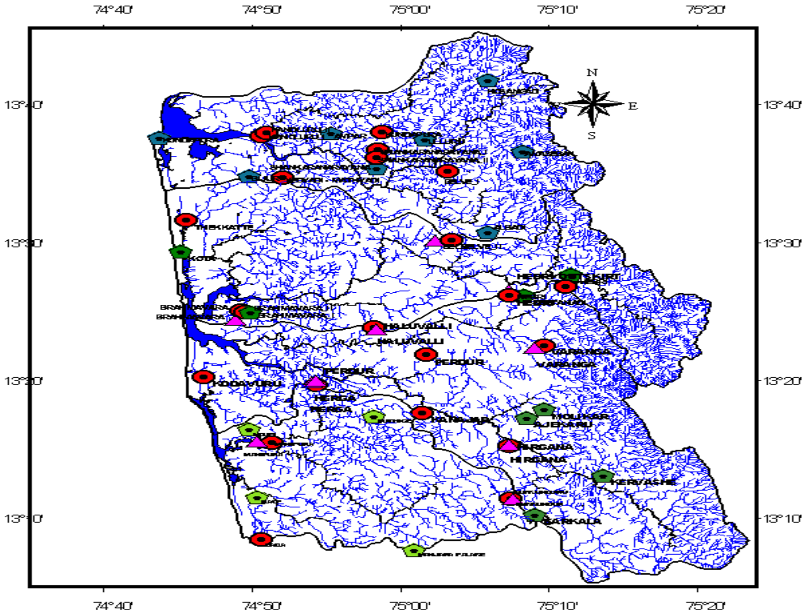


Fig. 1.3 Map showing river water shed drainage basins in Udupi district.

The selection of watershed basin for the study has been decided based on the (i) existence of maximum number of observation open wells (ii) rain gauge stations in the individual basin area and actual storage of water. The Haladi river basin has been selected for the present research study purpose. This river basin has sufficient number of observation open wells, bore wells installed with digital water level recorder (DWLR) and rain gauge stations as per the norms suggested by the GEM 97 (one open well for 100 sq. km). All these open wells, rain gauge stations, and bore wells are maintained by CGWB and Dept. of Mines and Geology (DMG) Govt. of Karnataka. The details of data available for all the river basins in Udupi district are shown in the Table 1.1

Table 1.1 Udupi district river's drainage basin details

Sl. No.	Name of river basin	Latitude in °	Longitude in °	Area in Km^2	No. of OW's	RG S's	No. of BW'S	No. of DWLR	Total No.
1.	Haladi	13.52 to 13.76	74.67 to 75.06	614.87	10	10	06	04	30
2.	Seetha	13.36 to 13.59	74.68 to 75.16	539.0	04	04	03	01	12
3.	Swarna	13.14 to 13.48	74.70 to 75.19	719.1	09	04	05	04	22
4.	Udyavara	13.17 to 13.36	74.72 to 75.00	301.2	03	04	02	01	10

1.3.9 Soil and overburden

The coastal tract has a pervasive distribution of sandy soil and lateritic soil. The thickness of soil usually is less than 3 m. The semi consolidated marine alluvium along the beach line and the coastal tract has an average thickness of about 20 m. The thickness of lateritic overburden, mostly indurate, is in the order of about 10 to 30 m in general. These top soils lead to greater seepage of water through soil and laterite.

1.3.10 Geological setting

In the central part of Udupi District mainly in parts of Udupi, Karkala and Kundapura taluks evidences of emplacement of grey granite can be seen. The entire coastal region west of the Western Ghat has been intensely lateritic due to high rainfall and tropical climatic conditions during the post cretaceous period.

1.3.11 Hydrogeology

The ground water aquifers in hard rocks are controlled by structural discontinuities such as fractures, faults and joints. In the lateritic overburden, characterized by high porosity and permeability conditions ground water storage occurs very rapidly with onset of monsoon and with decline of rainfall the water storage gradually dwindles causing acute shortage of water in shallow open wells in some areas during peak summer.

1.4 LOCAL GW OCCURRENCE AND AQUIFER TYPES.

In the Udupi District, ground water is the principal source of supply for domestic use. Here, the principal aquifer materials are alluvium, laterite and fractured crystalline rock. A significant majority of drinking ground water supply is through bore wells and open wells, tapping the semi confined and unconfined aquifers. The majority of irrigation water supply is from ground water mostly as open wells tapping the weathered zone aquifer as well as semi confined aquifers (CGWB 2008).

1.4.1 Recharge

Of late, ground water recharging is the talk of the day owing to the alarming decline in ground water table in many parts of the River Basins. It has to be noted that in spite of the increase in the water exploitation over the years, the annual recharge peak is almost the same level. The point of anxiety is the sudden fall in the water table. This leads to scarcity of water during summer in certain highly elevated parts of the basin. This fall is due to the outflow of ground water as base flow.

1.4.2 GW Development, management opportunities and constraints

Ground water is the principal drinking water and irrigation source in the district. The individual users have largely managed the development and management of ground water of irrigation, while the governmental departments are involved in providing the community drinking water facilities. The changing scenarios with respect to ground water recharge, base flow are issues that need to be understood by the planners and managers.

1.4.3 Typical Ground water Issues

Udupi district is blessed with copious rainfall: hence, problems of drought are generally unheard of in this region. However, there are number of other ground water related issues. The Western Ghats with high slopes brings flash floods during monsoon, which result in heavy soil erosion. During high intensity rainfall, the runoff generated is very heavy as compared to recharge. The long coastal line and presence of tidal creeks are potential for sea water intrusion.

1.4.4 Loss of fresh water as base flow into sea

Heavy base flow (sub-surface flow) into the sea is observed in the district. The physical characteristics of the area (steep slopes) combined with heavy monsoon rainfall and nearness to the coast results in heavy subsurface flow into the sea. Considerable volumes of water flow in the streams even during the non-monsoon months indicate the discharge of ground water into the streams. The need is to optimize the base flow for making them available during the months of ground water stress or make it available in areas where there is a water quality problem or deficiency in ground water availability. In the district, the flow of water and moisture under the land surface clearly occurs in two distinct forms. In the first from the moisture, movement occurs vertically as unsaturated flow beneath the land surface up to the ground water table. The ground water table forms the upper boundary of second form of flow where the preferred path of movement is horizontal, toward aquifer discharge areas, which is the Arabian Sea.

1.5 PROBLEM FORMULATION AND SCOPE

Udupi district is one of the three coastal districts of Karnataka, which spreads along the west coast of India covering coastal track of about 90 km. The chief occupation of the people in the district is agriculture and fishery. However, due to the recent developments, many business houses have established their industries in and around Udupi city. Udupi is the districts headquarter which is located in the coastal region. Due to this, the flow of people towards this area is increased. Hence the water requirement of the region has increased enormously. Increased population and growing industries will be changing the region into a water scarce area (CGWB 2008).

The main hydrological problem of the coastal districts of Karnataka is the uneven rainfall and runoff. In the Haladi river basin, the rock type and its formation makes the problem more severe. Peak flows in the rivers of the region are very high during the monsoon whereas there is very low or insignificant flow during the summer. With increasing population and urbanization, the water demand is continuously increasing whereas the sources of fresh water are disappearing. Due to this, the ground water resource, which is comparatively more reliable, is getting more attention. Over- exploitation of ground water is threatening the ecosystem.

Though the basin receives heavy rainfall during monsoon season of about 4500 to 5000 mm, it is confined to four months (June to September) only. It experiences severe fresh water scarcity during April and May months. Most of the wells in this region will dry up in the month of May, because of rapid fall in water table. Main reason for shortage of water in this region during the months of April and May is the lateritic formation, which is very common in the river basin

(CGWB 2008). To characterize, the infiltration capacity of this region, study has been conducted by dividing the river basin into ten regions based on the existence of observation open wells. The infiltration tests were carried out using double ring infiltrometer in each region.

Under these circumstances, it is becoming more and more difficult for the administrators to provide drinking water to the habitant. This research project intends to find the optimum average yearly recoverable ground water reserve that can be exploited from the aquifer in the basin.

1.6 RESEARCH OBJECTIVES

Keeping in view the above aspects, the following objectives are set for the investigation.

1) To quantify the average infiltration rate of the basin using double ring infiltrometer.
2) To investigate the aquifer type, thickness of aquifer and water table depth.
3) To determine the annual ground water table variations in the river basin.
4) To assess the Annual replenishable ground water resources of the River basin.

1.7 DATA USED

In the present study the historical rainfall time series of 10 Rain gauge stations and 10 observation open wells water table levels for 15 years period of Haladi river basin is used and the data is shown in Table. 1.2.

Table 1.2 Details of observation open wells and monthly GWL data period

Station No	Station name	Latitude(^{o}N)	Longitude(^{o}E)	Altitude(m)	Data Period(Yr)
1.	Alur	13.75	74.75	98	15(1991-05)
2.	Amasebail	13.6	74.98	85	15(1991-05)
3.	Ampar	13.63	74.87	72	15(1991-05)
4.	Albardi-Ardi	13.52	74.97	76	15(1991-05)
5.	Haladi	13.57	74.86	61	15(1991-05)
6.	Yelajith	13.85	74.71	30	15(1991-05)
7.	Vandse	13.71	74.76	35	15(1991-05)
8.	Ullur	13.78	74.65	23	15(1991-05)
9.	Siddapura	13.67	74.92	67	15(1991-05)
10.	Kundapura	13.63	74.69	22	15(1991-05)

1.8 ORGANIZATION OF THE THESIS

The descriptions of the study area, problem formulation and Scope of the work, research objectives, data used, are presented in chapter1. Literature review about the management of water resources, national water policy, infiltration studies, aquifer characteristics, determination of aquifer parameters, assessment of ground water recharge, have been discussed in chapter 2. The infiltration field study has been conducted at different locations of 10 observation open wells by using two sets of double ring infiltrometer and the rate of infiltration of the study area is found out and presented in chapter 3. Aquifer characterization, geophysical investigations, electrical resistivity test, geo-electrical survey methodology, hydraulic conductivity from soil parameters, analysis of the pumping test are highlighted in chapter 4. Ground water recharge estimation, Statistics on ground water availability and development, ground water resource potential in the Western Ghats basins and different methodology of ground water estimation techniques are discussed in chapter 5. The detailed discussions of infiltration study, aquifer characterizations, rain fall and ground water level analysis, ground water recharge estimations are presented in chapter 6 and the conclusions from the investigations are provided in chapter 7.

CHAPTER - 2

LITERATURE REVIEW

2.1 INTRODUCTION

For utilization of maximum available water resources, river basin management and development policies need to be formulated. Policies should encourage good practices and holistic management of water in catchments and aquifers (Dillon 2005). The policies must be planned for a hydrological unit such as drainage basin as a whole (UNESCO-IHP 2006).

2.1.1 Management of water resources

Out of the available fresh water resources, 98% of fresh water occurs as ground water while less than 2% occurs in the more visible form of streams and lakes which often are fed by ground water. Water usage depends on various factors, significant among them are the parameters which are climate dependent (Gato et al., 2007). These factors in addition to changing living standards affect the availability of water resources. Water shortages are due to the imbalances between population concentration and precipitation distribution. In places where it is difficult to store water as surface storage through construction of dams, it is stored as ground water. Ground water is a more dependable source of water and less affected by the vagaries of climate. In view of the vital importance of ground water in maintaining ecological balance and for developmental activities, management of this resource and its optimal, economical and equitable use is gaining more importance.

2.1.2 National water policy

The National Water Policy (NWP) was first adopted in September 1987. Since then, a number of new issues and challenges have emerged in the development and management of water resources and hence the policy is revised and updated. The policy suggests bringing all the water resources under the category of utilizable water resources and recommends a periodical assessment of the ground water potential on a scientific basis considering the quality of water and economic viability of its extraction. Water allocation priorities recommended in the policy are for drinking water with highest priority followed by irrigation, hydro-power, ecology, industries and navigation. The policy suggests regulation on exploitation of ground water so as not to exceed the recharging possibilities to control the continuous depletion of ground water table. The over-exploitation of ground water should be avoided near the coast to prevent ingress of salt water into fresh water aquifers. The committee report on irrigation for the tenth five year plan (GoI 2002) has suggested the government to ensure substantial progress in the implementation of measures recommended in the NWP 2002. It also recommends centrally coordinated water related activities instead of fragmentation of these activities which exists at present.

2.1.3 Participation of stakeholders in decision making

Water resources management in the 21st century requires a radical reorientation and an effective dialogue between decision-makers, stakeholders and the scientific water community. Experiences from all over the world demonstrate the need for multi-stakeholder advocacy and the importance of compromise-building mechanisms. Stakeholders have a stake in the decisions made in formulating a water resource strategy therefore stakeholder consultation is required for a comprehensive understanding of the water resource related issues and problems in a river basin. It provides an opportunity for the researchers to interact closely with the water users as well as the agencies involved in the management of water resources, joint analysis and preparation of action plans.

2.2 INFILTRATION STUDY

Behaviour of unsaturated layered soil columns during infiltration, on two soil columns of finer over coarser soil subjected to simulated rainfall has been studied (Yang et al., 2006). The delayed response of recharge indicates the redistribution of soil water in infiltration. Different paths of water content versus matric suction were followed during the tests indicating the apparent hysteretic behaviour of soil water. In addition, the coarser layer restricted the increase of pore pressure in the finer layer. A minor variation of saturated soil permeability had minimal effect on infiltration (Yang et al., 2006).

All the water that infiltrates does not contribute to the ground water table. Studies have shown that up to 50% of the depth of water infiltrated in a recharge zone contributes to the ground water below the root zone (Singh et al., 2003). Construction of various structures for the purpose of recharge has been successful in many parts. Before the construction of such structure, ground water was declining, whereas after the construction of such structures a rise in ground water level is observed (Karve 2003). Near surface infiltration rates are highly variable in time and space and are different from non-uniform recharge at the water table. Hence the ground water recharge methodology to be used needs to be selected carefully which will take spatial and temporal variations into account (Flint et al., 2002).

2.3 AQUIFER CHARACTERISTICS

2.3.1 Determination of aquifer parameters

Ground water resources of an area largely depend upon the characteristics of the aquifers. The most important characteristics in this regard are the transmissivity, hydraulic conductivity and storage coefficient or specific yield. The hydraulic properties of aquifers can be determined by pumping tests. It involves pumping of water from a well at a controlled rate and observation of water level at the observation well with respect to time. Pumping tests provide information on the yield and drawdown of wells. Normally recuperation test also be conducted along with the pumping test (Cheng and Chen 2007).

A frequently used method for estimating the hydraulic properties is the graphical type-curve analysis in which dimensionless type curves derived from an assumed analytical model of ground water flow to a pumped well are used to analyze the time-drawdown measurements of hydraulic head in the observation wells. These analyses are carried out to estimate the hydraulic conductivity and specific yield of water table aquifers (Pakhmode et al., 2003). They evaluated the characteristics of the drainage network of a basin using quantitative morphometric analysis which gave information about the hydrological nature of the rocks exposed within the drainage basin. Using hydro-geological observations it was found that more permeability to infiltration was indicated by the lower values of drainage density (Dd) and stream frequency (Fs).

Two conceptual approaches have been used to analytically model the release of water from the zone above the water table in unconfined aquifers. In the first approach (Boulton 1954) drainage from the zone above the water table is assumed to occur gradually in a manner that varies exponentially with time in response to a unit decline in the elevation of the water table. As a part of his mathematical treatment of the problem, Boulton introduced an empirical drainage constant. In the second approach (Neuman 1972) water is assumed to be released instantaneously from the zone above the water table in response to lowering of the water table. Neuman (1975) justified this assumption, in part, based upon the numerical models that appeared to show that effects of flow from the unsaturated zone upon drawdown in the saturated zone were negligible.

When the pumping well and the observation well are penetrated throughout the entire saturated thickness of the aquifer, the drawdown in the observation well is given by Neuman. The equation was derived by assuming that the decline of the water table remains small in comparison to the saturated thickness of the aquifer. From this it is evident that the Dupuit's assumption does not hold well in an unconfined aquifer with delayed gravity response as long as the drawdown data do not fall on the late Theis curve. The (Neuman 1972) solution, which allows for evaluation of both pumped well and observation piezometer data, accounts for effects of bore well storage allows for the non-instantaneous release of water from the unsaturated zone the solution approaches line source solution derived by Neuman as the diameter of the pumped well approaches zero. However, it has been found out that the (Neuman 1972) model, when properly applied, can be used to estimate the most important water table aquifer parameters. Many relationships and procedures were tested for estimating the average K values. None of the current generation methods provide information away from the vicinity of the wells (Butler 2005). The hydraulic conductivity values change with the percent of fines in the soils, quantity of lime and the compaction (Kolawole 1998). In order to determine these hydraulic parameters methods available are either costlier or complex and time consuming.

Barr (2001) suggested a method in which water and soil properties like density, dynamic viscosity of the fluid, porosity of the media and the hydraulic radius of the particles are used.

The results obtained from the grain size analysis are smaller than the horizontal but larger than the vertical hydraulic conductivity determined by the pumping / recovery test (Cheng and Chen 2007). The permeability range observed for laterite soil is from 1.48 x 10^{-4} to 5.39 x 10^{-7} cm/ sec (Gidigasu 2012). Rushton and Rathod (1985) have determined the velocity components from information about the ground water-head distribution, ground water potential, confined unconfined aquifers, time-variant behaviors of aquifer and hydraulic conductivity.

2.4 RIVER TREND ANALYSIS

The global average surface temperatures are expected to rise by about 1.4–5.8^{0}C by the end of the century. This temperature increase is likely to affect the ecosystems and the hydrologic cycle of the earth and its atmosphere (Mooij et al., 2007). With the exception of the year 2000, all the years of this century rank among the 10 warmest years of the whole observational period since 1850 (WMO 2007). The assessment of climate change impacts on the water resources of a country is the most important assessment to be carried out before planning any long term water resources development project. The climate change has a significant impact on every process of the hydrological cycle, which affects the surface water availability, soil moisture and ground water recharge (UNEP 2006). All these factors are important in planning a river basin development program.

The Inter-government Panel for Climate Change (IPCC) report reveals that the frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increase of atmospheric water vapor (Haywood and Schulz 2007). Studies have been carried out in the past to find out the river flow trends in various countries in view of the global climate change concerns and the likely stress on water resources system. At the global level, in many of the river flow series, in general, a decreasing trend was observed. This study includes 8 stations from Asia, of which, statistically significant decreasing trends were found in three cases. It was also reported that, in a number of cases, the highest value in a long time series was more than twice as high as the second highest annual maximum flow.

As per IPCC report (Haywood and Schulz 2007) in Asian region many of the major rivers targets for development projects. As a consequence, although there has been a very high fresh water flow during the rainy season, there exists low to no fresh water flow in the dry season. Fresh water availability in central, south, east and south-east Asia, particularly, in the large river basins is projected to decrease due to the climate change. This could adversely affect more than a billion people by the year 2050. Investigations suggest that for axis symmetrical shapes of recharge basins, and rectangular shape of recharge basin is preferred over other shapes (Rastogi and Pandey 1998).

2.4.1 Ground water recharge near streams

The seasonal variability of stream flow within permeable catchments can be high particularly in upstream areas where, water table heights tend to vary more significantly. The use of water resources must therefore be carefully managed in order to reduce the potential risk of both drought and flooding. Nearly all of the water pumped from the aquifers near to streams is derived from stream flow depletion by the process of captured ground water discharge (Singh 2001).

It is observed that increase in aquifer withdrawal by as much as 50% is possible with reduction in summer stream flow to the extent of 35% (Barlow et al., 2003). The observations show that soil water moves vertically downward in the bedrock during the storm events in the shale watersheds, whereas subsurface storm flow is parallel to the slope in granite watersheds in central Japan (Onda et al., 2006). Intermediate scale heterogeneity has significant effect on the spatial distribution of river seepage. The low river flows are commonly controlled by river aquifer exchange, the magnitude of which is governed by hydraulic properties of both aquifer and aquitard beneath the river. These low flows are often important ecologically (Fleckenstein et al., 2006).

2.5 ASSESSMENT OF GROUND WATER RECHARGE

The climate, geology, morphology, soil conditions and vegetation determine the recharge process of a region. Deep percolation in humid region is mainly controlled by the surplus precipitation over the evapo-transpiration needs, infiltration capacity of soil and storage and transport capacity of subsurface. In arid region, ground water recharge depends upon the rainfall, events of high concentration accumulation of rainwater in depressions and streams, evapo-transpiration and rapid percolation to deep water.

Rangarajan and Athavale (2000) developed regression equation for the estimation of natural recharge from precipitation based on hydrogeological parameters. Chand (2005) developed a cross correlation model for an unconfined aquifer system where in a simple relationship between precipitation and rise in water level is established.

The over-exploitation of ground water leads to degradation of quality of water (Morris et al., 2006). Water conservation and ground water augmentation are the two ways of maintaining the ground water levels. Water conservation implies improving the availability of water through storage or augmentation by means of storage of water in surface and sub-surface reservoirs. The conjunctive use of surface water and ground water is preferred wherever possible for augmenting the ground water. Unconfined aquifers are the most readily available and affordable sources of water which are also most susceptible to depletion and contamination. These aquifers need to be recharged to overcome the problem of depletion (De Vries and Simmers 2002) and environmental consequences of unplanned large scale ground water utilization (Gupta and Babel 2005).

The direct recharge of ground water by precipitation occurs only where the vadose zone is thin. The ground water table enrichment depends upon the monsoon rains as these are the major sources of recharge. It is observed that with the failure of rainfall, water table depletes faster depending upon the deficiency of the rainfall (Thiyagarajan and Rangaswami 2003). The infiltration will be greater for a higher pounding depth than for a shallow depth (Warrick et al., 2005). Increase in daily river flow and rainfall leads to increase in water table in the adjoining forums. Relatively cleaner water can be collected for recharge through interconnected vertical well, galleries, chambers and small diameter radiating bores through natural alluvial deposits in a river bed (Wang and Zhang 2007)**.**

The mechanisms of interactions between ground water and surface water (GW–SW) as they affect recharge–discharge processes are comprehensively outlined, and the ecological significance and the human impacts of such interactions are emphasized (Sophocleous 2002). The water-table fluctuation method may be the most widely used technique for estimating recharge; it requires knowledge of specific yield and changes in water levels over time. Advantages of this approach include its simplicity and an insensitivity to the mechanism by which water moves through the unsaturated zone (Scanlon et al., 2002).

2.5.1 Quantification of ground water recharge

The range of recharge rates that can be estimated using different approaches should be matched to expected recharge rates at a site. The reliability of recharge estimates using different techniques is variable. Techniques based on surface-water and unsaturated-zone data provide estimates of potential recharge, whereas those based on ground water data generally provide estimates of actual recharge. Uncertainties in each approach to estimating recharge underscore the need for application of multiple techniques to increase reliability of recharge estimates (Scanlon and Cook 2002). In areas where the annual variability of recharge is very high, measurement techniques with long timescales will be required to estimate the long-term mean annual recharge rates with any accuracy. Where the annual variability of recharge is lower, measurement techniques with shorter timescales will be suitable (Sophocleous 2002).

Scanlon et al. (2002) reviewed the methods which are based on ground water level data for recharge estimation. The advantage of estimation from ground water table data is its simplicity and insensitivity to the mechanism by which water moves in unsaturated zone (Sanford 2002). Water table fluctuation method is best applied to shallow water tables that display sharp rise and declines **(**Rushton 1985) reviewed methods of estimating ground water recharge in temperate climates.

The multiple tracer approaches offer the best potential for reliable recharge estimate in studies that require point information (De Vries and Simmers 2002) Variety of approaches, based on stream flow data, basin characteristics, climate topography, land use data and remote sensing techniques, etc. are adopted to estimate recharge. A few among them are, linear regression model to quantify recharge at regional level (Lorenz and Delin 2007) estimation of ground water recharge from soil temperature data (Cheviron et al., 2005) and weekly, 10 daily and monthly potential evapo-transpiration data (D'Silva 1999).

Field measurement is a necessary component of recharge investigation because it is the only means to determine success of the technique adopted (De Vries and Simmers 2002). Choosing appropriate technique for a particular site from a wide variety of techniques available for quantifying ground water recharge is a complex task. The surface water and unsaturated zone approaches usually provide estimates of potential recharge whereas ground water techniques provide information on actual recharge **(**Scanlon and Cook 2002). A variety of approaches must be adopted and compared in order to reduce uncertainties and increase the confidence in recharge estimation. The hydraulic properties of stream bed and lake bed control the interaction between the surface water and ground water systems which are difficult to measure directly. Most of the ground water models used are either one or two dimensional models and hence are not well equipped to handle this type of problems (Sophocleous 2002).

The water table fluctuation method used for estimation of aquifer recharge is based on the assumptions that rise in ground water level in unconfined aquifer is due to recharge arriving at the water table. The recharge is calculated as the change in water level over time multiplied by specific yield. This method requires no assumptions on the mechanisms for water movement through the unsaturated zone. Long term and spot measured river flow data can also be used for the estimation of base flow (Griffith et al., 2006). Water balance approach is used for the long term mean annual ground water recharge estimation (Lee et al., 2008). Hydrologic budget method is considered as the most appropriate method for determination of seepage losses. To verify the data from field for long reaches of river flows are controlled and required to be maintained (Gu and Deutschman 2001).

The most appropriate way to represent recharge in a ground water model depends upon both physical factors and study objectives. Where the water table is close to the land surface, as in humid climates or regions with low topographic relief, a constant-head boundary condition is used. Conversely, where the water table is relatively deep, as in drier climates or regions with high relief, a specified-flux boundary condition is used. In most modeling applications, mixed-type conditions are more effective, or a combination of the different types can be used (Sanford 2002).

In arid regions the rate of recharge depends on the deep infiltration whereas in relatively wet climate the rate of recharge is controlled by the amount of water that the aquifer system can transmit to the discharge area. This transmission is controlled by the permeability of the geologic formation (Sanford 2002). The study results (Hu et al., 2007) demonstrate that the hydraulic connection between the river and the aquifers has transferred from the coupling to decoupling at some reaches in Weihe river basin of China. In order to re-establish these connections and maintain sustainability it is necessary to reduce ground water withdrawal and to rationalize the use of ground water and surface water.

The cost characteristics, fractional recovery, initial storage, maximum recharge, pumping rates and uncertainties regarding the future availability of water for extraction influences the recharge and withdrawal of ground water (Rosenberg and Lund 2006). Increasing demand for recharge estimates is forcing the research community to develop approaches for building a more thorough understanding of recharge and more comprehensive approaches for delineating recharge zones and quantifying recharge rates that reduce uncertainties and increase confidence in recharge estimates **(**Scanlon and Cook 2002)

2.5.2 Parameters considered for ground water potential prediction

Microwave remote sensing techniques are used to map the spatial domain of surface soil moisture and to monitor its temporal dynamics, information that cannot be measured using other techniques. The physical basis of this approach is presented with examples of how microwave remote sensing is utilized in ground water recharge and related studies (Jackson 2002).

Ettazarini (2007) found a ground water potentiality index, a strategically conceived tool for water research in fractured aquifers. The targeting of fracturing, lithology, drainage, topography and rainfall, as parameters controlling the water occurrence in fractured aquifers, is beneficial to locate successful drilling wells. The use of strategic documents, such as the map of ground water potential index (GPI), allows the ability to predict sites favorable for well positioning and to optimize expenses of new water resources research. The most recognized parameters are the geological features leading to fracturing state, the drainage, the topography and the rainfall. A ground water potential index (GPI) was proposed and computed on the basis of the five factors and the results of statistical analysis. The GPI is noted as follows:

$$\mathrm{GPI} = \alpha F + \beta L + \gamma D + \delta T + \varepsilon R \qquad (2.1)$$

Where GPI is ground water potentiality index, F, L, D, T and R are parameters, respectively, relative to fracturing, lithology, drainage, topography and rainfall and α, β, γ, δ and ε are relative factor weights (Ettazarini 2007).

Rao et al. (2004) proposed a ground water potential index in a crystalline terrain using remote sensing data for relative evaluation of ground water potential zones. Computation was done by integrating all factors such as rainfall, slope, run-off, infiltration, soil cover, moisture content, lineaments, weathered and fractured rocks, drainage, ground water levels and vegetation related to occurrence and movement of ground water resources, which was done by assigning weightage to each of the factors. It was also concluded that higher yield occur wherever the lineaments are parallel to the stream courses, tanks and at the intersection of the lineaments.

Sander et al. (2006) has studied lineaments in ground water exploration and found that high lineament and drainage density may imply poor recharge conditions rather than areas suitable for ground water exploration. Lineaments are manually classified into four categories during the onscreen digitizing, based on their association with topography, drainage and vegetation. Three classes of potential fracture zones and a fourth class representing dykes are introduced.

Solomon and Quiel (2006) have done ground water study using remote sensing and geographic information systems (GIS) in the central highlands of Eritrea showing good correlation between well yield from existing boreholes and proximity to satellite imaged lineaments, supporting the fact that ground water flow is predominantly in the fracture systems. The four parameters considered were lithology, slope, geomorphology and lineaments. In weathered crystalline mantles, aquifers tend to occur at the base of the mantle where less aggressive weathering is associated with saturated conditions and where coarse, partly weathered sand-sized casts predominate (Taylor and Howard 2000).

Sreedevi et al. (2005) conducted integrated approach for delineating potential zones to explore for ground water in the Pageru River basin of Cuddapah District in Andhra Pradesh. The geomorphology, hydrogeology and resistivity interpretations were integrated to make a map of the potential zones for obtaining ground water. Remote sensing data have been used to identify zones in landforms suitable for ground water prospecting. Ground water development in the various geomorphic units is promising in flood plains, alluvial plains and valley fills, which are associated with thick alluvium and weathered material that has high porosity and permeability.

Sener et. al. (2005) concludes that, indicators of ground water occurrence are related to rainfall distribution, land use, geology, topographic elevation, slope and drainage features of the area. Satellite data proved to be very useful for surface study, especially in detecting surface features and characteristics such as lineaments and geology. The final stage involved combining all thematic layers using the method that is modified from. The formula of the ground water potential model (GPM) as shown below:

$$GP = Rf + Lt + Ld + Lu + Te + S + Dd \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

Where; Rf = annual rainfall, Lt = lithology (geology), Ld = lineament density, Lu = land use, Te = topography elevation, S = slope, Dd = drainage density.

The variation in water level helps us to identify the difference in ground water potential. This study facilitates to spatially identify the regions with high discharge and good recharge. It also brings out the rate of recharge and discharge and thereby to discriminate the regions.

The study also reveals that the discharge and recharge is higher at one specific location which is mainly due to agricultural extraction and return flow respectively. This study also reveals a fact that though both the process takes place simultaneously in nature, there can be specific demarcation of period for discharge and recharge process. The discharge is noted for a longer period, while the recharge is for a shorter period due the lesser availability of water.

