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Influence of Landscape Dynamics on Hydrological Regime in Central Western Ghats

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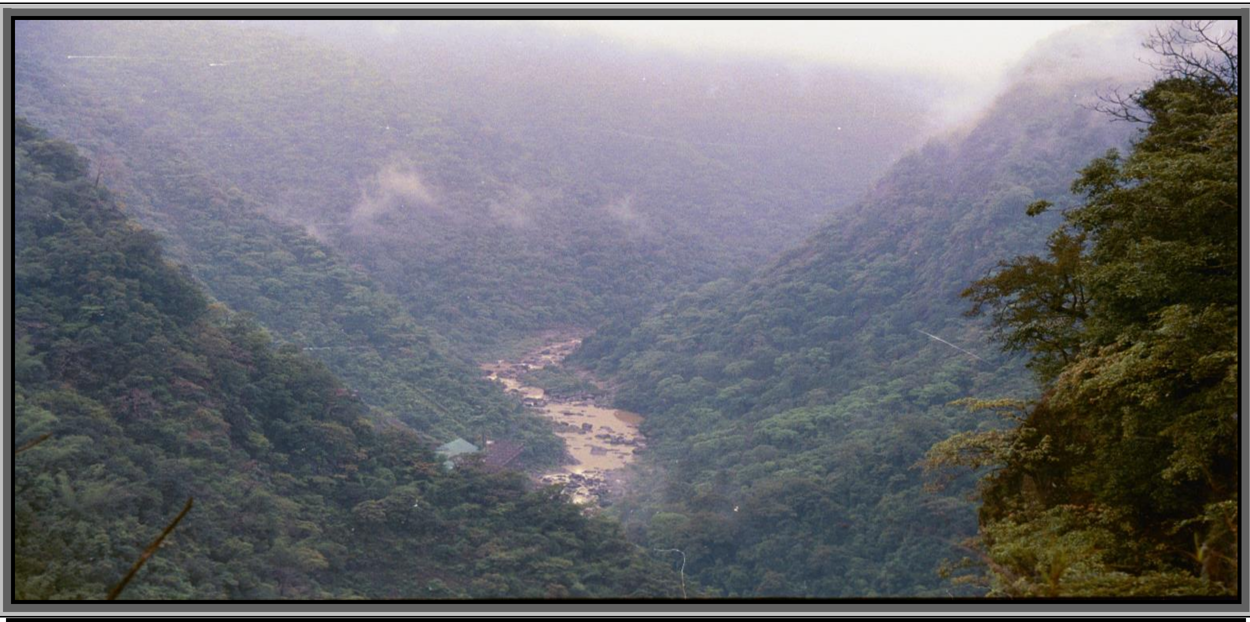

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Influence of Landscape Dynamics in a River Basin on Hydrological Regime

Summary

Pristine forests rich in flora and fauna are being cleared especially in the tropical areas to meet the growing demand of burgeoning populations. This has given rise to concerns about land use/land cover changes with the realization that land processes influence climate. Studies have further indicated its impact on the hydrological cycle and thus the water budget of a region. The present study is an attempt to quantify the hydrological components using Sharavathi river basin as a case study and to determine its changes over time using remote sensing and GIS. Western Ghats region is species rich with a fair degree of endemism in both flora and fauna. A dam was put across the Sharavathi River in 1964 for harnessing electricity. Over the years there have been changes in the land use/land cover owing partly due to unplanned anthropogenic activities subsequent to setting up of the dam. This study explores and quantifies the hydrological parameters that have altered due to large scale land use and land cover changes. In this regard, satellite data has offered excellent inputs to monitor dynamic changes through repetitive, synoptic and accurate information of the changes in a river basin. It also provided a means of observing hydrological state variables over large areas, which was useful in parameter estimation of hydrologic models. GIS offered means for merging various spatial themes (data layers) that was useful in interpretation, analysis and change detection of spatial structures and objects. Studies reveal the linkages among variables such as land use, hydrology and ecology. Regions with significant forest cover and low anthropogenic activities resulted in lesser runoff, higher recharge and thus higher yield to stream resulting in perennial streams whereas regions with poor forest cover and higher anthropogenic activities showed higher runoff, significant reduction of recharge and thus lower yield to streams resulting in ephemeral streams.

Keywords: Hydrology, Western Ghats, Land use, Land cover, Biodiversity

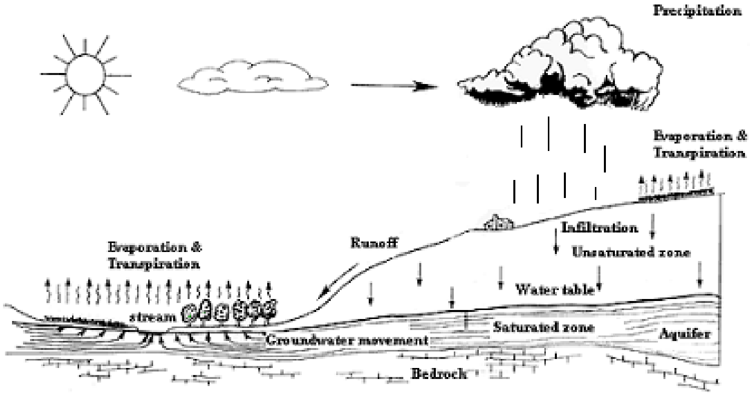
1.0 Introduction

There has been a growing need to study, understand and quantify the impact of major land use changes on hydrologic regime, in terms of both water quantity and quality. Land use influences catchment hydrological responses by partitioning rainfall between return flow to the atmosphere as evaporation and transpiration ("green water") and flow to aquifers and rivers ("blue water") (Hope et al. 2003). Increasing attention is now being paid to understanding the dynamic inter-relationships between "green" and "blue" water, as these are considered to underpin essential terrestrial and aquatic ecosystem services (Falkenmark, 2003). FAO suggests that almost all "green" water and a large proportion of "blue" water are needed to sustain ecosystem structures and functions, and maintain sustainable water supplies. For example, conversion of grassland and forests to pasture, plantations and arable land alters the hydrological response of a catchment by modifying the various physical processes such as infiltration rates, evaporation and runoff.

Developing countries in the tropics are facing threats of rapid deforestation due to unplanned developmental activities based on ad-hoc approaches and also due to policies and laws that considers forest as national resource to be fully exploited. Anthropogenic activities coupled with skewed policies have resulted in the disappearance of pristine forests and wetlands in the form of logging, afforestation by plantation trees, dam constructions, and conversion of lands for other uses. Agricultural activities have led to a widespread deterioration in soil structures, a process that causes soil sealing and crusting, and reduced rates of infiltration and soil storage. Various studies (Sikka, et al. 1998, Van Lill et al. 1980; Scott and Lesch, 1997) provide evidence to support the supposition that land use changes, involving conversion of natural forests to other land uses agriculture (enhanced grazing pressure and intensive cultivation practices) and plantation (widespread acacia and eucalyptus planting) have led to soil compaction, reduced infiltration, groundwater recharge and discharge, and rapid and excessive runoff. These structural changes in the ecosystem will influence the functional aspects namely hydrology, bio-geo chemical cycles and nutrient cycling. These are evident in many regions in the form of conversion of perennial streams to seasonal and disappearance of water bodies leading to a serious water crisis. Thus, it is imperative to understand the causal factors responsible for changes in order to improve the hydrologic regime in a region. It has been observed that the hydrological variables are complexly related with the vegetation present in the catchment. The presence or absence of vegetation has a strong impact on the hydrological cycle. This requires understanding of hydrological components and its relation to the land use/land cover dynamics. The reactions or the results are termed hydrological response and depends on the interplay between climatic, geological and land use variables. Hydrological responses can be understood by analysing land use changes using temporal remote sensing data and traditional approaches. Traditional approaches considers spatial variability by dividing a basin into smaller geographical units such as sub-basins, terrain-based units, land cover classes, or elevation zones on which hydrological model computations are made, and by aggregating the results to provide a simulation for the basin as a whole. Modelling is thus simplified because areas of the catchment within these units are assumed to behave similarly in terms of their hydrological response. Remote sensing and GIS techniques have been used to determine some of the model parameters. The main applications of remote sensing in hydrology are to 1) determine watershed geometry, drainage network and other map type information for hydrological models 2) provide input data such as land use/land cover, soil moisture, surface temperature etc. GIS on the other hand allows for the combination of spatial data such as topography, soil maps and hydrologic variables such as rainfall distribution or soil moisture. But prior to modelling, it is necessary to get a complete understanding of the hydrological cycle operating in a river basin. The following section deals with the description of the cycle and the water balance equation.

1.1. **Hydrological Cycle:** Water is constantly circulated between earth and atmosphere. This global circulation is accomplished by the heat of the sun and the pull of gravity. Precipitation is water released from the atmosphere in the form of rain, snow, sleet or hail. During precipitation, some of the moisture is evaporated back into the atmosphere before reaching the ground. Some precipitation is intercepted by plants, a part of it infiltrates the ground, and the remainder flows off the land into lakes, rivers or oceans. Some may be directly evaporated if adequate transfer from the soil to the surface is maintained. This occurs where a high groundwater table (free water surface) is within the limits of capillary transport to the ground surface. Water that is infiltrated replenishes soil moisture deficiencies and enters storage provided in groundwater reservoirs, which in turn maintains dry weather stream flow. Vegetation using water from soil and groundwater returns the infiltrated water into the atmosphere by transpiration. Water that is stored in depressions will eventually evaporate or infiltrate into the ground. Surface runoff reaches minor channels (gullies, rivulets and the like), flows to major streams and rivers and finally reaches the ocean. Along the course of a stream, evaporation and infiltration can also occur (Viessman et al., 1989).

Figure 1.1: Hydrological Cycle



Even though the hydrological cycle is continuous in nature, it is not uniform throughout the world: the residence time of water varies often dramatically among different portions of the cycle. Fig.1.1 depicts a hydrological cycle. In addition to the variability in residence time, the processes associated with the hydrologic cycle are not evenly distributed throughout the world.

The hydrological cycle is defined as a closed system whereby there is no mass or energy created nor lost within it. In this case, the mass under consideration is water. This can be represented by an equation, which is normally termed as the water balance equation. The basic form of the equation is as follows:

$$I = O \pm \Delta S \tag{1.1}$$

where,

I – input, O-output and ΔS –change in storage

or

$$P \pm R \pm ET \pm E \pm GWR \pm GWD \pm \Delta S \pm Q = 0 \tag{1.2}$$

Where,

P –precipitation, R- runoff, T- transpiration from vegetation E – evaporation from open water (reservoirs or lakes) and soil, GWR- groundwater recharge, GWD- groundwater discharge; Q – runoff, ΔS- change in storage.

1.2 Water: Soil and Plant Interactions: Water is one of the most common and most important substances on the earth's surface. It is essential for the existence of life, and the kinds and amounts of vegetation occurring on the various parts of the earth's surface depend more on the quantity of water available than on any other single environmental factor. It is important quantitatively as well as qualitatively, constituting 80-90% of the fresh weight of most herbaceous plant parts and over 50% of the fresh weight of woody plants. The ecological importance of water is the result of its physiological importance (Kramer, 1983). The only way in which an environmental factor such as water can affect plant growth is by physiological processes. Figure 1.2 describes the quantity and quality of plant growth controlled by hereditary potentialities and environmental factors, operating through the internal processes and conditions of plants.

1.2.1 Plant Water Use: Plants use water in biochemical reactions, as a solvent and to maintain turgor, but most of the water taken up by plants is transpired to the atmosphere. Globally, plants recycle more than half of the ~110 000 km^3/yr of precipitation that falls on land each year. Transpired water moves from soil to plant to atmosphere along a continuum of increasingly negative water potential, flowing 'downhill' thermodynamically but 'uphill' physically from root to shoot.

Figure 1.2: Hereditary Potentialities and Environmental Factors Operating through Plants

Hereditary Potentialities
1. Depth and extent of root systems
2. Size, shape and total area of leaves and ratio of internal to external surface
3. Number, location and behavior of stomata

Environmental factors
1. Soil-texture, structure, depth, chemical composition, pH, water holding capacity, hydraulic conductivity
2. Atmospheric- amount and distribution of precipitation
3. Ratio of precipitation to evaporation
4. Radiant energy, wind, vapour pressure and other factors affecting evaporation and transpiration

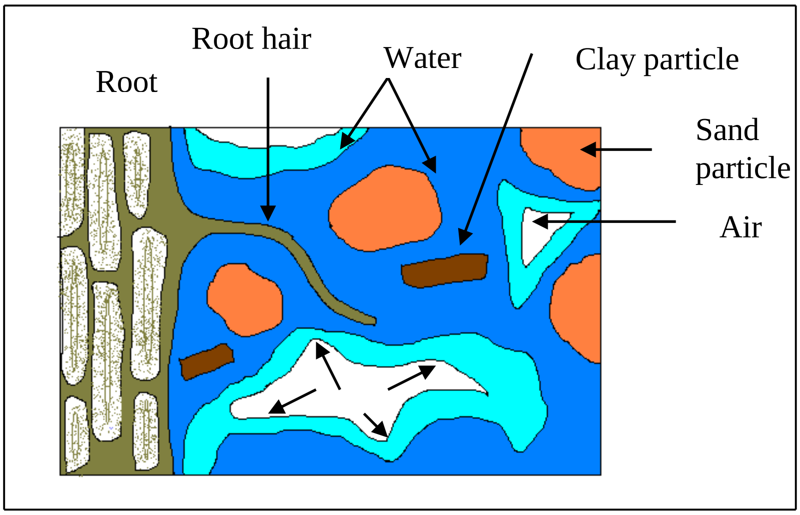
Plant Processes and Conditions
1. Water absorption
2. Ascent of sap
3. Transpiration
4. Internal water balance reflected in water potential, turgidity, stomatal openings and cell enlargements
5. Effects on photosynthesis, carbohydrate and nitrogen metabolism and other metabolic processes

Quantity and Quality of Growth
1. Size of cells, organs and plants
2. Dry weight, succulence, kinds and amounts of various amounts of various compounds and accumulated
3. Root-shoot ratio
4. Vegetative versus reproductive growth

Plants get water from the soil through roots. This water then passes through the stem, leaves and into the atmosphere. The following sections will briefly describe each process.

Movement through Soil: Root hairs make intimate contact with soil particles and greatly amplify the surface area that can be used for water absorption by the plant (Taiz and Zeiger, 2002). Figure 1.3 depicts the contact surfaces between root hair and soil. Soil is a mixture of sand, clay and silt, water, dissolved solutes and air and sometimes organic matter. As the plant adsorbs water, the soil solution recedes into smaller pores and interstices between the soil particles. At the air-water interface, this recession causes the surface of the soil solution to develop concave menisci and brings the solution into tension. As more water is removed from soil, the menisci become more acute resulting in greater tension (negative pressures). As the water filled pore spaces are interconnected, water moves to the root surface by bulk flow through these channels down a pressure gradient.

Figure 1.3: Root-Soil Interface



Movement of water through plants can be divided into 3 parts viz. roots, stem and leaves

Movement through Roots, Stem and Leaves: Water moves through the root by two paths:

- Symplast pathway: It consists of the living cytoplasm of the cells in the root (10%). Water is absorbed into the root hair cells by osmosis, due to low water potential of cell than the water in the soil. Water then diffuses from the epidermis through the root to the xylem down a water potential gradient.

- Apoplast pathway: It consists of the cell walls between cells (90%). The cell walls are quite thick and open to water diffusion through cell walls without having to cross any cell membranes by osmosis. However, the apoplast pathway stops at the endodermis because of the waterproof casparian strip, which seals the cell walls. At this point water has to cross the cell membrane by osmosis and enter the symplast. This allows the plant to have some control over the uptake of water into the xylem.

The main pathway for longitudinal flow in the plant stem is the xylem. The xylem vessels form continuous pipes from the roots to the leaves. The driving force for the movement in these vessels is transpiration in the leaves. This causes low pressure in the leaves, so water is sucked up the stem to replace the lost water. From the xylem, water is drawn into the cells of leaf called mesophyll and along the cell walls. The mesophyll cells within the leaf are in direct contact with the atmosphere through an extensive system of intercellular spaces. The moisture on the surface of the mesophyll cells vapourises and escapes from the leaves through stomata. Each stoma is controlled by two guard cells that "open" and "close" the pore. When water is abundant, stomata remains open during the day when the plant needs sufficient carbon dioxide for photosynthesis and closed at night. When soil water is less abundant, the stomata will remain closed on a sunny morning. By keeping its stomata closed in dry conditions, the plant avoids dehydration. Figure 1.4 depicts the transverse section of a leaf showing movement of water.

1.2.2 Water and Soil: The water content of a soil is usually stated as the amount of water lost when the soil is dried at 105^{0}C expressed either as the weight of water per unit weight of soil or as the volume of water per unit volume of soil. Terms used to describe the water content are field capacity (water content after downward drainage of gravitational water has become very slow and has become relatively stable), wilting point (soil water content at which plant remain wilted unless water is added to the soil) and available water capacity (amount of water retained in a soil between field capacity and permanent wilting point).

Figure 1.4: Transverse Section (Movement of Water from Leaf to Air)

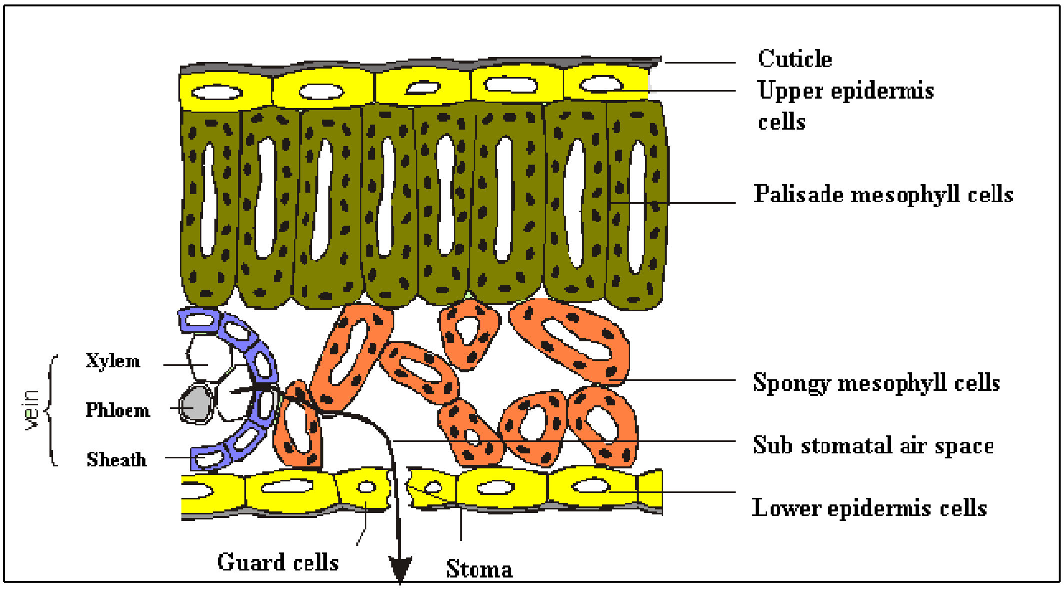


Table 1.1 below lists the field capacity, wilting point and water holding capacity of different soil textures.