The spatial extent of the results will help the water managers to provide scientific solutions for the resource. So, the volume of the extraction and recharge in a particular area with the aid of GIS reduces the adhoc experimentation and this method is also less expensive. Hence the monthly water level data of a region along with GIS software can assist in evolving the maximum recharge and discharge regions along with the volume of the water recharged or discharged in a specific area (Sivaraman et al., 2010).

Soumya et al. (2013) stated that actual seasonal patterns are identified using ‘recharge–discharge’ concept based on rainfall intensity instead of traditional monsoon–non-monsoon concept. The wells, which are subjected to pumping, still exhibit dilution chemistry though water level fluctuations are high due to annual recharge. Other wells which do not receive sufficient rainfall and are constantly pumped showed high concentrations in recharge period rather than in discharge period (Anti-dilution). In summary, recharge–discharge concept demarcates the pumped wells from natural deep wells thus, characterizing the basin.

The review of literature reveals that a number of techniques are available for ground water recharge estimation. Each method has its own merits and limitations. For assessment of ground water resources, no single comprehensive technique is available, which is capable of giving an accurate ground water assessment. Ground water resource estimation must be seen as an interactive procedure. The methodologies adapted for computing ground water recharge potential have undergone a continuous change and a number of works has been carried out in this regard. The evaluation of parameter estimation of aquifer is an important aspect of any scheme of ground water resource assessment. The suitable recharge estimation method may need to be investigated for the region under study.

The following Research Gaps have been identified from the literature review study:

1. There is no single method or technique is available to find the natural rate of infiltration of a hydrological unit.
2. Understanding of the aquifer characteristics like K, T, aquifer thickness, depth of salt water intrusion and litholog of the river basin has not been studied.
3. Groundwater level fluctuations in observation open wells and bore wells before and after the monsoon period of the basin has not been addressed.
4. Methodology of finding optimum annual dynamic groundwater reserve of the basin has not been established.

CHAPTER 3

INFILTRATION STUDY

3.1 INTRODUCTION

Infiltration study is a useful tool for most of the hydrological studies. This is one of the important factors of water loss in the hydrological cycle. Infiltration phenomenon assumes a greater significance in the study of water resources. This phenomenon can be defined as the process of water entering vertically into a soil through the soil surface. Infiltration affects not only the timing but also the distribution and magnitude of surface runoff. Infiltration capacity is the maximum rate at which water can pass through the surface of a soil at a, given time (Jury and Horton 2004).

Infiltration is the process by which water on the ground surface enter the soil. Infiltration rate in soil science is a measure of the rate at which soil is able to absorb rainfall or irrigation. It is governed by two forces: gravity and capillary action. While smaller pores offer greater resistance to gravity, very small pores pull water through capillary action in addition to and even against the force of gravity. The infiltrated water first meets the soil moisture deficiency, if any, and thereafter the excess water moves vertically downwards to reach the ground water table. The movement under hydrostatic pressure of water through the interstices of a rock or soil, except the movement through large openings such as caves (Meinzer 1923). This vertical movement is called percolation.

A distinction is always made between infiltration and percolation. The two operations are no doubt closely related since infiltration cannot continue unimpeded unless percolation removes the infiltrated water from the surface soil. The soil is permitted by non-capillary channels through which gravity water flows downward, to meet the ground water table by following the path of least resistance. Capillary forces continuously divert gravity water into capillary pore spaces, so that the quantity of gravity water passing through lower horizons is steadily diminished. This leads to increasing resistance to gravity flow in the surface layer and a decreasing rate of infiltration as a storm progresses. The rate of infiltration in the early phases of a storm is less if the capillary pores are filled by a previous storm.

The infiltration rate depends on the physical condition of the soil and the hydraulics of the water in the profile both of which may change rapidly with time. The actual infiltration rate equals the infiltration capacity only when the supply rate equals or exceeds the infiltration capacity (Raju 1985). The factors affecting the infiltration capacity rate ‘f’ are, rate of rainfall, soil particle size (flow resistance capillarity), vegetal cover, soil type, moisture content, organic matter, season, air entrapment, formation of surface seals or crusts etc.

3.2 INFILTRATION PROCESS

The infiltration process was initially discussed by Horton. The infiltration relationship is expressed as,

$$f = f_c + (f_o - f_c)\, e^{-kt} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

Where

f = infiltration capacity (depth /time), at time t.

k = a constant representing the rate of decrease in f

F_c = final or equilibrium infiltration capacity

f_o = initial infiltration capacity

Two sets of ‘f’ and‘t’ values are selected from the curve and substituted in the above equation. The equations having two unknowns are thus obtained and solved for ‘f_o’ and ‘k’. Infiltration index is the average rate at which water passes through the surface of the soil during a storm. A loss rate is the average rate of loss to surface runoff throughout a storm period. Loss rate is more useful concept. It includes interception, depression storage as well as infiltration.

Infiltration indices are based on the fact that infiltration occurs at some constant or average rate throughout a storm. The most common index is the index for which the total volume of loss throughout the period is estimated and distributed uniformly across the storm pattern. Then the volume of precipitation above the index line is equivalent to the surface runoff. The equation for the index is given as

$$\phi = \frac{P - Q - f_{ir}}{t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ (3.2)$$

Where,

P= total precipitation

Q= total surface runoff

f_{ir} = infiltration that occurs at less than capacity rate

t= time for which infiltration is occurring at capacity rate.

3.3 CLASSIFICATION OF INFILTRATION MODELS

Six infiltration models (Table 3.1) were chosen for inclusion in this document based on several considerations: (1) relatively simple approach, easy to use, and realistic in applications (2) ability to handle various field conditions including surface ponding, non-ponding, various rainfall rates, surface runoff, and wetting and drying (3) application to both homogeneous or non-homogeneous soil profiles. The categories presented are not considered to be all-inclusive, but do provide a wide range of model applications.

Infiltration models can be divided into various categories, depending on the purpose of the model, boundary conditions, and the nature of subsurface systems. In this study, six categories were identified and are shown in Table 3.1. The categories were chosen for representativeness to site-specific conditions, which is discussed in the following sections (3.3.1 to 3.3.6).

Table 3.1 Infiltration model classification.

Sl No.	Category	Model Selected	Reference
1.	Semi-Empirical	SCS model	USDA-SCS, 1972
2.	Homogeneous	Philip’s two-term model	Philip, 1957
3.	Non homogeneous	Green-Ampt model for layered systems	Flerchinger et al., 1988
4.	Ponding	Green-Ampt explicit model	Salvucci and Entekhabi, 1994
5.	Non-ponding	Constant Flux Green-Ampt model	Swartzendruber, 1974
6.	Wetting and Drying	Infiltration/Exfiltration mode	Eagleson, 1978

3.3.1 Semi-Empirical Model

As indicated by the term empirical, these type infiltration models are developed entirely from field data and have little or no physical basis. The empirical approach to developing a field infiltration equation consists of first finding a mathematical function whose shape, as a function of time, matches the observed features of the infiltration rate and then attempting a physical explanation of the process (Jury and Horton 2004). Most physical processes in semi-empirical models are represented by commonly accepted and simplistic conceptual methods, rather than by equations derived from fundamental physical principles. The commonly used semi-empirical infiltration models in the field of soil physics and hydrology are Kostiakov’s model, Horton’s model, and the SCS (Soil Conservation Service) model (Hillel 1998).

3.3.2 Homogeneous Model

Most infiltration models have been developed for application in homogeneous porous media. These models are commonly derived from mathematical solutions based theories of infiltration (e.g., Richards’s equation). Since this mechanistic infiltration model is derived from the water flow equation, considerable insight is given to the physical and hydraulic processes governing infiltration. Infiltration models commonly used for homogeneous soil profiles include the Green-Ampt infiltration model, the Philip infiltration model, the Burger infiltration model, and the Parlange infiltration model. Descriptions of these models are provided in documentation by (Hillel and Baker1988; Yeh and Tripathi 1989).

3.3.3 Non-Homogeneous Model

Naturally developed soil profiles are seldom uniform with depth or the water content distribution uniform at the initiation of infiltration. Because of the non-uniform soil profile, field infiltration measurement data frequently show different characteristics than the models based on theoretical calculations for the uniform soil profile. For most field observations of infiltration rates, the field observations would be less than what would be predicted by models designed for homogeneous systems.

In conceptualization of a non-homogeneous soil profile, it is usually more convenient to divide the profile into layers or horizons, each of which is assumed to be homogeneous (Childs and Bybordi 1969; Hillel and Gardner 1970). The application of the Green-Ampt equation to calculate cumulative infiltration into non uniform soils has been studied by (Bouwer 1969; Childs and Bybordi 1969; Fok 1970; Flerchinger et al., 1988).

3.3.4 Infiltration Model for Ponding Conditions

When the application rate of water to the soil surface exceeds the rate of infiltration, free water (i.e., surface water excess) tends to accumulate over the soil surface. This water collects in depressions, thus ponding on the soil surface. Depending on the geometric irregularities of the surface and on the overall slope of the land, some of the ponded water may become runoff, if the surface storage becomes filled. Under ponded conditions, the cumulative infiltration is a function of soil properties, initial conditions and the ponding depth on the soil surface. Several infiltration models for ponding conditions have been developed (Salvucci and Entekhabi 1994).

3.3.5 Infiltration Model for Non-ponding Conditions

When the rate of water supply to the soil surface does not exceed the soil infiltrability, all water can percolate into the soil and no surface ponding of water occurs. Here the supply of water is up to the soil infiltration capacity. Thus the infiltrated water will be converted as percolation. This process depends on the rate of water supply, initial soil water content and the saturated hydraulic conductivity. Infiltration models for non-ponding conditions have been developed by several researchers (Childs and Bybordi 1969; Hillel and Gardner 1970). Probably the most common approach is an implementation of the Green-Ampt model in an explicit approach.

3.3.6 Wetting and Drying Model

Alternate infiltration and exfiltration of water at the soil surface will result in an unsteady diffusion of water into the soil. The presence of transpiring vegetation adds another mechanism for moisture extraction distributed over a depth which is related to root structure. Infiltration models for such conditions have been developed by (Eagleson 1978 and Corradini et al., 1997).

3.4 INFILTRATION MODEL CONCEPTUALIZATION

Water infiltration into unsaturated porous media for various climatic conditions, soil physical, hydraulic properties and geological conditions is very complex, resulting in a challenge to mathematically simulate observed conditions. An understanding of the principles governing infiltration and factors affecting infiltration processes must be attained. Since a universal mathematical model is not available to address water infiltration for all field conditions, assumptions are commonly made and limitations are identified during the model development and application process. Assumptions used in developing water infiltration models commonly include the following.

3.4.1 Initial soil water content profile

Most infiltration models assume a constant and uniform initial soil water content profile. However, under field conditions, the soil water content profile is seldom constant and uniformly distributed.

3.4.2 Soil profile

There are two types of soil profiles which exist under field conditions (a) homogeneous (b) heterogeneous. Infiltration models developed for the homogeneous soil profile cannot be used for heterogeneous soil profile without simplifying assumptions concerning the heterogeneity.

3.4.3 Saturated soil water content at the soil surface

This is a common assumption for most infiltration models, which will allow for ignoring the initial high hydraulic gradient across the soil surface. The time interval for the surface saturation is very small when compared to the time associated with the infiltration event.

3.5 DIFFERENT TYPES OF MODELS

3.5.1 SCS Model

The empirical approach of developing a water infiltration equation consists of first identifying a mathematical function whose shape, as a function of time, matches the observed features of the infiltration rate, followed by an attempt at providing a physical explanation of the process (Jury and Horton 2004). For semi-empirical models, most physical processes are represented by commonly accepted and simplistic conceptual methods rather than by equations derived from fundamental physical principles. The Soil Conservation Service (SCS) 2 model is a commonly used semi-empirical infiltration model in the field of soil physics and hydrology.

3.5.2 Philip's Two -Term Model

The Philip's two-term model (PHILIP2T) is a truncated form of the Taylor power series solution presented by (Philip 1957). During the initial stages of infiltration (i.e. when t is very small), the first term of Equation 3 dominates. In this stage, the vertical infiltration proceeds at almost the same rate as absorption or horizontal infiltration due to the gravity component, represented by the second term, being negligible. As infiltration continues, the second term becomes progressively more important until it dominates the infiltration process (Philips 1957) suggested the use of the two-term model in applied hydrology when it is not too large.

3.5.3. Green-Ampt Model for Layered Systems

The Green-Ampt Model has been modified to calculate water infiltration into non uniform soils by several researchers (Bouwer 2002) developed a model, based on the Green-Ampt model for calculating infiltration over time in vertically heterogeneous soils. This model is referred to as the Green-Ampt model for layered systems (GALAYER).

3.5.4 Explicit Green-Ampt Model

The Green-Ampt model is the first physically based equation describing the infiltration of water into a soil. It has been the subject of considerable development in soil physics and hydrology owing to its simplicity and satisfactory performance for a wide variety of water infiltration problems. This model yields cumulative infiltration and infiltration rates as implicit functions of time (i.e., given a value of time, t, q and I cannot be obtained by direct substitution). The equations have to be solved in an iterative manner to obtain these quantities. Therefore, the required functions are q (t) and I (t) instead of t (q) and t (I). The explicit Green-Ampt model (GAEXP) for q (t) and I (t), developed by (Salvucci and Entekhabi 1994), facilitated a straightforward and accurate estimation of infiltration for any given time. This model supposedly yields less than 2% error at all times when compared to the exact values from the implicit Green-Ampt model.

3.5.5 Constant Flux Green-Ampt Model

The constant flux Green-Ampt model (GACONST) can be used to simulate the water infiltration for non-ponding conditions, where the water flux application rate is represented by ‘r’ (cm/h). Two cases are presented, that where the application rate is less than the saturated hydraulic conductivity ($r < K$), and where the application rate is greater than the saturated hydraulic conductivity ($r > K$). When $r < K$, the infiltration rate (q) is always equal to the surfaces application rate (r) and the surface is never saturated; when $r > K$, surface saturation first occurs at time t.

3.5.6 Infiltration/ Exfiltration Model

The vertical movement of soil water between the surface and the water table can be divided into two processes according to the predominant forces involved: (1) infiltration and (2) Exfiltration (evapotranspiration). An infiltration/Exfiltration model (INF/EXF) developed by (Eagleson 1978) was selected to estimate the water infiltration during a wetting season and Exfiltration during a drying season. Philip’s equation, which can be used to simulate both infiltration and Exfiltration, assumes the medium to be effectively semi-infinite and the internal soil water content at the beginning of each storm and inter-storm period to be uniform at the long term space-time average. The Exfiltration equation is modified for presence of natural vegetation through the approximate introduction of a distributed sink representing the moisture extraction by plant roots.

3.6 PHENOMENA OF WATER INFILTRATION AT UNSATURATED ZONE

Water applied to the soil surface through rainfall and irrigation events subsequently enters the soil through the process of infiltration. If the supply rate of water to the soil surface is greater than the soil’s ability to allow the water to enter, excess water will either accumulate on the soil surface or become runoff. The process by which water enters the soil and thus the vadose zone through the soil-atmosphere interface is known as infiltration. Infiltrability is a term generally used in the disciplines of soil physics and hydrology to define the maximum rate at which rain or irrigation water can be absorbed by a soil under a given condition. Indirectly, infiltrability determines how much of the water will flow over the ground surface into streams or rivers, and how much will enter the soil, and thus assists in providing an estimate of water available for downward percolation through drainage or return to the atmosphere by the process of evapotranspiration.

Understanding water movement into and through the unsaturated zone is of great importance to both policy and engineering decision-makers for the assessment of contaminant fate and transport, the management of agricultural lands and natural resource protection. The process of water movement is very dynamic, changing dramatically over time and space. Knowledge of the infiltration process is a prerequisite for managing soil water flux and thus the transport of contaminants in the vadose zone.

Five zones are illustrated for the infiltration process, considering soil water distribution in a homogeneous soil.

1) Saturated zone: The pore space in the saturated zone is filled with water or saturated. Depending on the length of time elapsed from the initial application of the water; this zone will generally extend only to a depth of a few millimeters.

2) Transition zone: This zone is characterized by a rapid decrease in water content with depth and will extend approximately a few centimeters.

3) Transmission zone: The transmission zone is characterized by a small change in water content with depth. In general, the transmission zone is a lengthening unsaturated zone with

uniform higher water content. The hydraulic gradient in this zone is primarily driven by gravitational forces.

4) Wetting zone: In this zone, the water content sharply decreases with depth from the water content of the transmission zone to near the initial water content of the soil.

5) Wetting front: This zone is characterized by a steep hydraulic gradient and forms a sharp boundary between the wet and dry soil. The hydraulic gradient is driven primarily by metric potentials. Beyond the wetting front, there is no visible penetration of water. Comprehensive reviews of the principles governing the infiltration process have been published by (Philip 1957) and (Hillel 1998).

Soil water infiltration is controlled by the rate and duration of water application, soil physical properties, slope, vegetation and surface roughness. Generally, whenever water is ponded over the soil surface, the rate of water application exceeds the soil infiltrability. On the other hand, if water is applied slowly, the application rate may be smaller than the soil infiltrability. In other words, water can infiltrate into the soil as quickly as it is applied and the supply rate determines the infiltration rate. This type infiltration process has been termed as supply controlled. However, once the infiltration rate exceeds the soil infiltrability, it is the latter which determines the actual infiltration rate and thus the process becomes profile controlled. Generally, soil water infiltration has a high rate in the beginning, decreasing rapidly and then slowly decreasing until it approaches a constant rate. The infiltration rate will eventually become steady and approach the value of the saturated hydraulic conductivity (Ks).

The initial soil water content and saturated hydraulic conductivity of the soil media are the primary factors affecting the soil water infiltration process. The wetter the soil initially, the lower will be the initial infiltrability (due to a smaller suction gradient) and a constant infiltration rate will be attained more quickly. In general, higher the saturated hydraulic conductivity of the soil, higher will be the infiltrability. As might be expected, the slope of the land can also indirectly impact the infiltration rate. Steep slopes will result in runoff, which will impact the amount of time the water will be available for infiltration. In contrast, gentle slopes will have less of an impact on the infiltration process due to decreased runoff. When compared to the bare soil surface, vegetation cover tends to increase infiltration by retarding surface flow, allowing time for water infiltration. Plant roots may also increase infiltration by increasing the hydraulic conductivity of the soil surface. Due to these effects, infiltration may vary widely under different types of vegetation.

A number of mathematical models have been developed for water infiltration in unsaturated zone (Philip 1957; Bouwer 1986; Fok 1970). A thorough review of water infiltration models used in the fields of soil physics and hydrology has been presented by (Ravi and Williams 1998).

3.7 METHODOLOGY OF INVESTIGATION

A river basin is the land that water flows on its way to a river. It is normally made up of all the land drained by a river and its tributaries. Features of a river basin include; tributaries, a watershed, a confluence, source and a mouth. In the present study, Haladi river basin is considered. The details of the Haladi river basin are described in section 1.3. The purpose of this study is to find the infiltration capacity of the river basin. The river basin is divided into ten regions based on the existence of observation open wells and double ring infiltrometer tests were conducted at each region.

Two sets of double ring infiltrometer were used for the investigation purpose. Each consists of outer and inner diameter 35 and 30 cm, 25 and 15 cm rings respectively to measure infiltration rates (Karanth 1987). Water is applied in both the inner and outer rings to maintain a constant depth of about 5 cm. Water is replenished after the level falls by about 1 cm. The water depth in the inner and outer rings should be kept same during the observation period. Readings of volume of water added at successive time intervals to maintain constant depth of flooding in the inner ring are taken to facilitate the computation of infiltration capacity rate. As the purpose of outer ring is to suppress the lateral percolation of water from the inner ring, the water added to it need not be measured though water is added to maintain the same depth as in the inner ring. The experiment has to be carried out till a constant infiltration rate is observed.

20 field tests were conducted (10 set of 25 and 35 cm dia and 10 set of 15 and 30 cm dia) at all 10 observation open well places of the Haladi river basin. The double ring infiltrometer used for conducting the field test are shown in Fig. 3.1(a) and 3.1(b). The field tests conducted near the observation open wells is shown in Fig. 3.2 (a) to 3.2(j). The field tests conducted @ 1 metre below the ground surface is shown in Fig. 3.3(a) to 3.3(c). The sample of double ring infiltrmeter test ground surface mark is as shown in Fig. 3.3(d).

Fig. 3.1(a) DRI of dia 30 and 15 cm

Fig. 3.1(b) DRI of dia 35 and 25 cm

Fig. 3.2(a) Field test at Zone No. 1

Fig. 3.2(b) Field test at Zone No. 2

Fig. 3.2(c) Field test at Zone No. 3

Fig. 3.2(d) Field test at Zone No. 4

Fig. 3.2(e) Field test at Zone No. 5

Fig. 3.2(f) Field test at Zone No. 6

Fig. 3.2(g) Field test at Zone No. 7

Fig. 3.2(h) Field test at Zone No. 8

 Fig. 3.2(i) Field test at Zone No. 9	 Fig. 3.2(j) Field test at Zone No. 10
 Fig. 3.3 (a) DRI of dia 30 and 15 cm at 1 m Below Ground Level	 Fig. 3.3 (b) DRI of dia 35 and 25 cm at 1 m Below Ground Level
 Fig. 3.3 (c) DRI of dia 30 and 15 cm at 1 m Below Ground Level	 Fig. 3.3 (d) DRI Test Mark

CHAPTER 4

AQUIFER CHARACTERIZATION

4.1 GEOPHYSICAL INVESTIGATIONS -ELECTRICAL RESISTIVITY TEST

The electrical resistivity methods have been widely used for various hydro-geological applications. In ground water studies, it is used to find the aquifer type, thickness of aquifer, water table depth and contamination. It is also used for the determination of aquifer properties like subsurface resistivity distribution, ground water exploration and soil hydrological properties. Coastal aquifers, which are prone to salt water intrusion, are identified by the relatively low resistivity values. Ground water resources of an area are largely depending upon the characteristics of the aquifers. The most important characteristics in this regard are the transmissivity, hydraulic conductivity and the storage coefficient. Long duration pumping test is one of the methods adopted for the determination of these parameters. The surface geo-electric measurements provide an alternative approach for the estimation of these parameters. Several investigators (Binley and Kemna 2005; Nath et. al., 2000) have tried to establish empirical relationship between the hydraulic transmissivity and transverse electric resistance.

The direct measurement of permeability of subsurface aquifers is very difficult. In the past, several correlations were established between the hydraulic conductivity and other parameters which are site specific and are applicable only where similar kind of aquifers exist. For areas comprising of laterite, older alluvium, newer alluvium and where the depth of water table is less than 25 m, the relationships are as (Nath et. al. 2000).

$$T' = 834.4 + 0.8795\ T \qquad \text{……..………} \quad (4.1)$$

Where ‘T’ – Hydraulic transmissivity; T – Transverse resistance

$$K = 16.02 + 92.75\ F \quad \text{where F- The formation factor ……. ………} \ (4.2)$$

The area selected for the tests is between Ampar and Kundapur (Fig.4.1), (Google image scale 1:50,000) from 74.45° to 74.55° E and 13.35° to 13.40° N, which has the Haladi River on one side and the hills on the other side. The Arabian Sea is at a distance of about 10 km from the area selected. The Haladi River being a tidal river carries salt water as backwater reaching up to a distance of 12 km during the summer. As a result of this, the wells which are near to the banks of the river get contaminated by the salt water.

4.1.1 Geo-electrical survey methodology

The electrical resistivity technique is one of the geophysical methods that enable for the determination of sub-surface resistivity by sending an electric current into the ground and measuring the potential field generated by the current using aquameter (Fig. 4.2). The electrical resistivity test is also known as vertical electrical sounding (VES) and was conducted at nine locations in the study area using the Schlumberger configuration. At some places, the spacing was restricted by the physical obstructions and the tests are carried out for the maximum spacing available at each location. The electrode half spacing (AB/ 2) range was from 10 to 80 m. The soil samples were collected from these locations for the determination of porosity, specific gravity, grain size analysis etc.

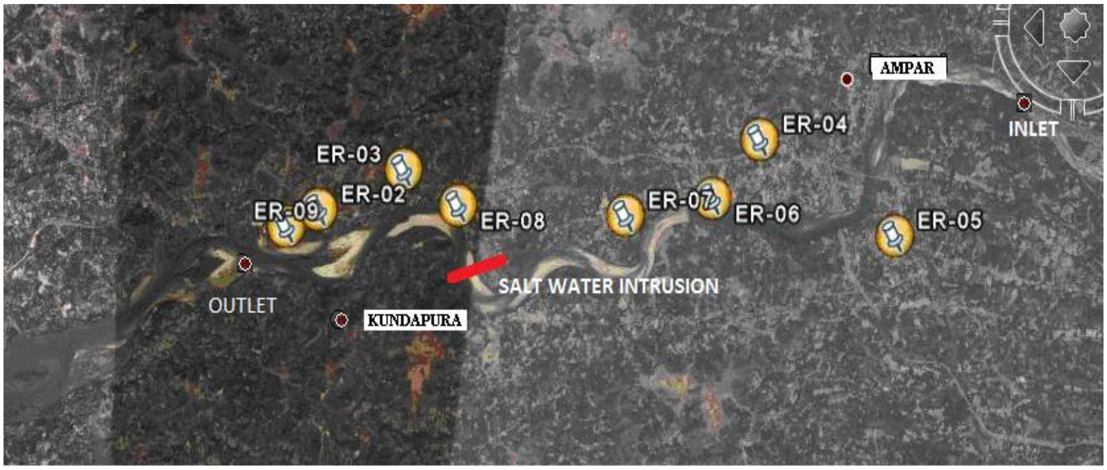


Fig.4.1 Map showing the locations of electrical resistivity tests

Fig. 4.2 Electrical Resistivity Meter (Aquameter CRM- ANVIC Systems Pune)

4.2 HYDRAULIC CONDUCTIVITY FROM SOIL PARAMETERS

Another method recommended for the determination of aquifer properties is by the measurable parameters (Barr 2001). In this method, hydraulic conductivity is determined from various soil and fluid properties which are available in the literature or can be measured by using the standard tests. This method is applicable for the laminar flow where the inertial forces are assumed to be negligible. The equation given for the determination of the hydraulic conductivity K is;

$$K = \rho\, g\, \alpha\, m^2 / 5\, \mu \text{ (Barr 2001)} \qquad \text{…….. …….. (4.3)}$$

Where ρ – Density of fluid (for water = 1.0); g - acceleration due to gravity; α – porosity (0.15); μ – dynamic viscosity of water (0.00086); m – hydraulic mean radius = Porosity / Surface area.

The soil samples were collected from 7 different locations (Fig. 4.3) from 74.45° to 74.55° E and 13.35° to 13.40° N. These locations are selected approximately 3 m to 6 m away from the well locations depending upon the local site conditions. These samples are given serial numbers with the well number near which it is collected. For example Sample 02/07 is the sample number 02, collected near the well W_{07}.

Fig. 4.3 Soil sample locations (74.45° to 74.55° E and 13.35° to 13.40° N)

4.3 PUMPING TESTS

The hydraulic properties of aquifers can be determined by the pumping tests. The test involves abstraction of water from a well at a controlled rate and noting observations of water levels with respect to time. Theoretically, pumping test should be carried out for a long duration till the pumping rate equals the recharge rate to get accurate results. Practically, the long duration pump tests may not be possible and the tests are carried out for short duration of 1-2 hrs and the results are computed.

Software description: The software used for the calculation of hydraulic conductivity from the observations of pumping test is AQTESOLVE ver. 3.5 for Windows developed by Glenn M. Duffield, Hydro solves, Inc. This software is a package for the analysis of aquifer tests with analytical solutions, curve matching tools and report graphics. With the data set wizard data is entered for the pumping or recovery test and by choosing an appropriate method for confined, unconfined or leaky aquifer the results are obtained. The aquifer properties are obtained using visual or automatic curve matching. Output results are available in graphical or report formats. New features are forward solution (prediction) wizard, multi-well slug tests, visual matching guides for slug tests, enhanced options for type curve families. Assumptions are 1). Theis (1935) analytical solution assumes isotropic and homogeneous conditions. 2). Assumes the silty clay unit is a competent confining unit and leakance from this unit is negligible 3). The aquifer has a consistent thickness of 20 feet.

Theoretical background of the software AQTESOLVE: AQTESOLV by HydroSOLVE Inc. is software designed to calculate hydraulic conductivity, storativity and other aquifer properties from data sets collected during slug and aquifer (pumping) tests. AQTESOLV is user friendly. It can be mastered using the tutorial and help file. Most students pick up the software quickly. The Slug Test and Pumping Tests Wizards do a good job of walking the user through the input of data. A useful feature is the basic pictures on each input screen that show what each variable represents. AQTESOLV can import text files generated by commonly used pressure transducers. Also, data can be manually entered or pasted from a spreadsheet. It is easy to change the input values once you have entered them, and to switch between English and SI units. After importing, the raw data can be manipulated using mathematical functions. For example, hydraulic head data can be converted to drawdown data.

Once the data are entered, the software offers a variety of solutions. This is where user-knowledge is important. AQTESOLV gives little guidance on selecting the appropriate solution for the data and hydrogeologic setting and the user is referred to the relevant literature for details on each solution. The user must also know how to correctly display the data (e.g. on linear or log scales), and how to transform the raw data into the form used by each solution. The software provides an automated matching feature, but the automated match is usually poor, and manual fitting of the solution lines to the data is ecommended. In corporating output from AQTESOLV into a presentation or report is functional, but not fancy. A hard copy of the graphed data, your best fit line, and calculated parameters can be sent to a printer, or, exported as a Windows metafile. Overall, the software is easy to use, offers a variety of solutions, creates presentation -quality output, and saves time when compared to performing the analysis by hand.

CHAPTER 5

GROUND WATER RECHARGE ESTIMATION

5.1 INTRODUCTION

India has a very long coastline and 25% of the country's population lives in the coastal zone. Similarly, urban centers are located mostly along the coast when compared to other parts of the country and three out of the four metros are located on the coast. The coastal zone is the most industrialized area in the country. Fourteen major, forty four medium and fifty five minor rivers/streams discharge into the sea through the entire length of the coast. The coastal river aquifers have to be managed carefully and cautiously to avoid problems like sea water intrusion and land subsidence.

Ground water constitutes about 3% of the total available freshwater resources on the earth. The ever-increasing demand for fresh water against the limited potential has resulted in a stress on the fresh ground water resources, Out of the total fresh water resources 77 % occurs in the form of ice, 22% as ground water and about 1% as surface water in the form of rivers, lakes etc. Ground water being easily available and easy to develop for private entrepreneurs, its development, especially in the rural areas were not in a planned manner thus resulting in over exploitation at places, while scanty development at other places. The optimal management of water resources becomes absolutely necessary to meet the growing demand for which proper planning and management is required. A review of current mechanism indicates that adequate availability of appropriate data is many times a limiting factor that is the input for proper planning and management. In order to have a scientific development strategy, it is important to have the precise assessment of the available ground water resources.