Table 1.1: Typical Values for Soil Water Parameters by Texture

Texture class	Field capacity (%)	Wilting point (%)	Available capacity (%)
Sand	12	4	8
Loamy sand	14	6	8
Sandy loam	23	1	13
Loam	26	12	14
Silt loam	3	15	15
Silt	32	15	17
Silt clay loam	34	19	15
Silty clay	36	21	15
Clay	36	21	15

The next section will deal with the structure of a tropical forest and an individual tree and the important hydrological functions of each.

1.2.3 Hydrological and Other Functions of Tropical Trees: Some hydrological characteristics of tropical trees and their hydraulic functions are discussed below:

Leaves: Compound leaves are common in tropical forests. Leaves or leaflets vary in size, shape, texture and chemical and physiological ways. Mature leaves in the lowland forests are generally 7-13 cm in length, somewhat elliptical in shape and of an entire, sclerophyllous type (leathery evergreen leaves with a thick waxy cuticle to conserve water during the long, dry summer). They become progressively smaller at higher elevations.

The leaves of the understorey trees often develop an extended drip tip or acumen, which allows water to drain quickly from the surface. This may increase photosynthetic efficiency of the leaf by increasing light absorption and transpiration rates, or by discouraging the growth of algae and lichens. The leaves are smaller, more leathery in texture and have less pronounced drip tips in the taller trees. The varying leaf types in tropical forests may result from increased water stress in the upper canopy caused by higher insolation, stronger winds and periodic droughts.

Roots: They are important life support system for plants and thus for all life in terrestrial ecosystems. Some of the functions of roots are given below:

- Carbon pumps that feed soil organisms and contribute to soil organic matter
- Storage organs
- A sensor network that helps regulate plant growth
- Absorptive network for limiting soil resources of water and nutrients

- Mechanical structures that support plants, strengthen soil, construct channels, break rocks, etc.
- Hydraulic conduits that redistribute soil water and nutrients
- Habitats for mycorrhizal fungi and rhizosphere organisms

The first root to emerge from a seed is the radicle or primary root. In most dicots, the radicle enlarges and forms a prominent taproot. Smaller branches or lateral roots grow from the taproot. It functions as food reserves such as carbohydrate storage or for reaching water deep in the ground. Taproots usually control growth and development of branch roots. Taproots grow longer than branch roots. Compared to this, most monocots have a fibrous root system consisting of an extensive mass of similarly sized roots. In these plants, the radicle is short lived and roots are adventitious, which means they can grow from plant organs other than roots e.g. stems.

A tree, which has a deep and thick taproot immediately beneath the trunk, can transmit forces directly into the ground. However, many trees have their largest roots radiating from the base of the trunk in the upper layers of the soil, creating a shallow plate of woody roots. These woody roots eventually form buttresses to prevent the tree from uprooting when there is wind loading. Appendix I give the rooting depths of some tree species in Western Ghats.

Tree root systems can be divided based on diameter into two portions namely fine and coarse. Coarse roots are generally woody and provide a mechanical and conductive service to the tree. Water and minerals are taken up by the fine roots that separate through the mineral soil and sometimes litter layer as well.

The effectiveness of water uptake by trees depends on the effectiveness with which soil is exploited by roots, contact between roots and soil and the hydraulic potential gradients between roots and soil (Landsberg and Gower, 1997). Tree root architecture varies between species and is affected by soil type and growing conditions. From a water collection and transport point of view, the optimum system will be a considerable root biomass, with high root length per unit volume of soil, in the surface layers of the soil to harvest as much water as possible, with larger more, widely spaced roots deeper in the soil. These will absorb more water slowly, but the deeper soil layers do not dry as fast as the surface layers; therefore deep roots are likely to play an important role in maintaining water uptake and transpiration during dry periods. Soil textural characteristics and hard pans can greatly alter the development and vertical distribution of large roots.

Belowground root system architecture of forests can influence patterns of soil water utilization by trees and ultimately canopy transpiration. Deeply rooted trees and other plants can lift water hydraulically from moist soil horizons several meters below ground to drier portions of the soil profile where it is released into the soil (Brooks et al. 2002). The process is considered passive, as it requires only a water potential gradient from moist soil layers through the root xylem to dry soil layers, and a relatively low resistance to reverse flow from the roots. Although the direction of water movement is typically upward, towards drier, shallow soil layers, measurements of sap flow in taproots and lateral roots of trees have demonstrated that roots can also redistribute water either downward or laterally from moist surface soils to drier regions of soil (Burgess et al. 1998, 2001; Sakuratani et al. 1999; Smith et al. 1999). Since it can be bidirectional and is apparently passive, “hydraulic redistribution” has been proposed as a more comprehensive term than “hydraulic lift” to describe the phenomenon (Burgess et al. 1998). Hydraulic redistribution usually occurs at night when transpiration has diminished sufficiently to allow the water potential of the roots to exceed that of the drier portions of the soil profile (Brooks et al. 2002).

The above sections dealt with a tree, which is a higher plant and its hydrological characteristics. The next section discusses the water need of an agricultural crop.

1.2.4 Crop Water Need: The water need of a crop consists of transpiration plus evaporation. Therefore, the crop water need is also called "evapotranspiration". When the plants are very small evaporation will be more important than transpiration and when the plants are fully grown, transpiration is more important than the evaporation. Table 1.2 summarises the effect of climatic factor on crop water needs.

A certain crop grown in a sunny and hot climate needs per day more water than the same crop grown in a cloudy and cooler climate. There are, however - apart from sunshine and temperature - other climatic factors, which influence the crop water, need. These factors are humidity and wind speed. When it is dry, the crop water needs are higher than when it is humid. In windy climates, the crops will use more water than in calm climates.

Table 1.2: Effect of Major Climatic Factors on Crop Water Needs

Climatic factor	**Crop water need**	
	High	**Low**
Solar energy	Sunny (no clouds)	Cloudy (no sun)
Temperature	Hot	Cool
Humidity	Dry	Humid
Wind speed	Windy	Little wind

Table 1.3 gives the seasonal crop water needs of certain crops.

Table 1.3: Approximate Values of Seasonal Crop Water Needs

Crop	Crop water need (mm/total growing period)
Alfalfa	800-1600
Tomato	400-800
Cotton	700-1300
Potato	500-700
Pepper	600-900
Sugarcane	1500-2500
Rice (paddy)	450-700

Percolation is more in submerged rice lands. In lighter soils, such losses amount to about 60% percent of total water requirement. Soil compaction and puddling is done to reduce these losses. Transpiration accounts for about 40%. Evaporation depends upon the climatic factors and range from 20-40%.

1.3 Land use/Land cover Change and its Effect on the Hydrological Cycle

Land cover is the observed physical cover at a given location and time as might be seen on the ground or from remote sensing. This includes the vegetation (natural or planted) and human constructions (buildings etc.), which cover the earth's surface. Land use is, in part a description of function, the purpose for which the land is being used. Land use and cover changes are the result of many interacting processes. Each of these processes operate over a range of spatial, temporal, quantitative, or analytical dimension used by scientists to measure and study objects and processes.

Land-use and land-cover are linked to climate and weather in complex ways. Key links between changes in land cover and climate include the exchange of greenhouse gases (such as water vapor, carbon dioxide, methane, and nitrous oxide) between land surface and atmosphere, the radiation (both short and longwave) balance of land surface, the exchange of sensible heat between land surface and atmosphere, and roughness of the land surface and its uptake of momentum from atmosphere. Artificial changes to the natural cycle of water have produced changes in aquatic, riparian, wetland habitats and agricultural landscape. These interferences have had both positive and negative impacts on the problems that they were intended to solve. Some of these activities have greatly constrained the degree of interactions between the river channel and the associated floodplain with catastrophic effects on biodiversity.

1.4 Use of Remote Sensing and GIS Techniques in Hydrology

Remote sensing uses measurements of the electromagnetic spectrum to characterize the landscape or infer properties of it. There are 3 characteristics of remote sensing that make it a potentially very powerful tool for advancing hydrologic sciences (Schultz and Engman, 2000).

- Measuring system states- Thermal infrared and microwave remote sensing due to their unique responses to surface properties important to hydrology, such as surface temperature, soil moisture and snow water content, have the capability to measure these system states directly.
- Area versus point data- Use of data representing an area in which the spatial variability of specific parameters of the area have been integrated may help provide one of the keys to understand scaling and scale interdependence in hydrologic systems.
- Temporal data- Remote sensing data from satellite platform can provide unique time series data for hydrologic use. The actual frequency of observation can vary from continuous to once every two weeks or so, depending upon the sensors and type of orbit. Temporal data may provide means for imparting hydrologic interpretation to certain observations. For example, observing the time changes in soil moisture may provide information on soil types and even hydraulic properties such as hydraulic conductivity.

A major focus of remote sensing research in hydrology has been to develop approaches for estimating hydro-meteorological states and fluxes. The primary set of state variables include land surface temperature, near surface soil moisture, snow cover/water equivalent, water quality, water quantity, landscape roughness, land use and vegetation cover (Schmugge at al., 2002). The hydrometerological fluxes are primarily soil evaporation and plant transpiration or evapotranspiration and snow melt runoff.

Remote sensing data has been used to understand the vegetation dynamics, which are acquired by sensors on various remote platforms, such as multi spectral and thermal scanners and active microwave (radar) imaging systems. Since satellite observations are available since the early 1970s, it is possible to relate trends such as vegetation cover densities to stream flow.

The land cover maps derived by remote sensing are the basis of hydrologic response units for modelling. Effective utilization of spatial data involves the existence of an efficient, geographic handling and processing system that can transform the data into usable information. A major tool for handling spatial data is geographic information system (GIS). Data analysis and spatial modeling capability are the most important characteristics of a GIS (Schultz and Engman, 2000).

Geographic information systems deal with information about features that is referenced by a geographical location. These systems are capable of handling both locational data and attribute data about such features through database management system (DBMS). Geographic information systems are useful in hydrological studies as it allows the integration of a combination of spatial data such as soil, topography, hydrologic variables such as soil moisture.

1.5 Objectives

The objectives of the study are:

i). Quantification of hydrologic components of Sharavathi River Basin, Western Ghats using Remote Sensing and GIS.

ii). Study the effect of land use/land cover changes on hydrologic components.

Significance of the Study

The Western Ghats comprise the mountain range that runs along the western coast of India, from the Vindhya-Satpura ranges in the north to the southern tip. This range intercepts the moisture laden winds of the southwest monsoon thereby determining the climate and vegetation of the southern peninsula. The steep gradients of altitude, aspect and rainfall make the region ecologically rich in flora and fauna.

There is a great variety of vegetation all along the Ghats: scrub jungles, grassland along the lower altitudes, dry and moist deciduous forests, and semi-evergreen and evergreen forests. Out of the 13,500 species of flowering plants in India, 4500 are found in the Western Ghats and of these 742 are found in Sharavathi river basin (Ramachandra et al. 2007). Climax vegetation of the wet tract consists of *Cullenia*, *Persea*, *Diptercarpus*, *Diospyros* and *Memecylon*. The deciduous forest tract is dominated by *Terminalia*, *Lagerstroemia*, *Xylia*, *Tectona* and *Anogeissus*. The region also contains potentially valuable spices and fruits such as wild pepper varieties, cardamom, mango, jackfruit and other widely cultivated plants. There is an equal diversity of animal and bird life. Noticeable reptile fauna in the evergreen forests include burrowing snakes (uropeltids) (Gadgil & Meher-Homji, 1990) and the king cobra and among amphibians, the limbless frog (caecilians). The Nilgiri langur, lion-tailed macaque, Nilgiri tahr and Malabar large spotted civet are some examples of endangered endemic mammals belonging to this area.

Sharavathi river valley lies in the Central Western Ghats and represents an area of 2985 km^2. Sharavathi is a west flowing river originating at Ambuthirtha in Shimoga district and during its course, falls from a height of around 253 m at the famed Jog Falls. It flows through Honnavar and eventually into the Arabian Sea.

Karnataka Power Cooperation (KPCL) set up a dam across Sharavathi in 1964 known as Linganamakki Dam to harness electricity, which has divided the river basin into upstream and downstream. The construction of this dam has made considerable hydrological and ecological alterations in the river basin. The dam resulted in the submergence of wetlands and forest areas of unmeasured biodiversity. The effects are particularly seen in the upstream of the river basin where the dam submerged many villages and forests to give rise to small isolated islands. These island and surrounding areas have created niches for 150 species of birds, 145 species of butterflies and 180 species of beetles along with mammals such as spotted deer, barking deer, civet, leopard and the Indian gaur.

The reservoir has provided further impetus to farmers and plantation agriculturists. Large tracts of forestlands have been cleared for paddy cultivation and plantation trees such as areca and acacia. Apart from these, vast tracts of natural vegetation has been cleared and replaced with monoculture plantations of *Acacia auriculiformis*, Eucalyptus sp. and *Tectona grandis*. As a result of these activities, there is evidence of changes in runoff and stream flow regimes. There are instances where wells have 'run dry' in the wet spots of the basin, mainly because percolation of rainwater into the ground has decreased due to deforestation. Studies are thus required to quantify the hydrological responses in order to gain an understanding of the effect of anthropogenic activities on the hydrological components and thus the vegetation of study area.

2.0 Review of Literature

This section presents a review of the major components in the hydrological cycle along with their conventional and remote sensing measurement techniques.

Precipitation: It is the principal component of the hydrological cycle, and as such is of primary importance in hydrology. The form and quantity of precipitation are influenced by static and dynamic factors. Static influences are those that do not vary between storm events such as aspect and slope (Davie, 2003). The influence of aspect plays an important part in the distribution of precipitation throughout a catchment (Davie, 2003). Aspect refers to the direction in which the slope of a mountain faces. In Western Ghats, the predominant source of rainfall is through monsoons arriving from the west. Slopes with aspects facing away from the predominant weather patterns will receive less rainfall than their opposites. The influence of slope is only relevant at a very small scale. Dynamic influences are those that changes and are caused by the variation in the weather and the variation and type of vegetation. Weather patterns influence precipitation especially on a global scale. Solar energy is the primary driver for weather. Consequently, all motion in the atmosphere and ocean is a result of distribution of heating and cooling around the earth. Monsoon rain and winds are the result of such heating patterns. Another important dynamic influence is vegetation such as forests. Forests create additional roughness for air masses moving in the lower atmosphere, slows down their movement and causes turbulence, which leads to the formation of ascending air fluxes, air cooling, cloud formation, and, consequently, greater precipitation on forested areas.

Western Ghats experience two main rainfall seasons. They are:

- South-west monsoon (June-September)
- North east monsoon (October-November)

The Western Ghats is considered an important barrier for the Arabian Sea branch of the monsoon. The moist air currents, which approach the Western Ghats are forced to ascend the mountains. In this process, they shed their moisture in the form of frequent and heavy rains over the Ghats. After ascending, the monsoon winds advance into the Deccan plateau and beyond.

Western Ghats region experiences heavy rainfall but studies have proved that monsoons may not be the only one responsible for it. A westerly stream of air, such as the monsoon does not have sufficient energy to climb the Ghats unless fed by another source. Investigation by Sarkar, (1979) suggests that the Western Ghats may be responsible for about 60% of the observed rainfall and, on rare occasions, even 80%, by forcing the monsoon air to ascend. The peak rainfall occurs on the windward side at a distance of 10 to 12 km from the crest of the Western Ghats. Thus, high rainfalls in the Western Ghats can be attributed to a secondary source of moisture. If this is the case, then the forest cover on this mountain range could have a major role in generating humidity in the air.

Precipitation is one of the most challenging variables to quantify due to its extreme transience and spatial heterogeneity. Remote sensing techniques have made advances in quantifying precipitation using different bands viz. visible and microwave. The following section will review the conventional and remote sensing techniques in estimating rainfall.

Some of the conventional techniques are given in Table 2.1

Table 2.1: Conventional Techniques in Measuring Rainfall

Type of measurement	Method	References
Point measurement	Rain gauge	Mutreja, 1986
Areal measurement	Arithmetic mean	Mutreja, 1986
	Thiessen's polygon	Mutreja, 1986
	Isohyetal	Mutreja, 1986
	Hypsometric	Davie, 2003
	Weather radar	Collier, 2000

In India, the installation and observation of rain gauges throughout the country are controlled by the Indian Meteorological Department and a standard rain gauge called the Symon's gauge is used at almost all the places. Rainfall is measured by either non-recording gauges or recording gauges and 3) weather radars.

Areal measurement of precipitation includes arithmetic average, Thiessen's polygon, isohyetal and hypsometric method. Arithmetic mean method is used if the gauges are uniformly distributed and the topography, flat (Mutreja, 1986). Disadvantages of this method are that it gives poor results when gauges are relatively few and requires a denser network of gauges. Raingauges outside the boundary of the watershed should not be used for arithmetic averaging (Singh, 1992). Thiessen's method attempts to define the area represented by each gauge in order to weigh the effects of non uniform rainfall distribution (Singh, 1992). Thiessen's method is usually more accurate than arithmetic average and gives consistent results when storm means are computed by different people. However, this method has the disadvantage of not accounting for orographic influences and also station weights have to be re-determined whenever rain gauge networks changes. Isohyetal method is generally considered the most accurate method for computing average rainfall over a drainage basin. In this method, topographic influences have been taken into account and the stations outside the basin can also be used. Nevertheless, it is a laborious method and different persons may obtain varying results from the same data. Hypsometric method assumes that the relationship between altitude and rainfall is linear, which is not always the case and warrants exploration before using the technique (Davie, 2003).

Ground based radar offers areal measurements of precipitation from a single location over a large area in near real-time. Both single and mutlipolarisation radars have been used over a range of wavelengths (Collier, 2000). While weather radar does offer a means of making wide area measurements over specific important land and coastal areas, it does not offer a practical method of making measurements over large remote river catchments or oceans. The use of satellite has been investigated to compensate for these difficulties. Meteorological satellites now provide a realistic means to monitor the spatial and temporal distributions of precipitation. Table 2.2 below lists some of the platforms and sensors commonly used to estimate precipitation overland.

Table 2.2: Operational Sensors to Measure Precipitation

Platform	Sensors	Orbit	Resolution
GOES-7 GOES-8 GOES-9	VISSR GOES I-M imager GOES I-M imager	Geostationary	1 km (VIS) and 4 km (IR)
Meteosat-5	Meteosat imager	Geostationary	2.5 km(VIS) and 5 km (IR)
NOAA-12,14	AVHRR	Sun synchronous	1.1 km (VIS/IR)
DMSP F-10,11,13	SSM/I	Sun synchronous	15 km

There is a large number of satellite estimation algorithms documented in literature. For example, 55 algorithms were evaluated in the Third Algorithm Intercomparison Project (AIP-3) of the Global Precipitation Climatology Project (GPCP), including 16 using visible and infra red images, 29 using microwave images and 10 using mixed infrared/microwave images. Table 2.3 gives the estimation methods using visible/infrared and microwave bands. Visible/infrared techniques derive qualitative or quantitative techniques estimates of rainfall from satellite imagery through indirect relationships between solar radiance reflected by clouds (cloud brightness temperatures) and precipitation (Collier, 2000). However, relationships derived using life history and cloud indexing techniques for a given region and a given time period may not be valid for a different location and/or season. Other problems include difficulties in defining rain/no rain boundaries and inability to cope with rainfall patterns at the meso or local scales. RAINSAT is a supervised classification algorithm, which is trained to identify areas of precipitation from a combination of visible and infrared imagery. The advantage of this method is that at night since visible imagery is unavailable it can revert to a pure infrared technique.

Microwaves on the other hand have great potential for measuring precipitation since the microwave radiation is directly related to the raindrops. Measurement of rainfall using passive microwaves falls into two categories: by emission/absorption and by scattering, depending on the particular effect used to detect precipitation. With the emission/absorption approach, rainfall is observed by the emission of thermal energy by the raindrops against a cold uniform background. A number of algorithms have been developed to estimate the precipitation using microwaves such as GSCAT, Bristol algorithm and Hydrometer profile retrieval algorithms.

Table 2.3: Rainfall Estimation Methods Using Various Spectral Bands

Estimation methods	**Spectral bands**	**References**
Life history method	Visible/infrared	Doneaud et al. 1984
Cloud indexing technique	Visible/infrared	Richard and Arkin, 1981
GOES precipitation index	Visible/infrared	Arkin and Meisner, 1987
Negri-Adler Wetzel technique	Visible/infrared	Negri et al. 1984
Convective stratiform technique	Visible/infrared	Adler and Negri, 1988
RAINSAT	Visible/infrared	Hogg, 1990
SRL scattering index	Microwave	Grody, 1991
Goddard Scattering algorithm (GSCAT)	Microwave	Adler et al. 1994
Bristol algorithm	Microwave	Spencer et al. 1989
Hydrometeor profile retrieval algorithms	Microwave	Kummerow and Giglio, 1994a & b

Interception: Interception constitutes a significant portion of the incident precipitation in certain watersheds (Calder 1977) and has a significant influence on the energy and water budgets at the land surface. The size of interception depends on two variables: the canopy water storage capacity and evaporation during the storm (Gash, 1979). Changes in either will impact the quantity of water available for soil recharge, plant water uptake and the discharge of streams and rivers.

Interception capacity (generally expressed in units of volume per unit area) refers to the maximum volume of water that can be stored on the projected storage area of the vegetation It is influenced by factors such as leaf area index, precipitation intensity, and surface tension forces resulting from leaf surface configuration, liquid viscosity and mechanical activity (Ramirez and Senarath, 2000). It is observed that canopies experience large interception under misty, drizzle- like conditions with light intensities, and small interception under intense precipitation conditions. Rainfall interception loss accounts for 10 to 40% of rainfall entering a forest canopy (Zinke, 1967).

The following discussion on interception by different kind of forests has been adapted from Crockford and Richardson (2000).

Valente et al. (1997) studied interception of a Pinus pinaster plantation and a Eucalyptus globulus plantation in Portugal, with an annual rainfall of 800 mm. Interception values were 17.1% and 10.8% of gross rainfall for the pines and eucalyptus respectively. The interception/LAI ratio for the pines is 6.3 compared with 3.4 for the eucalypt forest, i.e. on a per LAI basis the pine needles intercepted almost twice as much rainfall as the eucalypt leaves. This could be due to the pine needle clusters being able to hold intercepted rainfall more securely than the vertically aligned eucalypt leaves.

Asdak et al. 1998 in a study of rainfall interception in a tropical rainforest (annual rainfall of errors in the estimation of throughfall. It is also seen that interception from rainforest is much higher than temperate forests due to the large intercepting surfaces (leaf and wood).

In an undisturbed Amazon rainforest Lloyd et al. (1988) found interception to be 8.9% of gross rainfall, from 625 days of data. Rainfall for this period was 4804 mm. Stemflow was 1.8% of rainfall.

In a study of two tropical montane rainforests, at different elevations, in Columbia (Veneklaas and Van Ek, 1990), it was found that the forest at higher elevation (3370 m) had higher interception loss than the forest at lower elevation (2115 m). The values were 18.2 and 12.4% respectively. The site at higher elevation site had fewer trees than site at lower elevation site, but were larger. It was stated that the upper canopy at lower elevation was more open than at higher elevation, but total crown cover was greater in the former owing to the presence of smaller sized trees. Herbs and shrubs also dominated the understorey in the low elevation forests. Rainfall at the higher elevation site was less than the low elevation site as well as being of lower intensity and longer duration. This combination of factors would favour greater interception in the forests at higher elevation site. Also, the epiphyte population was greater at this site. As the epiphytes were concentrated in the upper parts of the trees they could enhance interception.

Bruijnzeel and Wiersum, 1987 studied rainfall interception in Acacia *auriculiformis* in West Java, Indonesia and found increase in interception from year 1 (11.2%) and year 2 (17.9%). The reason attributed to this was an increase in biomass- about 20% for basal area and leaf area index (LAI). Stemflow decreased from 7.9% in year 1 to 6.2% in year 2. Thus, change in plant structure such as growth of second order branches particularly on the lower side can increase interception. Some techniques for measuring interception are given below.

Knowledge about the interception processes was first formulised by Horton, (1919). It was a semi-empirical model of rainfall interception, constructed by plotting precipitation against throughfall. Horton's model is considered to be the simplest empirical approach to model interception. Another variant of Horton's model describes interception as a function of canopy storage capacity, evaporative fraction and rainfall (Singh, 1992). It is commonly used in areas where rainfall is high and has been adopted to calculate interception from different kinds of vegetation in the study area. Horton (1919) describes interception as a function of canopy storage capacity C and evaporative fraction (α) and is given by the equation

$$I = C + \alpha P \quad (2.1)$$

Putty and Prasad (2000) have suggested the following canopy storage capacities for Western Ghats.

Table 2.4: C Values for Different Vegetation Types in Western Ghats

Land use	Canopy storage capacity (mm)
Evergreen forest (dense)	4.5-5.5
Deciduous/open forests (plantations)	4-5
Scrub	2.5-3.5
Grass	1.8-2.0
Paddy (valley)	1.8-2

In the classical model of Rutter et al, (1971), canopy was considered to be a single compartment filled by rain and emptied by evaporation and drainage. The canopy water balance was calculated with a time step of one hour. This direct throughfall fraction was assumed to be proportional to the fractional canopy cover (Aston, 1979). The drainage rate was an exponential function of the amount of storage in the canopy. The evaporation rate was calculated from atmospheric data according to Penman (1948).

Other complicated models based on Rutter simulate the atmospheric transport within the horizontal layers of the canopy and calculate the atmospheric transport between these layers. The drainage rate has been set proportional to the rainfall intensity. A recent model considered individual leaves in the canopy as tipping buckets: when the total force, acting on the leaf surface as a result of both the water stored and the raindrop hitting the leaf, was greater than a certain factor, the leaf tipped, and the water storage on the leaf was reduced to a minimum storage. The leaves were ordered in horizontal layers that could be hit by rain with a horizontal component (Xiao et al., 2000).

Interception can also be considered as the function of aboveground biomass (Savabi and Stott, 1994)

$$I = 0.001(3.7\ VE - (1.1 \times 10^{-4}\ VE^2))$$

Where, VE –above ground biomass in kg/m^2

Field measurements have been carried out to determine throughfall and stemflow. Throughfall is variable in most forests and its accurate estimation is quite difficult. It has been measured with a range of devices, from troughs of various sizes, to plastic funnels and standard rain gauges. For collection of stemflow, Crockford and Richardson (1990b) suggests the use of split plastic hose, internal diameter =14mm. It was wrapped around the tree and attached with galvanized iron staples then sealed with neutral silicone sealant.

In current global circulation models land surfaces schemes, interception is described as a function of seasonal leaf area index (LAI) and fractional vegetation cover (Sellers et al. 1986). Viessman et al., 1989 considers interception as a function of leaf area index

$$I = C + LAI \times E \times t$$

where, I – interception; C-canopy storage capacity in mm; LAI –leaf area index;
E – evaporation in mm; t-duration of rainfall in hours

Surface Runoff: It occurs when precipitation moves across the land surface-some of which eventually reaches natural or artificial systems and lakes. Runoff is an important process at the basin or watershed scale, since it can recharge reservoirs and replenish rivers that may subsequently recharge the groundwater. It can also cause erosion and excess runoff that can lead to flooding. Runoff is one of the most important hydrologic variables used in most of the water resources applications. Conventional models for prediction of river discharge require considerable hydrological and meteorological data. Collection of these data is expensive, time consuming and a difficult process.

Robert Horton in the 1930s suggested that storm runoff is often purely surface runoff or overland flow (Hortonian overland flow). Horton put forward the theory that the soil surface acted as a separating surface between surface runoff and subsurface runoff (interflow). However, further studies revealed that this is not often the case and a watershed cannot experience overland flow in the entire area. Hewlett and Hibbert (1967) suggested another mechanism for the occurrence of overland flow. They hypothesised that during a rainfall event all the water infiltrated the surface. Due to a mixture of infiltration and percolation, the water table would rise until in some places it reached the surface. At this stage, overland flow will occur as a mixture of return flow (i.e. water that has been beneath the ground but returns to the surface) and rainfall falling on saturated areas. This type of overland flow is called saturated overland flow and occurs in places where the water table is closest to the surface. The saturated areas immediately adjacent to a stream acted as extended channel networks. This is referred to as the variable source area concept.

Another concept called the partial areas concept states that the entire area within the watershed may not contribute to runoff (Viessman et al., 1989). Precipitation falling on or flowing into depressed or blocked areas can exit only by seepage or evaporation or by transpiration if vegetated. If sufficient rainfall occurs, such areas may overflow and contribute to runoff. Thus, the total area contributing to runoff varies with the intensity and duration of the storm.

Studies in river basins have proved that the processes suggested by Horton and Hewlett and Hibbert hold good. It is also accepted that saturated overland flow is the dominant overland flow occurring in humid midlatitudes and the variable source area concept is considered the most valid when describing storm runoff (Davie, 2003). However, where the infiltration capacity of a soil is low or the rainfall rates are high, Hortonian overland flow occurs. Examples of low infiltration soil include, compacted soil, pavements, roads and hydrophobic soils.

Many methods for estimating runoff exist. Runoff volume or rate estimation involves estimating the amount of rainfall exceeding infiltration and initial abstractions, which must be satisfied before the occurrence of runoff. Infiltration excess runoff can be estimated using different techniques. Conventional and remote sensing techniques are discussed below. Some conventional techniques for estimation of runoff are as follows:

Table 2.5: Conventional Methods in Estimating Runoff

Methods	**References**
Empirical formulae, curves and tables	Raghunath, 1985
Rational method	Raghunath, 1985
Unit hydrograph	Singh, 1992
Geomorphologic instantaneous unit hydrograph (GIUH)	Rodriguez-Iturbe and Valdes (1979)
Geomorphology-based artificial neural network (GANN)	Zhang and Govindaraju (2003)

Several formulae, curves and tables have been developed. The usual form of the equation is either $R = aP+b$ or $R = aP^n$. However, these equations are empirical and derived values are applicable only when the rainfall characteristics and the initial soil moisture conditions are identical to those for which these are derived. Another common method of runoff estimation is the rational approach to obtain the yield of a catchment by assuming a suitable runoff coefficient, which is given in Table 2.6.

Table 2.6: Runoff Coefficients

Type of drainage area	Value of C
Forest	0.1-0.2
Pastures, farms, parks	0.05-0.3
Cultivated or covered with vegetation	0.4-0.6
Residential	0.8-1
Slightly permeable, bare	0.6-0.8

A unit hydrograph results from the direct surface discharge measured at the outlet of drainage area, which produces a unit depth of direct runoff resulting from a unit storm of specified duration.

Rodriguez-Iturbe and Valdes (1979) developed a geomorphologic instantaneous unit hydrograph (GIUH) as the direct runoff response of a watershed to a unit impulse of excess rainfall. This is based on the premise that runoff resulting from rainfall is affected by compositional characteristics of the drainage basin, which can be described by empirical laws of geomorphology (Horton, 1945; Smart, 1972; Strahler, 1957). Zhang and Govindaraju (2003) developed a geomorphology-based artificial neural network (GANN) that combines GIUH theory and artificial neural network (ANNs), resulting in an improved modeling tool of watershed runoff. The geometric nature of a stream network and an ANN have many similarities, suggesting that the geomorphologic properties of a river network may be represented in an explicit fashion in the architecture of an ANN. Chang and Chen (2001) included fuzzy logic along with ANNs to simulate the rainfall-runoff relationship in central Taiwan.

Remote sensing technology can augment the conventional methods to a great extent in rainfall-runoff studies. It can be used to determine runoff values indirectly with the aid of hydrological models. It can be used either as model input (e.g. precipitation in rainfall/runoff modelling) or for the determination of hydrological model parameters. Some of the techniques are explained below.

The Rational Formula can be used to estimate peak runoff rate using a runoff coefficient, which can be obtained through remotely sensed land use data and soils information. It is widely used as a tool for drainage design especially for water conveyance structures and was originally developed for use on watersheds of 80 hectares but has been modified by (Jackson et al., 1976;

Still and Shih, 1985; 1991) for application to larger watersheds, principally by land-cover based area weighting of coefficients.

The USDA Natural Resources Conservation Service-Curve Number (NRCS-CN) combines remotely sensed land use data and soil information to determine soil's abstraction. This method for estimating direct runoff volume has become widely used as a tool for drainage design, particularly for impoundment structures on ungauged watersheds. Although originally designed for use on watersheds of 1,500 ha, it has been modified by some users e.g. Jackson et al., (1976) for application to larger watersheds, principally by land-cover based area weighting of curve numbers.

Other types of runoff models that are not based on land use have been developed such as runoff regression model based on cloud indexing technique. Cloud area and temperature are the satellite variables used to develop a temperature weighted cloud cover index (Schultz and Engman, 2000). This index is then transformed linearly to mean monthly runoff. Rott et al. (1986) also developed a daily runoff model using Meteosat data for a cloud cover index.

Sub Surface Runoff: Field observations in the Western Ghats have shown that in the upper reaches of streams, a significant contribution to runoff is by sub surface flow or pipe flow (called Jala in Kannada). Pipes have been found in several continents and climatic conditions. It occurs in sizes ranging from a few centimeters to more than 20 m. They are commonly but largely erroneously thought to result from the activity of burrowing animals or decay of plant roots, but can also form by subsurface erosion, starting with seepage erosion at the outlet and working backward or erosion of existing macropores and desiccation cracks apart from solution. Study of pipe flow hydrology is hampered by difficulties in measurement and tracing pipe networks. Some pipes can be perennial and others ephemeral.

In the Western Ghats area, valley regions are covered with dense evergreen forests and mountain tops with grass overlain by deep soil. The pipe outlets are near the valley bottoms and the high density of forest vegetation makes it difficult for further exploration. However, models have been developed to take into account varying source area and pipe flow, when applied to large streams in the Western Ghats and suggest that pipe flow contribution to even quick flow during storm periods is significant (Putty and Prasad, 1992; 1994b).

Evapotranspiration: The importance of evapotranspiration within the hydrological cycle depends very much on the amount of water present and the available energy. Available water supply can be from water directly on the surface in a lake, river or pond. In this case, it is open water evaporation. When the water is present in the soil, the water supply becomes more complex (Davie, 2003). As the water is removed from the soil surface and vegetation, it sets up a moisture gradient that will draw water from deeper in the soil towards the surface, but it must overcome the force of gravity and the withholding force exerted by the soil capillaries**.**

In the absence of restrictions due to water availability at the evaporative surface, the amount of radiant energy captured at the earth's surface is the dominant control on regional evaporation rates. The energy available for evaporation, or the energy used in evaporation is balanced by energy from several sources such as solar radiation, sensible heat and soil heat.

Surface albedo (i.e. the proportion of radiation reflected from a surface) is of major importance in determining the absorption of solar energy. Generally albedo decreases for a given vegetation type as the height of the vegetation increases because of internal reflections. Albedo also decreases generally for soil and vegetation as the surface wetness increases (http://www. unu.edu/unupress/unupbooks/80635e/80635E0n.htm). Albedo is the least for evergreen forests and increases in moist deciduous forests, plantations and grasslands/crops.

Charney et al. (1977) have emphasized the role of lower albedo in increasing rainfall in a forested region. Albedo is one of the factors that govern the energy balance of a surface and therefore the rate of evapotranspiration. The total energy (i.e the sum of sensible heat, latent heat and potential energy) imparted to the lower layers of the atmosphere increases as the albedo decreases. The albedo of deserts or dry bare soil is much greater than that of vegetated or forested surfaces, so the net energy imparted to the atmosphere over deserts is less in contrast to a vegetated region where net radiation is converted into both sensible and latent heat. Thus, the air may be cooler over a vegetated region, but its total energy content may be even greater than air over a desert. Eventually, the water evaporated from vegetated region condenses and fall as rain and the released latent heat warms the atmosphere. Therefore, a decrease in albedo causes a slight decrease in large-scale atmospheric temperatures. The more complex the vegetation structure, the greater the trapping of radiation by multiple reflection between leaves and lower the albedo. An increase in albedo reduces the absorption of solar radiation by the ground; consequently, there is less transfer of sensible and latent heat from the ground to the atmosphere. In addition, the intensity of cloud cover diminishes as does the longwave flux from the clouds to the surface of the earth, so that the net absorption at the ground (short and longwave) is decreased. Thus, regions with increased albedo become sinks of energy and the general motion of the atmosphere above such regions is downward. An essential prerequisite for precipitation is upward motion, thus Charney's model provides a basis for deforestation leading to a decrease in rainfall.
(http://www. unu.edu/unupress/unupbooks/80635e/80635E0n.htm).

Transpiration is essentially the same as evaporation except that the surface from which the water molecules escape is not a free water surface (Veihmeyer, 1964). The surface for transpiration is largely in leaves. Some typical canopy transpiration of different vegetation types are given in Table 2.7.

Table 2.7: Canopy Transpiration of Different Vegetation

Vegetation	**Canopy transpiration in mm**	
	Per year or per growing season	**Per day**
Tropical tree plantations	1000-1500	2.5-4
Tropical rainforests of the lowlands	900-2000	2.5-4
Tropical montane forests	500-850	2.5-4
Eucalyptus stands	700-800	6-7
Deciduous forests of the temperate zone	300-600	2.5-4.5
Prairies and savannas	400-500	4-6
Meadows and pasture	250-400	4-6

Source: Larcher, 2003

Water for evapotranspiration from land is supplied mainly by the soil, and in relatively mesic systems, most water leaves the soil through plant roots and out of plant canopies, rather than by direct evaporation at the soil surface (Chahine 1992).