There is an overall increase in ground water development in 2009 as compared with 2004, particularly in the areas where future scope for ground water development existed (GEC 2009). The ground water development should be sustainable and optimal to avoid deterioration in quality and quantity. In order to achieve these objectives it is required to know the available resources, its sustainability and the spatial as well as temporal distribution. Hence the estimation of ground water resources assumes great significance. There are several methodologies world over aimed at assessment of the ground water resource and each of these methodologies has their own merits and demerits addressing different problems encountered in the estimation. Thus, the methodologies undergo continuous refinement and updating but none of them gives very precise results due to the involvement of extremely complex and dynamic parameters.

These methods were either based on rainfall infiltration factor or water level fluctuation method, without giving much importance to other controlling facts (GEC 1984) which was the first systematic approach based on water balance method. The committee recommended slight modification to the GEC 1984 to make it more realistic and the methodology is known as ground water resource estimation methodology (GEM 1997), Ministry of Water Resources, Government of India, New Delhi.

5.1.1 Definition and Aspects of Ground water Recharge

Many terms are used to describe the resource potential; optimal yield, safe yield, mining yield and sustainable yield, but in general, they are not well defined and in most cases are mainly described by the recharge component. Ground water recharge is defined in a general sense as “the downward flow of water reaching the water table, forming an addition to the ground water reservoir”. The process of downward movement of soil water in excess of soil moisture deficit and evapotranspiration (infiltration excess) is termed as percolation. However not all the water reaches water table. It might be hampered by low-conductivity horizons and disappear as interflow to nearby local depressions, where it runs off or evaporates instead of joining the regional ground water system. Four main modes of recharge can be distinguished as follows (GEMS 2008).

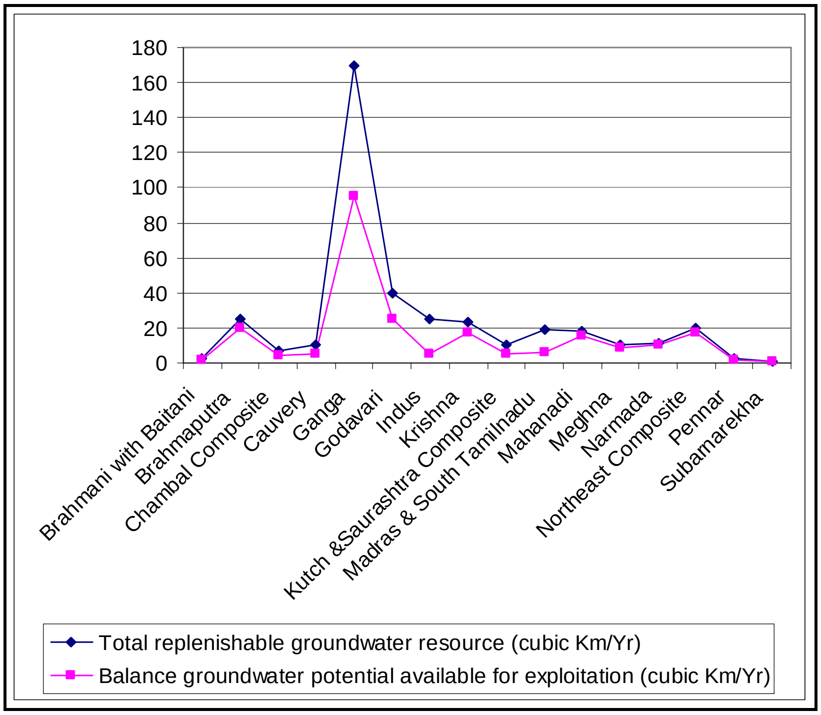
- Downward flow of water through the unsaturated zone reaching the ground water table.
- Lateral and/or vertical inter-aquifer flow.
- Induced recharge from nearby surface water bodies resulting from ground water abstraction.
- Artificial recharge such as from borehole injection or man-made infiltration ponds.

Natural recharge by downward flow of water through the unsaturated zone is generally the most important mode of recharge in any climatic setting. The main sources of recharge are rainfall, surface water bodies (ephemeral or seasonal rivers, lakes, etc.) and irrigation losses. It is widely known that ground water recharge is one of the most difficult parameters to quantify. Various methods appear to provide a reasonable estimate of the total recharge to the ground water basin, but they do not provide a way to quantify the spatial distribution of the total recharge within the basin (GEMS 2008).

5.1.2 Statistics on Ground water Availability and Development

India's ground water resources are almost ten times its annual rainfall. According to the Central Ground Water Board of the Government of India, the country has an annual exploitable ground water potential of 26.5 M ha-m like surface water, nearly 85% of currently exploited ground water is used only for irrigation. But ground water exploitation is not uniform across the country. At the national level, only 30% of the actual ground water potential has been harnessed. However, in a few states such as Punjab, against a critical level of 80%, the level of exploitation is over 98%. Haryana is a close second at 80%, and Tamilnadu is reaching criticality at 60% (GEC 2009).

Fig. 5.1 represents comparison between total available replenishable ground water and ground water balance left in the basins for exploitation after being used for irrigation, industrial, domestic and other uses. It has been reported that Ganga basin possesses maximum amount of 170.99 cubic km/year of total available replenishable ground water and 96.37 cubic km/year is left for exploitation. Ground water status with respect to Karnataka is summarized in Table 5.1.



Source: Data from Ministry of Water Resources (2003)

Fig. 5.1 Total replenishable GW and GW balance left in the basins for exploitation

Table 5.1: Ground water status in Karnataka

State	Total replenishable ground water Resources (Mm^3/Yr)	Utilizable ground water resources for irrigation (Mm^3/Yr)	Net G. W. Draft (Mm^3/Yr)
Karnataka	9621.18	8178.00	2725.00

Source: Water and Related Statistics, March 2003 CWC

5.1.3 Ground water Resource Potential in the Western Ghat Basins

The rivers in the Western Ghat region generally originate at an elevation ranging from 400 metres to 1,600 metres above the mean sea level, close to the Western Ghat ridge. The rivers generally flow westward and meet the Arabian Sea after a short run varying from 50 km to 300 km. Ground water potential of these river basins is summarized in Table 5.2.

Table 5.2 Ground water potential in river basins of the Western Ghats

Ground water resources	**Potential**
Total replenishable ground water	274.861 Mm^3 /yr
Provision for domestic, industrial and other uses	40.861 Mm^3 /yr
Available ground water for irrigation	234. Mm^3 /yr
Balance for future use in net terms	165.297 Mm^3 /yr
Level of ground water development	29.36%

Source: Ministry of Home Affairs, Censes of India 2001

5.2 GROUND WATER RESOURCE ESTIMATION METHODOLOGY

The ground water Estimation Committee (GEC) was constituted by the government of India in 1982 to recommend methodologies for estimation of the ground water resource potential in India. It was recommended by the committee that the ground water recharge should be estimated based on ground water level fluctuation method. However, in areas, where ground water level monitoring is not being done regularly or where adequate data about ground water level fluctuation is not available, adhoc norms of rainfall infiltration may be adopted. In order to review the recommended methodology, the Committee was reconstituted in 1995, which released its report in 1997. This Committee proposed several improvements in the existing methodology based on ground water level fluctuation approach. Salient features of their recommendations are given below (GEM 1997).

The methodologies adopted for computing ground water resources, are generally based on the hydrologic budget techniques. The hydrologic equation for ground water regime is a specialized form of water balance equation that requires quantification of the components of inflow to and outflow from a ground water reservoir, as well as changes in storage therein. Some of these are directly measurable, few may be determined by differences between measured volumes or rates of flow of surface water and some require indirect methods of estimation. Water balance techniques have been extensively used to make quantitative estimates of water resources and the impact of man's activities on the hydrological cycle.

The study of water balance requires the systematic presentation of data on the water supply and its use within a given study area for a specific period. The water balance of an area is defined by the hydrologic equation, which is basically a statement of the law of conservation of mass as applied to the hydrological cycle. With water balance approach, it is possible to evaluate quantitatively individual contribution of sources of water in the system, over different time periods and to establish the degree of variation in water regime due to changes in components of the system. A basin wise approach yields the best results where the ground water basin can be characterized by prominent drainages.

A thorough study of the topography, geology and aquifer conditions should be taken up. The limit of the ground water basin is controlled not only by topography but also by the position, structure and permeability of rocks and the configuration of the water table. Once the study area is identified, comprehensive studies can be undertaken to estimate for selected period of time, the input and output of water and change in storage to draw up water balance of the basin. The estimation of ground water balance of a region requires quantification of all individual inflows to or outflows from a ground water system and change in ground water storage over a given time period. The basic concept of water balance is, in a system,

Inflow - outflow = change in storage (over a period of time)

The general methodology of computing ground water balance consists of the following

- Identification of significant components
- Evaluating and quantifying individual components and
- Presentation in the form of water balance equation. (Kumar and Seethapathi 2002)
- Estimation of ground water balance components

5.2.1 Ground water Estimation Methodology – 1997 (GEM 97)

The GEM–97 is an improvement over the GEC-84. The major improvements over the GEC 1984 are as follows:

- Water shed is taken as assessment unit. Sub areas viz hilly area is excluded, poor quality areas as per local standards separately dealt with and the rest of the area is classified as command and non-command for ground water assessment.
- Season wise ground water resource assessment is done for each monsoon, pre-monsoon,

post monsoon sub area.

- Methodology has been provided for determination of specific yield based on ground water balance approach in dry season for non-command area in hard rock terrain.
- Norm for return flow from irrigation is based on type of source, type of crop and depth to water table.
- Categorization based on stage of development and long term trend in pre and post monsoon water levels.
- Allocation for domestic and industrial use is more realistic based on population density and relative load on ground water for the purposes.

5.2.2 Ground water Resource Estimation Committee Norms

If adequate data of ground water levels are not available, rainfall recharge may be estimated using the rainfall infiltration method. The same recharge factor may be used for both monsoon and non-monsoon rainfall with the condition that the recharge due to non-monsoon rainfall may be taken as zero, if the rainfall during non-monsoon season is less than 10% of annual rainfall. GEM (1997) has recommended a value of 3% for lateritic formation as rainfall infiltration factor. An additional 2% of rainfall recharge factor may be used in areas where watershed development with associated soil conservation measures is implemented. This additional factor is separate from contribution due to water conservation structures such as check dams, nalla bunds, percolation tanks etc., for which the norms are defined separately.

5.2.3 Ground water Balance Approach

In this method, all components of the ground water balance equation except the rainfall recharge are estimated individually. The algebraic sum of all input and output components is equated to the change in ground water storage, as reflected by the water table fluctuation, which in turn yields the single unknown in the equation, namely, the rainfall recharge. A pre-requisite for successful application of this technique is the availability of very extensive and accurate hydrological and meteorological data. The ground water balance approach is valid for the areas where the year can be divided into monsoon and non-monsoon seasons with the bulk of rainfall occurring in former.

Ground water balance study for monsoon and non-monsoon periods is carried out separately. The former yields an estimate of recharge coefficient and the later determines the degree of accuracy with which the components of water balance equation have been estimated. Alternatively, the average specific yield in the zone of fluctuation can be determined from a ground water balance study for the non-monsoon period and using this specific yield, the recharge due to rainfall can be determined using the ground water balance components for the monsoon period (GEM 2009).

5.3 RECHARGE ESTIMATION TECHNIQUES

Estimating the rate of aquifer replenishment is probably the most difficult of all measures in the evaluation of ground water resources. The methods available for the estimation of ground water recharge directly from precipitation can be broadly divided into three-inflow, aquifer response and outflow methods according to how the studies are conducted (Kumar and Seethapathi 1987). The following methods are commonly in use for estimating natural ground water recharge (Chandra 1980).

i) Soil water balance method
ii) Zero flux plane method
iii) One-dimensional soil water flow model
iv) Inverse modeling technique
v) Ground water level fluctuation method
vi) Hybrid water fluctuation method
vii) Ground water balance method
viii) Isotope and solute profile techniques
ix) Numerical Modeling

5.3.1 Soil Water Balance Method

This method is essentially a book keeping procedure, which estimates the balance between the inflow and outflow of water. Here, the volume of water required to saturate the soil is expressed as an equivalent depth of water and is called soil water deficit. One condition

enforced is that if the soil water deficit is greater than a critical value (called the root constant), evapotranspiration will occur at a rate less than the potential rate.
The magnitude of the root constant depends on the vegetation, the stage of plant growth and the nature of soil. Various techniques for estimating Ea, usually based on Penman-type equations can be used.

The data requirement of the soil water balance method is large. When applying this method to estimate the recharge for a catchment area, the calculation should be repeated for areas with different precipitation, evapotranspiration, crop type and soil type. This method is of limited practical value, because depth of water is not directly measurable. Another aspect is that the depth of the root zone may vary in semi-arid regions between 1 and 3 meter’s. Results from this model are of very limited value without calibration and validation, because of the substantial uncertainty in input data. The model parameters do not have a direct physical representation, which can be measured in the field.

5.3.2 Zero Flux Plane Method

Amitha (2000) suggested the zero flux plane method relies on the location of a plane of zero hydraulic gradients in the soil profile. Recharge over a time interval is obtained by summation of the changes in water contents below the plant. The position of the zero flux planes is usually determined by Tensiometers. Darcy's law gives the flux q, defined as the volume of water per unit time passing through the unit area at any depth: Thus, knowing the unsaturated hydraulic conductivity and potential gradient the flux may be determined. Tensiometers or the neutron scattering technique may be used to measure water potentials. The hydraulic conductivity estimation presents more problems such as (i) K may vary by a factor of 103 or so over the normal moisture content of a typical soil and (ii) K differs depending on the place even in partly homogeneous soil.

5.3.3 One Dimensional Soil Water Flow Model

For recharge to occur, water has to move through the unsaturated zone until it reaches the water table. Flow conditions within this zone are more complex than the flow mechanisms in a saturated aquifer. The equation of moisture retention curve is a non-linear relation to the water content. Since the moisture retention curve can only be determined experimentally, its true behavior in practice is only known at a finite number of points. Two methods to obtain values at non-experimental points can be used. The best and most obvious method is by interpolation, but this method can only be successful in those cases where the experimental points are closely spaced. The most recent approach fits an equation to the experimental points. The equations commonly used are the Brooks and Corey function and the Van Genuchten function.

5.3.4 Inverse Modeling Technique

The inverse modeling technique is a two-dimensional finite element (or finite difference) ground water model of the saturated zone. Current methods of calibrating ground water flow models are either direct or indirect. The indirect approach is essentially a trial and error procedure that seeks to improve an existing estimate approach of the parameters in an iterative manner, until the model response is sufficiently close to that of the real system. The direct approach is different in that it treats the model parameters as dependent variables in a formal inverse boundary value problem (Amitha 2000).

The inherent non-uniqueness of solution is one of the major difficulties faced in dealing with the inverse problem. Much of the data entered into the inverse modeling technique represent imprecise measurements and processed information that give a distorted picture of the system's true state. The calculation of recharge of an aquifer by the inverse modeling technique must be regarded with caution, if the true ‘S’ (Storage coefficient) values of the aquifer are not known. If, however, the calibrated ‘S’ values can be regarded as being very close to the real values, this technique can be of much use in describing the behavior of the aquifer to the recharge phenomena in general (Amitha 2000).

5.3.5 Ground water Level Fluctuation Method

This is an indirect method of deducing the recharge from the fluctuation of the water table. The rise in the water table during the rainy season is used to estimate the recharge, provided that there is a distinct rainy season with the remainder of the year being relatively dry. The basic assumption is that the rise in the water table is primarily due to the rainfall recharge.

It is recognized that other factors such as pumping or irrigation during the rainy season do not have an influence. When pumping is reduced or ceases during the rainy seasons, a redistribution of ground water heads occurs so that part of the observed increase in water level may be due to normal well recovery.

5.3.6 Hybrid Water Fluctuation Method:

Sophocleous (1991) proposed a hybrid water fluctuation approach to recharge estimation. This method is generally reliable for estimating natural ground water recharge in relatively flat areas with a shallow water table (less than 10m). By associating water table rises with specific precipitation events and by combining the recharge estimates from the soil water balance analysis with the consequent water table rises, one can obtain effective storativity values for each recharge study site, especially after averaging several such values. The site calibrated effective storativity value can then be used to translate each major water table rise tied to a specific storm period into a corresponding amount of ground water recharge.

Estimation errors in the hybrid water fluctuation method are reduced by running a 'storm period' based soil water balance throughout the year in combination with the associated water level rise. This method gives more reliable results of the recharge estimation than any other approach.

5.3.7 Ground water Balance Method

One of the factors influencing the change in water table is the effective porosity, n_e, of the zone in which the water table fluctuations occur, n_e changes as the depth of water table changes, especially for water table less than 3 metre’s depth. Moreover, it should be noted that if the water drops, part of the water is retained by the soil particles; if it rises, air can be trapped in the interstices that are filling with water. All elements of the water balance equation are computed using independent methods wherever possible. Computations of water balance elements always involve errors, due to shortcomings in the techniques used. The discrepancy of water balance is given as a residual term of the water balance equation and includes the error in the determination of the components, which are not taken into account (Amitha 2000).

The water balance may be computed for any time interval. To apply the above equation correctly, it is essential that both the area and the period for which the balance is assessed be carefully chosen. All components of the water balance equation other than the rainfall recharge are estimated using the relevant hydrological and meteorological information. The rainfall recharge is calculated by substituting these estimates in the water balance equation. This approach is valid for the areas where the year can be divided into monsoon and non-monsoon periods and the water balance is carried out separately. The former yields an estimate of recharge coefficient and the latter determines the degree of accuracy with which the components of water balance equation have been estimated (Amitha 2000).

5.3.8 Isotope and Solute Profile Techniques

Isotopes ^{2}H, ^{3}H, ^{18}O and ^{14}C are commonly used in recharge studies, of which the first three most accurately simulate the movement of water, because they form a part of the water molecule. A radioactive tracer provides a means of tracing water movement through the unsaturated zone. In principle, any traces with negligible adsorption may be used, but tritium is preferred. Tritium may either be artificially introduced or environmental tritium may be used (Amitha 2000). However, environmental tritium has several disadvantages.

i) Tritium is not conservative and is lost from the system by evapotranspiration.

ii) Contamination during sampling and processing is a factor, which is enhanced in remote areas and at low total moisture levels.

iii) Analysis is highly specialized and costly.

iv) Quantitative studies are difficult to achieve, since it is difficult to determine a tritium mass balance (Amitha 2000).

An environmental tracer suitable for determining the movement of water must be highly soluble, conservative and not substantially taken up by vegetation. The chloride ion satisfies most of these criteria and is therefore considered a suitable tracer, particularly in coastal areas. In this case the ground water recharge is given by, Ri = D/C (mm/year) where, D = wet and dry chloride deposition ($mg/m^2/year$) and C = concentration in ground water (Amitha 2000).

This method is convenient, fast and cheap. The chief drawback is the uncertainty in the determination of the wet and dry deposition. The principle source of chloride in ground water is from the atmosphere. In this case the recharge can be expressed as Ri = Rainfall x (Cl of rainfall/Cl of ground water). The chloride method must be treated with caution. Recharge under conditions of extremely high rainfall with a long recurrence period, is likely to influence the chloride concentration of ground water to a high degree resulting in an over estimate of the mean annual recharge.

5.3.9 Numerical Modeling

This approach has largely been replaced by the ground water flow models. Ground water model calibration or inversion is used to predict the recharge rates from the information on the hydraulic heads, hydraulic conductivity, and other parameters (Sanford 2002). Since the recharge and hydraulic conductivity are often highly correlated, model inversion using hydraulic head data is only limited to estimating the ratio of recharge to hydraulic conductivity. The reliability of the recharge estimates depends on the accuracy of the hydraulic conductivity data. Uncertainties in the hydraulic conductivity are greater in the unsaturated systems than in the saturated systems because of nonlinear relationships between the hydraulic conductivity and water content. These uncertainties in the hydraulic conductivity could result in the uncertainties in recharge estimates.

In general, models are conceptual descriptions or approximations that describe physical systems using mathematical equations. They are not the exact descriptions of physical systems or processes. By mathematically representing a simplified version of a hydro-geological system, reasonable alternative scenarios can be predicted, tested and compared. The applicability or usefulness of a model depends on how closely the mathematical equations approximate the physical system being modeled. In order to evaluate the applicability or usefulness of a model, it is necessary to have a thorough understanding of the physical system and the assumptions embedded in the derivation of the mathematical equations.

5.4 NATURAL GROUND WATER RECHARGE ESTIMATION IN INDIA

Rainfall is the most important source of ground water recharge in the country. The most commonly used methods for estimation of natural ground water recharge in India include empirical methods, ground water level fluctuation method and the ground water balance method.

Based on the studies undertaken by different scientists and organizations regarding correlation of ground water level fluctuation and rainfall, some empirical relationships have been developed for computation of natural recharge to ground water from rainfall. Some of these empirical relationships for different hydrogeological situations in India are

5.4.1 Recharge from Rainfall (R_r)

Rainfall is the major source of recharge to ground water. Part of the rain water that falls on the ground is infiltrated into the soil. A part of this infiltrated water is utilized in filling the soil moisture deficiency while the remaining portion percolates down to reach the water table, which is termed as rainfall recharge to the aquifer. The amount of rainfall recharge depends on various hydro meteorological and topographic factors, soil characteristics and depth to water table. The methods for estimation of rainfall recharge involve the empirical relationships established between recharge and rainfall developed for different regions, ground water Resource Estimation Committee norms, ground water balance approach, and soil moisture data based methods.

5.4.2 Chaturvedi Formula

Based on the water level fluctuation and rainfall amounts in Ganga-Yamuna doab, Chaturvedi (1973) derived an empirical relationship to arrive at the recharge as a function of annual precipitation (when rainfall exceeds 40 cm) $R = 2.0\,(P - 15)^{0.4}$ ……………….(5.1)

Where, R = net recharge due to precipitation during the year, in inches

P = annual precipitation, in inches

This formula was later modified by further work at the UP Irrigation Research Institute, Roorke, and the modified form of the formula is, $R = 1.35\ (P\text{-}14)^{0.5}$ ……………….(5.2)

The Chaturvedi formula has been widely used for preliminary estimation of ground water recharge due to rainfall (Kumar 1996). It may be noted that there is a lower limit of the rainfall below which the recharge due to rainfall is zero. The percentage of rainfall recharged commenced from zero at P = 14 inches, increases up to 18% at P = 28 inches, and again decreases. The lower limit of rainfall in the formula may account for the soil moisture deficit, interception losses and potential evaporation. These factors being site specific, one generalized formula may not be applicable to all the alluvial areas.

5.4.3 Amritsar formula

Using regression analysis for certain doabs in Punjab, Sehgal developed a formula in 1973, for Irrigation and Power Research Institute, Punjab. The formula was found to hold good for areas where rainfall was between 60 and 70 cm. $R = 2.5\ (P - 0.6)^{0.5}$.... (5.3)

Where, R and P both are measured in inches (Kumar 1996).

5.4.4 Krishna Rao formula

Krishna Rao gave the following empirical relationship to determine the ground water recharge in limited climatologically homogenous areas. $R = K\ (P - X)$ ……. (5.4)

the following relation is stated to hold good for different parts of Karnataka;

$R = 0.20\ (P - 400)$ for areas with P between 400 and 600mm

$R = 0.25\ (P - 400)$ for areas with P between 600 and 1000mm

$R = 0.35\ (P - 600)$ for areas with P above 2000mm, where R and P are expressed in mm (Kumar 1996).

5.4.5 Recharge assessment based on rainfall infiltration method

The recharge computed based on WTF method should be in agreement with RI method since the source for both these are the same. Hence the recharge is computed separately by rainfall infiltration method also. It is done using following formula (GEC 2009).

$$R_{rf} = f * A * R_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.5)$$

Where, R_{rf} = Rainfall recharge, f = Rainfall infiltration factor

R_m = Normal monsoon rainfall/non-monsoon rainfall, A = Area of watershed / unit

5.4.6 Rainfall Infiltration Factor

The rainfall infiltration depends upon formation, soil type, slope, vegetative covers etc. It also depends upon compactness, clay content and degree of weathering and fracturing of the formation. The recommended Rainfall Infiltration factor for Lateritic formation is 2 to 4 (GEM 2009).

5.4.7 Recharge from other sources

In addition to recharge from rainfall, the recharge from other sources are also computed and added to ground water resource, which are

a. Return flow from ground water irrigation
b. Return flow from surface water irrigation
c. Seepage from tank/pond Water bodies
d. Seepage from water conservation structure.

5.4.7.1 Return flow from Ground water Irrigation

Amount of ground water used for irrigation is computed by crop water requirement as well as by unit draft method. Return flow has been computed taking same factors as given GEM -97 based on depth to water level.

5.4.7.2 Return flow from surface water irrigation

Volume of water used for surface water irrigation has been computed by cropped area and crop water requirement method. Return flow has been determined by taking factors as given by GEM-97 based on depth to water level.

5.4.7.3 Seepage from Tank / Pond / Reservoirs

Seepage from tanks / reservoirs will be computed by taking average water spread area, days of water availability during monsoon and non monsoon period and recharge factor as recommended by GEM 97.

5.5 COMPUTATION OF GROUND WATER RESOURCES

The dynamic behavior of the ground water is mainly due to the recharge and withdrawal of water. Various factors need to be considered when choosing a method of quantifying recharge. Techniques for estimating recharge are subdivided into various categories namely surface water, unsaturated zone and saturated zone. Techniques based on surface water and unsaturated zone data provide estimates of potential recharge, whereas those based on ground water data generally provide estimates of actual recharge. Uncertainties in each approach underscore the need for application of multiple techniques to increase reliability of recharge estimates (Scanlon et al., 2002). Within each zone, the techniques are generally classified into physical, tracer or numerical modeling approaches. The water table fluctuation method is based on the premise that rise in ground water level in the unconfined aquifer is due to recharge. The method is best applied over the regions having shallow water tables that display sharp rise and decline in water levels.

5.5.1 Sustainable/Safe Yield Estimation

The time has passed when abundant supplies of water were readily available for developmental works at low economic, social and environmental costs. The great challenge facing the world today is to cope up with the impact of economic growth on environmental processes. The concept of sustainable development emerged during the late 1980’s as a unifying approach addressed to the concerns over environment, economic development and the quality of life. Safe yield refers to long term balance between the water that is naturally and artificially recharged to an aquifer and the ground water that is pumped out (CWAG 2005).

When more water is removed than is recharged, the aquifer is described as being out of safe yield. When the water level in the aquifer then drops, it is termed as mining of ground water. Maintaining the safe yield is important primarily because the continuous reduction in the ground water level in the aquifer cannot go on forever. The aquifer at some point of time will not be able to supply water in an economical or even physical sense. Existing wells will go dry and have to be drilled deeper with higher installation and operating costs. The drop in the water level will change the soil structure which may then get compressed leading to ground subsidence.

In general, the sustainable yield of an aquifer must be considerably less than recharge if adequate quantity of water is to be available to sustain both quantity and quality of streams, springs, wetlands, and ground water dependent ecosystems. To ensure sustainability, it is imperative that water limits be established based on hydrologic principles of mass balance. To establish water-use policies and planning horizons, the transition curves of aquifer systems from ground water storage depletion to induced recharge of surface water need to be developed.

The appropriate steps towards sustainable development of ground water resources (Sophocleous, 2002) include the adoption of minimum stream flow standards, use of modified safe yield policies, implementation of integrated resources planning and sub-basin water resources management program. Maintaining the water demand within the safe yield can be achieved by a combination of several measures. Water conservation will reduce the demand. The purposes of research in the field are focused on analyzing ground water flow systems and evaluating the safe yield of ground water basins through field studies numerical simulations.

Methods of determining safe yield are generally based on mass conservation considerations expressed in the hydrologic balance equation. Methods of determining safe yield or sustainable yield of a basin are well explained by Sophocleous (2004).

5.5.2 Drafts from Ground water

Draft is the amount of water lifted from the aquifer by means of various lifting devices. To estimate ground water draft, an inventory of wells and a sample survey of ground water draft from various types of wells (state tube wells, private tube wells and open wells) are required.

For state tube wells, information about their number, running hours per day, discharge and number of days of operation in a season is generally available in the concerned departments. To compute the draft from private tube wells, pumping sets and rahats etc., sample surveys have to be conducted regarding their number, discharge and withdrawals over the season.

In areas where wells are energized, the draft may be computed using power consumption data. By conducting tests on wells, the average draft per unit of electricity consumed can be determined for different ranges in depth to water levels. By noting the depth to water level at each distribution point and multiplying the average draft value with the number of units of electricity consumed, the draft at each point can be computed for every month.

5.5.3 Changes in Ground water Storage (∆S)

To estimate the change in ground water storage, the water levels are observed through a network of observation wells spread over the area. The water levels are lowest immediately after monsoon and highest just before rainfall in the month of May (GEM 1997). During the monsoon season, the recharge is more than the extraction; therefore, the change in ground water storage between the beginning and end of monsoon season indicates the total volume of water added to the ground water reservoir. Similarly the change in ground water storage between the beginning and end of the non-monsoon season indicates the total quantity of water withdrawn from ground water storage.

1. Rapid pace of urbanization, leading to reduction in recharge of aquifers.
2. Increasing demand in agriculture and industrial sectors as well as domestic needs for the ever growing population.
3. A change in cropping patters in order to raise cash crops in certain areas.
4. Stress laid on ground water extraction during drought periods when all other sources shrink.
5. Unplanned withdrawal from subsoil aquifer (GEM 2009)

5.6 TIME SERIES ANALYSIS OF RAINFALL AND GROUND WATER LEVEL

The statistical preprocessing and analysis for their further use in ground water resources evaluation. Preprocessing includes rejection of erratic water level and rainfall data using a probability distribution function of data from the same period of the previous years. Time

Series plots; trend of rainfall and water level over year, lag time analysis, rainfall events, change detection of rainfall on water level and other event based analysis are available in analyzing ground water regime (GEMS 2008).

5.6.1 Open Well Water Level Analysis

Ground water level fluctuation is the ground water level change between any two specific time intervals. Generally seasonal fluctuation like monsoon or non monsoon is considered for rough estimation. However for precise calculation monthly, weekly or daily data may be considered. Measurements of water levels or piezometric heads are used in the analysis of ground water with respect to its occurrence, storage, movement, recharge and discharge. From a record of water level fluctuation the following interpretations such as pattern of fluctuation, period of recharge and discharge, correlation with pumpage, hydraulic gradient, direction of groundwater flow, quantity of subsurface flow, troughs and mounds, average groundwater fluctuation, monthly change in ground water storage, cumulative change in ground water storage can be made (Raghunath 1987).