Plant root systems show a remarkable ability to adapt to soil depth and to changes in availability of water and nutrients and the chemical properties (e.g., salinity) in soils. Plant roots transfer water between soil layers of different water potential thereby significantly affecting the distribution and availability of water in the soil profile (Burgess et al., 1998). The availability of water to individual plants depends in part on local climatic and edaphic factors and also on the depth, lateral spread and degree of overlap of plant root systems. Actual water use also depends on plant vascular architecture and on the balance of above- and below-ground plant dimensions (West *et al*. 1999). The zone of influence of trees is generally related to the extent of their root growth. The lateral spread of roots is typically 2 to 4 times the height of the tree. For most tree species, 80% of roots are found in the upper 30 cm of soil. Most of the remaining 20% of roots are typically found within the top 1.0 to 1.5 metres of soil, with some growing to 2.0 metres, and less frequently to as deep as 3.0 metres. In clay soils, root penetration is difficult and the percentage of roots in the upper layer can be expected to be greater than 80%, and the maximum depth of deeper roots is likely to be shallower. Generally, trees take up water where the soil is in contact with the fine or small feeder roots.

Rooting depths also have an impact on transpiration. It is generally thought that roots in the evergreen tropical forest tend to be very shallow but mean maximum rooting depth of 6 observations is 6.5 ± 2.5 m have been observed (Canadell et al., 1996). Nepstad et al. (1974) have observed rooting depth of 18 in the tropical forests of Brazil. Deep roots have the ability to tap soil moisture at greater depths to facilitate transpiration process during dry season. The unlimited supply of water tends to increase transpiration, which in turn affects the local surface energy balance leading to lower air temperatures. This enhanced transpiration leads to a wetter atmosphere, causing large-scale differences in the atmospheric moisture and heat transport. More moisture is transported towards the intertropical convergence zone causing enhanced precipitation and an overall strengthened atmospheric circulation. Hence, deep-rooted vegetation forms an important part of the tropical climate system. This conclusion appears to be true for some temperate forest ecosystems as well (Dawson 1993).

Many methods for estimating evaporation from free water surfaces and evapotranspiration from soil and plants exist. Some of the methods for estimating evapotranspiration apply also to estimation of potential evapotranspiration provided the area under observation has sufficient water at all times (Veihmeyer, 1964). A few conventional methods of estimation are given in Table .2.8

Table 2.8: Conventional Methods in Estimating Evapotranspiration

Methods	**Input variables**		**References**
Field measurements			
Evaporation pans		Evaporation from lakes	Raghunath, 1985
Lysimeters		Evapotranspiration	van Bavel and Myers (1962) and Howell, et al (1985)
Neutron soil water probe		Evaporation from soil	
Phytometer		Transpiration	Veihmeyer, 1964
Analytical approaches			
Water budget	P, I, O	Evaporation	Veihmeyer, 1964, Singh, 1992
Energy budget	Q_s, Q_r, Q_a, Q_a, Q_{bs}, Q_v, Q_x, L, BR, T_0	Evaporation	Veihmeyer, 1964, Singh, 1992

Mass transfer method (Thornthwaite and Holzman equation)	U_2, e_2, e_8, K	Evaporation	Mutreja, 1986
Empirical approaches			
Thornthwaite equation	T_m	Evaporation/ Evapotranspiration	Singh, 1992
Penman equation	s, U_2, e_0, e_a	Evaporation/ Evapotranspiration	Winter et al. 1995
Priestly-Taylor equation	α, s, γ, Q_n, Q_x	Evaporation/ Evapotranspiration	Winter et al. 1995
DeBruin-Keijman equation	γ, Q_n, Q_x, SVP	Evaporation/ Evapotranspiration	Winter et al. 1995
Papadakis equation	e_o-saturated vapour pressure	Evaporation/ Evapotranspiration	Winter et al. 1995
Hamon	T_d	Evaporation from lakes	
Turc's equation	Tm, S_n, α, n, N, S_o	Evapotranspiration	Shuttleworth, 1993

Note: Q_s- incident shortwave radiation; Q_r- reflected shortwave radiation; Q_a-incident longwave radiation; Q_{ar}- reflected longwave radiation; Q_{bs}-longwave radiation emitted by lake; Q_v- net energy advected by stream flow, groundwater and precipitation; Q_x- change in heat stored in water body; Q_x- change in heat stored in water body; Q_n- net radiation; L- latent heat of vapourisation; BR- Bowen ratio; T_0- water surface temperature; U_2-wind speed at 2 meter height; e_2- vapour pressure at 2 meter height; e_8- saturation vapour pressure of air at 8 meter height; K- von Karman's constant; α -1.26 (empirically derived constant); s – slope of the saturated vapour pressure gradient; γ- psychrometric constant; SVP-saturated vapour pressure at mean air temperature; P – precipitation; I – inflow; O –outflow; T_m mean monthly temperature; T_d – daily mean temperature; e_0- saturated vapour pressure; e_a- actual vapour pressure; S_n – net shortwave radiation; α - albedo; n- no. of sunshine hours; N- maximum possible sunshine hours; S_o – extra terrestrial solar radiation.

Field measurements of evaporation range from simple to complex and have a range of spatial scales and accuracies. Evaporation pan measurements are the simplest but are affected by the size, depth and location of pans. Lysimeters are open-top tanks filled with soil in which crops are grown under natural conditions. Lysimeters though difficult and expensive to install have long established use, primarily in research applications to test alternative measurement techniques or in the calibration of empirical equations to estimate evaporation. Another method to determine evaporation is by using neutron soil water probe, which monitors the change in soil water storage over a period of time. However, this method does not account for drainage from the zone samples or the upward movement of water from a saturated zone into the zone sampled.

A phytometer provides a practical method for measuring transpiration. This method gives satisfactory results provided the simulated testing condition is comparable with the natural environment under investigation (Veihmeyer, 1964).

The lack of basic data and the difficulties in measurement required in the field methods have led to great efforts in developing evapotranspiration equations using readily available climatic data.

Water balance or water budget method is a measurement of continuity of flow of water. This method is good theoretically for the determination of evaporation from lake or reservoir but is difficult practically due to the effects of error in measuring each component (Veihmeyer, 1964). The energy balance or budget is similar to water budget but it deals with the continuity of flow of energy than water. This equation assumes the principle of conservation of energy but neglect items of small magnitude such as heat transformed from kinetic energy, heating due to chemical and biological processes and conduction of heat through bottom (Veihmeyer, 1964). The simplest mass transfer methods relate evaporation with wind speed and vapour pressure deficit, which is the difference between saturated vapour pressure at the water surface and the vapour pressure of air at some height above the water surface. But the errors can be high as 30% and if the area is larger than 4×10^6 m^2, it is not advisable to use this equation (Singh, 1992). Thornthwaite method is based on exponential relationship between mean monthly temperature and mean monthly evapotranspiration and requires only temperature data. However, the Thornthwaite approach has been found to underestimate under arid conditions (Pruitt, and Doorenbos, 1977) and overestimate in humid climates (Camargo et al. 1999). Penman equation is a weighted average of the rates of evaporation due to net radiation and turbulent mass transfer. Penman equation yields the most accurate estimates of evaporation from saturated surface if model assumptions are met and input data is available. However, this equation requires several input data that is difficult to obtain and thus it is not feasible to use this equation in evapotranspiration studies. Priestly Taylor equation is based on the fact that under certain conditions, knowledge of net radiation and ground dryness may be sufficient to determine vapour and sensible heat fluxes at the Earth’s surface. When large land areas become saturated, net radiation is the dominant constraint on evaporation. The form of equation developed by Priestly Taylor is a constant times the Penman’s radiation terms. This equation has shown good estimates with lysimeter measurements for both peak and seasonal evapotranspiration in humid climates; however, it substantially underestimates both peak and seasonal evapotranspiration in arid climates. Turc’s equation has been in common use and is used to calculate transpiration and evaporation. The accuracy of this method is dependent on the accuracy of the albedo.

Monitoring evapotranspiration has important implications in modelling regional and global climate and the hydrological cycle as well as assessing environmental stress on natural and agricultural ecosystems. Evapotranspiration cannot be measured directly by means of spectral radiometric observations. However, the latter provides information on atmosphere and land surface conditions useful to estimate evaporation. Moreover, satellite measurement can provide spatial patterns of evapotranspiration at heterogeneous land surfaces. Some techniques have been listed in Table 2.9.

Table 2.9: Model Types Used to Estimate Evapotranspiration

Model Type	Input variables	Temporal scale of ET estimate	References
Semi-empirical /statistical	T_{rad}, T_a, R_n	Daily	Jackson et al. 1977, Seguin & Itier, 1983
Semi-empirical /statistical	T_{rad}, u, T_a, e_a, R_s	Daily	Niewenhuis et al. 1985 Thunissen & Niewenhuis, 1983
Physical/Analytical	T_{rad}, T_a, u, e_a	Daily	Price, 1982
Physical/Analytical	T_{rad}, T_a, u, R_n	Instant	Norman et al. 1995b
Numerical	T_{rad}, θ_a, U, E_a, VIS, NIR	Instant to daily	Sellers et al. 1992

Note: T_{rad} – radiometric surface temperature; T_a – air temperature; R_n – net radiation; e_a – surface vapour pressure; R_s -incoming solar radiation; θ_{rad} – potential radiometric surface temperature; θ_a –potential temperature in atmospheric boundary layer; U – wind speed in the atmospheric boundary layer; E_a – vapour pressure/ humidity in the atmospheric boundary layer; VIS, -visible reflectance ; NIR –near infrared reflectance ; R_L – incoming atmospheric longwave radiation

Semi empirical/statistical methods have been developed to predict daily evapotranspiration using instantaneous remote sensing observations and assumptions about the relationship between midday sensible heat and latent heat and sum of net radiation and soil heat. Experimental observations analysed by Hall et al. 1992 suggest that the evaporative fraction ($EF = -LE/(R_n+G)$ remains fairly constant over the daytime period. Several studies have found this technique can give reasonable results (Brutsaert and Sugita, 1992: Hall et al. 1992) with differences in daily ET of less than 1 mm/day. Physically based analytical approaches such as the one proposed by Price (1982) gives appropriate ET values when compared to local estimates using standard meteorological and pan evaporation data. But these approaches provide only an instantaneous estimate of the fluxes because these models require radiometric temperature, which means that only one estimate of LE can be computed during the daytime except when using radiometric observations from satellites such as GOES or METEOSAT (Kustas and Norman, 2003).

A significant number of numerical models have been developed over the past decade to simulate surface energy flux exchanges using remote sensing data for updating the model parameters (Camillo et al. 1983; Taconet et al. 1986). The advantages of these approaches are that fluxes can be simulated temporally and it can be periodically updated with remote sensing data. The disadvantage is that these models require many input parameters related to soil and vegetation properties not readily available at regional scales.

An alternative approach in determining evapotranspiration is by exploring its relationship with vegetation indices. Vegetation indices have been used in the past quarter century for crop yield monitoring. Satellite derived vegetation indices such as normalized difference vegetation index have become essential for obtaining information on the vegetation status. Since the vegetation status (e.g. greenness) integrates the effects of numerous environmental factors, these indices can be correlated with hydrological variables such as actual evapotranspiration (Seevers and Ottmann, 1994; Nicholson et al. 1996). Seevers and Ottmann (1994) and Nicholson et al. (1996) pointed out that NDVI-AET relationship performs better in humid environment.

Recharge and Discharge: Natural groundwater fluxes are typically slow; water may reside in an aquifer for as little as few hours (river bank storage) or for hundreds of years (Sorooshian and Whitaker, 2003). Accordingly, groundwater itself is often perceived, on the average as a relatively slow-moving reservoir in the global hydrological cycle. At the catchment scale, however where stream-aquifer interactions are relatively rapid and substantial, the average groundwater fluxes are relatively fast moving.

The Chaturvedi formula has been widely used for preliminary estimation of groundwater recharge due to rainfall. Since the factors used are site specific, a generalized formula may not be applicable to all the alluvial areas. Amritsar formula and Krishna Rao's relationships were tentatively proposed for specific hydrogeological conditions and needs to be examined and established or suitably altered for application to other areas.
Table 2.10 lists some conventional techniques used to estimate groundwater recharge/discharge.

Table 2.10: Conventional Techniques in Estimating Recharge/Discharge

Component	**Method**
Groundwater recharge	Chaturvedi formula (Ganga Yamuna doab)
	Amritsar formula (doabs in Punjab)
	Krishna Rao relationship (Karnataka)
	Groundwater Resource Estimation Committee norms (1997)
	Groundwater balance method
	Nuclear technique
	Recharge from canal seepage
	Recharge from field irrigation
	Recharge from tanks
Groundwater discharge	Evapotranspiration from groundwater (wetlands and phreatophytes)
	Draft from wells
	Groundwater level fluctuation method

Source: www.angelfire.com/nh/cpkumar/publication/Lgwa.pdf

Rainfall recharge may be estimated using the rainfall infiltration method. Recharge factors have proposed by the Groundwater Resource Estimation Committee (1997). Table 2.11 lists some factors for specific geological formations. 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.

Table 2.11: Recharge Factors

Alluvial areas	Recharge factor (%)
Indo Gangetic and inland areas	22
East coast	16
West coast	10
Hard rock areas	
Weathered granite, gneiss and schists with low clay content	11
Weathered granite, gneiss and schists with high clay content	8
Granulite facies like charnockite etc	5
Weathered basalt	7
Laterite	7
Semi consolidated sandstone	12
Consolidated sandstone, quartzites, limestone	6
Phyllites, shales	4
Massive poorly fractured rocks	1

In this method, all components of the groundwater balance equation, except the rainfall recharge, are estimated individually. This method requires extensive and accurate hydrological and meteorological data. This method is valid for areas where the year can be divided into monsoon and non-monsoon months with the bulk of the rainfall occurring during the monsoon months.

Soil moisture data based method consists of soil water balance method and nuclear methods. Soil water balance method consists of lumped and distributed models. In the lumped model, the variation of soil moisture content in the vertical direction is ignored and any effective input into the soil is assumed to increase the soil moisture content uniformly. In the distributed model, variation of soil moisture content in the vertical direction is accounted and the method involves the numerical solution of partial differential equation (Richards equation) governing one-dimensional flow through unsaturated medium, with appropriate initial and boundary conditions.

Water balance models were developed by Thornthwaite (1948) and later revised by Thornthwaite and Mather. The method is essentially a bookkeeping procedure, which estimates the balance between the inflow and outflow of water. The disadvantage of this method is that 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. Results from this model are of very limited value without calibration and validation, because of the substantial uncertainty in the input data.

Nuclear techniques can also be used for the determination of recharge by measuring the travel time of moisture through a soil column (www.angelfire.com/nh/cpkumar/publication/Lgwa.pdf). A mixture of Beryllium (Be) and Radium (Ra) is taken as the source of neutrons. Another method is the gamma ray transmission method based upon the attenuation of gamma rays in a medium through which it passes. The extent of attenuation is closely linked with moisture content of the soil medium.

Water requirements of crops are met by rainfall, soil moisture and irrigation water. Recharge from irrigation fields are estimated from water balance method. For a correct assessment of the quantum of recharge by applied irrigation, studies are required to be carried out on experimental plots under different crops in different seasonal conditions. Groundwater Resource Estimation Committee has proposed the following standards in percentages for crop such as paddy watered either by surface water and groundwater given in Table 2.12.

Table 2.12: Recharge Factors for Crops

Source of irrigation	Type of crop	Water table below ground surface		
		< 10m	10-25m	> 25m
Groundwater	Non paddy	25 (%)	15 (%)	5 (%)
Surface water	Non paddy	30(%)	20 (%)	10 (%)
Groundwater	Paddy	45 (%)	35 (%)	20 (%)
Surface water	Paddy	50 (%)	40 (%)	25 (%)

Groundwater can be discharged by evapotranspiration from wetlands and phreatophytic vegetation. The potential evapotranspiration from such areas can be computed using standard methods and the discharge estimated.

Groundwater is essentially a subsurface phenomenon and the common current remote sensing platforms record features on the surface (Meijerink, 2000). Most of the information for groundwater, as yet has to be obtained by qualitative reasoning and semi-quantitative approaches.

Image interpretations are used to locate areas where the groundwater table is probably shallow. The appearance of groundwater at or near the surface is caused by either the intersection of topographic depressions or a static phreatic groundwater level or by discharge zone of an upwelling groundwater flow system. In both cases, there will be an effect on vegetation, relative soil moisture, land use or on details of the drainage systems and these effects can be identified on remotely sensed imageries.

With this in mind, groundwater discharge can be estimated by determining evapotranspiration from phreatophytes and wetlands (D'Agnese et al, 1996) Phreatophytes are plants whose roots can tap water from the groundwater table and thus are indicators of the presence of shallow groundwater.

Various indices have been used to map various types of vegetation such as phreatophytes, wetland vegetation and riparian vegetation which discharge groundwater through evapotranspiration. Among these are perpendicular vegetation index (PVI), greenness vegetation index (GVI), transformed vegetation index (TVI) etc. PVI is used (mainly used in arid regions) to minimize the effects of soil reflectance in low-density vegetation communities. GVI is used to distinguish between different levels of greenness while minimizing effects of soil brightness and TVI is used to produce vegetation density map and to discriminate between light coloured soils and dead or dying vegetation.

Recharge in dry areas can be promoted by the presence of mountains. Typically, precipitation is greater at higher elevations (concept of Maxey-Eakin method) and relief promotes rapid and efficient runoff. Water running off the mountains effectively infiltrates alluvial fans bordering the mountain ranges. Alluvial fan sediments are highly permeable. A modified Maxey-Eakin's method has been derived that calculates a recharge potential map from slope, elevation, soil permeability and vegetation map. It is expressed as a percentage and is further multiplied with average annual precipitation (D'Agnese et al, 1996).

Land use and its Effect on Hydrology: Human activities have been recognized as a major force shaping the biosphere in recent years. Human actions rather than natural forces are the source of most contemporary change in the states and flows of the biosphere (Turner and Meyer 1994). Understanding these actions and the social forces that drive them is thus of crucial importance for understanding, modeling and predicting environmental change and for managing and responding to such change.

Concerns about land use/land cover change emerged in the research agenda on global environmental change several decades ago with the realization that land surface processes influence climate (Lambin et al., 2003). In the mid 1970s, it was recognized that land cover change modifies surface albedo and thus surface-atmosphere energy exchanges, which have an impact on regional climate. In the 1980s, terrestrial ecosystems as carbon sources and sinks were highlighted and later the important contribution of local evapotranspiration to the water cycle-that is precipitation recycling-as a function of land use/land cover highlighted yet another considerable impact of land use/land cover change on the climate. A much broader range of impacts of land use/land cover change on ecosystem goods and services were further identified (Lambin, et al., 2003). Of primary concern are impacts on biotic diversity worldwide, soil degradation and the ability of biological systems to support human needs. It also determines the vulnerability of places and people to climatic, economic or sociopolitical disturbances.