Ground water level fluctuates from season to season due to the seasonal variations of rainfall. The water levels are deepest before the commencement of southwest monsoon i.e., in May and shallowest while recorded in August/November. Rise after rains indicate the building up of ground water storage in the ground water reservoir, which gets depleted by evaporation and exploitation during non-monsoon period. Dug wells have been recommended for development in areas of shallow ground water levels. Based on the hydrogeological conditions, the diameter and depth range from 3 to 6m and 10 to 12m respectively have been recommended (Udupi Brochure 2008).

5.7 ESTIMATION OF GROUND WATER RECHARGE

The annual replenishable ground water resource of the area is the sum of recharge during monsoon and non monsoon seasons. An allowance is kept for natural discharge during non monsoon season by deducting 5% of annual replenishable ground water resource, wherever WLF method is employed to compute rainfall recharge during monsoon season (GEM 2009).

5.7.1 Specific yield

The Specific yield of a soil or rock is the ratio of the volume of water, after saturation can be drained by gravity to its own volume (Todd and Mays, 2005). The Specific yield data were either arrived through field studies, including long-duration pumping tests and dry season ground water balance (in hard rock areas) or adopted from the norms recommended by (GEM 1997), which were derived from the various water-balance studies carried out by CGWB, SGWD and academic/research institutions (GEM 2009).

The specific yield value recommended for the aquifer of lateritic formation by GEM-97 has been used for the computation. The recommended specific yield value is 2 to 4 %. As per the aquifer characteristic study, the present study area consists of lateritic formation. Hence, for the computation of ground water recharge of Haladi river basin, the specific yield S_y is taken as 3% (0.03).

5.7.2 Water table Fluctuation Method

This method is based on the fact that a well hydrograph follows a definite trend like stream hydrograph with peak followed by a recession limb. The recession limb in a post-recharge period is characterized by two distinct slopes-one a steep one (from August to October/ November) and other a gentler one (from October/November to June). The steeper limb signifies the quick dissipation of a major part of recharge during the later part of recharge period itself. The utilizable recharge is estimated based on pre-monsoon (April-May) to post-monsoon (November) water level fluctuation for the area receiving South-West Monsoon.

The latest refinement of ground water resource estimation is based on ground water level fluctuation data generated from CGWB and State Observation Network Stations (Singh 2001).

Recharge was computed separately by water table fluctuation method. This method is based on ground water balance equation, which is as follows:

$$\text{Input} - \text{Output} = \text{Change in ground water storage}$$

Thus the recharge was computed from the equation $R = h * S_y * A$ …………………. (5.6)

Where, R = Possible recharge,

h = Rise or fall of fluctuation in ground water table due to rainfall

S_y = Specific Yield, A = Area of the aquifer

The above equation 5.6 gives the total recharge in the area during the season and it may include recharge from rainfall as well as recharge from ground water irrigation, from water conservation structures, and from tanks and ponds. In equation 5.6, 'h' represents the water level fluctuation difference between two successive months for the entire study period (15 years). If the value is negative with respect to the month of May then the estimation of recharge becomes ground water discharge i.e. called ground water draft.

The area in the above equation is the area of influence of the well in the basin. This is obtained by Thiessen Polygon Method (Fig 5.2). By this method, the watershed area is subdivided into polygonal sub areas using the wells as nodes. The Thiessen polygon around each well permits the assignment of weights on the basis of the relative areas of the respective polygons. The sub areas are used as weights in estimating the average depth of fluctuation for each well.

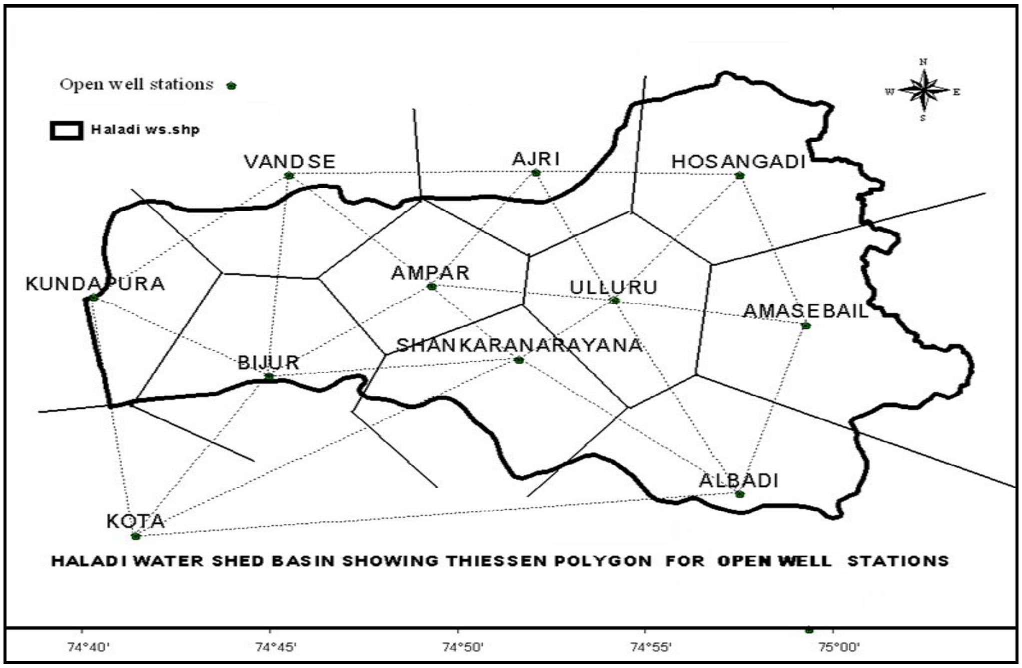


Fig. 5.2 Thiessen polygon of open well

A major part of the ground water withdrawal takes place from the lower unconfined aquifers, which are also the active recharge zones and holds the replenishable ground water resource. The dynamic reserve has been computed by knowing the net change in level of the aquifer phreatic line. The ground water storage in the aquifer is dependent upon the input components such as precipitation, seepage and return flow of irrigated water during various seasons. The estimation and management of these replenishable resources, optimum dynamic ground water reserve can be assessed by the following four methods.

1. Recharge by Krishna Rao formula
2. Recharge by average water level difference over ten years
3. Recharge by water level difference over ten years
4. Recharge by yearly water level difference

CHAPTER -6

RESULTS AND DISCUSSIONS

6.1 INFILTRATION STUDY

The double ring infiltrometer test results obtained are shown in table 6.1. Representative infiltration rate curves are plotted separately for 25 and 35 cm, 15 and 30 cm infiltrometer are shown in Figs. 6.1(a), 6.1(b), 6.2(a) and 6.2(b) respectively. Similarly the plot of representative cumulative infiltration vs. time are plotted separately for 25 and 35 cm, 15 and 30 cm infiltrometer are shown in Figs. 6.3(a) and 6.3(b). Using Horton's equation, initial rate of infiltration (f_0), final rate of infiltration (f_c) and constant k are obtained. From table 6.1 it is observed that highest infiltration rate is 71.3 cm/hr followed by 36.18 cm/hr. The range values for fo, fc and k and statistical parameters in respect of all the 20 field tests are presented in the table 6.2.

In the present Infiltration study, infiltration tests were carried out on the surface level by varying the diameter of the infiltrometer to check the variation of rate of infiltration with respect to change in diameter and also at a depth of 1 meter below the ground surface. It is observed that the variation of infiltration rate with respect to change in dia doesn't vary much. It has been found that the rate of infiltration at 1 m below the ground surface is 2.5 cm/hr. less than on the ground surface as shown in Fig. 6.4. It clearly indicates that the rate of infiltration decreases as the increase in depth of vertical soil column due to the increased compactness of the soil column as the depth increases.

Table 6.1 Details of double ring infiltrometer test results

Sl. No.	**Location**	**d=15 and D=30 cm**			**d=25 and D = 35 cm**		
		f_0 in cm/hr	**f_c cm/hr**	**k=(f_0-f_c) /F_c**	**f_0 in cm/hr**	**f_c cm/hr**	**k=(f_0-f_c) /F_c**
1	Vandse	54.32	9.39	0.04	42.78	10.43	0.03
2	Kundapura	61.11	6.56	0.03	36.67	6.52	0.03
3	Ulluru	57.04	12.90	0.03	39.11	7.64	0.03
4	S. Narayana	62.47	14.71	0.04	40.09	11.61	0.05
5	Albardi-Ardi	65.55	13.35	0.03	36.67	8.96	0.03
6	Ampar	64.51	8.15	0.04	39.11	8.80	0.03
7	Ajri	70.17	11.03	0.03	42.78	11.08	0.04
8	Hosangadi	66.21	9.96	0.04	41.56	7.58	0.03
9.	Amasebail	71.30	12.45	0.04	48.89	12.88	0.05
10.	Bijur	61.11	9.28	0.03	36.18	7.82	0.03
		Average k = 0.035			Average k = 0.035		

Table 6.2 Summary of statistical parameters of infiltration tests

Statistical parameters	15 and 30 cm dia			25 and 35 cm dia			No. of tests
	f_0 in cm/hr	f_c cm/hr	k	f_0 in cm/hr	f_c cm/hr	k	
Maximum	71.3	14.71	0.043	48.89	12.88	0.052	10+10
Minimum	54.32	6.56	0.028	36.18	6.52	0.029	
Range	16.98	8.15	0.031	2.71	6.56	0.027	
Mean	63.38	10.78	0.034	40.38	9.33	0.034	
Median	63.49	10.49	0.032	39.60	8.88	0.037	
Std. deviation	5.34	2.56	0.009	3.86	2.07	0.009	

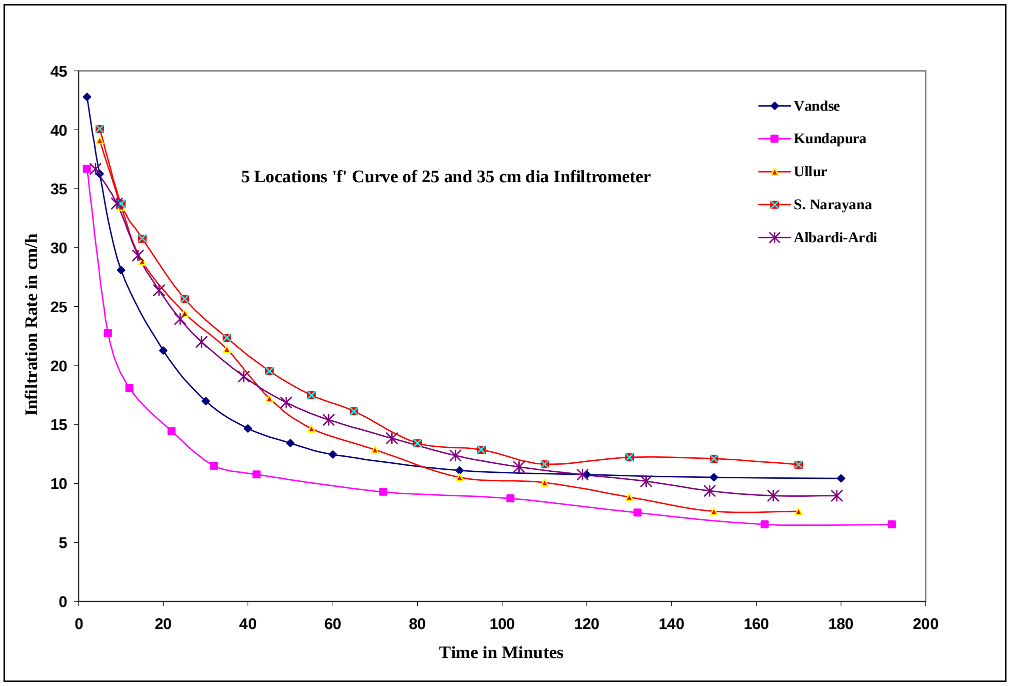


Fig. 6.1(a) Infiltration Rate vs. Time at 5 places

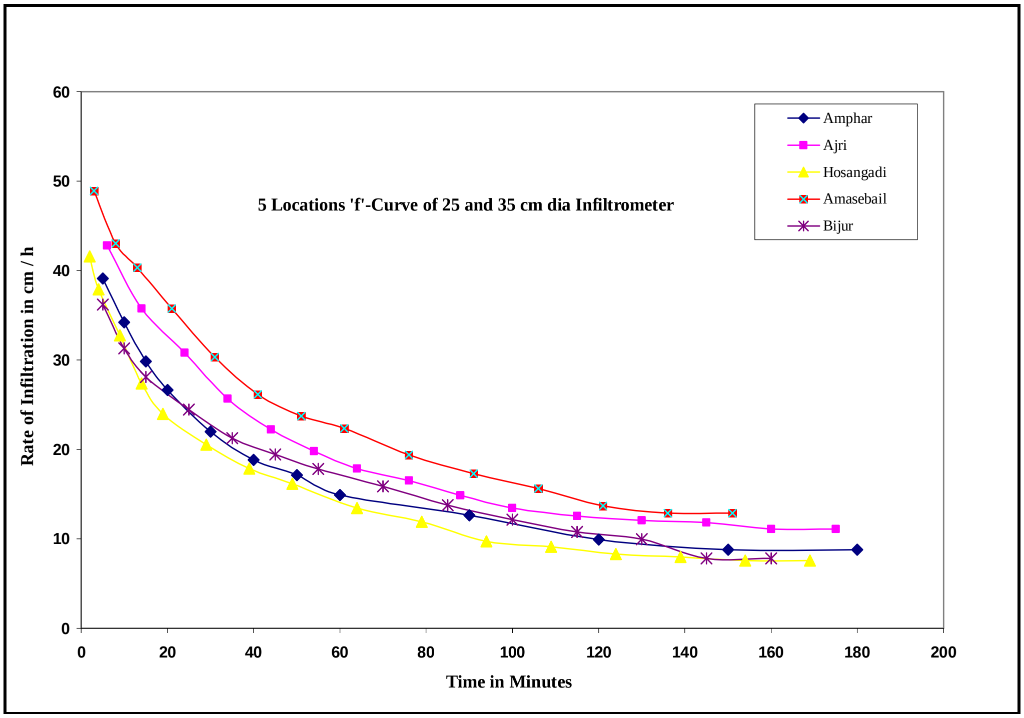


Fig. 6.1(b) Infiltration Rate vs. Time at 5 places

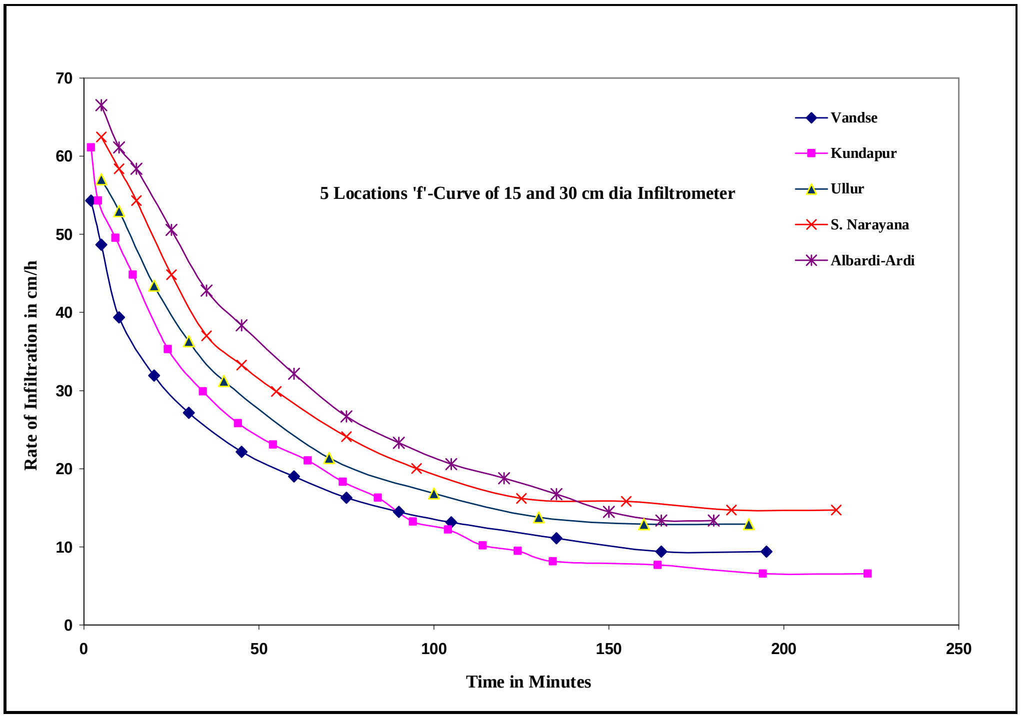


Fig. 6.2(a) Infiltration rate vs. Time at 5 places

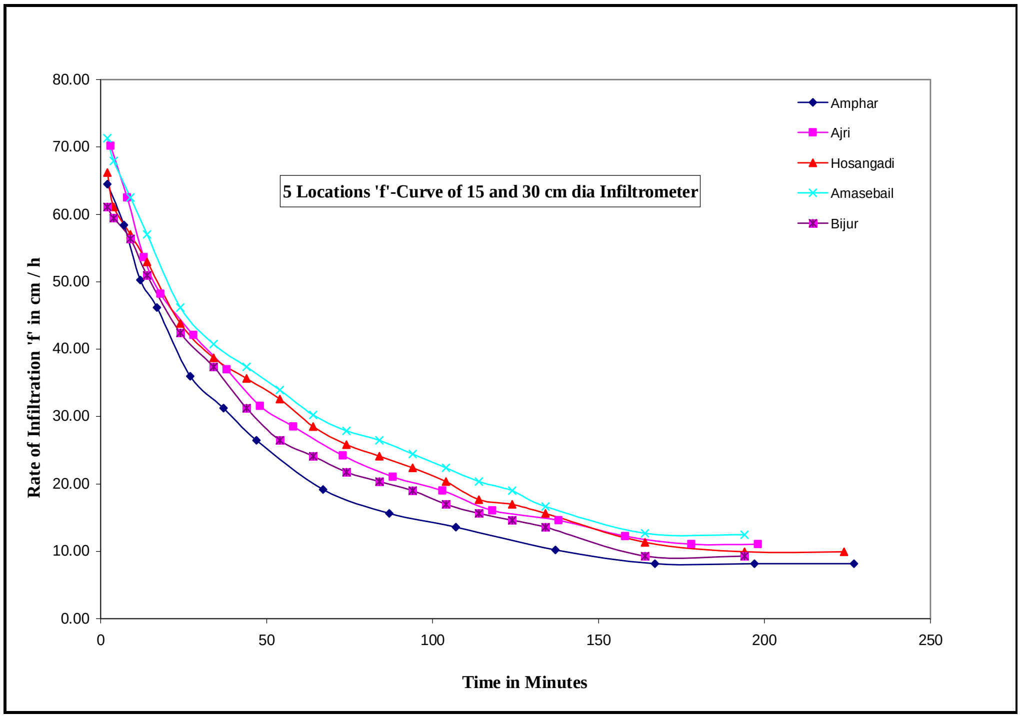


Fig. 6.2(b) Infiltration rate vs. Time at 5 places

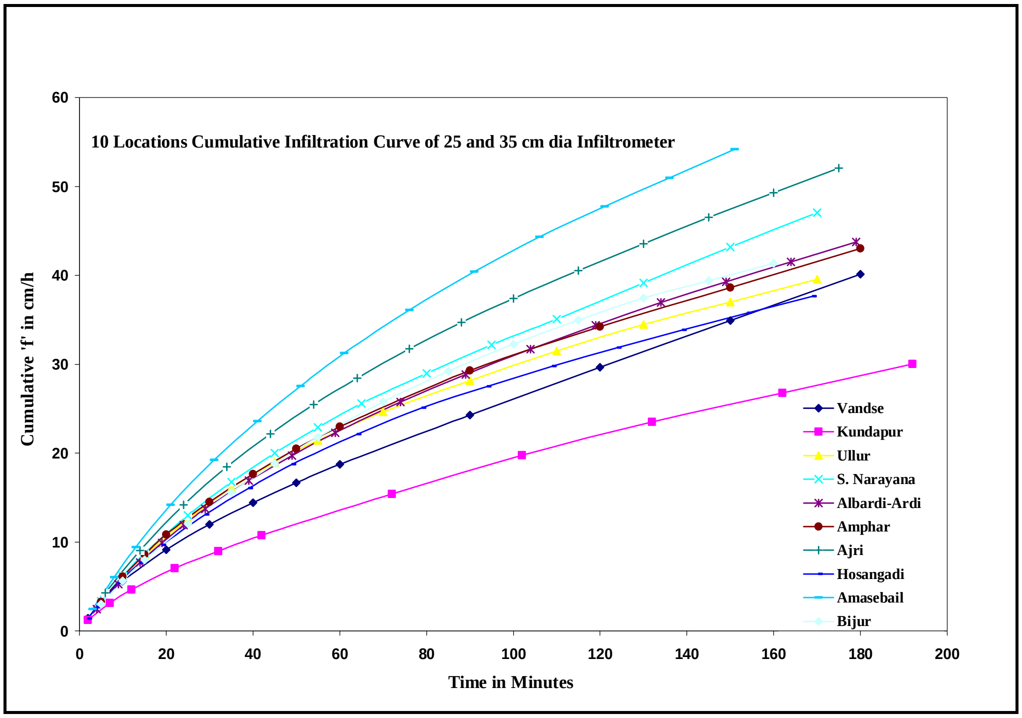


Fig. 6.3(a) Cumulative infiltration vs. Time at 10 places

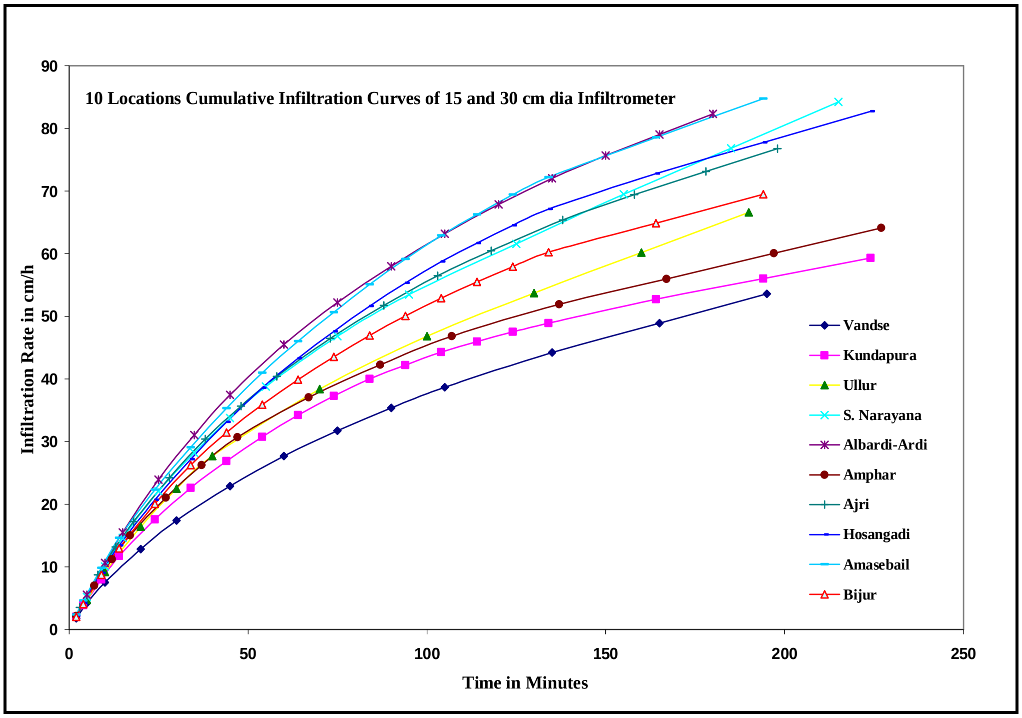


Fig. 6.3(b) Cumulative infiltration vs. Time at 10 places

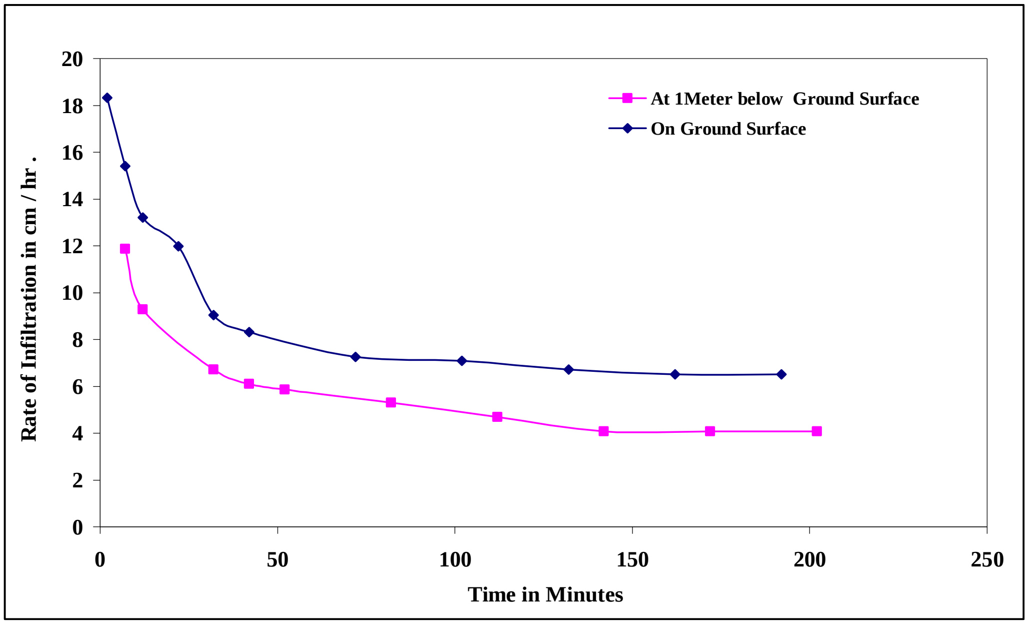


Fig. 6.4 Comparison of F-Curve on and 1 m below the ground surface

6.2 GEO-ELECTRICAL SURVEY METHOD

The electrical resistivity survey is based on the principle that the earth material being tested acts as a resistor in a circuit. After inducing an electrical current into the ground, we measure the ability of that material to resist the current. Since various earth materials exhibit characteristic resistivity values, they can be distinguished using this method. Factors that affect the resistivity of earth materials include degree of saturation, porosity, pore-fluid content, temperature, salinity, and thicknesses of clay or sand layers. Applications of the electrical resistivity method include locating aquifers, saltwater intrusions, and other groundwater contamination problems. We can also characterize bedrock by locating weathered zones, fractures, and voids attributed to solution activity, or determine depth to bedrock, and thickness of clay or sand layers. Electrical resistivity can also aid in evaluating soils for corrosivity or their potential grounding capabilities.

The locations selected for conducting VES are close to the observation wells. The VES tests were conducted with the help of Senior Geologist from the Department of Mines and Geology (A Government of Karnataka Organization), Bangalore. The results of the VES tests are given in Table 6.3. The numbers given to the tests are test number and the well number near to which the test was conducted e.g. ER_1/W_{02} is the electrical resistivity test one conducted near well number 02. The graphs representing the apparent resistivity obtained for various depths by VES are shown in Figs. 6.5a and 6.5b.

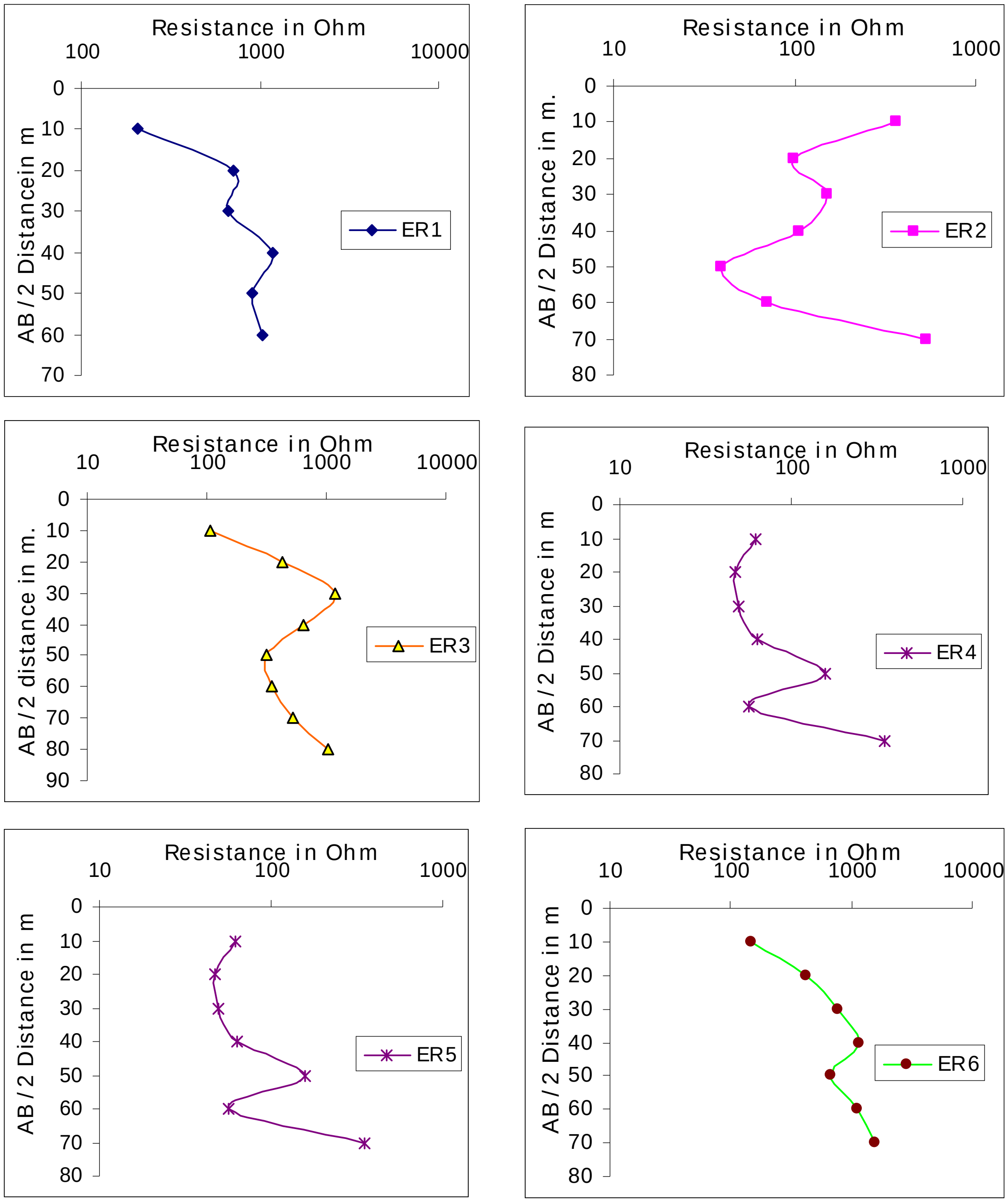


Fig. 6.5(a) Graph showing apparent resistivity offered by aquifer for various distances (ER_1 to ER_6)

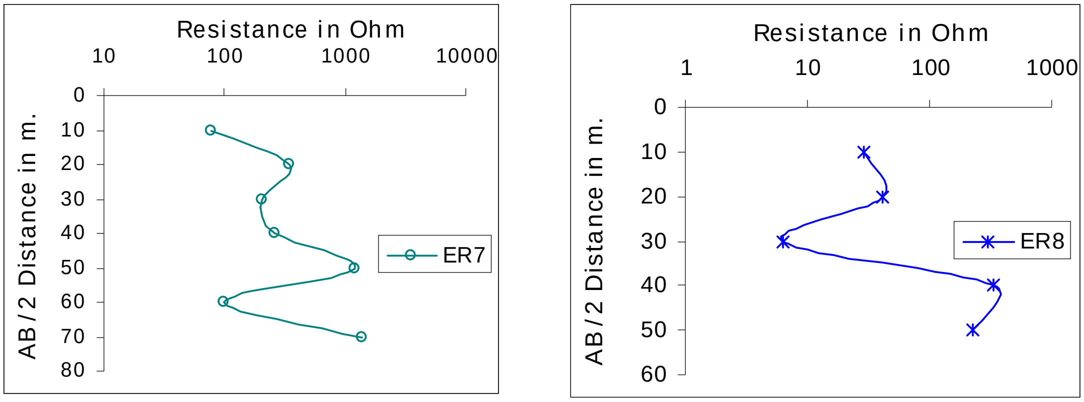


Fig. 6.5(b) Graph showing apparent resistivity offered by the aquifer for various distances (ER_7, ER_8)

The increase in depth of the aquifer normally shows increase in apparent resistivity but when it decreases it is an indication of change in strata, fracture zone or presence of salt water.

The test results indicate that the aquifer thickness in the study area ranges from 12 m to 18 m. At three locations i.e. near to wells W_4, W_9 and river location F_{01}, salt water intrusion effect in the form of reduced apparent resistivity is observed. It is predicted that the depth to salt water could be 40, 16 and 24 m respectively. Probable fracture zones are also detected at depths ranging from 25 to 55m. In most of the places the litholog consists of soil, laterite, clay and gneiss. The detailed hydraulic conductivity calculations are shown in Table 6.3 and 6.4.

Table 6.3 Observations and results from the electrical resistivity tests

Schlumberger configuration (AB /2)	**Resistance offered by the aquifer for various depths in Ohm**								
	ER$_1$/W$_{02}$	ER$_2$/W$_{04}$	ER$_3$/W$_{06}$	ER$_4$/W$_{12}$	ER$_5$/W$_{14}$	ER$_6$/W$_{16}$	ER$_7$/W$_{17}$	ER$_8$/W$_{01}$	ER$_9$/W$_{19}$
10 m	205.90	366.30	107.16	342.70	62.30	148.20	78.20	28.80	37.20
20 m	713.40	99.10	435.00	163.60	46.90	426.30	341.10	41.70	5.20
30 m	671.60	152.30	1194.20	43.50	49.70	771.28	205.20	6.20	18.60
40 m	1168.10	106.60	653.20	533.80	62.80	1149.20	263.70	332.80	87.90
50 m	911.40	39.20	313.60	245.00	156.80	686.00	1205.40	225.40	9.80
60 m	1043.40	70.50	352.50	310.20	56.40	1128.00	98.70	-	1283.10
70 m	-	538.50	523.30	215.40	353.97	1569.70	1385.10	-	246.20
80 m	-	-	1024.60	2692.10	-	-	-	-	-
Over-burden (Thickness)	12 m	17 m	16 m	12 m	16 m	12 m	12 m	16 m	18 m
Depth to salinity zone	-	40 m	-	-	-	-	-	24 m	16 m
Depth of probable fractures	25, 40 m	32, 40 m	40, 48, 56 m	25,40,55m	32, 50 m	40, 50 m	50, 60 m	40 m	25,40,55m
Litholog	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
	-	Sand, Silt	-	-	-	-	-	Sand, Silt	Sand, Silt
	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite
	Clays	Clays	Clays	Clays	Clays	Clays	Clays	Clays	Clays
	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss

Table 6.4 Analysis and results from the electrical resistivity test

	ER_1/W_{02}	**ER_2/W_{04}**	**ER_3/W_{06}**	**ER_4/W_{12}**	**ER_5/W_{14}**	**ER_6/W_{16}**	**ER_7/W_{17}**	**ER_8/W_{01}**	**ER_9/W_{19}**
Aquifer resistance for 10 m thickness (ρ_0) Ohm	205.90	366.30	107.16	342.70	62.30	148.20	78.20	28.8	7.20
Transverse resistance, Ohm	2059.00	3663.00	1071.60	3427.00	623.00	1482.00	782.00	288.00	372.00
Predicted transmissivity m^2/day	2649.29	4060.01	1780.87	3852.45	1386.33	2141.82	1526.17	1091.70	1165.57
Hydraulic conductivity (m/day)	**264.93**	**406.00**	**178.09**	**385.24**	**138.63**	**214.18**	**152.62**	**109.17**	**116.56**
Conductivity of water	180.00	83.00	145.00	99.00	245.00	243.00	67.00	326.00	135.00
Pore resistance (ρ_0) Ohm	55.56	120.48	68.97	101.01	40.82	41.15	149.25	30.67	74.07
Formation factor = Aquifer resistance/ pore resistance	3.71	3.04	1.55	3.39	1.53	3.60	0.52	0.94	0.50
Hydraulic conductivity (m/day)	**359.77**	**298.01**	**160.14**	**330.70**	**157.59**	**350.04**	**64.62**	**103.10**	**62.60**

6.3 HYDRAULIC CONDUCTIVITY FROM SOIL PARAMETERS

For the determination of surface area, sieve analysis is carried out and the numbers of particles retained on each sieve are calculated (Figs. 6.6a, 6.6b). It is assumed that the particles are spherical in shape and diameter of particle is same as sieve size. The surface area of one particle retained on each sieve is calculated which is multiplied by the number of particles on each sieve to get the total surface area of all the particles.

Observations of the tests performed for the determination of specific gravity, grain size analysis, calculation of surface area and determination of hydraulic conductivity from these soil properties are given in Tables 6.5 to 6.9. The range of hydraulic conductivity obtained from the analysis is 150 m/day to 250 m/day.

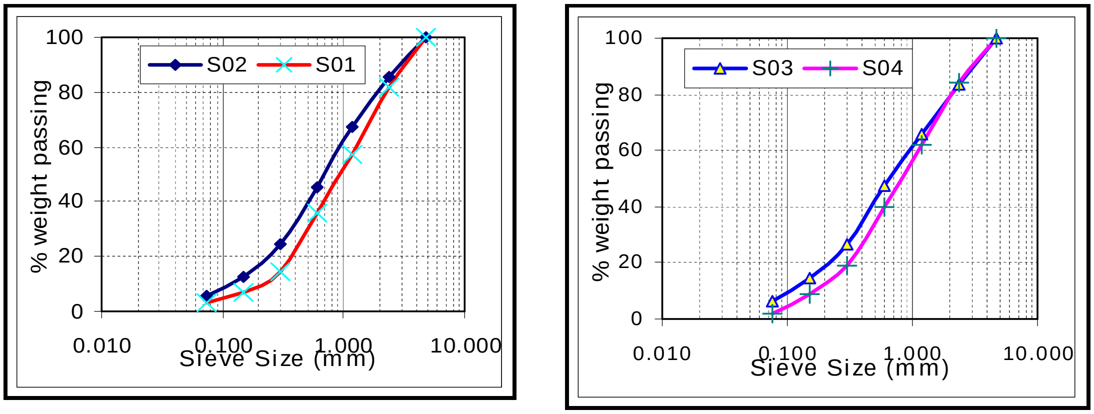


Fig. 6.6(a) Grain size distribution curves for samples S_{01}, S_{02},S_{03} and S_{04}

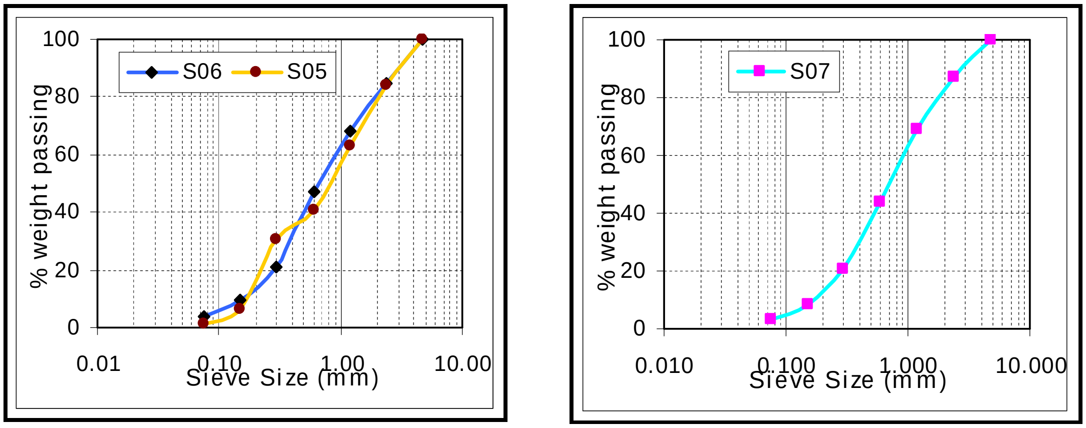


Fig. 6.6(b) Grain size distribution curves for samples S_{05}, S_{06} and S_{07}

Table 6.5 Grain size distribution

Sieve size mm	**Weight of empty sieve (gm)**	**Weight in gm. (soil + sieve) for various soil samples**						
		Sample S_{02}/W_{07}	**Sample S_{07}/W_{18}**	**Sample S_{03}/W_{05}**	**Sample S_{01}/W_{02}**	**Sample S_{06}/W_{17}**	**Sample S_{05}/W_{16}**	**Sample S_{04}/W_{04}**
4.750	395.10	525.60	523.30	559.50	574.40	548.80	652.10	554.40
2.360	403.10	584.20	587.30	577.80	649.80	570.70	621.50	620.70
1.180	333.30	552.20	580.60	522.60	548.90	541.80	556.60	560.00
0.600	372.30	572.00	619.00	576.90	586.70	629.80	473.80	578.00
0.300	209.90	322.50	331.60	330.40	285.40	325.50	485.80	312.70
0.150	458.30	525.60	509.20	544.50	496.00	516.70	376.90	529.90
0.075	319.70	364.40	340.60	363.30	340.60	346.30	332.80	330.50
Pan	451.70	483.30	463.60	476.60	458.30	462.50	454.50	454.40

Sieve size mm	**Weight in gm (Soil retained)**							
	Sample S_{02}/W_{07}	Sample S_{07}/W_{18}	Sample S_{03}/W_{05}	Sample S_{01}/W_{02}	Sample S_{06}/W_{17}	Sample S_{05}/W_{16}	Sample S_{04}/W_{04}	Volume of particles (mm^3)
4.750	130.50	128.20	164.40	179.30	153.70	257.00	159.30	56.1376
2.360	181.10	184.20	174.70	246.70	167.60	218.40	217.60	6.8851
1.180	218.90	247.30	189.30	215.60	208.50	223.30	226.70	0.8606
0.600	199.70	246.70	204.60	214.40	257.50	101.50	205.70	0.1131
0.300	112.60	121.70	120.50	75.50	115.60	275.90	102.80	0.0141
0.150	67.30	50.90	86.20	37.70	58.40	81.40	71.60	0.0018
0.075	44.70	20.90	43.60	20.90	26.60	13.10	10.80	0.0002
Pan	31.60	11.90	24.90	6.60	10.80	2.80	2.70	

Table 6.6 Specific gravity calculations (ASTM D 854-00)

Specific gravity calculations	**Sample S_{02}/W_{07}**	**Sample S_{07}/W_{18}**	**Sample S_{03}/W_{05}**	**Sample S_{01}/W_{02}**	**Sample S_{06}/W_{17}**	**Sample S_{05}/W_{16}**	**Sample S_{04}/W_{04}**
Weight (Empty bottle) g	29.40	29.40	29.40	29.40	29.40	29.40	29.40
Weight (Bottle + water) g	80.10	80.10	80.10	80.10	80.10	80.10	80.10
Weight (Bottle + soil) g	43.40	43.30	39.60	42.30	45.90	42.60	41.70
Weight (Bottle + soil + water) g	87.70	88.20	86.20	86.30	89.40	87.30	86.20
Specific gravity	2.1875	2.3965	2.4878	1.9253	2.2916	2.2000	1.9838

Table 6.7 Weight of soil particles retained in each sieve

Weight of one particle retained on each sieve (gm)							
Sieve size mm	Sample S_{02}/W_{07}	Sample S_{07}/W_{18}	Sample S_{03}/W_{05}	Sample S_{01}/W_{02}	Sample S_{06}/W_{17}	Sample S_{05}/W_{16}	Sample S_{04}/W_{04}
4.750	1.23E-01	1.35E-01	1.40E-01	1.08E-01	1.29E-01	1.24E-01	1.11E-01
2.360	1.51E-02	1.65E-02	1.71E-02	1.33E-02	1.58E-02	1.51E-02	1.37E-02
1.180	1.88E-03	2.06E-03	2.14E-03	1.66E-03	1.97E-03	1.89E-03	1.71E-03
0.600	2.48E-04	2.71E-04	2.81E-04	2.18E-04	2.59E-04	2.49E-04	2.24E-04
0.300	3.09E-05	3.39E-05	3.52E-05	2.72E-05	3.24E-05	3.11E-05	2.81E-05
0.150	3.87E-06	4.24E-06	4.40E-06	3.40E-06	4.05E-06	3.89E-06	3.51E-06
0.075	4.83E-07	5.30E-07	5.50E-07	4.25E-07	5.06E-07	4.86E-07	4.38E-07
Pan	1.15E-09	1.26E-09	1.30E-09	1.01E-09	1.20E-09	1.15E-09	1.04E-09

Table 6.8 Number of soil particles retained in each sieve

Sieve size mm	Sample S_{02}/W_{07}	Sample S_{07}/W_{18}	Sample S_{03}/W_{05}	Sample S_{01}/W_{02}	Sample S_{06}/W_{17}	Sample S_{05}/W_{16}	Sample S_{04}/W_{04}
4.750	1.17E+03	9.53E+02	1.18E+03	1.66E+03	1.19E+03	1.26E+03	1.43E+03
2.360	1.20E+04	1.12E+04	1.02E+04	1.86E+04	1.06E+04	1.41E+04	1.59E+04
1.180	1.18E+05	1.20E+05	8.84E+04	1.30E+05	1.06E+05	1.18E+05	1.33E+05
0.600	8.40E+05	8.67E+05	7.27E+05	9.84E+05	9.93E+05	4.08E+05	9.16E+05
0.300	3.80E+06	3.58E+06	3.42E+06	2.77E+06	3.57E+06	7.83E+06	3.66E+06
0.150	1.74E+07	1.20E+07	1.85E+07	1.09E+07	1.44E+07	1.33E+07	2.04E+07
0.075	8.42E+07	3.95E+07	7.35E+07	5.85E+07	5.51E+07	1.56E+07	2.46E+07
Pan	1.66E+10	9.48E+09	1.91E+10	6.54E+09	9.00E+09	2.43E+09	5.29E+09

Table 6.9 Surface area and the hydraulic conductivity calculations

Sieve size, mm	**Sample S_{02}/W_{07}**	**Sample S_{07}/W_{18}**	**Sample S_{03}/W_{05}**	**Sample S_{01}/W_{02}**	**Sample S_{06}/W_{17}**	**Sample S_{05}/W_{16}**	**Sample S_{04}/W_{04}**
4.750	3.31E+05	2.70E+05	3.34E+05	4.71E+05	3.39E+05	3.59E+05	4.06E+05
2.360	8.42E+05	7.82E+05	7.14E+05	1.30E+06	7.44E+05	9.86E+05	1.12E+06
1.180	2.07E+06	2.10E+06	1.55E+06	2.28E+06	1.85E+06	2.06E+06	2.32E+06
0.600	3.80E+06	3.92E+06	3.29E+06	4.45E+06	4.49E+06	1.85E+06	4.15E+06
0.300	4.30E+06	4.06E+06	3.87E+06	3.14E+06	4.04E+06	8.85E+06	4.15E+06
0.150	4.92E+06	3.40E+06	5.22E+06	3.07E+06	4.08E+06	3.76E+06	5.77E+06
0.075	5.95E+06	2.79E+06	5.20E+06	4.14E+06	3.90E+06	1.11E+06	1.74E+06
Pan	2.08E+05	1.19E+05	2.40E+05	8.23E+04	1.13E+05	3.05E+04	6.65E+04
Total surface area mm^2	2.24E+07	1.74E+07	2.04E+07	1.89E+07	1.95E+07	1.90E+07	1.97E+07
Hydraulic conductivity (m/day)	**149.58**	**247.47**	**180.50**	**209.84**	**196.91**	**208.35**	**193.50**

6.4 PUMPING TESTS

6.4.1(a) Analysis of the pumping test observations by using software

Before starting the test, steady state of the water level should be ensured. The observations to be made during the test include measurement of the water level and discharge at various time intervals (Table 6.10). The pumping test is carried out in an open well in the study area. The details of the well and the time drawdown relationships are given in Table.6.10

Diameter of well D= 2.45 m	Date of pumping= 06-02-2007
Owner : Govt. F.G. College, Kundapura	Pump capacity = 5 H.P.
Depth of well : 6.35 m below ground level.	
Depth of water level (initial) = 1.30 m	Pumping rate =0.0023581 m^3/sec

Table 6.10 Time drawdown curve for the pumping test

Time (min)	Drawdown (m)	Time (min.)	Drawdown (m)	Time (min.)	Drawdown (m)
1	1.37	30	2.04	95	3.28
2	1.40	35	2.15	100	3.38
3	1.44	40	2.24	105	3.48
4	1.46	45	2.34	110	3.57
5	1.49	50	2.43	115	3.67
6	1.52	55	2.52	120	3.77
7	1.54	60	2.62	125	3.87
8	1.57	65	2.71	130	3.97
9	1.59	70	2.81	135	4.08
10	1.62	75	2.92	140	4.18
15	1.74	80	3.00	145	4.28
20	1.82	85	3.10		
25	1.94	90	3.19		

The results obtained from the pumping test observations and the solution by Neuman method (1972) for unconfined aquifers is shown in Fig 6.7.

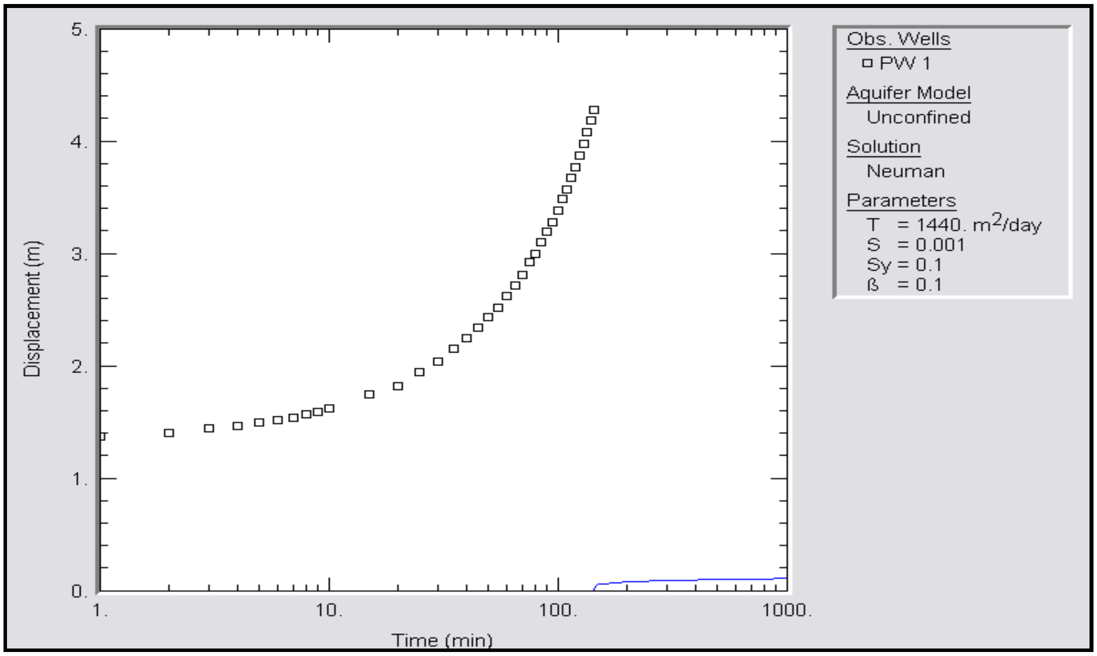


Fig. 6.7 Time v/s drawdown curve for the pumping test

Saturated Thickness	= 5.05 m	Anisotropy ratio = Kz/Kr = 1	
Pumping well data			
Number of pumping wells	= 1	Casing Radius	=1.225
Well radius	= 1.225	Pumping periods	= 1
Pumping rate	= 0.0023581 m^3/sec	Time	= 145 min
Number of observations	= 37		
Water level before starting the test = 1.30 m			
Hydraulic Conductivity K = 285.1 m/day		Transmissivity T=1440 m^2/day	

6.4.1(b) Analysis of the pumping test observations by Theis method

The analysis of the pumping test data is also carried out by modified Theis method. Fig. 6.8 shows the time drawdown graph and the results obtained are as follows.

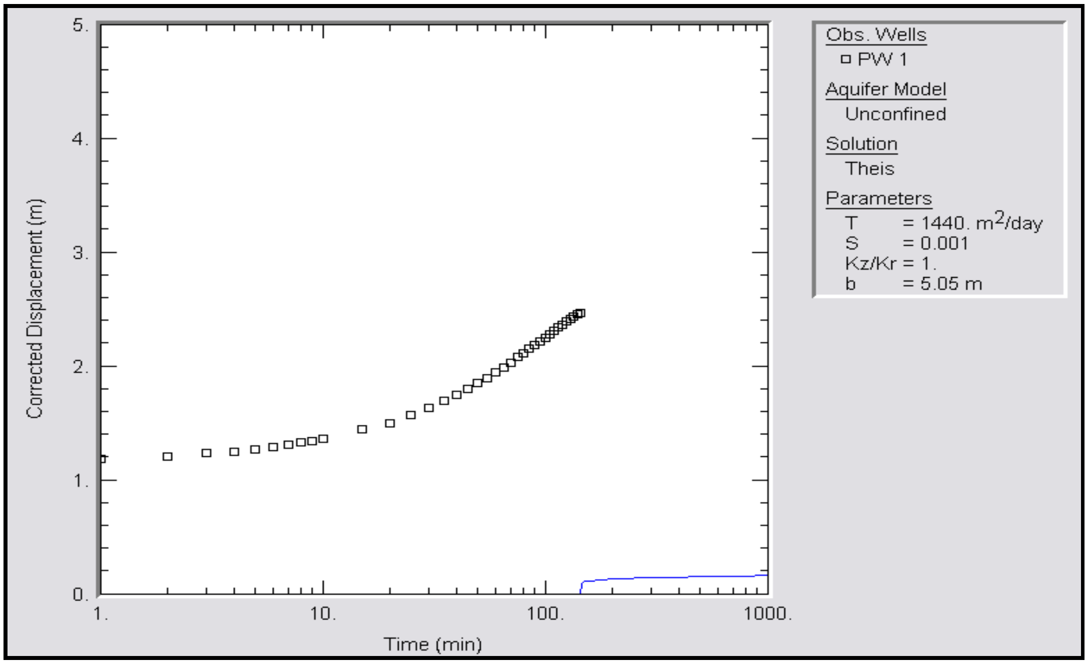


Fig. 6.8 Time v/s corrected displacement curve for pump test

Results by Theis test			
Aquifer model	: Unconfined	Solution Method	: Theis
Estimated Parameters			
Hydraulic conductivity = 285.1 m/day		Transmissivity =	1440 m^2/day

6.4.1(c) Recovery test results

Observations of the recovery test are given in Table 6.11. The recovery test analysis is carried out using the Fig.6.9. The result indicates hydraulic conductivity 261.8 m/day.

Table 6.11 Recovery test observations

Time (min)	Displacement (m)	Time (min.)	Displacement (m)	Time (min.)	Displacement (m)
1	4.26	30	3.90	95	3.17
2	4.25	35	3.84	100	3.12
3	4.23	40	3.78	105	3.08
4	4.22	45	3.72	110	3.02
5	4.21	50	3.65	115	2.98
6	4.20	55	3.60	120	2.93
7	4.19	60	3.54	125	2.89
8	4.17	65	3.49	180	2.51
9	4.16	70	3.43	190	2.43
10	4.15	75	3.37	200	2.38
15	4.09	80	3.32	210	2.32
20	4.03	85	3.27	220	2.26
25	3.96	90	3.22	230	2.21

Saturated thickness	= 5.5 m	Anisotropy ratio kz/kr	= 1
Recovery test well data			
Initial displacement	= 4.28 m	Static water column height	= 5.05
Casing radius	= 1.225 m	No. of observations	= 39

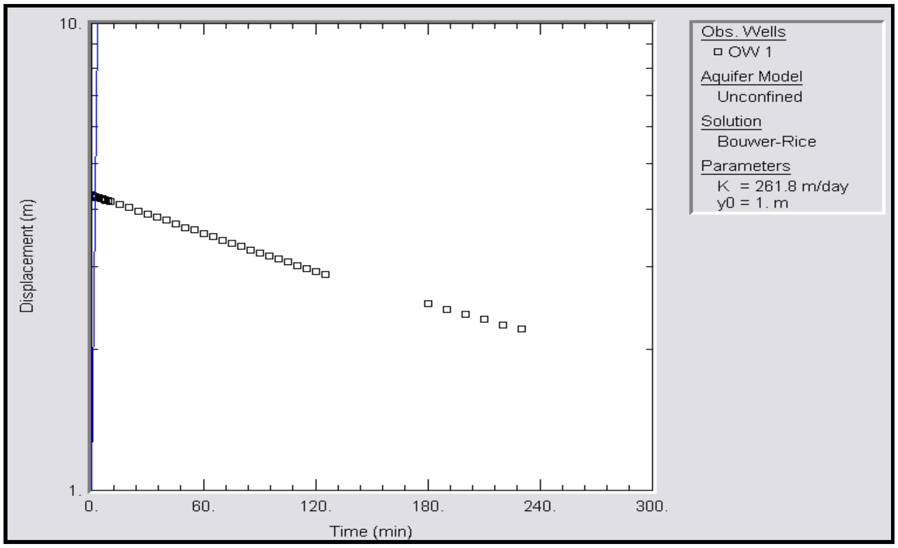


Fig. 6.9 Recovery test - Time v/s Displacement curve

Aquifer model	: Unconfined	Solution method	: Bouwer- Rice
Parameter Estimate	: Hydraulic Conductivity K = **261.8 m/day**		

From the above analyses, it is evident that the area is a shallow unconfined aquifer with good ground water potential. The hydraulic conductivity values are generally high which indicates the pervious nature of the aquifer. This will ensure adequate ground water storage in the well fields adjoining the reservoir. Also, the effect of saltwater intrusion along the river during the summer would have adverse impact on the adjoining well fields.

Selection of pumping system has to be done keeping in view of the following conditions like requirement of water to be pumped and total pumping head. It is recommended to have 3 HP pumps in dug wells and 3 to 5 HP submersible pumps in the dug cum bore wells. In coastal areas collector wells are more suitable and the effective radius of collector wells ranges from 20 to 60m with 90 m as radius of Influence. In all cases for effective use of ground water, precise ground water development and management practices should be adopted in the river basin. As a general rule, pumpage must be distributed in time and space and there should not be any concentration of wells along the coast to avoid the saline water ingress (CGWB, 2008).

6.5 DATA ANALYSIS

6.5.1 Rain fall and open well data analysis

Rainfall is the most important source of ground water recharge. Monthly rain fall data measured at 10 rain gauge stations for 15 years (1991-2005) in the Haladi River basin has been used for the purpose of analysis. Fig.6.10 shows the monthly average rainfall distribution over the above said period. It clearly indicates that more than 80% of the rainfall occurs during the months of June, July and August (monsoon period). As the study area originates in the Western Ghats and ends in the Arabian Sea, the average annual rainfall received during the period is 5167 mm as per the available data of study period (Appendix-III).

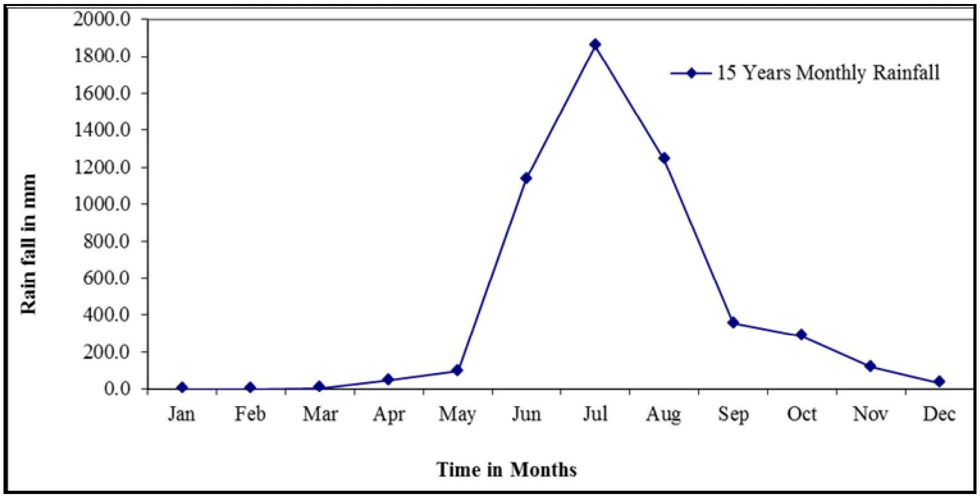


Fig 6.10 Monthly average rainfall of 15 years for 10 Rain gauge stations

Fig 6.11 shows the distribution of monthly ground water level fluctuation for selected fifteen years period (1991-2005). Prior to the monsoon, ground water level will be negative. During monsoon period (June, July, and august) it will bounce back to positive rising up to 4 to 5 m. As the rainfall recedes, it falls back to negative up to 2 m. It shows that ground water discharge is taking place more during non-monsoon period from the basin. So the dynamic water level fluctuation varies around 6 to 7 m. It is observed that every year the rise and fall of the ground water level takes place in the same order with a slight upward trend. High variations in annual recharges to ground water body are observed during monsoon period.