Thus, it becomes necessary to estimate the temporal and spatial development of land use changes to assess their impact on the ecosystems and the environment. A most efficient way of capturing the spatial and temporal details is by remote sensing. Hydrological models coupled with remote sensing data can efficiently characterize temporal and spatial effects of land use changes on the ecology and hydrology.

Changes in land cover alters the hydrological cycle and in most of the mass and energy fluxes that sustain the biosphere and geosphere. Due to agriculture, forest management and urbanisation, the physical characteristics of the land surface and upper soil as well as the transpiration process that is strongly related to the type of vegetation are changed. As a result the amount of runoff, the soil moisture and groundwater recharge are also strongly affected.

Some of the effects of land use changes such as changes in forest cover, agricultural activities and urbanisation are discussed below:

Felling trees for the combined objectives of obtaining wood for construction, shelter and tool making; of providing fuel to keep warm, to cook food, and to smelt metals; and above all, of creating land for growing food, has culminated in one of the main processes whereby humankind has modified the world's surface cover of vegetation (Williams, 1994). Forests covered about half of the earth's surface up to the development of early civilizations but today cover less than one-third of that area (FAO, 1993). Between 1980 and 1995, the extent of the world's forests decreased by some 180 million ha, an area about the size of Indonesia or Mexico. This represents a global annual loss of 12 million ha, an area equivalent to the size of Greece or Bangladesh (Ball, 2001). During this 15-year period, developing countries lost nearly 200 million ha of natural forests, mostly through clearing for agriculture (shifting cultivation, other forms of subsistence agriculture, and the establishment of cash crop plantations such as oil palm and ranching).

Forest cover influences climatic and soil conditions and therefore the amount of water flowing from forested areas (Bruijnzeel, 2001). As compared with grass or low vegetation, forests may exert a major influence on what happens to the precipitation once it reaches the ground. Rain may be redistributed to some degree, although this effect is probably more important for local vegetation patterns than it is for any influence on water yield and timing. When there is rainfall of sufficient intensities, a large portion of total storm precipitation will eventually reach the ground, although it may be redistributed by stem-flow and drippage. That portion of the rainfall intercepted by the vegetation canopies eventually evaporates, reducing transpiration.

The following sections will discuss some aspects of the hydrological effects of i) forest clear felling on water yield and stream flow regimes and ii) effects of reforestation.

i) *Effects of forest clear felling on water yield and stream flow regimes:* Total annual water yield appears to increase with the percentage of forest biomass removed, but actual amounts differ between sites and years due to difference in rainfall and the degree of surface disturbance (Bruijnzeel, 2004). If surface disturbance remains limited most of the water yield increase occurs as lowflows (baseflows), but in the long term, rainfall infiltration is reduced to the extent that insufficient rainy season replenishment of groundwater reservoirs results in strong declines in the dry season flows. Reports of greatly diminished stream flow during the dry season after forest clear felling abound in the literature, particularly in the tropics. The continued exposure of bare soil after forest clearing to intense rainfall, the compaction of topsoil by machinery, or overgrazing, the gradual disappearance of soil faunal activity and increases in the area occupied by impervious surfaces such as roads and settlements, all contribute to gradually reduced rainfall infiltration opportunities in cleared areas. As a result, catchment response to rainfall becomes more pronounced and the increases in storm runoff during the rainy season may become large as to seriously impair the recharging of soil water and ground water. When this critical stage is reached, the result is diminished dry season flow. It should be noted that comparing stream flow totals for catchments with contrasting land use types might produce misleading results because of the possibility of geologically determined differences in catchment groundwater reserves or deep leakage. Catchments underlain by sandstones, limestones, basalts and volcanic tuffs are noted for this. Under mature tropical rain forest, typically 80-95% of incident rainfall infiltrates into the soil, of which around 1000 mm per year is transpired again by the trees when soil moisture is not limiting, whereas the remainder is used to sustain stream flow. As such the bulk of the increase in flow upon clearing in the form of baseflow, as long as the intake capacity of the surface soil is not impaired too much (Bruijnzeel, 1990).

ii) *Effect of reforestation:* Water yields have been reported to return to original levels within 8 years where pine plantations replaced natural forest such as in upland Kenya (Blackie, 1979a,b). Bruijnzeel, 1997 have pointed out the lack of sufficient information about the hydrological consequences of planting fast growing tree plantation species such as *Acacia mangium, Gmelina arborea, Paraserianthes falcatarai* and Eucalyptus spp. and pines. Recent observations in 10 year old stands have confirmed the high water use of Acacia mangium in East Malaysia even during a period of drought (Cienciala et al., 2000). Plantations of *Eucalyptus camaldulensis* and *Eucalyptus tereticornis* in southern India exhibited similar behaviour with transpiration rates upto 6 mm per day when unrestricted by soil water deficits at the end of the monsoon, although values fell to 1 mm per day when soil water contents were low during the subsequent long dry seasons (Roberts and Rosier, 1993).

Historically, humans have increased agricultural output mainly by bringing more land into production. The mix of cropland expansion and agricultural intensification has varied geographically (UN FAO, 2001). Despite claims to the contrary, the amount of suitable land remaining for crops is very limited in most developing countries (Young, 1999). The main hydrological effect of cropped land is a change in the partitioning of the rainfall into evaporation, overland flow, and infiltration. In places where irrigation is practiced, typically 80-90% of the water is ‘consumed’ or evapotranspired (not returned to flow) by irrigation. Irrigation therefore has a greater impact on the hydrological cycle. Activities such as land improvement, land drainage, merging of small areas, as well as the type of tillage, type of crop cultivated, simplification of crop rotation, single-crop farming, etc. can disturb the water balance of rural areas (decrease in the groundwater renewal rate, decrease in the groundwater table, increase of water discharge, etc.) and increases the risk of erosion (erosion caused by precipitation, wind-erosion, mudflow, flooding (inundation). Soil compaction due to movement of heavy vehicles and deterioration of the soil structure increases the surface runoff and, therefore, will reduce the groundwater renewal rate of the area. The increase of biomass of the crops increases the water consumption and therefore reduces the soil moisture and the groundwater renewal rate. In some regions often the associated irrigation completes the increased water demand. The main causes of increased erosion are seen as single-crop farming, simplification of crop rotation, soil compaction, changing from grassland to arable land and land drainage. This will reduce the water storage capacity and the filtration capability of the soil, and the surrounding surface waters may become eutrophic.

Settlement represents the most profound alteration of the natural environment by people through the imposition of structures, buildings, paved surfaces and compacted bare soils on the ground surface (Douglas, 1994). Settlements also lead to other land cover changes, such as the storage of water in reservoirs; the removal of vegetation and soil to extract sand, gravel, brick clays and rock; and the use of land for transportation routes. Urban and suburban development of forested watersheds can increase the percentage of impervious surfaces on a watershed from nearly zero in a rural setting to, almost 100 percent in commercial or industrial areas. It can be concluded that urbanization in forested watersheds tend to reduce interception, infiltration, soil-moisture storage and evapotranspiration, and increases overland flow. Several studies of peak flows have shown that they may be increased by 1.2 to 5 times over peaks from rural conditions. During development and construction of suburban areas, sedimentation may be increased greatly; even after construction, sedimentation in these areas may be 5 to 10 times that from protected watersheds. They also find that annual maximum peak flows increase, although maximum daily flows decrease. Total flow volume increases because a greater percentage of summer precipitation appears as runoff, while protected stream banks will yield minimum impacts (http://samab.org/saa/reports/aquatic/chapter5.pdf).

Even through tropical rural people are much more vulnerable to perturbations of the natural environment than their urban counterparts, they have large collective impacts on the natural world. In great areas of paddy cultivation and irrigation agriculture of Asia, the whole landscape is a pattern of fields, water channels and settlements. Water flows are usually tightly controlled. Settlements in these areas are often compact to maximize the amount of land available for cultivation. In areas cultivated or grazed less intensively, rural settlements may sprawl and have crop production intermingled with the houses. A tightly knit series of dwellings with only compacted ground between them will modify the radiation balance and the hydrological cycle much more than a dispersed village with gardens all around the house and trees shading much of the roof area.

Another major land use change is the construction of dams and reservoirs for hydro electrical power, flood control, irrigation and water supply. In the past half-century, dams and reservoirs have become an increasingly important part of anthropogenic land cover change. Today there are over 45,000 large dams (dams over 15 m height, or with reservoirs containing 3 million cubic meters of water), and total annual freshwater withdrawals today are estimated at 3,800 cubic km, twice as much as 50 years ago. Even though they make up only a small percentage of total land cover, these artificial water bodies often facilitate other forms of land cover change, such as development of large-scale irrigated areas and urbanization that cover far larger areas. According to the World Commission on Dams (2000), large dams can have numerous impacts on ecosystems. These include the loss of forests and wildlife habitat, the loss of species populations and the degradation of upstream catchment areas due to inundation of the reservoir area; the loss of aquatic biodiversity, of upstream and downstream fisheries, and of the services of downstream floodplains, wetlands, and riverine, estuarine and adjacent marine ecosystems; and cumulative impacts on water quality, natural flooding and species composition where a number of dams are sited on the same river.

Furthermore, dams and reservoirs impact the hydrological cycle by increasing evaporation (dams in arid areas can lose 5 percent of total withdrawals to evaporation) and loss of downstream aquifers due to reduced replenishment. Environmental flow requirements (which include managed flood releases) are increasingly used to reduce the impacts of changed stream flow regimes on aquatic, floodplain and coastal ecosystems, downstream. Sedimentation and the consequent long-term loss of water storage is a serious concern globally, and the effects will be particularly felt by basins with high geological or human-induced erosion rates. Thus, land cover change that promotes increasing sediment loads, such as agricultural land uses or deforestation, affect the water storage and electricity generation capacity of dams.

3.0 Study Area

Sharavathi river rises at Ambuteertha, near Kavaledurga in Tirthahalli taluk. It flows in a northwesterly direction and receives the Haridravathi on the right and Yenneholé on the left. Near the border the district, it bends to the west and hurls down the ghats near Jog where it is harnessed for generating electricity. It discharges into the sea at Honnavar in Uttara Kannada. It’s total length is 128 km and in Shimoga district its length is 32.2 km. According to a legend, the name Sharavathi means ‘arrow-born’ and the river was formed from a dart of Ramachandra’s arrow (KSG, 1975). Figure 3.1 depicts the location of the study area in India and Karnataka.

Figure 3.1: Study Area – Sharavathi river basin

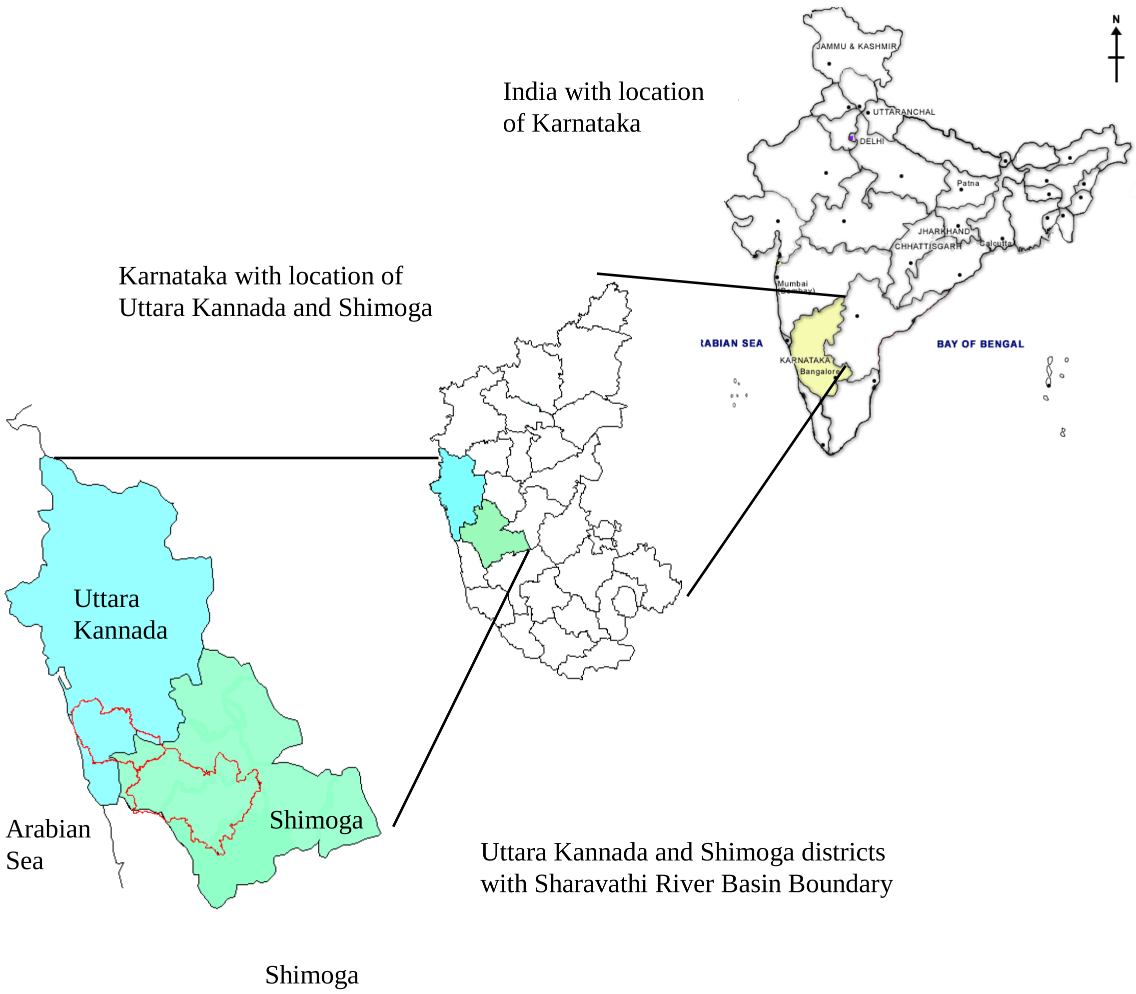


Figure 3.2: Sharavathi River Basin –Upstream and Downstream

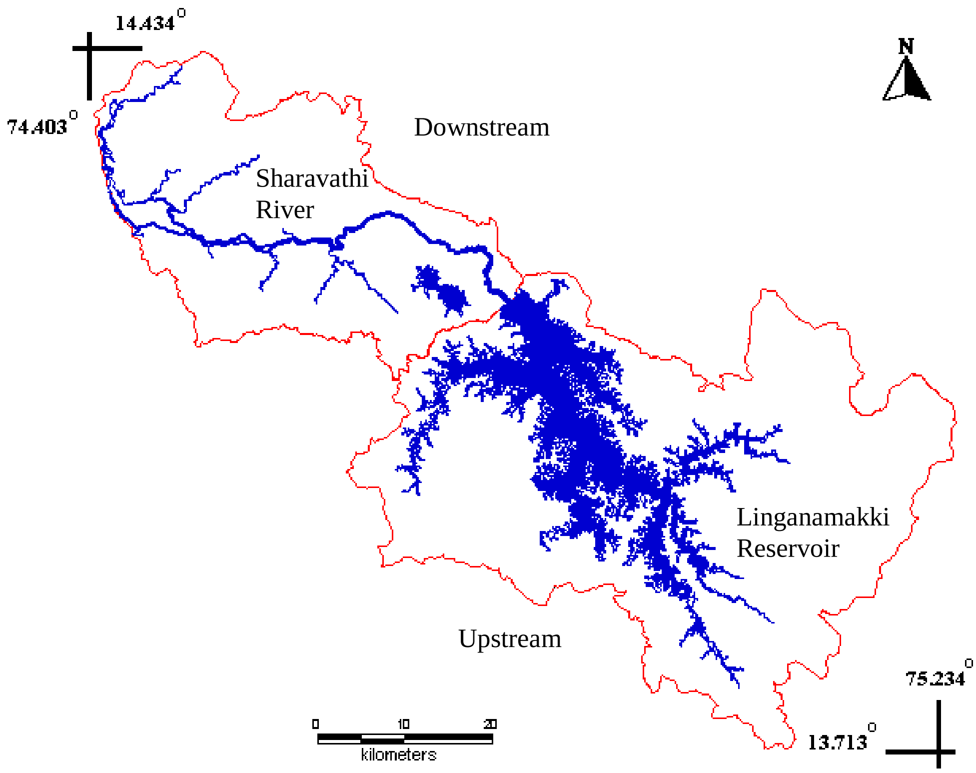
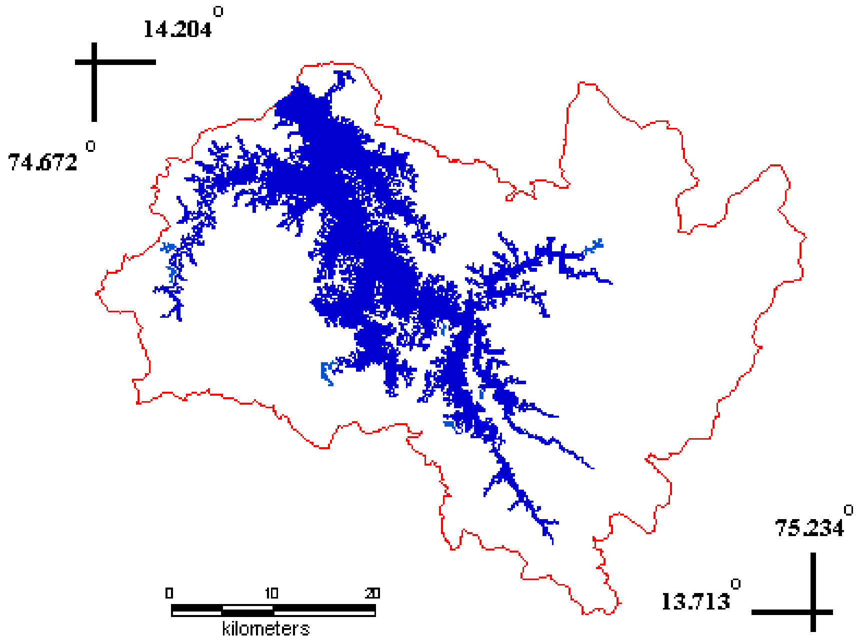


Figure 3.3: Upstream River Basin

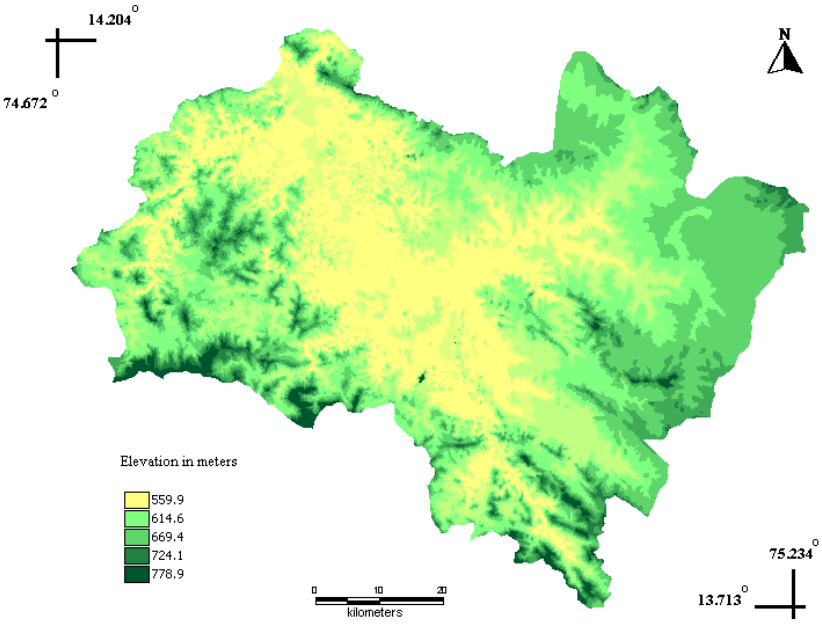


3.1 Topography

Sharavathi river basin falls in two districts namely Uttara Kannada and Shimoga. Upstream river basin extends to two taluks in Shimoga viz. Hosanagara and Sagara. The entire basin has an area of 2985.66 km^2 with upstream and downstream respectively are 1988.99 km^2 and 996.67 km^2 each. The basin slopes from west to east. The general elevation along the basin is about 640 m above sea level in the west

The western side of the upstream river basin rests upon the Western Ghats also known as the Sahyadri, which is a very mountainous area. The raise towards the crest of the Ghats is very rapid, a height of 1343 meters according to the Survey of India, being attained at Kodachadri. The southwestern portion of Sagar taluk presents the appearance of a rolling stretch of bare hill tops, the sides and valleys of which are densely wooded. The Hosanagara taluk is enclosed on three sides by hills, the drainage of which flows northwest into the Sharavathi (KSG, 1975). Figure 3.4 gives the digital elevation model of upstream.

Figure 3.4: Digital Elevation Model



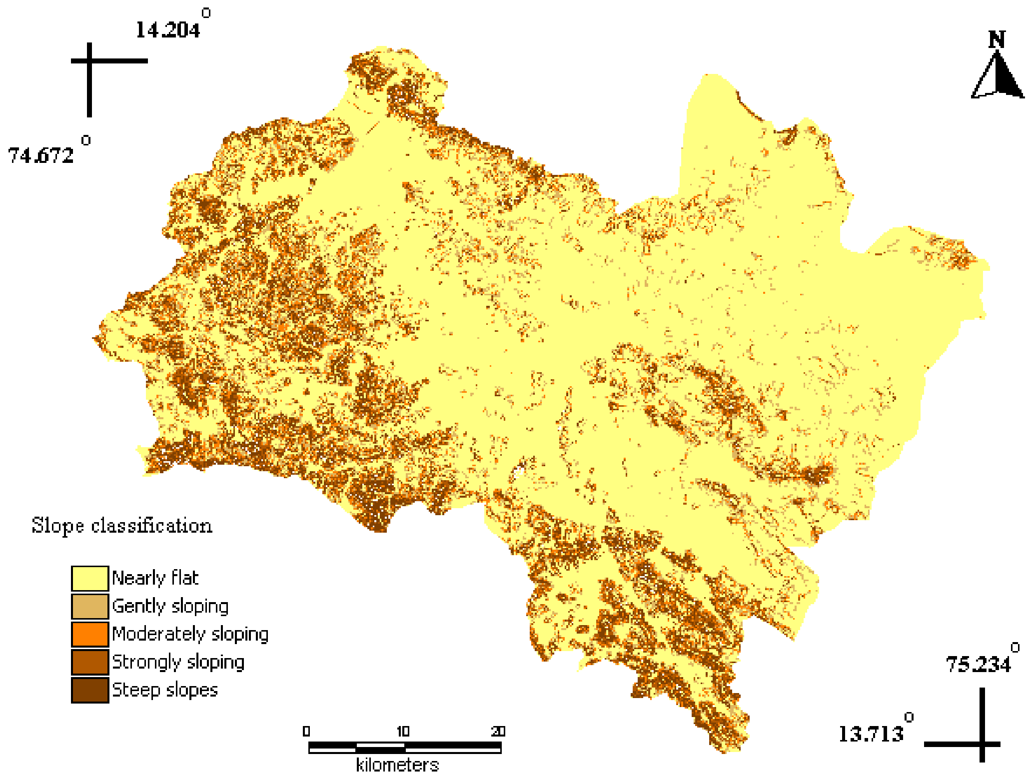
Slope percentage map derived from digital elevation model was classified into various slope groups.

Table 3.1: Slope Classifications

Slope in percentage	Slope group
0-10	Nearly flat
10-15	Gently sloping
15-20	Moderately sloping
20-30	Strongly sloping
30-80	Steep sloping

Figure 3.5 classifies slope map into 5 major slope groups. This classification is given in Table 3.1. Steep to strongly sloping are characteristics of malnadu (mountainous region) on the western side and is covered by dense vegetation such as evergreen/semievergreen and moist deciduous forests. Slopes attain nearly level ground at the centre of the basin (reservoir) and gently slopes upward towards the east. Eastern portion especially Haridravathi and Nandiholé sub basins consists of nearly level or flat land, where paddy cultivation is practiced.

Figure 3.5: Slope Classification



3.2 Geology

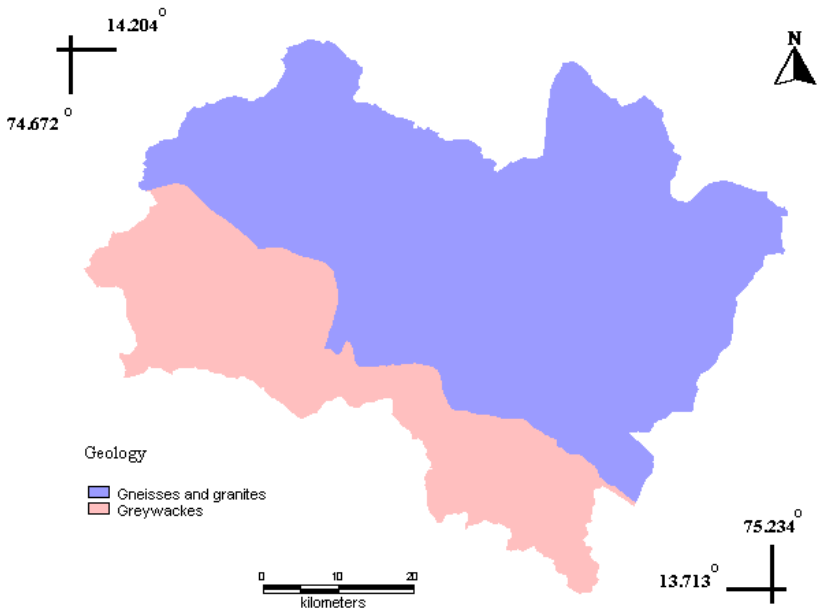
The geology of Sharavathi river basin consists of Pre-Cambrian rocks, which are devoid of fossils. Apart from being heterogeneous in their origin (consolidated intrusive magmas, ancient sediments, volcanic rocks) they were more less thoroughly reshuffled by new intrusions, faults and metamorphism (Pascal, 1988). The two major groups of rocks found in the study area are the Dharwar system and the peninsular gneiss.

The Dharwar system: It is named after the township of Dharwar on the Karnataka plateau. This system includes metamorphic rocks that are considered to be among the oldest in India. These rocks are derived from metamorphosed ancient sediments: conglomerates, more or less ferruginous quartzites, greywackes, schists and limestones. They are rich in iron and manganese and sometimes in copper, lead and gold too.

Peninsular gneiss: These are crystalline rocks and consist of a heterogeneous mixture of gneiss and different kinds of intrusive granites. They are made up of granite, granodiorite, granito-gneiss, migmtatite etc. These 'peninsular gneiss' are encountered almost all along the Ghats but they are predominant only between 11^0N and 14^0N.

Geology map of Sharavathi upstream river basin given in Figure 3.6, has been created by combining the geology map of Department of Mines and Geology and the French Institute. This has been done for simplification of groundwater analysis

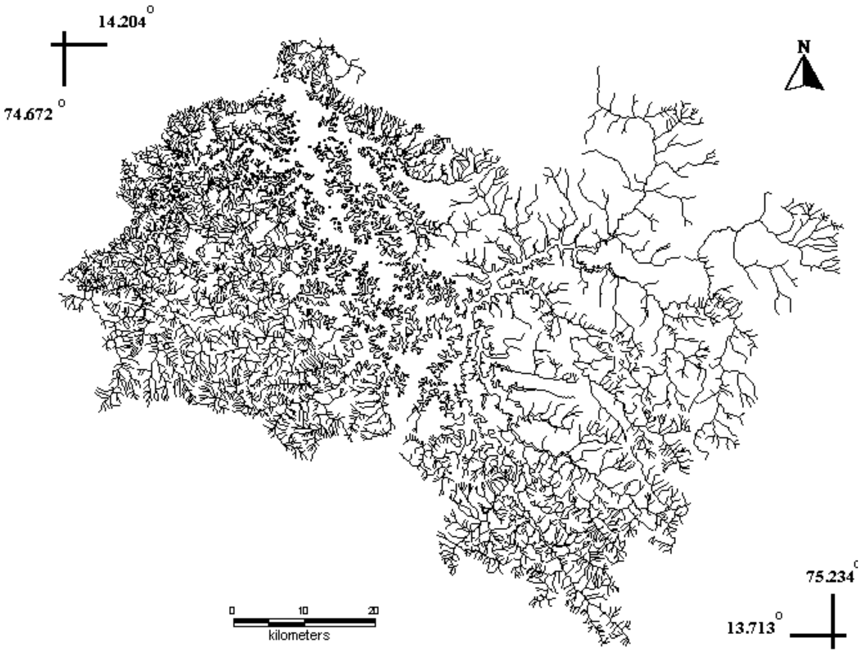
Figure 3.6: Geology



3.3 Drainage and Sub basins

As can be seen from Figure 3.7, dense drainage network is observed in the western portion of the basin. These are areas of very steep to steep slopes. Eastern portion especially, Nandiholé and Haridravathi basins are characterized by less dense network due to the gentle slope. The pattern of drainage in the basin is mainly dendritic. Dendritic drainage pattern takes the form of "dendrites" and looks like the branching roots of a tree. In areas of high permeability soil such as sand viz. in Haridravathi and Nandiholé, the drainage density is low as compared with low permeability soil (clay) and high drainage density on the western side e.g. Yenneholé, Hurliholé etc. Drainage density is the ratio between the total length of the stream and the area drained by them.

Figure 3.7: Drainage



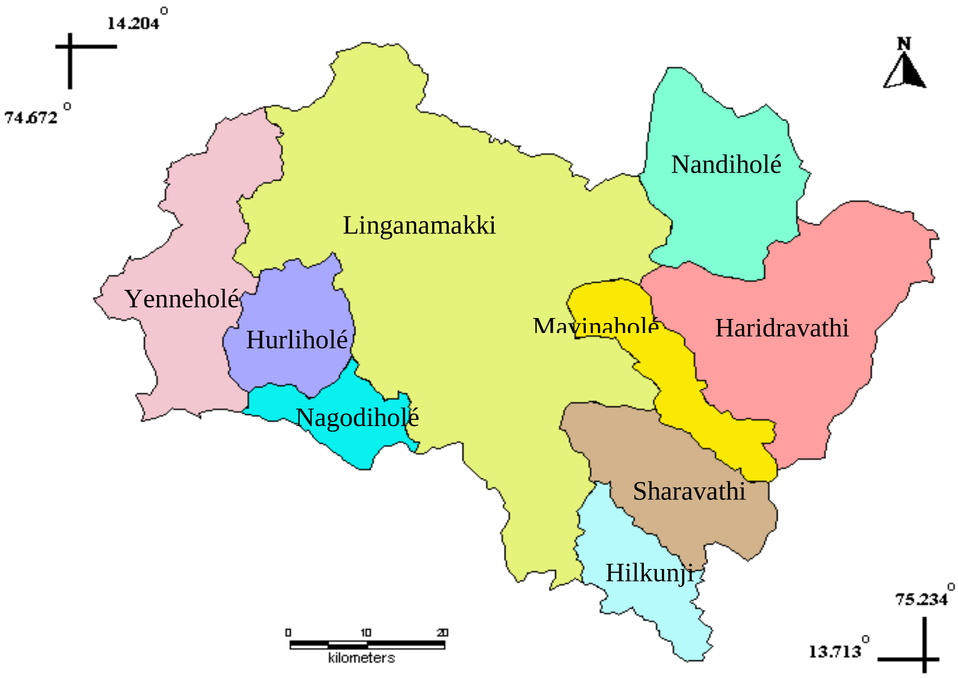
Sub-basins have been delineated according to the main tributaries flowing into the reservoir as depicted in Figure 3.8.

3.4 Climate

The climate in the study area is characterized by the monsoon regime, which superimposes itself over a regime of thermic convectional rainfall lined to the zenithal passage of the sun. The cold season is from December to February and is followed by the hot season which is from March to May.

a) Rainfall: The rainfall is very heavy in the region of Western Ghats especially along the western side of the river basin. Mean annual rainfall ranges from 6000mm in the western side to 1700mm in the eastern side of the basin. About 95% of the rainfall is received during the south west monsoon months, June to September, July being rainiest (KSG, 1975). There is some rainfall in the post monsoon season, particularly in October, and it is mostly in the form of thundershowers. Some rainfall in the form of thundershowers also occurs during the summer months of April and May.
b) Temperature: After January, there is a rapid increase of temperatures. April is usually the hottest month with the mean daily maximum temperature at 35.8^{o}C and the mean daily minimum at 22.2^{o}C.
c) Humidity: The relative humidity during the mornings throughout the year generally exceeds 75%. During the monsoon months, the relative humidity in the afternoon is quite high and is ~60 %. The driest part of the year is the period from January to March when the relative humidity in the afternoon is less than 35%.
d) Winds: It is generally light with some increase in force during the monsoon season. Winds are mostly from directions between northwest and southwest during the period May to September. In the rest of the year, they are predominantly from the south east.

Figure 3.8: Sub basins of Upstream



3.5 Soil

i) Four soil orders are found in upstream viz. ultisols, alfisols, inceptisols and entisols.

ii) Moisture regime of the soils in upstream river basin is characterized by an ustic moisture regime.

Ustic moisture regime*:* (ustic-burnt)-Ustic moisture regime is one that is limited but is present at a time when conditions are suitable for plant growth. It means that the soil is dry in some or all parts for 90 days or more in normal years and moist in some parts either for 90 days or more consecutive days or 180 cumulative days per year. Moisture regime is ustic in tropical and subtropical regions if there is atleast one rainy season of 3 months or more.

ii) Soils in upstream are classified as isohyperthermic (mean annual temp 22^{0}C).

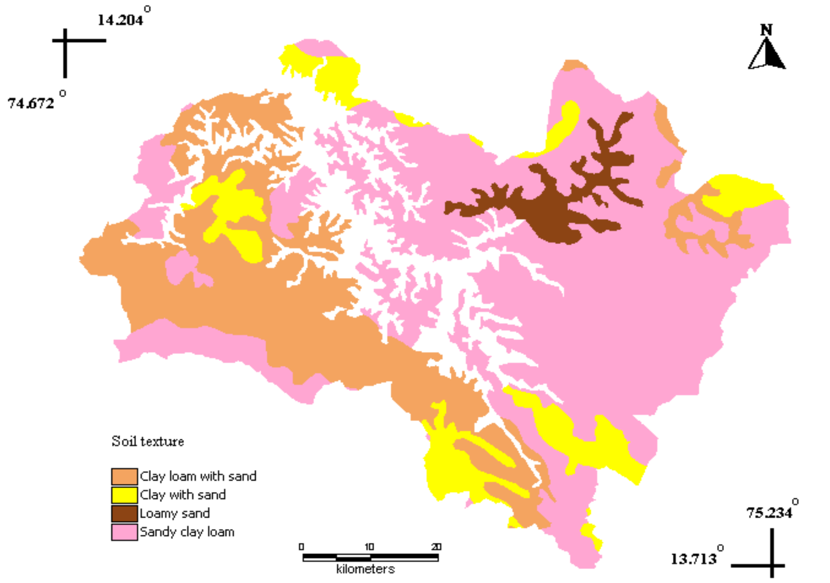
iii) The soils of Western Ghats are generally dark to brown to dark reddish brown and black in colour due to accumulation of high organic matter under forests cover.

Table 3.2 gives the soil taxonomy of upstream river basin.

Table 3.2 Soil Taxonomy of Sharavathi Upstream River Basin

Order	Sub order	Great groups	Sub groups
Alfisols	Ustalfs	Kandiustalfs Haplustalfs Paleustalfs	Typic kandiustalfs Kanhaplic haplustalfs Kandic paleustalfs
Ultisols	Humults	Palehumults Kandihumults	Ustic palehumults Ustic kandihumults
Inceptisols	Tropepts	Dystropepts Ustropepts	Ustoxic dystropepts Aquic ustropepts
Entisols	Fluvents	Ustifluvents	Aquic ustifluvents

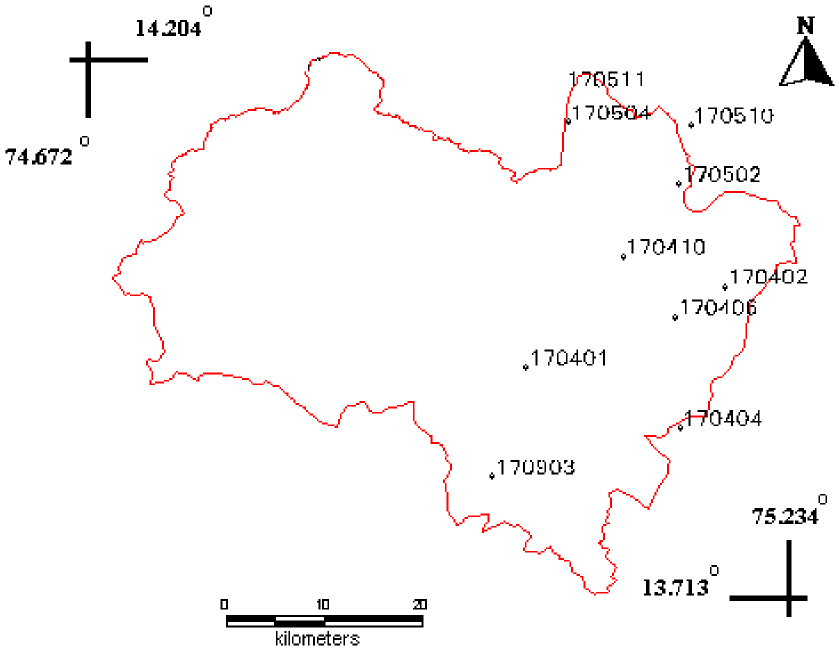
Figure 3.9: Soil Texture



3.6 Groundwater Conditions

Groundwater is present in the voids of rocks and soil and is an important source of irrigation in the basin. Figure 3.10 maps the wells in the region.