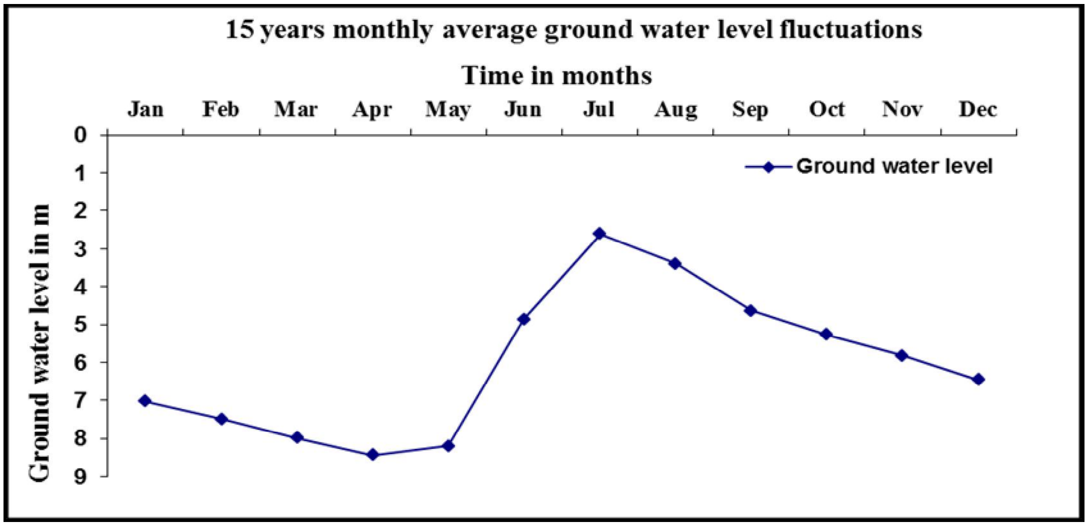


Fig. 6.11 Monthly average of ground water table level fluctuations for 15 years

The monthly fluctuation of ground water depth and rainfall of 10 observation well and rain gauge stations is analyzed for the 15 years and plotted considering rainfall and groundwater together and ground water fluctuations alone as shown in Fig. 6.12(a) and Fig. 6.12(b) to understand the behavior of the aquifer. The rise and fall is almost similar in every year. It indicates that the amount of water reaching the ground water reservoir is the same as the amount of ground water released from the aquifer. It clearly indicates that the major portion of the River basin area has lateritic formation (CGWB, Udupi Brochure, 2008).

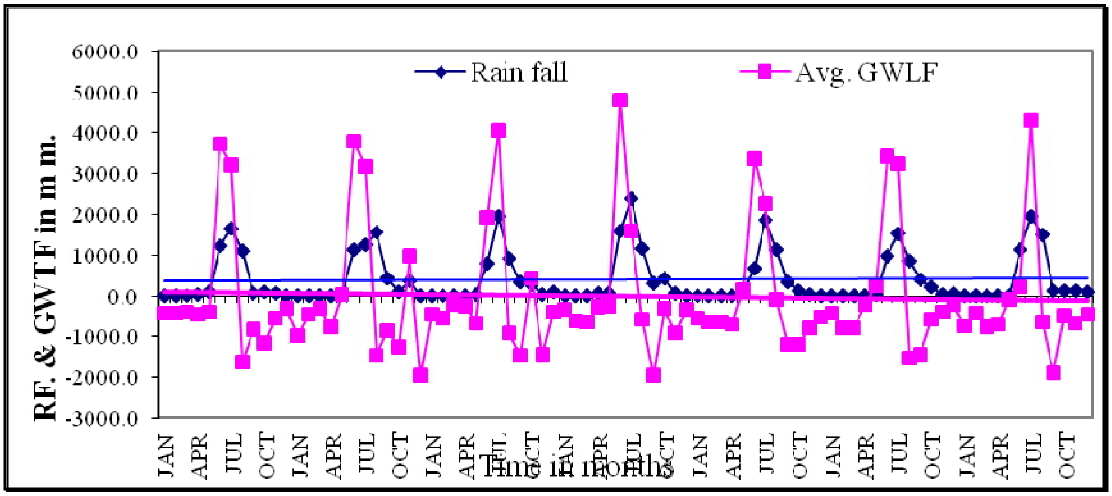


Fig. 6.12(a) Monthly average GWLF and Rainfall of 10 O W's for 15 years

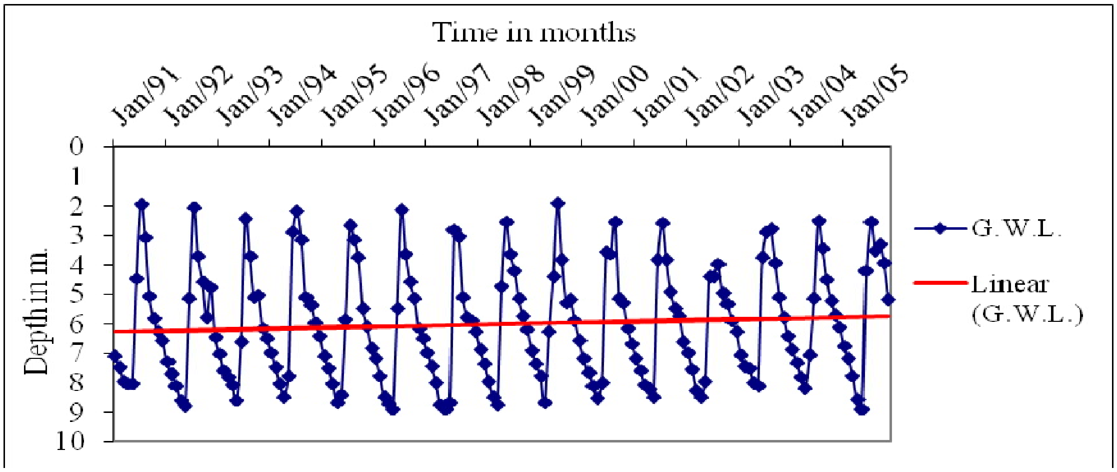


Fig. 6.12(b) Monthly average GWLF of 10 O W's for 15 years

Fig. 6.13 shows monthly average, maximum, minimum, and average variations of the basin were computed and plotted. The trend line of average and minimum monthly average values indicate upward trend whereas maximum monthly average levels slightly show downward trend. It clearly indicates that during non-monsoon period, ground water discharge increases year by year. At the same time, the aquifer gets recharged due to the natural rainfall in the successive years. The average and minimum monthly average trend line goes upward might be because of decrease in extraction during these periods.

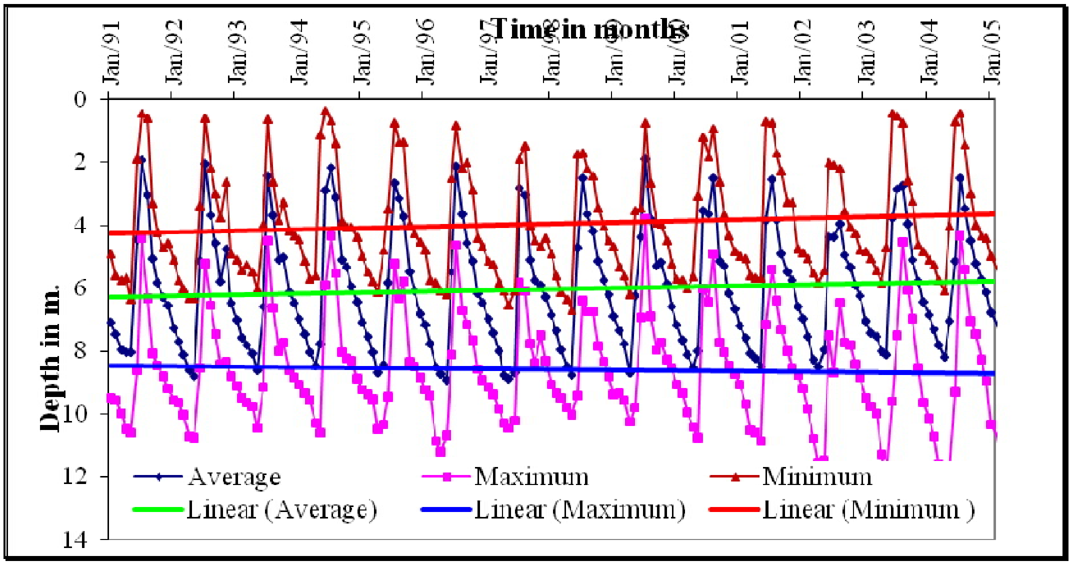


Fig. 6.13 GWLF of 10 OW monthly statistics

Fig. 6.14 shows the analysis of ground water level fluctuation during monsoon period (June-September). The upward trend lines were observed for average, maximum and minimum of 15 years monthly average of 10 open wells. It indicates that ground water recharge progressively increases during the monsoon period from 1991 to 2005. The variation of ground water table between the minimum and maximum is observed to be between 4.0 to 4.75 m.

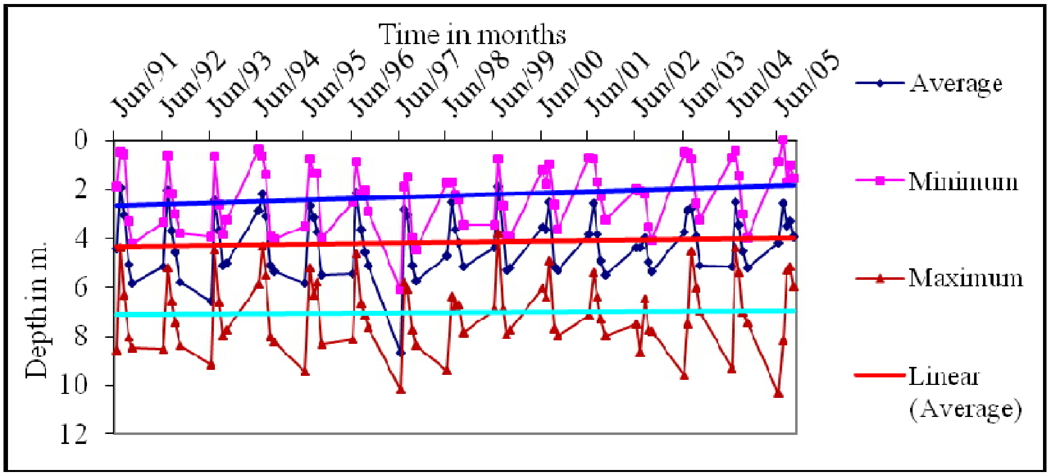


Fig. 6.14 GWLF of monsoon monthly (June-Sep) statistics of 10 observations OW.

Fig. 6.15 explains about the ground water level fluctuations during non-monsoon period (Jan-May). It reveals that during non-monsoon period maximum fluctuation has downward trend and the ground water extraction increases year by year. The minimum and average monthly ground water level has an upward trend. It also shows that during non-monsoon period discharge from the basin decreases for minimum and average ground water levels.

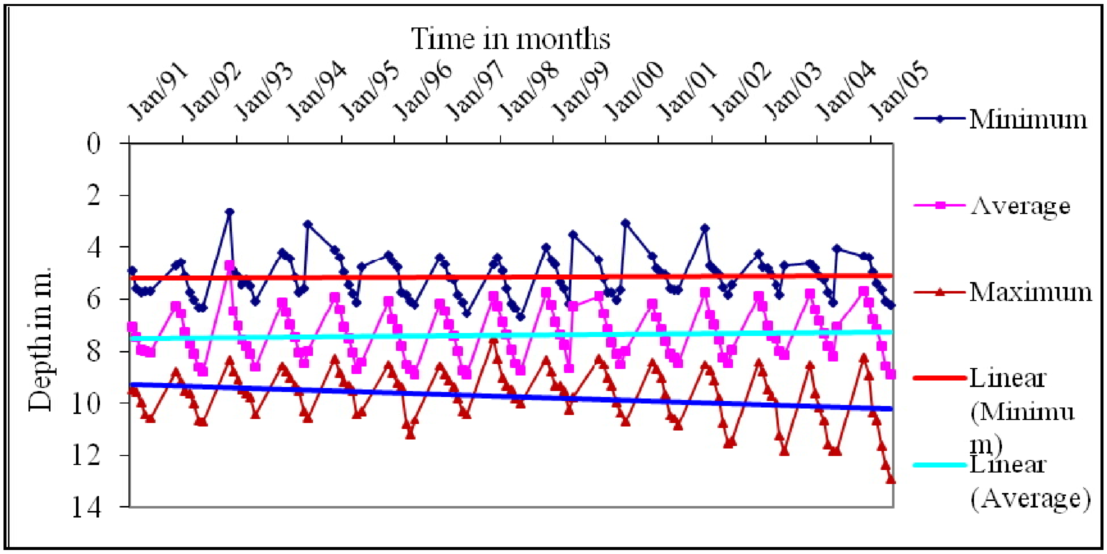


Fig. 6.15 GWLF of Non-monsoon monthly (Jan-May) statistics of 10 observation OW

Fig. 6.16 indicates ground water level fluctuations during monsoon (June-Sep), post monsoon (Oct-Jan) and pre-monsoon (Feb-May) period considering only 5 years data for the analysis. The trend of ground water level fluctuations during these periods almost remains same. In this case it can be concluded that when the ground water fluctuations during the three different seasons is analyzed, the variation averages automatically and becomes constant. It infers that during the three seasons, the ground water recharge and discharge is almost constant.

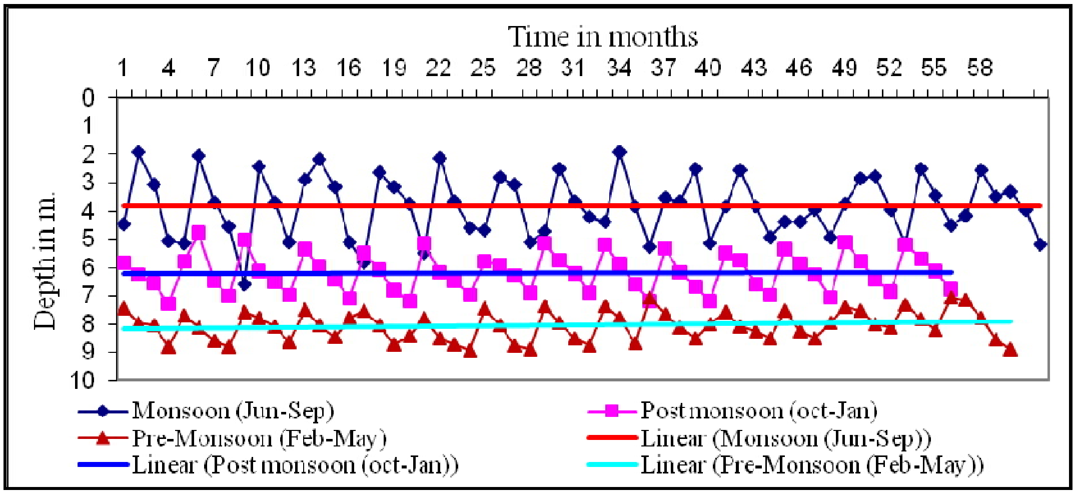


Fig. 6.16 GWLF of 15 years monthly avg. monsoon, post and pre-monsoon period

Fig. 6.17 explains about the ground water level fluctuations during peak month of pre-monsoon, monsoon and post-monsoon period (April, July and October). Here 15 years monthly ground water levels of 10 observation open wells data is considered for the analysis. During the month of April ground water level fluctuations is almost constant. It implies that over the 15 years of study period, in the month of April ground water table level remains constant because it has reached stagnation level every year. Again in the month of July, the ground water table has a decreasing trend. It indicates that the extraction gradually increases during the month of July. In the month of October ground water table has increasing trend. It implies that the delayed recharge is taking place and discharge from the basin decreases. The total ground water table variation of the basin is 6 m. and July to October (3 months) is 2.75 m and October to April (6 months) is 3.3 m. Hence the variation between July to October is relatively more than that between October to April. It is due to the increase in base flow taking place immediately after the monsoon period. During October to April base flow decreases drastically and becomes zero @ the end of March. During the month of April and May the ground water table level reaches stable conditions.

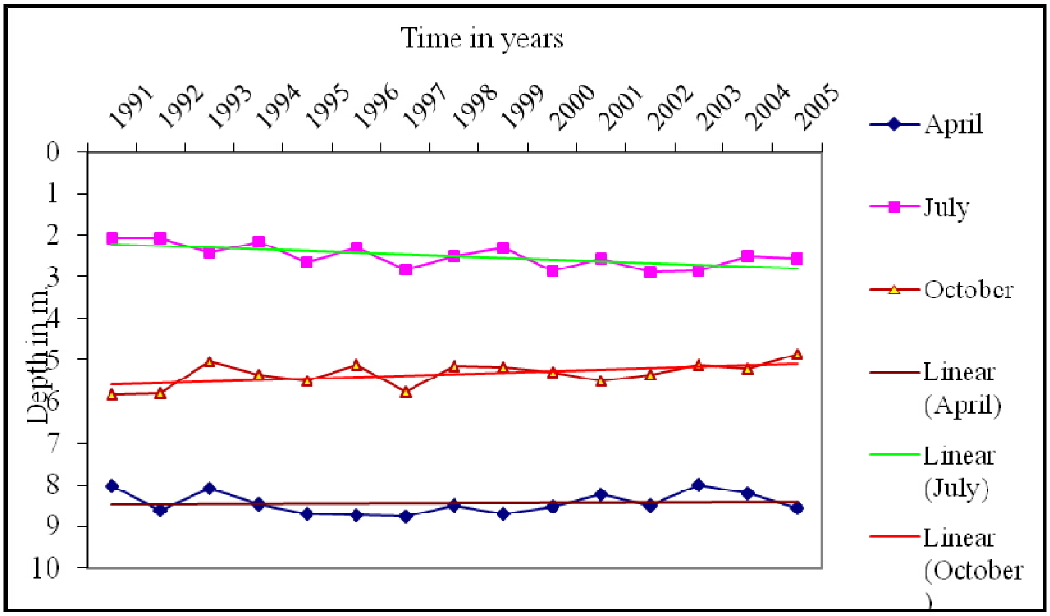


Fig. 6.17 GWLF during peak months of April, July and October

Ground water development in the study area mainly taking place through dug wells. All along the coastal line Dug wells are acts like recharging wells during monsoon period and used to with draw water during non-monsoon period (Udupi Brochure, 2008). The depth range of dug wells found within 2.00 to 7.00 m bgl, ground water development in the study area is, under "Safe" category, i.e., about 39.12% of the utilizable resources is developed as indicated by the latest ground water evaluation of the river basin by the GEM 2006.

Ground water level fluctuates from season to season due to the seasonal variations of rainfall. The water levels are deepest before the commencement of southwest monsoon i.e., in May and shallowest while recorded in August/November. Rise after rains indicate the building up of ground water storage in the ground water reservoir, which gets depleted by evaporation and exploitation during non-monsoon period. Dug wells have been recommended for development in areas of shallow ground water levels. Based on the hydrogeological conditions, the diameter and depth range from 3 to 6m and 10 to 12m respectively have been recommended (Udupi Brochure 2008).

6.5.2 Bore well ground water level analysis

Fig. 6.18 shows monthly water table fluctuations of 4 bore wells of the study area for a period of 5 years (2000-2005). The variation pattern of all the bore wells is almost same. The maximum- minimum depth of each bore well is 8.5-1.23 m, 9-1.6 m, 10.75-2.6 m and 11.6- 4.9 m. The variations of these bore wells during the study period is 7.27 m, 7.4 m, 8.15 m and 6.7 m. respectively. The average ground water table variation observed is 7.4 m. This value is 1.4 m high compared to the variation of ground water table with respect to observation open wells (unconfined aquifer to confined aquifer).

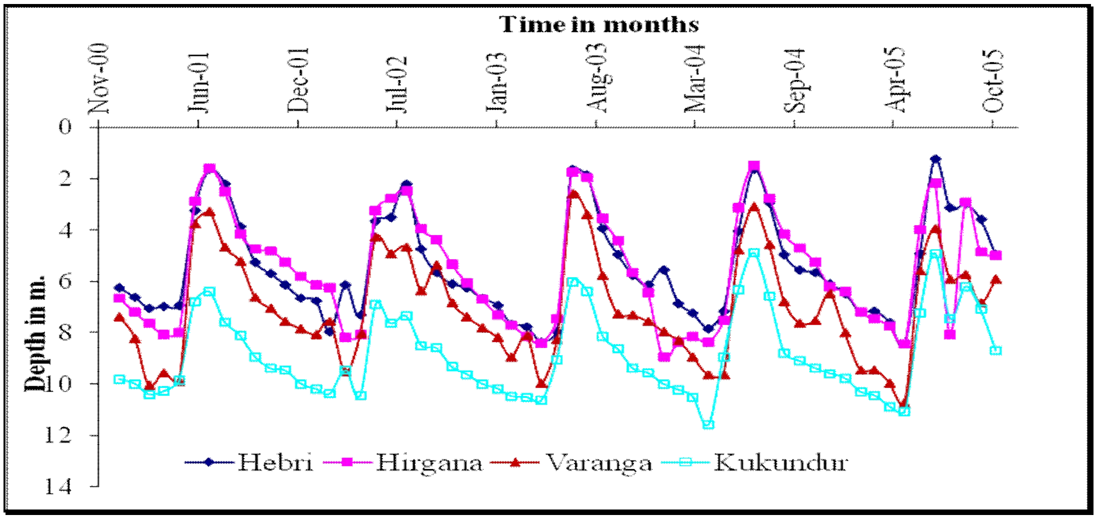


Fig. 6.18 GWLF of four Observation bore wells

Table 6.12. Statistical Analysis of Bore well GWLF

Sl. No.	Place	Minimum	Maximum	Average	Std. Deviation
1.	Hebri	1.23	8.45	5.45	1.97
2.	Hirgana	1.47	8.96	5.57	2.19
3.	Varanga	2.59	10.75	7.05	2.04
4.	Kunkundoor	4.9	11.6	8.89	1.62

Fig. 6.19 is a plot of average of monthly difference of four observation bore wells for a period of 6 years (1999-2005). Maximum rise or fall of water table can be calculated by taking successive monthly ground water table values. It is observed that the ground water table rises only during monsoon period. It indicates that basin receives maximum recharge during these months. Ground water table continuously falls down during rest of the

months. It indicates that basin releases water as base flow to the nearby streams. Maximum value of ground water rise and fall are 6 m and3 m. The maximum variation of ground water table is 9 m.

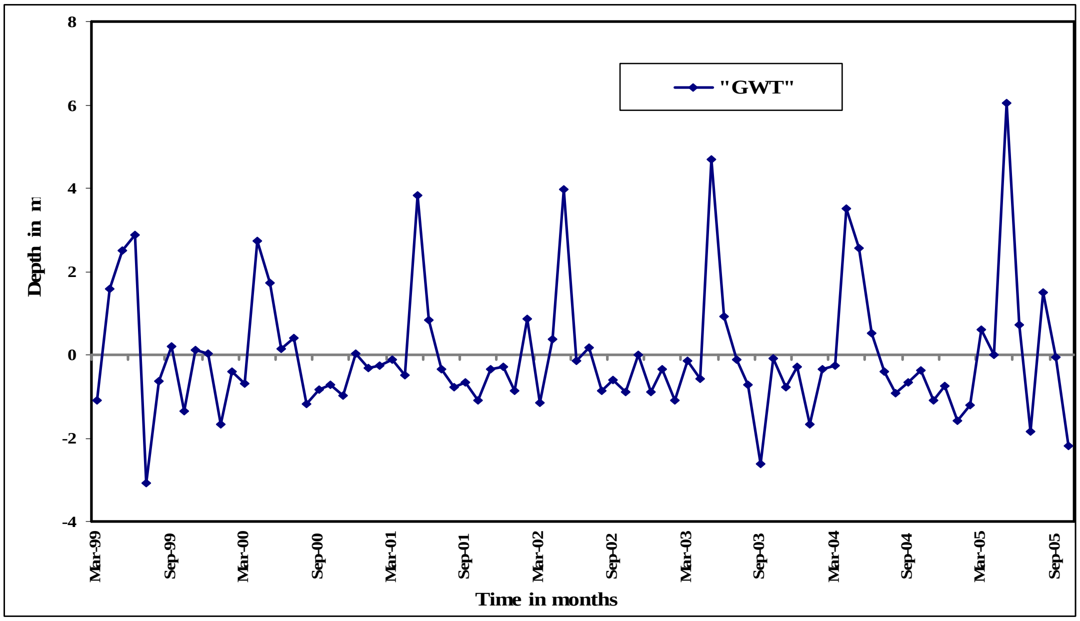


Fig. 6.19 Monthly average GWLF of four observation BW

6.5.3 Bore well ground water level analysis using data recorded by DWLR

Fig. 6.20 shows the ground water level fluctuation of two observations bore wells of Haladi River basin. Data was recorded by using 6 hourly digital water level recorders installed at each bore well location. These 6 hourly data was first converted into daily and monthly average data. It clearly shows that ground water table fluctuation of these observation wells varies uniformly over the years. In the month of May ground water table reaches almost the same level in both the bore wells during all the years. It shows that beyond this water cannot be extracted since the wells dry up. But the rise in both the observation bore wells was found to be increasing uniformly from July 2001 to July 2005. Data obtained from the digital water level recorder gave more accurate and precise values depicting the ground water level fluctuation more reliable. But most of the time the long period of digital water level recorder data was limited due to malfunctioning of the instrument.

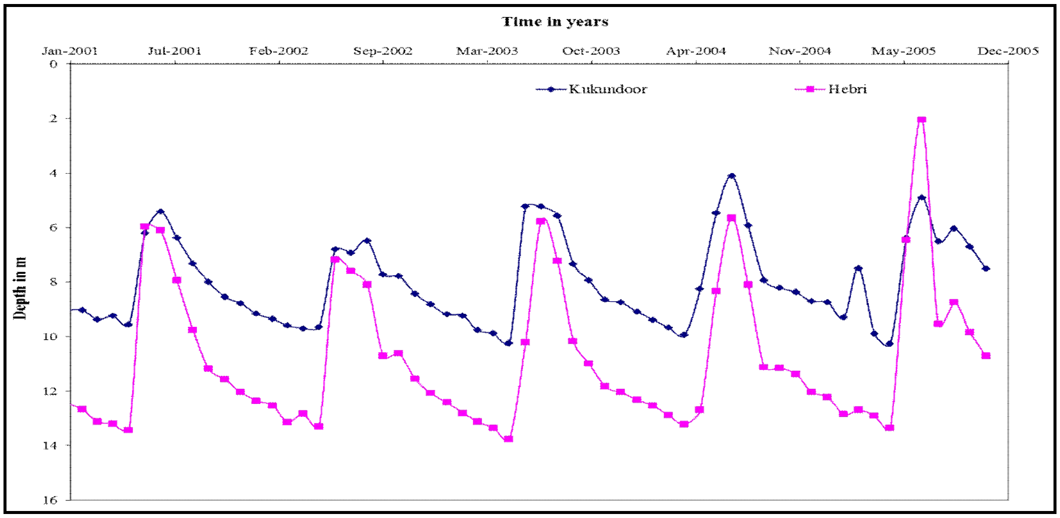


Fig. 6.20 GWLF of two BW data recorded using 6 hourly DWLR

The comparative study of ground water table fluctuation during last one and half decade (1991-2005) shows fall in water level by 0.13 to 0.39 m/year and rise in water level by 0.07 to 0.54 m/year during Pre monsoon season (May 1991- May 2005). Long term Water level trend during post monsoon (November 1991- November 2005) shows fall in water level by 0.02 to 0.35m/year and rise in water level by 0.02 to 0.25 m/year. Decadal mean water level of May 1991-2005 varies from 2.01 to 13.26 m below ground level and that of November 1991-2005 varies from 1.29 to 9.59 m below ground level.

6.6 GROUND WATER RECHARGE ESTIMATION

6.6 (a) Recharge by Krishna Rao formula: The estimation has been worked out using 15 years monthly mean rain fall in the basin. This is done for all the ten zones separately and the quantity of recharge is calculated zone wise. The estimated quantity of recharge is shown in Table 6.14. Thus, the assessment of ground water recharge potential is done in different time scale. This study is further extended to see the variations spatially. The recharge results are shown in Fig 6.21.

6.6 (b) Recharge by average water level differences over ten years

The estimation is worked out for the average fluctuations over ten years in the basin. The difference between the highest GWT level of pre monsoon season and the lower of the monsoon season for every year is taken and the average over the ten years is calculated.

This is done for all the ten zones and the quantity of recharge is calculated. The estimated quantity of recharge is given in Table 6.15. Thus, the assessment of ground water potential is done in different time scale. This study is further extended to see the variations spatially and the recharge results are shown in Fig 6.21.

6.6 (c) Recharge by water level differences over ten years

The study is further extended for a long span of water level fluctuations in the aquifer. Here, the depth of fluctuation is taken as difference between the highest level of pre monsoon season and the lowest of monsoon season over ten years. Considering these variations ground water recharge was estimated by using equation (5.1). This is repeated with 15 years of data and the recharge results are shown in Fig 6.21. Zone wise quantity of recharge has been computed and listed in Table 6.16.