Figure 3.10: Location of Selected Wells in Upstream



3.7 Vegetation and Agricultural Activities

Evergreen-semievergreen forests are confined to the western part of the basin. Many of the hills are covered with heavy forests while ravines and valleys produce luxuriant trees known for their great height and size (KSG, 1975). Scattered shrubs and thickets are found in the regions surrounding the reservoir. Moist deciduous forests are found in the northern and eastern part of the study area.

Plantations include acacia, teak, areca, rubber, eucalyptus etc. Areca nut also called betel nut is a widely used article of consumption and is grown in valleys. Acacia plantation is found in patches, amidst evergreen forests and is mainly used for paper production. Plantation constitutes 7-9% of the total vegetation in the upstream. Evergreen /semievergreen and moist deciduous forests constitutes 11% and 25% respectively.

Paddy and areca are cultivated extensively in eastern parts of the upstream. Paddy is grown as a kharif crop and some pulses are grown during the rabi season. Rabi season is short and the land is mostly left fallow. Paddy is grown under rainfed and irrigated conditions both in kharif and summer season. In irrigated areas, paddy cultivation is followed by sugarcane during kharif season.

Figure 3.11: Upstream River Basin

Ambuthirtha- Origin of Sharavathi River

Thick evergreen forests at Nagodiholé

Sharavathi River

Part of Linganamakki reservoir

Island inside the reservoir (rainy season)

Island inside the reservoir (summer season)

Portions of former submerged forest seen during the dry season

Another view

Teak plantations

Portions of cleared forest

4.0: DATA AND METHODS

4.1 Data

Remote sensing and collateral data used for the analysis are:

Satellite data: Table 4.1 gives information on the satellite data used in the study.

Table 4.1: Satellite/Sensor Details

Satellite/sensor	Date of Pass	Path/Row	Bands	Source
Landsat TM	Nov, 1989	146/50	2,3, 4,5,6 and 7	http:// glcf.umiacs.umd.edu
IRS LISS III	Mar, 1999	97/63	1,2,3 and 4	NRSA, Hyderabad

Note: Data for March 1989, was not available for IRS LISS III, while for 1989, only Landsat data was available.

Figure 4.1: Landsat TM, 1989 FCC

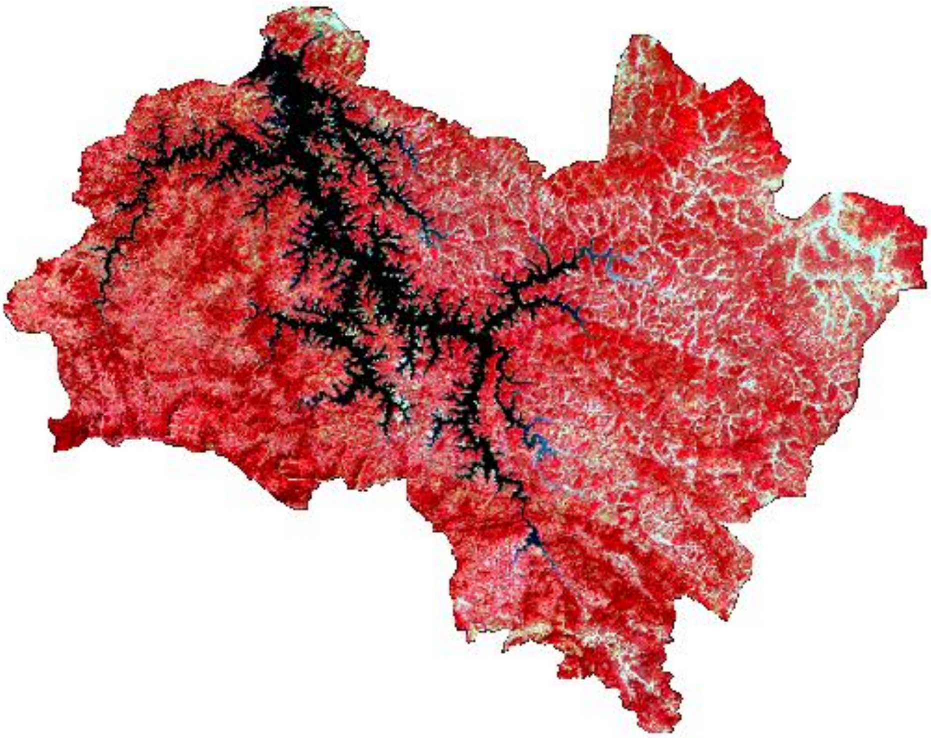
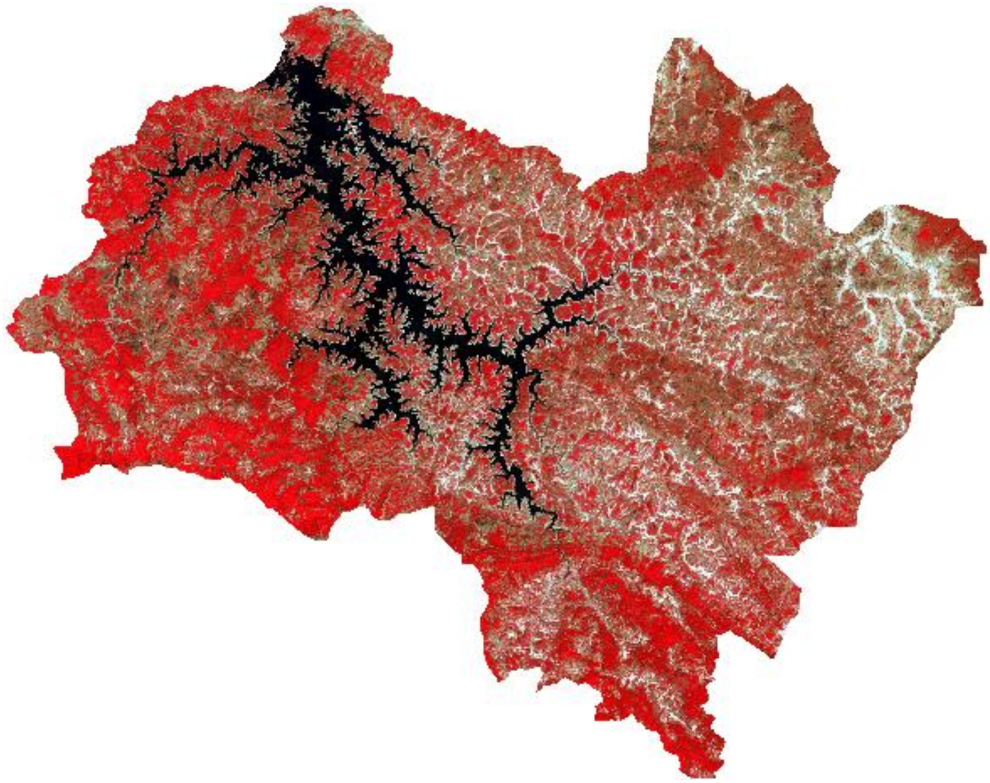


Figure 4.2: IRS LISS III, 1999 FCC



Note: TM – Thematic Mapper
IRS - Indian Remote Sensing Satellite
LISS - Linear Imaging Self Scanning

Toposheets: Survey of India toposheets of scale 1:50,000 have been used for geo referencing remote sensing data as well as for field investigations. Table 4.2 gives the list of toposheets used for the study.

Table 4.2: Toposheets of Upstream River Basin

	48 J/14		
48 J/11	48 J/15		
48 J/12	48 J/16	48 N/4	48 N/8
48 K/9		48 O/1	48 O/5
		48 O/2	48 O/6
		48 O/3	

Field and Ancillary Data: GPS points along with attribute information were collected upstream to determine the type of land cover and land use such as vegetation, which includes evergreen-semievergreen and moist deciduous forests and plantations, degraded vegetation, agricultural activities, settlements, etc.

Maps and other ancillary used for the study include:

i) Forest Map of South India (1982) by J.P. Pascal, French Institute of Pondicherry.
ii). Soil map published by the National Bureau of Soil Survey.
iii). Reconnaissance Soil Map of Forest Area, Western Karnataka and Goa
iv) Geology map, Department of Mines and Geology
v) Bioclimate of the Western Ghats (1982), J.P.Pascal, French Institute of Pondicherry.

Climate data:

i) IMD Talukwise rainfall data (1901-2001) for Sagara, Hosanagara, Soraba and
ii) Tirthahalli (Shimoga) and Honnavara, Kumta and Siddapur (Uttara Kannada).
iii) Daily rainfall data from Karnataka Power Corporation Limited for 18 rain gauge stations in Sharavathi river basin (1989-1999).
iv) IMD maximum and minimum temperature data (1969-2000) for Shimoga.
v) IMD extraterrestrial solar radiation and number of sunshine hours for Shimoga
vi) (1989-1999).
vii) Water table level data (1989-1999) for selected wells in and around the study area
viii) from Dept. of Mines and Geology.

4.2 Remote sensing data Analysis

4.2.1 Image Rectification and Restoration - This involves the initial processing of raw image data to correct for geometric distortions, to calibrate the data radiometrically and to eliminate the noise present in the data. In this study random and residual unknown systematic distortion are corrected by analysing well-distributed ground control points collected from known ground locations and GPS points in terms of latitude and longitude. These values are then submitted to a least squares regression analysis to determine coefficients for two co-ordinate transformation equations that can be used to interrelate the geometrically correct (map) coordinated and the distorted image co-ordinates (Lillesand and Kiefer, 2002). Expressing this in mathematical notation,

$$x = f_1(X,Y) \quad y = f_2 (X,Y) \qquad (4.1)$$

(x,y) – distorted image co-ordinates (column, row)

(X,Y) –corrected (map) co-ordinates

f_1,f_2 – transformation functions

The next step is to decide how best to estimate the values of pixels in the corrected image based upon information in the uncorrected image. This is done through resampling, using nearest neighbour technique as it was considered computationally most efficient and also due to its simplicity and ability to preserve original values in the unaltered scene.

Creation of false colour composite consisted of assigning colours to gray values from near infrared, red and green bands. This helped in identifying heterogeneous patches, which were chosen for ground data collection (training polygons).

4.2.2 Image Classification

The objective of this operation is to replace visual analysis of the image data with quantitative techniques for automating the identification of features in a scene. This normally involves the analysis of multispectral image data and application of statistically based decision. Common classification procedures can be broken down into two broad subdivisions: supervised classification and unsupervised classification.

In unsupervised classification, spectral classes are grouped first, based solely on numerical information in the data, and are then matched by the analyst to information classes (if possible). The basic premise is that values within a given cover type should be close together in the measurement space whereas data in different classes should be comparatively well separated. Unsupervised classification involves clustering algorithms that examine the unknown pixels in an image and aggregate them into a number of classes based on the natural groupings or clusters present in the image values (Lillesand and Kiefer, 2002).

In a supervised classification, homogeneous representative samples of the different surface cover types (information classes) of interest are identified. These samples are referred to as training areas. The selection of appropriate training areas is based on the knowledge of the geographical area and actual surface cover types present in the image. The computer uses a special program or algorithm (of which there are several variations), to determine the numerical "signatures" for each training class. Once the computer has determined the signatures for each class, each pixel in the image is compared to these signatures and labeled as the class it most closely "resembles" digitally.

There are various approaches for supervised classification viz. parallelopiped, minimum distance to mean, maximum likelihood etc. Maximum likelihood method was adopted for classification in this study. It tends to be more accurate if a large number of training sites are available. Here, the distribution of reflectance values in a training site is described by a probability density function, developed on the basis of Bayesian statistics. This classifier evaluates the probability that a given pixel will belong to a category with the highest probability of membership.

4.2.3 Accuracy Assessment

One of the most common means of expressing classification accuracy is the preparation of a classification error matrix (also called confusion or contingency matrix). Error matrix compare on a category-by-category basis, the relationship between known reference data (ground truth) and the corresponding results of an automated classification (Lillesand and Kiefer, 2002). Some descriptive measures can be obtained from the error matrix such as overall accuracy, user's accuracy and producer's accuracy.

Overall accuracy = total number of correctly classified pixels/total number of reference pixels

User's accuracy= correctly classified pixel in each category/total number of pixels classified in that category (row total)

Producer's accuracy =correctly classified pixels in each category (major diagonal)/number of training site pixels in that category (column total)

Example of an error matrix is shown in Figure 4.3.

Figure 4.3: Error Matrix

	Water	**Sand**	**Forest**	**Urban**	**Corn**	**Hay**	**Row Total**
Water							
Sand							
Forest							
Urban							
Corn							
Hay							
Column Total							

The diagonal elements represent the correctly assigned pixels.

4.3 Estimation of Hydrological Components

The hydrologic water balance equation is given as:

Input –Output = Change in Storage in the system (4.2)

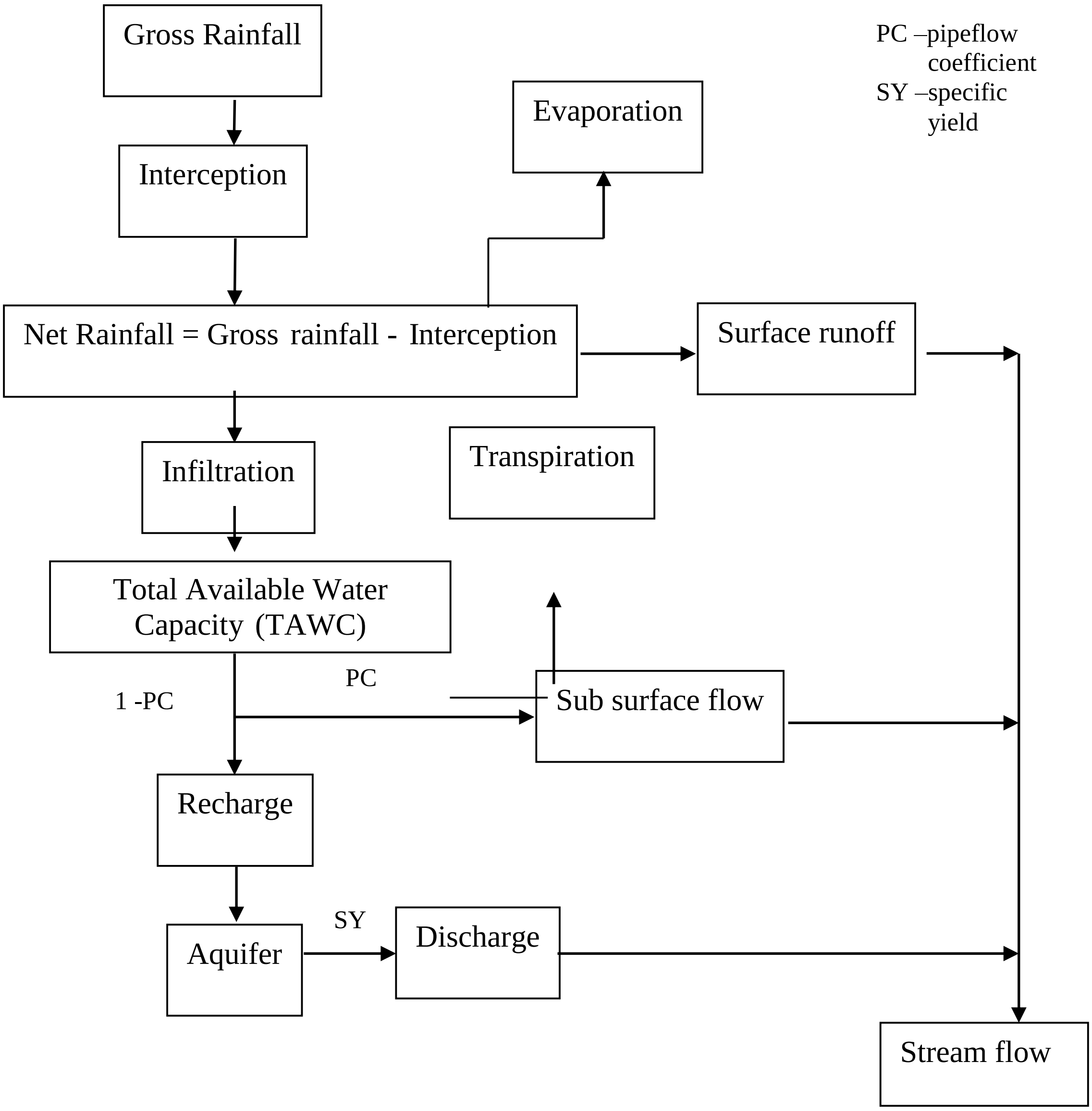
The following factors combine to express the water balance equation

Input: Direct precipitation and Groundwater discharge

Output: Interception; Surface runoff; Pipeflow (sub surface flow); Transpiration (vegetation);Evaporation (soil and open water); Groundwater recharge

Figure 4.4 gives the flow chart of the method used in estimating each hydrological component.

Figure 4.4: Flowchart of Method



4.3.1 Rainfall: The methods adopted to analyse rainfall includes:

a) nearest point method to determine areal precipitation
b) regression relationships to estimate rainfall relationship with other parameters

a) Nearest point method: Nearest point method attempts to define the area represented by each gauge in order to weigh the effects of non-uniform rainfall distribution. The rain gauge stations are plotted on a map and each gauge is connected to each adjoining gauge by a line (Singh, 1992). Perpendicular bisectors of these connecting lines are drawn to form a polygon around each gauge. The area within each polygon is assumed to be represented by each gauge. This percent area of a gauge defines its weighting factor A_i, i =1,2,3….n. It is given by the equation

$$P = \frac{P_1 A + P_2 A_2 .... + P_n A_n}{A} \quad (4.3)$$

where
$P_1, P_2 .. P_n$- precipitation (mm)
$A_1, A_2, ... A_n$-area enclosed by each polygon
A-total area

The weighted average rainfall for the drainage basin is computed by multiplying the rainfall at each station by its assigned area within the drainage basin, represented by the polygon area divided by the total drainage area and totaling the values.

b) Stepwise regression analysis was carried out for each rain gauge station considering rainfall as dependent variable and latitude, longitude, altitude and land cover as probable independent variables.

R = f(land cover, latitude, longitude and altitude) (4.4)

i.e. R = a_1(land cover) ±a_2(latitude) ±a_3(longitude) ±a_4(altitude) ± constant (4.5)

where a_1, a_2, a_3, a_4 – constants or coefficients of regression

4.3.2 Interception: Interception is considered as a function of canopy storage capacity C and evaporative fraction (α) (Singh, 1992) and is given by the equation:

$$I = C + \alpha P \quad (4.6)$$

The rate of evaporation of intercepted water from a wet canopy commonly exceeds the potential evaporation for open water surfaces and indeed often the energy locally available to support it (Shuttleworth, 1993). The additional energy is withdrawn from the atmosphere from warmer, drier wind upward. The net amount of water, which the canopy can store, i.e. the interception storage capacity, depends partly on the nature of rainfall, in particular the intensity and duration of the rainstorm since upto half the evaporation occurs during the storm itself. For forests with complete canopy cover, intense, short-lived, convective storms, more common in tropical regions are associated with a lower fractional interception loss or evaporative fraction, say 10-18 percent of precipitation (Lloyd et al., 1988; Shuttleworth, 1989). Storms associated with frontal rainfall, which may be less intense but lasts longer tend to give a higher fractional interception loss of say 20-30 percent of precipitation (Calder and Newson, 1979; Gash et al., 1980). Table 4.3 lists the canopy storage capacities and evaporative fraction for different vegetation types in the study area.