6.6 (d) Recharge by yearly water level fluctuation

In this method, the fluctuation of ground water level has taken as the difference between the highest level of pre monsoon season and the lower of the monsoon season in a year and the equation (5.1) is used for estimating the recharge values for 15 years from 1991 to 2005. Zone wise recharge quantity has been calculated and tabulated in Table 6.17. The recharge results are shown in Fig 6.21 and the recharge results are plotted area of influence and zone wise of each open well are shown in Fig 6.22(a) and 6.22(b). The comparative values of recharge potentials of all the methods are shown in table 6.13

Table 6.13 Comparison of annual ground water recharge estimation results

Sl. No.	Methodology	GW recharge in Mm^3	% deviation w.r.t GEC value
1	Recharge by Krishna Rao method	304.76	9
2	Recharge by avg. W.L. diff. over 10 years	288.04	3
3	Recharge by W.L. diff. Over ten years	386.93	38
4	Recharge by yearly W.L. fluctuation	288.22	3

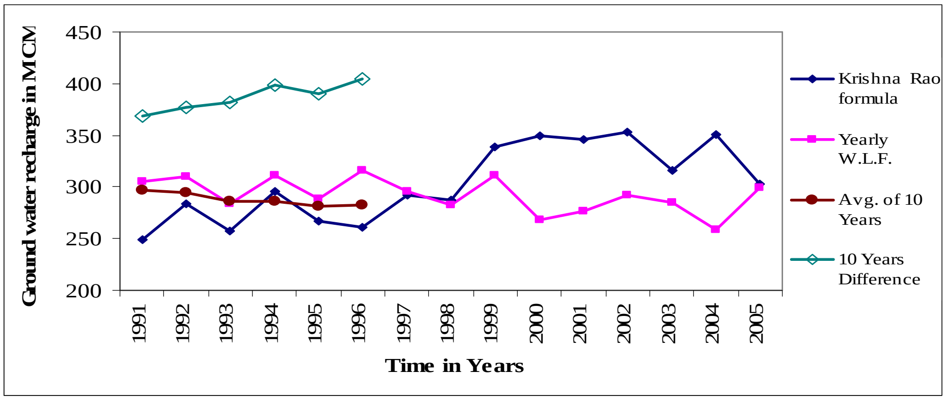


Fig. 6.21 Comparison of ground water recharges methods

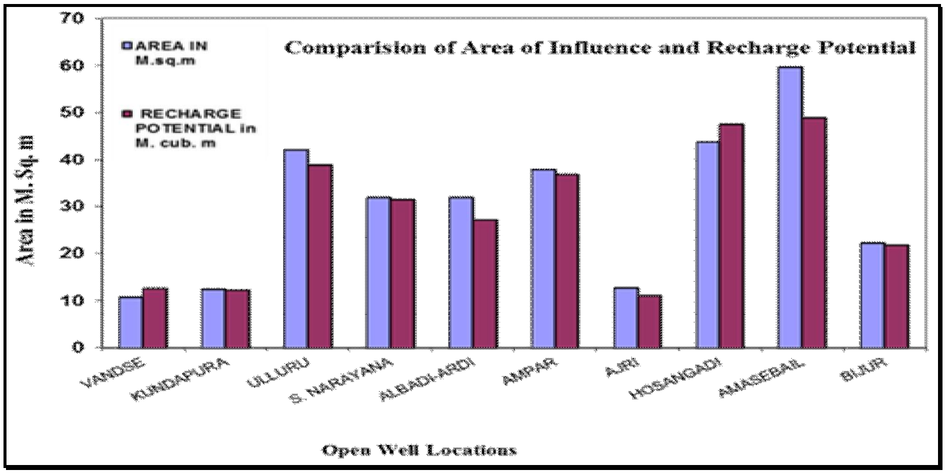


Fig. 6.22(a) Zone wise Comparison of Area of influence and Recharge

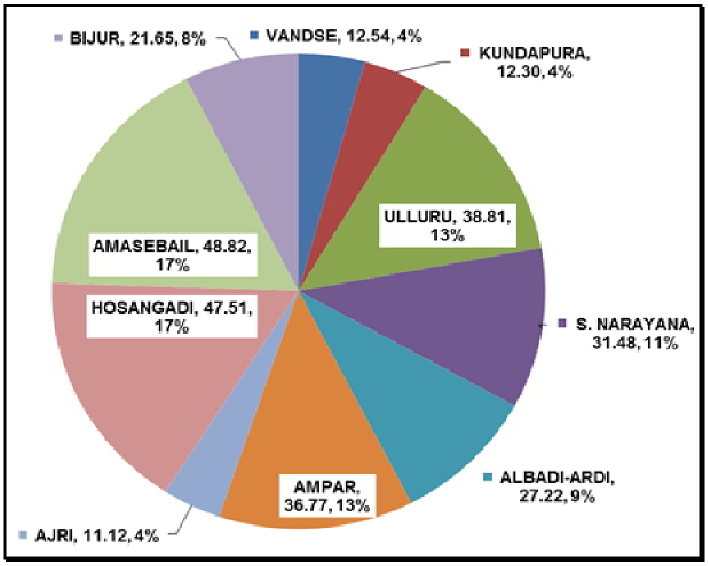


Fig. 6.22(b) Zone wise yearly ground water recharge in Mm^3 and percentage

6.6 (e) Recharge by monsoon season fluctuations

The ground water recharge is estimated for monsoon season. Assessment of ground water recharge variations of the basin during the period of monsoon season (June-September) was computed. The difference between the highest and lowest water levels is calculated by using the equation (5.1) to estimate the recharge of the basin. This is repeated for all ten zones of the basin by using 15 years of water level data (1991 to 2005). The estimated quantity of ground water recharge is listed in Table 6.18.

As per the Ground water Estimation Committee (GEC) norms, the recharge of 280 MCM has been computed by the GEC during 2006. The results obtained by the four methods show that the three methods are close to the results of the assessment made by GEC except the third method. The percentage of deviation is shown in Table 6.13. Among the four methods, the values obtained by third method of taking the extreme fluctuation over ten years seem to be undesirable. Hence, this method could not be recommended. In other words, the larger time scale in assessment proves to be incorrect. For example, when there is sudden drought in one year and is normal for the remaining nine years the average taken over ten years will give anomalous results which is not the case during that period. On the other hand, the results obtained by the remaining three methods are falling in line with the values of GEC, which was used for planning of water resources of Haladi River basin. Hence, they can be recommended for future studies. In particular, the result obtained by fourth method is best suited for estimation of ground water recharge since it is depicting the annual fluctuations of ground water table in the study area.

Table 6.14 Recharge by Krishna Rao formula

Sl. No.	**Year**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**Average in Mm^3**
1	Vandse	13.23	14.65	11.08	14.79	11.08	7.05	12.83	11.51	16.17	13.77	19.84	14.26	10.47	20.09	10.29	13.41
2	Kundapura	18.02	19.94	15.10	19.69	16.18	10.36	18.92	27.20	29.41	26.79	35.86	25.42	22.21	27.63	16.64	21.96
3	Ulluru	22.14	25.84	21.48	27.37	21.65	16.95	22.22	39.92	42.74	43.20	26.29	32.43	26.93	43.90	26.60	29.31
4	S. Narayana	32.81	29.38	35.47	27.92	47.02	30.45	28.71	35.38	39.74	48.86	43.91	60.44	42.96	39.94	58.99	40.13
5	Albadi-Ardi	23.50	27.81	43.27	31.90	26.44	21.70	27.48	32.40	42.68	33.52	47.81	30.57	26.87	37.79	22.35	31.74
6	Ampar	28.73	29.50	21.92	29.68	19.60	22.86	22.17	24.80	33.29	26.70	33.26	28.71	24.23	31.62	23.87	26.73
7	Ajri	10.30	11.38	9.89	17.30	9.19	16.72	22.47	9.44	14.09	17.68	14.72	21.03	14.89	14.31	16.17	14.64
8	Hosangadi	40.38	49.40	42.03	63.22	32.08	36.65	47.97	27.09	29.55	45.34	56.86	47.35	67.65	47.89	46.04	45.30
9	Amasebail	38.23	50.90	39.15	93.40	57.03	58.91	63.18	55.27	59.77	54.45	72.88	51.66	45.13	56.16	42.05	55.88
10	Bijur	22.13	24.98	17.82	30.88	27.27	18.81	25.96	23.87	31.63	38.88	34.95	41.55	34.19	31.78	40.41	29.67
	Average in Mm^3	249.47	283.77	257.20	356.14	267.53	240.44	291.91	286.86	339.07	349.19	386.38	353.41	315.52	351.12	303.41	**308.76**

Table 6.15 Recharge by average monthly ground water level difference over 10 years

Sl. No.	**Year**	**Area in Mm^2**	**1991-00**	**1992-01**	**1993-02**	**1994-03**	**1995-04**	**1996-05**	**Average in Mm^3**
1	Vandse	32.93	10.35	10.89	11.28	12.58	13.58	14.28	12.16
2	Kundapura	47.54	12.44	12.53	12.29	12.41	12.45	12.64	12.46
3	Ulluru	68.91	39.70	39.21	38.07	38.05	37.63	38.62	38.55
4	S. Narayana	67.51	31.00	31.49	31.06	31.69	31.62	31.96	31.47
5	Albadi-Ardi	63.85	26.79	26.38	26.16	27.14	27.64	27.70	26.97
6	Ampar	66.09	38.97	38.71	37.44	36.88	35.62	35.40	37.17
7	Ajri	27.92	13.73	13.05	12.15	11.41	10.30	9.68	11.72
8	Hosangadi	89.81	48.25	49.33	48.90	48.79	47.80	46.96	48.34
9	Amasebail	96.61	56.65	54.09	51.38	48.81	45.61	42.92	49.91
10	Bijur	53.72	19.27	18.60	17.74	18.81	19.15	22.24	19.30
	Average in Mm^3	614.88	297.14	294.27	286.46	286.57	281.38	282.40	**288.04**

Table 6.16 Recharge by water level difference over 10 years

Sl. No.	**Year**	**1991-00**	**1992-01**	**1993-02**	**1994-03**	**1995-04**	**1996-05**	**Average. in Mm^3**
1	Vandse	17.36	17.36	17.36	19.09	19.09	19.75	18.33
2	Kundapura	17.10	17.10	17.10	17.10	17.10	17.10	17.10
3	Ulluru	50.31	50.45	50.45	50.45	50.45	54.02	51.02
4	S. Narayana	38.80	43.14	43.14	43.14	40.50	40.50	41.54
5	Albadi-Ardi	32.49	32.81	33.83	35.26	35.26	34.59	34.04
6	Ampar	45.47	45.47	45.47	45.47	45.47	45.47	45.47
7	Ajri	16.75	16.75	16.75	16.75	15.91	15.91	16.47
8	Hosangadi	56.89	61.23	65.38	67.46	65.26	65.26	63.58
9	Amasebail	67.16	67.16	67.16	67.16	64.65	64.65	66.32
10	Bijur	26.14	26.14	24.93	36.63	36.70	47.76	33.05
	Average in Mm^3	368.47	377.61	381.58	398.51	390.40	405.02	**386.93**

Table 6.17 Recharge by yearly water level fluctuation

Sl. No.	**Year**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**Average in Mm^3**
1	Vandse	10.74	12.22	6.09	6.22	9.98	11.06	9.68	11.64	8.87	16.97	16.14	16.18	19.09	16.20	16.97	12.54
2	Kundapura	12.48	11.91	10.22	11.51	11.91	11.68	12.55	14.28	13.81	14.08	13.34	9.48	11.48	11.91	13.81	12.30
3	Ulluru	42.21	41.77	34.05	41.43	36.47	43.70	40.76	36.18	45.58	34.87	37.24	30.39	33.86	37.24	46.40	38.81
4	S. Narayana	31.90	32.18	26.84	32.13	29.58	30.57	32.37	29.30	28.97	36.15	36.84	27.83	33.13	31.42	33.03	31.48
5	Albadi-Ardi	31.96	29.23	21.90	19.35	28.92	28.02	25.92	29.27	29.27	24.05	27.84	27.00	31.73	24.31	29.59	27.22
6	Ampar	37.93	43.72	42.51	41.63	31.69	43.95	39.55	37.70	38.17	32.80	35.39	30.99	36.96	28.96	29.51	36.77
7	Ajri	12.70	13.68	13.72	16.18	13.74	14.38	12.33	12.62	12.96	14.95	5.96	4.65	6.35	5.06	7.50	11.12
8	Hosangadi	43.88	44.57	47.78	56.89	50.04	48.78	53.56	47.40	47.78	41.81	54.63	40.30	46.65	47.02	41.62	47.51
9	Amasebail	59.65	60.19	58.57	64.99	59.65	63.37	51.94	49.98	63.91	34.29	34.02	33.14	32.87	32.94	32.80	48.82
10	Bijur	22.19	20.76	22.30	20.31	16.89	20.27	16.47	13.65	21.47	18.35	15.57	12.07	33.02	23.73	47.76	21.65
	Average in Mm^3	305.63	310.23	283.97	310.67	288.86	315.80	295.13	282.02	310.79	268.31	276.96	232.04	285.13	258.80	298.99	**288.22**

Table 6.18 Recharge by ground water level fluctuation during monsoon season

Sl. No.	**Year**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**Average in Mm^3**
1	VANDSE	6.43	4.96	2.01	3.13	2.93	4.17	8.64	6.48	3.94	10.19	8.16	12.49	10.67	15.28	8.46	7.20
2	KUNDAPURA	6.79	6.32	6.69	5.46	5.42	6.19	10.98	5.82	9.35	4.86	8.15	3.06	5.12	10.02	6.56	6.72
3	ULLURU	33.76	23.68	29.47	21.22	32.66	28.89	28.35	20.45	21.22	20.40	22.82	13.65	25.66	21.71	21.42	24.36
4	S. NARAYANA	16.30	12.24	15.17	15.17	13.18	15.07	20.95	12.38	13.99	18.43	15.71	26.04	33.13	31.42	21.50	18.71
5	ALBADI-ARDI	14.08	10.32	4.83	6.84	12.60	10.59	24.36	7.96	12.07	7.46	7.42	6.08	10.06	7.37	5.50	9.84
6	AMPAR	23.73	29.42	36.50	16.56	16.65	30.30	28.40	20.49	24.52	12.49	19.06	9.85	19.66	13.97	11.80	20.89
7	AJRI	8.64	6.92	10.59	9.05	12.96	7.17	12.33	8.25	5.33	5.96	3.46	2.38	3.28	2.36	2.11	6.72
8	HOSANGADI	24.52	44.57	36.34	30.49	35.21	35.27	33.56	46.27	28.73	25.15	31.24	10.88	25.15	22.19	32.57	30.81
9	AMASEBAIL	40.98	37.87	36.32	35.50	34.90	23.13	27.40	21.44	29.76	20.96	16.97	14.20	14.74	18.87	19.27	26.15
10	BIJUR	15.31	11.96	16.36	14.63	12.37	11.51	15.72	9.63	15.61	11.66	9.70	4.89	10.45	14.44	5.57	11.99
	Average in Mm^3	190.54	188.27	194.26	158.06	178.88	172.30	210.69	159.16	164.52	137.56	142.70	103.53	157.93	157.64	134.74	**163.39**

CHAPTER -7

CONCLUSIONS

For sustainable development of water resources, it is necessary to maintain the ground water reservoir in a state of dynamic equilibrium over a period of time. The water level fluctuations have to be kept within a particular range over the monsoon and non-monsoon seasons. A critical study has been carried out on the different methods of estimating the ground water recharge potential and are compared to decide the most suitable technique for practical utility. In the present study, in HaladiRiver basin infiltration tests were conducted at 10 observation open well locations and the electrical resistivity tests were conducted at 7 sites. To estimate the annual dynamic ground water recharge of the river basin, monthly average rainfall and the monthly average ground water level fluctuation data of 10 observation open wells is used and different methods of ground water resources estimation is analyzed and compared.

Based on the present study, the following conclusions were drawn

(A) BY BASIN INFILTRATION TEST INVESTIGATION

- In the study area the infiltration rate exceeds 6.5 cm/hr which is typical in lateritic or sandy soil.
- Since the rate of infiltration is high in almost all parts of basin, adoption of artificial recharge through percolation tanks and by spreading methods will be very effective.
- The general infiltration equation formed for Haladi river basin region is found to be, $f = 10.055 + 41.825\, e^{-0.035\, t}$
- Infiltration value does not vary much with variation of diameter of infiltrometer.
- Infiltration value at 1m below ground level is slightly less than surface values.

(B) AQUIFER CHARACTERIZATION STUDY

- Geophysical investigations and electrical resistivity test results indicate that the aquifer thickness in the study area ranges from 12 m to 18 m. Probable fracture zones are also detected at depths ranging from 25 to 55 m.
- Hydraulic conductivity K from soil parametersobtained from the analysis ranges from 150 m/day to 250 m/day.
- From the pumping test observations and the solution by Neuman method and also by modified Theis method for unconfined aquifers, Hydraulic Conductivity value of 285.1 m/day and Transmissivity value 1440 m^2/day is obtained. The hydraulic conductivity values are generally high which indicates the pervious nature of the aquifer.

(C) TIME SERIES ANALYSIS

- It is observed that every year the rise and fall of the ground water level takes place in the same order with a slight upward trend.
- Observation open wells water level analysis indicates that the rise and fall is almost similar in every year. It is observed that every year the amount of water reaching the ground water table is almost the same as the amount of ground water released from the aquifer.
- Bore well water level analysisshowsthat the average ground water table variation is about 7.4 m. This value is 1.4 m high compared to the variation of ground water table w.r.t. observation open wells. Maximum value of ground water rise and fall are 6 m and 3 m respectively. The maximum variation of ground water table is 9 m.
- Bore well GWL analysis using Data recorded by DWLR gave more accurate and precise values depicting the ground water level fluctuations more authentically. In the month of May, ground water table reaches critical level beyond which water cannot be extracted further.

(D) ESTIMATION OF GROUND WATER RECHARGE

- Recharge by yearly water level difference method gave a value of 288.22 Mm^3which is on line with Central Water Commission (CWC-2006) estimate.
- Zone wise estimation of recharge is more appropriate than any other method of estimation since it takes care of area of influence of each observation well.
- Ground water recharge is estimated by different methods such as Krishna Rao formula, recharge by average monthly ground water level difference over 10 years, recharge by water level difference over 10 years, recharge by yearly water level fluctuations and the corresponding values found to be 308.76 Mm^3, 288.04 Mm^3, 386.93Mm^3 and 288.22 Mm^3 respectively.
- For the recharge estimation of ground water, recharge by yearly water level fluctuations method can be adopted as it gives the value on par with GEC value.

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APPENDIX – I

Observation open wells data

Monthly ground water level of 10 open wells in metres for the year 1991 (Dept. of Mines and Geology, Govt. of Karnataka)

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	5.51	5.74	6.04	5.69	6.44	3.77	1.78	2.01	4.57	4.3	4.71	4.58
2	Kundapura	5.41	5.59	5.74	6.18	6.37	4.12	2.62	2.96	3.31	4.66	5.07	5.21
3	Ulluru	8.53	8.91	9.43	10.14	10.35	8.6	1.6	3.61	6.03	5.88	6.09	6.25
4	S. Narayana	7.01	7.24	7.79	8.03	8.03	2.32	1.28	2.3	3.7	4.73	5.7	6.09
5	Albadi-Ardi	4.93	6.12	6.39	6.81	8.23	3.33	1.08	3.36	3.36	4.23	4.77	5.3
6	Ampar	9.47	9.57	9.98	10.47	10.58	6.58	2.38	4.84	4.84	7.51	8.09	8.43
7	Ajri	6.48	6.91	8.42	6.05	5.67	4.31	1.92	2.13	5.82	6.34	6.75	6.92
8	Hosangadi	7.77	8.11	8.78	7.25	6.14	1.9	1.8	2.42	5.2	5.7	5.92	6.11
9	Amasebail	6.61	6.89	7.4	9.28	8.88	2.62	0.46	0.59	5.92	6.52	6.77	7.52
10	Bijur	9.21	9.47	9.54	10.3	9.8	6.93	4.4	6.34	8.07	8.47	8.8	9.18

Monthly ground water level of 10 open wells in metres for the year 1992

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	5.1	6.05	6.19	6.43	7.45	3.95	2.15	4.1	4.18	4.3	4.22	4.93
2	Kundapura	5.6	5.76	6.01	6.31	6.33	4.65	2.75	2.95	3.02	4.51	3.64	5.11
3	Ulluru	8.83	9.44	9.8	10.59	10.6	5.13	1.94	3.33	5.25	6.85	5.34	7.11
4	S. Narayana	6.6	6.97	7.21	7.91	8	3.38	1.19	2.17	3.32	3.78	2.64	5.84
5	Albadi-Ardi	6.19	6.98	7.31	8.22	8.35	4	1.81	2.97	3.9	4.12	3.2	5.31
6	Ampar	8.87	9.23	9.61	10.7	10.35	7.61	1.25	4.8	5	7.5	7.03	8.16
7	Ajri	7.7	8	8.85	9.05	9.2	3.8	2.2	3.85	4.95	5.74	3.28	6.55
8	Hosangadi	6.38	6.75	7	7.25	7.4	8.55	1.46	3.17	3.24	6.38	5.09	7.18
9	Amasebail	8.02	8.27	9.12	9.28	9.52	5.1	0.62	3.12	5.38	6.22	4.71	5.61
10	Bijur	9.55	9.65	10	10.3	10.75	5.35	5.23	6.57	7.46	8.41	8.35	8.79

Monthly ground water level of 10 open wells in metres for the year 1993

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	5.09	5.83	5.25	5.88	6.14	3.96	3.5	3.8	4.35	4.37	4.4	4.35
2	Kundapura	5.11	5.43	5.53	5.49	6.05	4.99	2.98	3.21	3.9	3.27	4.65	5.13
3	Ulluru	8.22	8.5	9.16	9.55	10.1	9.15	3.04	3.74	5.82	5.09	7.17	7.74
4	S. Narayana	6.2	7	7.2	7.2	7.9	5.43	2.22	2.63	3.83	3.71	5.43	5.55
5	Albadi-Ardi	5.88	6.53	6.32	6.88	7.85	4	2.95	3.24	3.92	4.03	4.2	4.45
6	Ampar	8.43	9.18	9.49	9.76	10.35	9.05	1.16	4.09	6.69	5.98	7.74	8.26
7	Ajri	7.39	7.75	8.25	8.84	9.1	7.5	2.08	3.85	5.21	5.19	6.21	6.65
8	Hosangadi	7.53	7.98	8.46	8.86	8.89	7.07	1.29	3.13	5.29	5.83	6.67	7.3
9	Amasebail	7.19	8.09	8.72	8.78	9.31	6.02	0.65	2.78	4.08	5.12	6.38	6.65
10	Bijur	9.11	9.49	9.63	9.7	10.43	8.85	4.5	6.62	7.99	7.73	8.59	8.83

Monthly ground water level of 10 open wells in metres for the year 1994

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	4.45	5.14	5.73	5.59	6.05	4.22	3.6	3.35	3.88	4.71	4.89	4.92
2	Kundapura	5.29	5.58	5.93	5.94	6.08	3.95	2.74	2.62	4.05	4.26	4.67	5.24
3	Ulluru	8.2	8.84	9.52	9.99	10.6	5.9	2.01	2.23	6.04	6.41	7.08	7.29
4	S. Narayana	5.82	6.67	7.74	7.57	7.68	1.13	0.94	2.7	4.06	4.15	5.47	5.59
5	Albadi-Ardi	5.05	5.7	6.67	6.68	6.86	3.5	2.53	2.99	4.02	4.06	4.09	4.39
6	Ampar	8.49	9.1	9.23	10.28	10.43	3.17	1.43	2.01	4.14	5.01	7.08	7.53
7	Ajri	7.36	8.03	8.45	9.04	9.35	1.07	2.01	3.05	5.23	5.7	5.99	6.11
8	Hosangadi	7.79	8.01	8.34	10.18	1.13	1.22	1.47	5.47	6.07	6.07	6.43	6.71
9	Amasebail	8.16	8.35	9.28	9.74	10	0.39	0.67	1.42	5.64	4.89	5.52	7.62
10	Bijur	9.07	9.35	9.55	9.74	9.61	4.34	4.35	5.51	8.04	8.23	8.3	8.87

Monthly ground water level of 10 open wells in metres for the year 1995

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	4.97	5.51	6.25	7.26	4.8	3.98	2.93	3.48	4.2	4.11	4.28	4.52
2	Kundapura	5.28	5.47	5.78	6.14	6.2	4.25	2.62	2.86	3.48	4.08	4.69	5.06
3	Ulluru	8.11	8.8	9.35	10.25	10.1	9.46	3	2.69	4.79	6.15	7.35	8.03
4	S. Narayana	6.21	6.96	7.9	8.04	8	4.26	1.78	2.22	2.29	4.57	5.5	5.78
5	Albadi-Ardi	5.03	5.76	6.45	7.65	7.2	3.51	1.18	2.7	3.75	4	4.46	5.14
6	Ampar	8.13	8.91	9.54	10.46	10.32	3.61	5.2	3.77	5.8	7.21	7.96	8.48
7	Ajri	7.74	7.97	8.4	9.09	9.3	8.9	2.27	3.16	3	6.21	6.6	7.3
8	Hosangadi	7.92	8.08	8.33	8.88	9.58	7.22	1.62	2.87	3.17	4.32	5.4	7.64
9	Amasebail	8.32	8.41	8.89	9.58	8.92	4.72	0.76	1.37	1.37	5.92	6.07	7.36
10	Bijur	9.22	9.36	9.52	9.6	9.7	8.5	5.21	6.32	5.55	8.36	8.51	8.85

Monthly ground water level of 10 open wells in metres for the year 1996

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	4.8	5.75	6.03	6.88	7.45	4.21	2.65	3.65	4.28	4.46	5	5.28
2	Kundapura	5.3	5.75	5.83	6.09	6.22	4.57	2.71	3.4	3.99	4.34	4.7	4.89
3	Ulluru	8.55	9.4	10.85	11.2	10.65	8.13	2.14	3.6	5.72	6.45	7.2	7.45
4	S. Narayana	6.02	7.3	7.9	7.98	8.2	2.53	1.73	2.2	4.08	4.92	5.5	5.65
5	Albadi-Ardi	5.68	6.81	7.65	7.92	7.54	2.65	1.65	2.8	3.7	4.02	4.4	4.7
6	Ampar	9.07	9.28	10.32	10.41	9.8	7.46	0.91	4.68	6.4	6.99	6.9	7.12
7	Ajri	7.6	7.99	8.9	8.7	9.64	5.95	2.28	3.1	3.88	4.36	6.15	6.8
8	Hosangadi	7.98	8.26	9.02	9.08	9.4	7.25	1.64	3.68	4.6	5.25	6.87	7.3
9	Amasebail	7.55	7.94	8.82	9.29	10.22	4.27	0.85	2.62	2.02	2.91	6.28	6.67
10	Bijur	9.23	9.4	9.7	9.73	10.03	7.7	4.64	6.7	7.15	7.67	8.57	8.9

Monthly ground water level of 10 open wells in metres for the year 1997

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	5.15	5.26	5.85	7	7.35	6.9	3.3	3.15	4.3	5.1	5.15	4.4
2	Kundapura	5.2	5.57	5.84	6.1	6.57	6.1	2.8	3.3	4	4.75	5	5.2
3	Ulluru	8.4	8.75	9.58	10.3	10.45	9.95	2	2.4	6	6.7	6.9	7.7
4	S. Narayana	5.9	6.3	7.35	8.85	8	8.55	2	2.5	4.2	4.8	5.5	5.7
5	Albadi-Ardi	5.3	5.65	6.9	7.5	7.85	7.5	2.05	2.6	5	4.5	4.7	4.5
6	Ampar	8.7	9.35	9.82	10.2	10.45	10.2	1.9	3.1	4.2	5	7	8.3
7	Ajri	7.43	7.98	7.98	8.95	9.3	9.5	3.19	3.2	5.25	6.38	5.49	6.88
8	Hosangadi	7.8	7.95	8.7	9.18	8.4	10	2.4	1.48	5.28	6.38	5.84	6.03
9	Amasebail	6.85	8.02	8.64	9.52	10.32	8.17	2.72	2.64	5.09	5.72	5.85	6.2
10	Bijur	9.15	9.38	9.52	9.9	10.2	10	5.82	6.08	7.77	8.37	7.5	7.87

Monthly ground water level of 10 open wells in metres for the year 1998

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	4.9	5.9	6.15	6.36	6.8	2.61	1.75	4.4	4.2	4.56	4.66	4.52
2	Kundapura	5.8	5.6	6.4	6.63	6.7	4.16	2.41	2.88	3.25	3.98	4.71	4.9
3	Ulluru	8.1	8.1	9.4	9.8	9.7	6.54	2.3	3.42	4.11	5.06	5.64	6.04
4	S. Narayana	6.2	6.6	7.1	7.61	7.9	2.7	1.7	2.21	2.45	4.32	5.05	5.49
5	Albadi-Ardi	5	6.15	6.6	8.21	8.25	1.76	1.7	2.6	3.48	3.47	4.03	4.48
6	Ampar	8.6	8.9	9.4	9.7	10	2.15	1.85	3.65	4.89	6.28	7.36	7.89
7	Ajri	6.59	7.43	8.08	8.85	9.24	7	2.78	4.15	4.31	5.13	5.73	6.58
8	Hosangadi	7.5	8.03	8.84	9.03	9.58	9.4	2.04	2.95	4.47	5.75	6.41	7.28
9	Amasebail	6.97	7.56	8.05	8.97	9.28	1.89	2.32	3.42	4.11	5.06	5.64	6.04
10	Bijur	9.05	9.35	9.5	9.75	10.02	8.95	6.39	6.76	6.75	7.85	8.35	8.8

Monthly ground water level of 10 open wells in metres for the year 1999

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	4.75	5.35	5.6	6.6	4.37	4.25	2.75	4.45	4.46	3.96	4.59	5.2
2	Kundapura	5.37	5.6	5.8	6.19	5.15	3.56	2.04	3.7	4.17	4.85	5.18	5.41
3	Ulluru	7.34	7.82	8.27	10.22	5.2	3.57	0.77	3.08	5.17	4.74	6.02	6.68
4	S. Narayana	5.77	6.02	6.25	7.67	3.54	4.25	1.54	2.7	4.2	4.5	5	6.8
5	Albadi-Ardi	4.68	6.2	7.9	7.95	4.11	3.45	1.4	2.65	3.92	4.1	4.5	5.2
6	Ampar	9.36	9.2	9.55	10.25	9.78	5.54	2	3.82	7.3	6.6	7.4	7.92
7	Ajri	7.47	8.02	8.39	9.08	8.7	4.14	2.45	3.81	5.18	4.6	5.9	6.8
8	Hosangadi	7.8	8.16	8.52	9.15	7.97	4.43	1.55	4.05	5.42	6.12	6.89	7.47
9	Amasebail	7.34	7.82	8.27	10.22	5.2	3.57	0.77	3.08	5.17	4.74	5.02	5.75
10	Bijur	9.1	9.35	9.1	9.51	8.63	6.93	3.8	6.91	7.95	7.75	8.28	8.52

Monthly ground water level of 10 open wells in metres for the year 2000

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	6.48	6.91	8.42	9.05	9.28	4.31	1.92	2.13	5.82	6.34	6.75	6.92
2	Kundapura	5.72	6	6.18	7.18	5.42	3.4	3.4	2.95	4	4.41	4.9	5.35
3	Ulluru	7.05	7.67	8.06	8.54	8.12	1.84	3.92	1.31	5.17	5.54	6.22	6.87
4	S. Narayana	7.45	8.1	8.44	8.8	9.15	3.35	3.9	1.5	5.32	5.4	6.08	6.92
5	Albadi-Ardi	6.02	7.09	7.38	7.8	6.04	2.77	3.57	2.42	3.97	4.09	4.35	5.17
6	Ampar	8.68	9.35	9.95	10.4	10.74	5.87	4.65	3.88	6.35	3.65	7.6	8.23
7	Ajri	7.45	8.1	8.44	8.8	9.15	3.35	3.9	1.5	4.22	4.55	4.65	4.82
8	Hosangadi	7.88	8.35	8.85	9.2	9.65	3.35	3	3.7	6.25	7	7.75	8.72
9	Amasebail	5.89	5.75	6.03	5.65	3.08	1.22	1.81	0.96	2.61	4.06	4.86	5.26
10	Bijur	9.05	9.2	9.38	9.8	9.37	6.02	6.44	4.92	7.72	8.02	8.44	8.52

Monthly ground water level of 10 open wells in metres for the year 2001

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	7.7	8	8.85	9.05	9.2	3.8	2.2	3.85	4.95	5.74	3.28	6.55
2	Kundapura	5.7	5.95	6.15	6.27	6.42	4.15	2.41	4.86	3.95	4.2	4.92	5.35
3	Ulluru	7.37	7.92	8.46	7.92	7.97	0.74	1.34	3.53	4.69	5.47	5.99	6.4
4	S. Narayana	7.6	8.14	8.65	9.05	10.07	2.65	2.275	3.92	5.47	5.6	6.47	7.12
5	Albadi-Ardi	6.04	6.92	7.57	8.42	8.52	2.29	2.34	3.59	3.07	3.95	4.23	5.05
6	Ampar	8.9	9.5	10	10.45	10.55	6.73	2.9	4.68	6.73	7.02	7.6	8.15
7	Ajri	5	5.08	5.58	5.67	6.03	3.62	2.98	3.68	3.81	4.75	4.63	4.75
8	Hosangadi	9.05	9.68	10.5	10.6	10.87	7.15	3.06	2.18	7.01	6.87	7.14	8.45
9	Amasebail	5.42	5.66	5.79	5.66	5.66	1.04	0.76	1.7	2.28	3.27	4.74	5.32
10	Bijur	9.02	9.03	9.37	9.25	9.56	6.2	5.42	6.38	7.32	8	8.54	8.77

Monthly ground water level of 10 open wells in metres for the year 2002

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	7.39	7.75	8.25	8.84	9.1	7.5	2.08	3.85	5.21	5.19	6.21	6.65
2	Kundapura	5.65	5.92	6.39	6.61	6.03	3.84	4.68	3.76	4.26	4.38	4.96	5.36
3	Ulluru	6.66	7.04	9.11	7.89	7.28	3.1	2.81	3.73	5.46	5.64	6.22	6.81
4	S. Narayana	7.68	8.15	8.45	9.08	8.64	3.19	8.7	3.34	3.69	5.11	5.21	6.13
5	Albadi-Ardi	5.65	6.38	8.35	8.75	6.9	2.71	3.43	3.8	4.04	4.07	4.25	4.83
6	Ampar	8.7	9	9.89	10.4	9.51	3.79	3.75	3.7	5.15	5.83	6.02	7.27
7	Ajri	4.86	5.08	5.53	5.82	5.45	4.66	3.44	3.74	4.29	4.5	4.6	4.78
8	Hosangadi	8.64	9.84	10.79	11.53	11.46	6.22	5.71	5.12	6.18	6.85	7.77	6.37
9	Amasebail	5.45	6.9	6.21	6.35	5.6	2	2.3	2.19	3.53	4.1	5.23	5.6
10	Bijur	9.17	9.36	9.59	9.7	9.64	6.81	6.93	6.49	7.74	7.79	8.42	8.82

Monthly ground water level of 10 open wells in metres for the year 2003

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	7.36	8.03	8.45	9.04	9.35	1.07	2.01	3.05	5.23	5.7	5.99	6.11
2	Kundapura	5.98	6.03	6.35	6.48	6.78	4.01	3.33	3.43	3.99	4.87	5.28	5.7
3	Ulluru	7.33	7.95	8.25	8.37	4.73	2.23	1.35	2.27	4.91	6.67	6.58	6.95
4	S. Narayana	6.94	7.63	8.27	8.62	9.14	9.6	7.49	2.59	3.17	4.79	4.97	6.44
5	Albadi-Ardi	5.67	6.27	7.32	8.1	9.07	1.97	2.87	3.4	3.94	4.22	4.64	5.67
6	Ampar	7.94	8.12	8.8	9.12	9.94	5.15	1.95	2.2	2.6	6.2	6.84	7.44
7	Ajri	4.84	5.08	5.45	5.83	6.37	3.12	3.13	3.5	3.75	4.8	4.82	4.83
8	Hosangadi	9.48	9.74	9.97	11.27	11.86	8.44	4.44	4.54	6.06	6.97	8.54	9.62
9	Amasebail	5.85	6.1	6	6.2	6.4	1.56	1.54	1.8	3.18	3.72	5.35	6
10	Bijur	9.19	9.24	6.41	6.96	7.58	0.46	0.53	0.76	2.61	3.24	4.78	5.53

Monthly ground water level of 10 open wells in metres for the year 2004

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	7.74	7.97	8.4	9.09	9.3	8.9	2.27	3.16	3	6.21	6.6	7.3
2	Kundapura	6.03	6.38	6.53	6.83	6.26	6.26	3.25	3.55	4.45	4.5	5.03	4.4
3	Ulluru	7.18	7.65	8.23	8.82	6.77	2.83	1.1	3.8	5.6	5.4	5.73	6.41
4	S. Narayana	7.02	7.64	8.19	8.88	9.24	9.31	3.19	2.66	3.94	5.26	5.56	6.08
5	Albadi-Ardi	6.31	7.18	7.93	7.93	4.87	3.27	2.49	3.79	4.14	4	4.35	5.02
6	Ampar	7.72	8.25	8.86	9.36	8.75	5.05	3.1	4.55	5.78	6.12	6.6	7.3
7	Ajri	5.1	5.26	5.75	6.1	4.05	4.72	3.51	3.68	4.17	4.61	4.73	4.88
8	Hosangadi	10.14	10.69	11.59	11.84	11.84	7.89	4.36	5.39	7.04	7.46	8.25	8.95
9	Amasebail	5.92	6.06	6.2	6.3	4.75	2.5	1.43	2.5	3.28	4.22	5.07	5.5
10	Bijur	5.48	6.03	6.47	6.75	4.78	0.74	0.44	1.46	3.66	4.28	5.1	5.43

Monthly ground water level of 10 open wells in metres for the year 2005

Sl. No.	Month/Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
1	Vandse	7.6	7.99	8.9	8.7	9.64	5.95	2.28	3.1	3.88	4.36	6.15
2	Kundapura	5.8	5.85	6.3	6.4	6.8	4.62	2.65	3.64	2.85	3.33	3.95
3	Ulluru	7.02	7.28	7.41	7.45	9.62	0.86	0	4.44	3.89	3.57	6.92
4	S. Narayana	6.98	7.6	8.27	8.6	9.48	7.04	2.49	4.42	4.25	4.34	5.4
5	Albadi-Ardi	5.85	6.79	8.12	8.8	9.14	3	2.52	3.75	3.15	2.92	3.3
6	Ampar	7.8	8.15	8.7	9.18	6.8	3.1	2.8	3.2	4.07	5.35	6.08
7	Ajri	4.98	5.4	5.65	6.07	6.6	3.83	2.95	3.1	2.76	3.84	3.57
8	Hosangadi	10.33	10.7	11.65	11.77	11.65	10.33	8.21	5.31	5.15	5.99	7.59
9	Amasebail	5.76	5.98	6.15	6.2	6.23	2.02	1.38	2.38	2.02	4.23	4.86
10	Bijur	5.65	5.87	6.77	12.37	12.97	1.09	0.27	1.75	0.99	1.56	3.88

APPENDIX – II

Monthly Rainfall Data

Monthly rain fall over Haladi river basin for the year 1991 (Dept. of Mines and Geology, Govt. of Karnataka)

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	8.6	40.0	1701.6	1495.2	1019.6	76.4	20.4	36.8	0.0
2	Kundapura	0.0	0.0	0.0	55.2	91.2	1129.4	1707.9	961.6	71.0	167.4	24.6	0.2
3	Ulluru	0.0	0.0	0.0	13.4	38.9	1287.1	1298.4	917.3	79.4	67.7	17.0	7.0
4	S. Narayana	0.0	0.0	14.2	28.8	15.4	1036.8	1993.0	1255.6	163.8	335.6	169.6	84.6
5	Albadi-Ardi	0.0	0.0	0.0	53.5	127.3	1076.7	1452.0	1055.2	122.5	66.0	163.5	0.0
6	Ampar	0.0	0.0	0.0	28.2	110.0	1127.0	2022.1	1259.4	38.0	45.8	41.4	0.0
7	Ajri	0.0	0.0	0.0	27.0	72.0	1068.0	1712.0	1077.0	76.0	44.0	49.0	0.0
8	Hosangadi	0.0	0.0	0.0	41.6	114.1	1185.6	1840.2	1360.3	45.6	101.8	103.0	3.0
9	Amasebail	0.0	0.0	0.0	5.2	140.7	1142.2	1650.2	1029.1	60.6	154.4	165.4	0.0
10	Bijur	0.0	0.0	0.0	89.0	135.6	1119.5	1638.8	1143.8	57.8	167.6	129.8	0.0

Monthly rain fall over Haladi river basin for the year 1992

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	19.0	1225.4	1155.3	1514.9	356.0	81.4	402.8	0.0
2	Kundapura	0.0	0.0	0.0	8.0	121.8	1163.8	1091.9	1307.8	414.0	57.9	378.9	0.0
3	Ulluru	0.0	0.0	0.0	20.3	25.4	972.6	1100.9	1296.8	337.1	96.3	325.3	0.0
4	S. Narayana	0.0	0.0	0.0	55.2	194.0	1238.5	1547.4	1273.2	124.7	176.0	67.1	0.0
5	Albadi-Ardi	0.0	0.0	0.0	14.3	42.2	1069.2	1178.6	1354.8	550.1	110.3	358.7	0.0
6	Ampar	0.0	0.0	0.0	1.2	6.8	1066.6	1185.2	1653.8	281.0	85.3	488.6	0.0
7	Ajri	0.0	0.0	0.0	5.0	51.0	944.0	1314.0	1338.0	495.0	100.0	200.0	0.0
8	Hosangadi	0.0	0.0	0.0	0.0	42.9	1325.8	1402.2	1902.8	455.4	128.8	368.4	0.0
9	Amasebail	0.0	0.0	0.0	10.2	39.0	1010.4	1581.2	1865.0	525.6	81.0	322.2	0.0
10	Bijur	0.0	0.0	0.0	20.2	43.6	1253.4	1292.4	1299.2	560.6	133.2	320.4	0.2

Monthly rain fall over Haladi river basin for the year 1993

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	55.0	739.8	1866.5	570.0	292.6	233.6	43.2	52.4
2	Kundapura	0.0	0.0	0.0	0.0	32.1	694.9	1628.6	699.3	299.6	263.9	25.6	50.9
3	Ulluru	0.0	0.0	0.0	0.0	23.2	621.0	1714.1	692.2	322.2	203.9	22.3	46.6
4	S. Narayana	0.0	0.0	0.0	34.0	113.0	1105.2	1474.8	1374.8	634.9	310.0	376.2	0.0
5	Albadi-Ardi	0.0	0.0	0.0	0.0	0.0	1210.1	2949.9	1446.2	467.8	348.2	15.2	241.2
6	Ampar	0.0	0.0	0.0	0.0	18.6	781.3	1706.6	738.4	250.9	192.8	32.0	92.4
7	Ajri	0.0	0.0	0.0	0.0	9.0	657.6	1897.3	715.9	308.0	285.0	79.0	50.0
8	Hosangadi	0.0	0.0	0.0	0.0	32.8	761.0	1827.0	1330.6	443.4	390.2	20.2	142.4
9	Amasebail	0.0	0.0	0.0	0.0	52.6	753.8	1934.0	1042.6	208.0	390.0	45.8	0.0
10	Bijur	0.0	0.0	0.0	0.0	18.6	781.3	1706.6	738.4	250.9	192.8	32.0	92.4

Monthly rain fall over Haladi river basin for the year 1994

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	0.0	1493.2	1839.0	1083.7	177.8	190.5	6.4	0.0
2	Kundapura	0.0	0.0	0.0	102.5	83.2	1435.6	1492.1	859.9	169.3	294.4	64.8	0.0
3	Ulluru	0.0	0.0	0.0	104.5	72.3	1284.1	1555.4	739.3	213.3	391.4	0.0	0.0
4	S. Narayana	0.0	0.0	3.6	23.0	45.0	717.6	1745.5	892.1	268.2	568.6	167.4	64.8
5	Albadi-Ardi	0.0	0.0	0.0	0.0	77.6	1452.1	2055.7	831.3	227.6	451.2	113.4	0.0
6	Ampar	0.0	0.0	0.0	0.0	0.0	1493.2	1839.0	1083.7	177.8	190.5	6.4	0.0
7	Ajri	0.0	0.0	0.0	203.0	34.0	1797.6	2631.8	1113.2	232.0	154.0	35.0	0.0
8	Hosangadi	0.0	0.0	25.0	136.8	72.8	1908.6	2637.7	1186.7	379.8	466.5	80.0	0.0
9	Amasebail	0.0	0.0	0.0	42.0	39.6	2186.8	2815.0	2323.4	703.2	861.4	80.6	0.0
10	Bijur	0.0	0.0	18.0	79.4	90.6	1714.8	1804.2	1206.2	244.8	559.0	113.6	0.0

Monthly rain fall over Haladi river basin for the year 1995

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	65.8	806.2	1543.8	935.4	422.0	62.0	18.2	0.0
2	Kundapura	8.7	0.0	0.0	6.7	130.7	773.9	1521.7	976.8	272.9	175.6	18.0	0.0
3	Ulluru	0.0	0.0	0.0	0.0	40.4	780.6	1296.5	1194.8	231.0	112.3	10.6	0.0
4	S. Narayana	0.0	0.0	24.0	117.6	105.0	1966.4	2345.2	1263.4	281.0	648.4	82.2	0.0
5	Albadi-Ardi	0.0	0.0	0.0	19.0	237.6	670.2	1869.6	1011.4	426.2	166.8	100.2	0.0
6	Ampar	0.0	0.0	0.0	0.0	66.6	524.4	1693.4	891.5	282.4	59.8	0.0	0.0
7	Ajri	0.0	0.0	0.0	0.0	69.6	520.7	1643.4	1078.7	315.6	143.8	20.2	0.0
8	Hosangadi	0.0	0.0	0.0	9.6	153.0	590.0	1862.7	980.4	360.0	25.0	45.4	0.0
9	Amasebail	0.0	0.0	0.0	0.0	173.7	668.1	2746.5	1553.9	429.3	203.6	183.0	0.0
10	Bijur	0.0	0.0	0.0	3.2	349.3	775.7	1861.5	1132.8	917.8	196.9	38.9	0.0

Monthly rain fall over Haladi river basin for the year 1996

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	6.9	321.7	1305.8	579.6	428.0	119.0	18.0	41.0
2	Kundapura	0.0	0.0	0.0	0.6	16.8	743.2	1066.8	514.2	307.6	149.0	1.0	53.6
3	Ulluru	0.0	0.0	1.6	35.8	51.0	729.0	1053.0	474.7	452.2	214.6	6.4	72.8
4	S. Narayana	5.0	0.0	0.0	19.4	250.4	731.9	1951.7	941.0	578.2	248.9	80.6	0.0
5	Albadi-Ardi	0.0	0.0	0.0	0.0	37.6	910.8	1407.0	792.4	384.8	242.2	36.6	70.2
6	Ampar	0.0	0.0	0.0	0.0	2.2	813.0	1614.4	1049.8	207.4	187.2	0.0	57.6
7	Ajri	0.0	0.0	0.0	0.0	8.0	1680.6	2281.4	1271.2	427.8	240.6	37.6	81.4
8	Hosangadi	0.0	0.0	0.0	0.0	46.0	1169.2	1415.2	1167.8	308.8	263.0	0.0	80.8
9	Amasebail	0.0	0.0	0.0	0.0	17.0	1296.4	1989.3	1164.3	760.6	457.0	304.8	129.0
10	Bijur	0.0	0.0	0.0	26.4	54.2	1001.8	1330.6	878.8	368.2	256.8	22.4	27.8

Monthly rain fall over Haladi river basin for the year 1997

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	6.0	6.0	8.0	802.0	1756.2	1350.2	49.0	64.2	105.0	150.4
2	Kundapura	1.6	0.0	13.6	30.8	16.4	834.0	1965.8	1171.0	105.8	77.0	34.4	116.4
3	Ulluru	0.0	0.0	7.8	11.6	3.0	711.2	1510.2	1028.4	100.4	118.6	19.0	226.2
4	S. Narayana	0.0	1.8	0.0	11.2	38.6	1110.2	1410.5	1081.5	568.0	300.9	13.8	56.4
5	Albadi-Ardi	0.0	0.0	4.3	22.4	28.6	975.8	1686.6	1313.2	156.2	145.6	250.2	52.2
6	Ampar	0.0	0.0	0.0	0.0	0.0	978.0	1727.4	1042.1	56.2	16.0	25.0	0.0
7	Ajri	0.0	0.0	0.0	0.0	13.4	1742.4	3139.8	2278.2	152.0	144.4	118.0	135.6
8	Hosangadi	31.9	0.0	7.4	54.6	14.0	1276.4	2070.6	1541.6	134.6	112.4	183.6	67.8
9	Amasebail	0.0	0.0	0.0	0.0	0.0	1331.8	2204.0	2156.2	222.8	305.5	262.8	0.0
10	Bijur	0.0	0.0	13.6	37.4	13.6	1183.4	1867.2	1208.2	149.4	322.4	195.9	82.6

Monthly rain fall over Haladi river basin for the year 1998

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	76.2	22.0	1022.4	1016.2	1041.4	274.8	412.6	92.2	4.0
2	Kundapura	0.0	0.0	0.0	90.0	169.0	1479.0	2125.4	1519.4	121.6	152.6	151.0	0.0
3	Ulluru	0.0	0.0	3.2	62.8	63.8	1277.0	2062.4	1496.7	265.2	290.9	181.6	164.6
4	S. Narayana	0.0	0.0	1.2	22.4	10.4	1062.4	2000.1	1428.2	241.7	349.1	188.8	106.8
5	Albadi-Ardi	0.0	0.0	0.0	0.0	36.5	1482.8	2389.9	1179.1	69.2	94.0	22.3	0.0
6	Ampar	0.0	0.0	0.0	1.8	40.2	1095.6	1729.4	1181.0	37.4	71.2	19.4	0.6
7	Ajri	0.0	0.0	0.0	56.2	165.4	1125.6	1499.3	918.0	32.8	59.8	10.8	0.0
8	Hosangadi	0.0	0.0	15.2	4.2	277.2	569.4	1547.2	590.6	186.2	371.2	0.0	0.0
9	Amasebail	0.0	0.0	0.0	90.0	169.0	1479.0	2125.4	1519.4	121.6	152.6	151.0	0.0
10	Bijur	0.0	0.0	0.0	0.0	130.6	1142.8	1516.6	808.2	641.8	321.0	155.8	33.8

Monthly rain fall over Haladi river basin for the year 1999

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	5.8	177.2	1126.0	1311.6	1576.6	364.4	126.8	450.2	0.0
2	Kundapura	0.0	0.0	0.0	31.4	71.0	1119.6	1818.8	1955.8	590.0	294.4	311.0	0.0
3	Ulluru	0.0	0.0	0.0	24.8	32.7	1150.1	2149.9	1170.7	1010.0	552.5	108.1	7.0
4	S. Narayana	0.0	0.0	0.0	153.6	103.4	1449.7	2079.2	1363.0	254.6	451.8	89.8	0.0
5	Albadi-Ardi	0.0	0.0	0.0	3.8	69.0	1481.0	1745.4	2140.5	509.1	233.7	419.6	0.0
6	Ampar	0.0	0.0	0.0	0.0	66.8	1171.6	1351.4	1771.8	416.2	95.2	370.2	0.0
7	Ajri	0.0	0.0	0.0	103.2	127.2	1184.3	1857.2	1531.6	194.0	149.8	105.2	0.0
8	Hosangadi	0.0	0.0	0.0	21.6	124.6	971.0	1260.2	1023.8	294.2	95.2	0.0	0.0
9	Amasebail	0.0	0.0	0.0	31.4	71.0	1119.6	1818.8	1955.8	590.0	294.4	311.0	0.0
10	Bijur	0.0	0.0	0.0	153.6	103.4	1449.7	2079.2	1363.0	254.6	451.8	89.8	0.0

Monthly rain fall over Haladi river basin for the year 2000

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	44.0	58.6	648.0	2145.4	818.6	139.8	587.4	53.8	37.2
2	Kundapura	0.0	0.0	8.8	52.8	37.2	912.0	2146.4	1353.4	425.2	618.6	133.0	51.0
3	Ulluru	0.0	10.1	0.0	27.3	519.6	1042.1	2585.5	1290.9	290.8	493.7	0.0	0.0
4	S. Narayana	0.0	18.7	0.0	63.2	278.0	1442.2	1781.6	1592.8	1030.0	489.2	361.6	0.0
5	Albadi-Ardi	0.0	0.0	2.3	0.0	96.5	1045.4	2294.0	1202.6	384.6	254.8	6.0	133.0
6	Ampar	0.0	0.0	0.0	0.0	96.6	879.6	1963.8	794.6	304.2	249.2	65.2	63.4
7	Ajri	0.0	10.6	0.0	30.2	63.4	1336.4	1757.0	1706.4	657.6	416.6	333.4	0.0
8	Hosangadi	0.0	0.0	0.0	103.2	127.2	1184.3	1857.2	1531.6	194.0	149.8	105.2	0.0
9	Amasebail	0.0	0.0	8.8	52.8	37.2	912.0	2146.4	1353.4	425.2	618.6	133.0	51.0
10	Bijur	0.0	18.7	0.0	63.2	278.0	1442.2	1781.6	1592.8	1030.0	489.2	361.6	0.0

Monthly rain fall over Haladi river basin for the year 2001

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	12.6	0.0	16.0	69.8	53.0	1995.4	2171.4	1101.6	222.6	363.0	53.0	0.0
2	Kundapura	0.0	0.0	0.0	175.6	10.0	1826.2	2625.4	1436.4	454.8	648.6	132.0	0.0
3	Ulluru	0.0	0.0	0.0	158.2	86.4	1062.6	1662.6	993.8	51.6	120.0	94.2	0.0
4	S. Narayana	0.0	0.0	0.0	135.8	222.4	957.4	2037.2	1548.4	444.0	818.0	218.6	72.6
5	Albadi-Ardi	0.0	0.0	2.0	98.0	42.4	1949.4	2884.2	1395.7	398.5	489.9	3.0	0.0
6	Ampar	0.0	0.0	0.0	145.2	30.8	1384.2	1993.2	1048.6	265.4	367.0	4.6	0.0
7	Ajri	0.0	0.0	52.6	104.0	134.2	874.0	1687.2	1199.8	482.6	702.3	147.8	53.2
8	Hosangadi	0.0	10.6	0.0	30.2	63.4	1336.4	1757.0	1706.4	657.6	416.6	333.4	0.0
9	Amasebail	0.0	0.0	0.0	175.6	10.0	1826.2	2625.4	1436.4	454.8	648.6	132.0	0.0
10	Bijur	0.0	0.0	0.0	135.8	222.4	957.4	2037.2	1548.4	444.0	818.0	218.6	72.6

Monthly rain fall over Haladi river basin for the year 2002

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	207.3	929.2	1991.6	875.6	378.4	182.0	93.2	0.0
2	Kundapura	0.0	0.0	0.0	0.0	318.8	741.1	2284.8	1158.0	630.6	226.9	139.2	0.0
3	Ulluru	0.0	0.0	0.0	19.0	139.8	1195.2	1234.6	1276.0	505.4	219.6	380.2	0.0
4	S. Narayana	0.0	0.0	61.2	385.2	174.6	1901.0	2960.4	1529.6	414.6	910.0	129.0	0.0
5	Albadi-Ardi	8.2	0.0	0.0	39.6	90.2	791.3	2295.2	1014.2	528.0	242.1	27.9	0.0
6	Ampar	12.2	0.0	0.0	7.2	176.4	925.0	1753.6	1009.2	600.6	177.7	6.8	0.0
7	Ajri	0.0	0.0	4.2	134.3	149.0	1844.7	2547.4	1408.0	336.0	786.6	89.4	0.0
8	Hosangadi	0.0	0.0	52.6	104.0	134.2	874.0	1687.2	1199.8	482.6	702.3	147.8	53.2
9	Amasebail	0.0	0.0	0.0	0.0	318.8	741.1	2284.8	1158.0	630.6	226.9	139.2	0.0
10	Bijur	0.0	0.0	61.2	385.2	174.6	1901.0	1960.4	1529.6	414.6	910.0	129.0	0.0

Monthly rain fall over Haladi river basin for the year 2003

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	106.2	1187.2	1145.8	750.4	286.3	220.9	2.4	0.0
2	Kundapura	0.0	0.0	0.0	0.0	42.4	1292.4	1723.4	1178.2	433.2	157.4	13.8	99.4
3	Ulluru	0.0	0.0	0.0	38.4	70.2	715.6	1694.0	888.2	241.6	503.2	90.2	65.8
4	S. Narayana	0.0	0.0	0.0	117.4	501.2	845.2	2476.2	1113.4	659.8	406.6	218.2	0.0
5	Albadi-Ardi	0.0	0.0	0.0	0.0	16.3	1034.5	1705.0	889.2	578.7	242.8	0.0	89.4
6	Ampar	0.0	0.0	0.0	1.0	40.8	1004.7	1466.4	777.6	546.6	198.9	0.0	69.0
7	Ajri	0.0	0.0	0.0	42.8	366.8	696.0	2207.0	1165.2	699.2	236.3	74.0	0.0
8	Hosangadi	0.0	0.0	4.2	134.3	149.0	1844.7	2547.4	1408.0	336.0	786.6	89.4	0.0
9	Amasebail	0.0	0.0	0.0	0.0	42.4	1292.4	1723.4	1178.2	433.2	157.4	13.8	99.4
10	Bijur	0.0	0.0	0.0	117.4	501.2	845.2	2476.2	1113.4	659.8	406.6	218.2	0.0

Monthly rain fall over Haladi river basin for the year 2004

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	0.0	9.8	1230.3	2674.6	1713.3	158.0	151.4	78.3	106.3
2	Kundapura	0.0	0.0	6.8	0.0	11.4	1129.7	2151.4	1824.6	324.8	191.0	179.8	64.8
3	Ulluru	0.0	24.8	15.8	98.2	96.8	1917.4	2245.0	1022.2	218.2	662.8	42.8	0.0
4	S. Narayana	10.8	12.4	0.0	83.6	12.2	1173.0	1747.2	1758.8	640.2	327.0	92.0	112.0
5	Albadi-Ardi	0.0	0.0	0.0	67.0	37.6	1248.0	2560.4	1605.2	226.8	83.8	56.2	86.0
6	Ampar	0.0	0.0	0.0	18.2	7.2	1136.2	2060.8	1303.4	181.2	152.8	71.7	103.0
7	Ajri	0.0	0.0	0.0	86.8	60.6	1298.0	1605.8	1332.4	533.2	400.0	0.0	0.0
8	Hosangadi	0.0	0.0	0.0	42.8	366.8	696.0	2207.0	1165.2	699.2	236.3	74.0	0.0
9	Amasebail	0.0	0.0	6.8	0.0	11.4	1129.7	2151.4	1824.6	324.8	191.0	179.8	64.8
10	Bijur	10.8	12.4	0.0	83.6	12.2	1173.0	1747.2	1758.8	640.2	327.0	92.0	112.0

Monthly rain fall over Haladi river basin for the year 2005

Sl. No.	Month/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Vandse	0.0	0.0	0.0	16.4	33.8	908.0	1148.2	887.2	374.8	249.0	24.2	11.0
2	Kundapura	0.0	0.0	0.0	61.6	149.0	1069.8	1547.2	1029.0	22.0	43.6	44.0	0.0
3	Ulluru	0.0	0.0	0.0	10.2	288.8	774.6	1760.2	797.2	406.8	176.0	53.0	0.0
4	S. Narayana	0.0	0.0	68.4	128.2	49.0	1334.8	3062.6	2456.2	444.8	450.2	185.0	111.0
5	Albadi-Ardi	0.0	0.0	0.0	61.6	149.0	1069.8	1547.2	1029.0	22.0	43.6	44.0	0.0
6	Ampar	0.0	0.0	0.0	0.0	146.8	1136.4	1456.0	541.6	387.0	282.6	106.6	3.2
7	Ajri	0.0	0.0	3.2	62.8	63.8	1277.0	2062.4	1496.7	265.2	290.9	181.6	164.6
8	Hosangadi	0.0	0.0	0.0	86.8	60.6	1298.0	1605.8	1332.4	533.2	400.0	0.0	0.0
9	Amasebail	0.0	0.0	0.0	55.2	194.0	1238.5	1547.4	1273.2	124.7	176.0	67.1	0.0
10	Bijur	0.0	0.0	68.4	128.2	49.0	1334.8	2062.6	2456.2	444.8	450.2	185.0	111.0

APPENDIX- III

Annual rainfall data

Annual Rain fall over Haladi River Basin in mm

Sl. No.	Year/Station	1991	1992	1993	1994	1995	1996	1997
1	Vandse	4398.6	4754.8	3853.1	4790.6	3853.4	2820	4297
2	Kundapura	4208.5	4544.1	3694.9	4501.8	3885	2852.8	4366.8
3	Ulluru	3726.2	4174.7	3645.5	4360.3	3666.2	3091.1	3736.4
4	S. Narayana	5097.4	4676.1	5422.9	4495.8	6833.2	4807.1	4592.9
5	Albadi-Ardi	4116.7	4678.2	6678.6	5208.9	4501	3881.6	4635.1
6	Ampar	4671.9	4768.5	3813	4790.6	3518.1	3931.6	3844.7
7	Ajri	4125	4447	4001.8	6200.6	3792	6028.6	7723.8
8	Hosangadi	4795.2	5626.3	4947.6	6893.9	4026.1	4450.8	5494.9
9	Amasebail	4347.8	5434.6	4426.8	9052	5958.1	6118.4	6483.1
10	Bijur	4481.9	4923.2	3813	5830.6	5276.1	3967	5073.7
	Average	4396.9	4802.8	4429.7	5612.5	4530.9	4194.9	5024.8

Annual Rain Fall over Haladi River Basin in mm

Sl. No.	Year/Station	1998	1999	2000	2001	2002	2003	2004	2005	Average
1	Vandse	3961.8	5138.6	4532.8	6058.4	4657.3	3699.2	6122	3652.6	4439.3
2	Kundapura	5808	6192	5738.4	7309	5499.4	4940.2	5884.3	3966.2	4892.8
3	Ulluru	5868.2	6205.8	6260	4229.4	4969.8	4307.2	6344	4266.8	4590.1
4	S. Narayana	5411.1	5945.1	7057.3	6454.4	8465.6	6338	5969.2	8290.2	5990.4
5	Albadi-Ardi	5273.8	6602.1	5419.2	7263.1	5036.7	4555.9	5971	3966.2	5185.9
6	Ampar	4176.6	5243.2	4416.6	5239	4668.7	4105	5034.5	4060.2	4418.8
7	Ajri	3867.9	5252.5	6311.6	5437.7	7299.6	5487.3	5316.8	5868.2	5410.7
8	Hosangadi	3561.2	3790.6	5252.5	6311.6	5437.7	7299.6	5487.3	5316.8	5246.1
9	Amasebail	5808	6192	5738.4	7309	5499.4	4940.2	5884.3	4676.1	5857.9
10	Bijur	4750.6	5945.1	7057.3	6454.4	7465.6	6338	5969.2	7290.2	5642.4
	Average	4848.7	5650.7	5778.4	6206.6	5900	5201.1	5798.3	5135.4	5167.4