The following assumptions have been made for interception loss under each vegetation type in upstream river basin. Major portion of the rainfall is received from the southwest monsoon, which is of low intensity and longer duration. Thus, the evaporative fraction is considered similar to that of frontal precipitation. Table 4.3 gives the interception characteristics of different vegetation types. Table 4.4 lists the equations for each vegetation types following the assumptions.

Assumptions

Evergreen/semievergreen forests

- Dominated by evergreen trees
- Leaves all year around- high storage capacity
- Thick and multi layered canopy- higher evaporative fraction

Moist deciduous forests

- Dominated by deciduous trees
- Full leaves during monsoon season- maximum storage capacity
- Large leaves- higher evaporative fraction

Plantations

- Dominated by monoculture trees
- Full leaves during monsoon season- maximum storage capacity
- Narrow and vertically aligned leaves- lower evaporative fraction

Agricultural crops

- Young leaves (July-August)- lower storage capacity and evaporative fraction
- Mature leaves (September)- higher storage capacity and evaporative fraction

Grasslands and scrubs

- Fully grown grass and scrubs-(June-September)- higher storage capacity and evaporative fraction
- Dry grass and scrubs (October)-lower storage capacity and evaporative fraction

Table 4.3: Interception Characteristics of Western Ghats

Vegetation types	* Canopy storage capacity (C) (mm)	**Evaporative fraction (α) or net interception loss (%)
Evergreen/semievergreen	4.5-5.5	20-30
Moist deciduous forests	4-5	20-30
Plantations	4-5	20-30
Grasslands and scrubs	2.5-3.5	10-18
Agricultural crops (paddy)	1.8-2	10-18

*Source: Putty and Prasad, 2000

** Source: Modified evaporative fraction from Shuttleworth, 1993.

Table 4.4: Interception Equations for Upstream River Basin

Vegetation types	Period	Interception
Evergreen/semievergreen forests	June-October	I = 5.5 + 0.3 (P)
Moist deciduous forests	June-October	I = 5 + 0.3 (P)
Plantations	June-October	I = 5 + 0.2 (P)
Agricultural crops (paddy)	June	0
	July-August	I = 1.8+ 0.1 (P)
	September	I = 2 + .18 (P)
	October	0
Grasslands and scrubs	June-September	I = 3.5 +0.18 (P)
	October	I = 2.5 + 0.1 (P)

4.3.3 Surface Runoff

Surface runoff has been determined by rational method, which assumes a suitable runoff coefficient to determine the catchment yield. It is given by the formula,

$$\text{Yield} = C*A*P \qquad (4.7)$$

where,

A-area of catchment/basin (km^2)

P-precipitation in mm

C-runoff coefficient

Table 4.5 gives the runoff characteristics under each land cover type in the study area. The following assumptions have been made.

Agricultural lands

- Fallow period – high runoff
- Crop growing period- low runoff

Grasslands and scrubs

- Monsoon season- low runoff
- Non monsoon season –high runoff

Table 4.5: Runoff Equations for Upstream River Basin

Land use/land cover	Period	C	Runoff
Evergreen/semievergreen forests	June-Oct	0.2	R = 0.2 *A*P
Moist deciduous forests	June-Oct	0.2	R = 0.2 *A*P
Plantations	June-Oct	0.2	R = 0.2 *A*P
Grasslands and scrubs	June-Sept	0.3	R = 0.3 *A*P
	Oct	0.6	R= 0.6 *A*P
Agricultural lands (paddy)	June	0.6	R= 0.6 *A*P
	July-Sept	0.4	R = 0.4 *A*P
	Oct	0.6	R= 0.6 *A*P
Settlements	June-Oct	0.8	R = 0.8 *A*P
Open fields	June-Oct	0.6	R = 0.6 *A*P

4.3.4 Sub Surface Runoff (Pipeflow)

Sub surface runoff is considered to be the fraction of water that remains after infiltrated water satisfies the available water capacities under each soil. The available water capacity (AWC) for each soil texture is given in Table 4.6.

Table 4.6: Available Water Capacity

Soil texture	AWC(%)
Loamy sand	9
Sandy clay loam	10
Clay loam with sand	10
Clay with sand	15

Source: http://soils.usda.gov/sqi/files/avwater.pdf

The total available water capacities (TAWC) under each land cover type in the study area are given in Table 4.7.

Table 4.7: Total Available Water Capacity

Cover type	Soil texture	TAWC (%)
Evergreen/semievergreen forests	Sandy clay loam	39
	Clay loam with sand	40
	Clay with sand	45
	Loamy sand	64
Moist deciduous forests	Sandy clay loam	45
	Clay loam with sand	35
	Clay with sand	45

	Loamy sand	64
Plantations	Sandy clay loam	45
	Clay loam with sand	35
	Clay with sand	45
	Loamy sand	64
Agricultural lands (paddy)	Sandy clay loam	44
	Clay loam with sand	30
	Clay with sand	40
	Loamy sand	34
Grasslands and scrubs	Sandy clay loam	44
	Clay loam with sand	30
	Clay with sand	40
	Loamy sand	34
Open fields	Sandy clay loam	44
	Clay loam with sand	30
	Clay with sand	40
	Loamy sand	34
Settlements	Sandy clay loam	44
	Clay loam with sand	30
	Clay with sand	40
	Loamy sand	34

Coefficients for pipeflow are determined from comparing the relief ratio of each sub basin. It has been observed that higher the relief ratio, lower the pipeflow coefficients and vice versa (Putty and Prasad, 2000). Table 4.8 shows the coefficients selected for Sharavathi river basin.

Table 4.8: Pipeflow Coefficients

Sub basins	**Relief ratio (%)**	**Pipeflow coefficient (%)**
Yenneholé	3.03	10
Hurliholé	3.39	10
Nagodiholé	9.9	10
Hilkunji	4.45	10
Sharavathi	2.98	10
Mavinaholé	1.66	30

Sub surface flow recession equation is given by:

$$V_t = V_o k^t \qquad (4.8)$$

The recession constant 'k' ranges from 0.5-0.85 for sub surface flow (Subramanya, 1994).

The procedure is similar to baseflow recession equation and is described in detail later in the chapter. The recession constant for interflow is chosen as 0.85

Slope map has been used to derive the area under forested slopes. Pipeflow is assumed to occur on gentle sloping to strongly sloping land and since it needs a gradient for water flow, it cannot occur on flat lands. Pipeflows have been calculated only under natural forests, since afforestation activities such as plantations have damaged pipes.

4.3.5 Transpiration

The evaporation rates from forests are more difficult to describe and estimate than for other vegetation types. The difficulty in estimation arises because the turbulent diffusion in the atmosphere above the forests is much more efficient than for crops. For this reason, the rate of evaporation when the canopy is wet can be much greater than when it is dry. Thus, it becomes necessary to separate transpiration from evaporation of rainfall by forest canopy rather than considering the average effect of controlling processes within the canopy in terms of a single (effective) surface resistance (Shuttleworth, 1993). Present evidence is not yet definitive but suggests (Shuttleworth, 1989; Shuttleworth and Calder, 1979) that the transpiration rate of well watered forests is perhaps 80 ± 10 percent of reference crop evaporation, provided this has been calculated with an appropriate (forest) value of albedo.

Reference evaporation is determined using Turc's method (Turc, 1961) an empirical based radiation based equation, which is shown to perform well in humid climates (Homes, 1961).

$$E_{rc} = 0.4 \frac{T}{T+15}\left(S_n + 50\right) \qquad (4.9)$$

where

T – mean temperature (^{0}C)

$$S_n = S_t\left(1-\alpha\right) \qquad (4.10)$$

α -albedo

S_n – net shortwave radiation

$$S_t = \left(0.25 + 0.5\frac{n}{N}\right)S_0 \qquad (4.11)$$

Where, n – no. of sunshine hours (h)

N – maximum possible sunshine hours or day length (h)

S_o – extra terrestrial radiation (MJ/m^2/day)
λ -latent heat of vapourisation of water (2.501 MJ/kg)
ρ_w- density of water (≈ 1000 kg/m^3)

Thus, transpiration from forests is given by the equation

$$E_{forest} = (0.8 \pm 0.1)\, E_{rc} \qquad (4.12)$$

Crop Transpiration

Crop transpiration is computed considering crop coefficient with reference crop evaporation and is given by the equation

$$E = K_c\, E_{rc} \qquad (4.13)$$

where, E_{rc}- reference crop evaporation
K_c – crop coefficient (grasses = 0.8)

The following assumptions have been made in the selection of albedo values for reference crop evaporation under each vegetation type based on the months and season in the study area.

Assumptions

Evergreen/semievergreen forests

- Dominated by evergreen trees
- Leaves all year around- low albedo

Moist deciduous forests

- Clear felled with secondary vegetation (albedo increased by 0.02) (Dickinson, 1980)
- Dominated by deciduous trees
- Full leaves during monsoon season- low albedo
- Non monsoon season-high albedo

Plantations

- Mostly deciduous trees eg. acacia, eucalyptus
- Plantation is considered to be more open than an intact evergreen or moist deciduous forests and hence the albedo is increased by 0.03.
- Full leaves during monsoon season- low albedo
- Non monsoon season-high albedo

Agricultural crops

- Fallow period- high albedo
- Crop growing period (young leaves)-high albedo
- Mature crops-low albedo
- Paddy is assumed to grow during July-September considering it as a 90 days crop

Grasslands and scrubs

- Monsoon season (June-September)- low albedo
- Non monsoon (dry grass)(October)-high albedo

Table 4.9 lists the albedo values selected for vegetation according to months.

Table 4.9: Albedo Values for Vegetation

Vegetation types	Albedo Range	Albedo	Period
Evergreen forests	0.11-0.16	0.11	Jan-Dec
Moist deciduous forests	0.11-0.16	0.13*	May-October
		0.16	November-April
Plantations	0.11-0.16	0.14*	May-October
		0.16	November-April
Grasslands and scrubs	0.20-0.26	0.20	June-September
		0.26	October-May
Agricultural land (paddy)	0.20-0.26	0.08	June
		0.20	July-August
		0.26	September
		0.08	October

Source: Shuttleworth,1993 in Handbook of Hydrology
** Dickinson, 1980*

4.3.6 Evaporation

Turc's method is used to estimate evporation from soil and open water with the appropriate albedo values. Table 4.10 lists the albedo values selected for other land covers.

Open field and settlements

- Monsoon season- low albedo
- Non monsoon season- high albedo

Table 4.10: Albedo Values for Other land covers

Cover type	Albedo range	Albedo	Period
Open water	0.08	0.08	Jan-Dec
Open fields	0.1-0.35	0.1	June-October
		0.35	November-May
Settlements	0.1-0.35	0.1	June-October
		0.35	November-May

Source: Shuttleworth, 1993

4.3.7 Groundwater Recharge

Recharge is considered the fraction of infiltrated water that recharges the aquifer after satisfying available water capacity and pipe flow.

4.3.8 Groundwater Discharge

Groundwater discharge or base flow is estimated by multiplying the average specific yield of aquifer under each land cover with the recharged water. Specific yield represents the water yielded from water bearing material. In other words, it is the ratio of the volume of water that the material, after being saturated, will yield by gravity to its own volume. Base flow appears after monsoon and pipe flow has receded. This water sustains flow in the rivers during the dry season. Groundwater storage-discharge is considered to be linear after Maillet (1905) since it is widely used following tradition and due to the ease of mathematical manipulation (Wittenburg and Sivapalan, 1999). The exponential function has been widely used to describe base flow recession, where Q_t is discharge at time 't' and Q_0 is the initial discharge and a is a recession constant. The exponential function describes that the groundwater aquifer behaves like a single linear reservoir with storage linearly proportional to outflow i.e.

$$S = a\,Q \qquad (4.14)$$

This equation represents a first order process or an exhaustion phenomenon expressed by

$$\frac{ds}{dt} = -Q \qquad (4.15)$$

$$Q(0) = Q_0$$

The most widely used base flow recession equations are of the exponential forms such as Equation 4.16 by Barnes, (1939).

$$Q_t = Q_0\,k^t \qquad (4.16)$$

where, Q_0- initial discharge

k – base flow recession constant (0.85-0.99) (Subramanya, 1994).

t - time

In the absence of discharge data, volumes can be used. Replacing discharge with volume does not change its form and is less sensitive to errors than when using discharge data (Singh, 1992). Shirmohammadi et al. (1984) used volumes for partitioning stream flow data in surface and sub surface flows.

Groundwater volume at any time 't' is determined by the equation :

$$V_t = V_o\,k^{t} \qquad (4.17)$$

Assumptions

- The entire river basin is considered to be an unconfined aquifer
- Base flow recession constant is assumed to be 0.95

Table 4.11 gives the average specific yields of each sub basin.

Table 4.11: Average Specific Yields of Sub basins

Sub basins	Rock type (French Soil Map)	Avg. Specific yield (%)
Yenneholé	Gneisses/granites Greywackes	15
Nagodiholé	Greywackes	27
Hurliholé	Gneisses/granites Greywackes	15
Hilkunji	Gneisses/granites Greywackes	15
Sharavathi	Gneisses/granites Greywackes	15
Linganamakki	Gneisses/granites Greywackes	15
Mavinaholé	Gneisses/granites	3
Haridravathi	Gneisses/granites	3
Nandiholé	Gneisses/granites	3

5.0 Results and Discussions

Analysis was carried out for different hydrological components using the methods described earlier.

5.1 Land use dynamics:

Figure 5.1: Reserve Forest Area (1940)

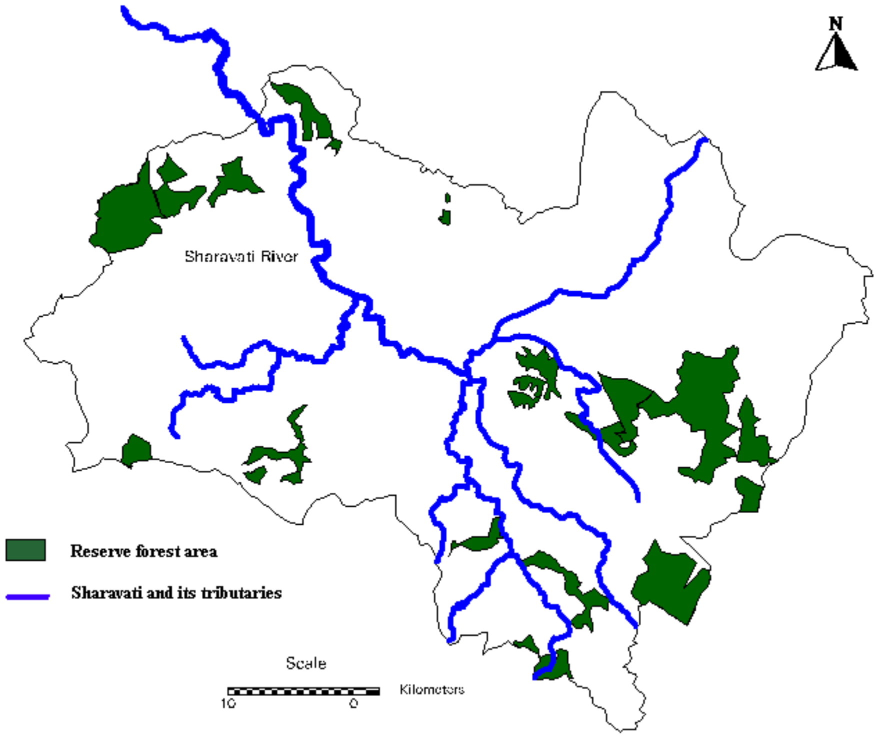


Table 5.1 gives the percentage forest cover (reserved forests) derived from 1940 toposheets (48K/13, 48J/16 and 48O/1), 1989 (Landsat TM) and 1999 (LISS III) imageries. More than 50% of the forests have decreased/removed by human activities and submergence due to damming the Sharavathi River.

Table 5.1: Changes in Reserve Forests Area (1940-1999)

1940 (sq.km)	1989 (sq.km)	1999 (sq.km)	Change in % (1935-1999)
185.09	99.46	89.73	-51.52%

Land use/Land cover maps of Sharavathi river basin (upstream) for 1989 and 1999 are given in Figure 5.2 and 5.3

Figure 5.2: Land use Classification (Landsat TM, 1989)

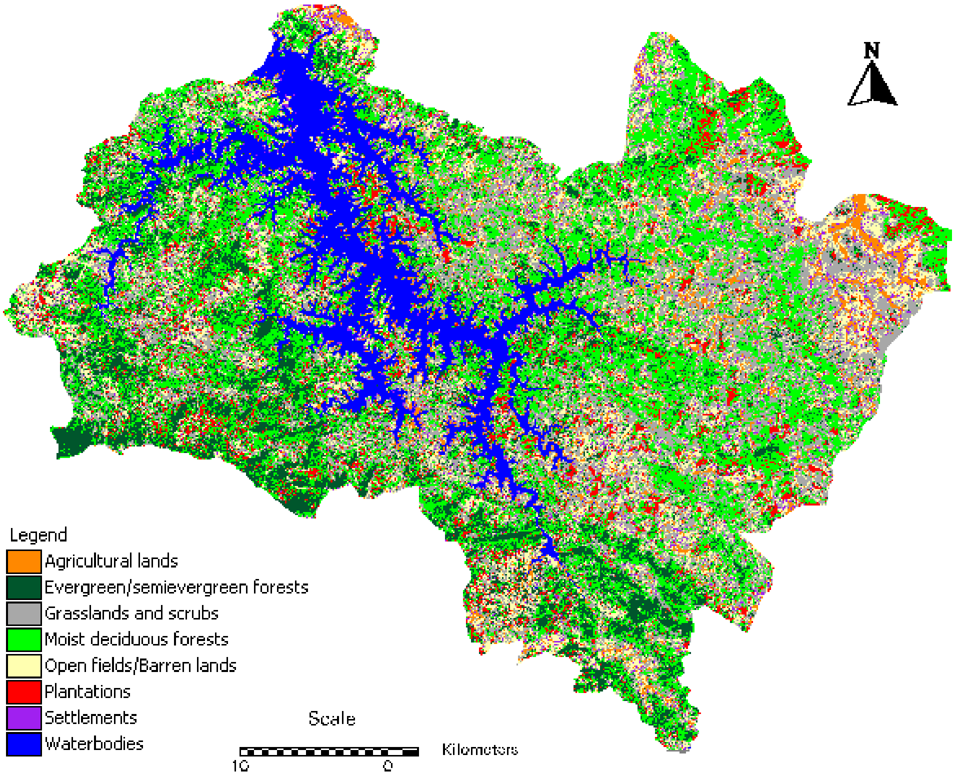
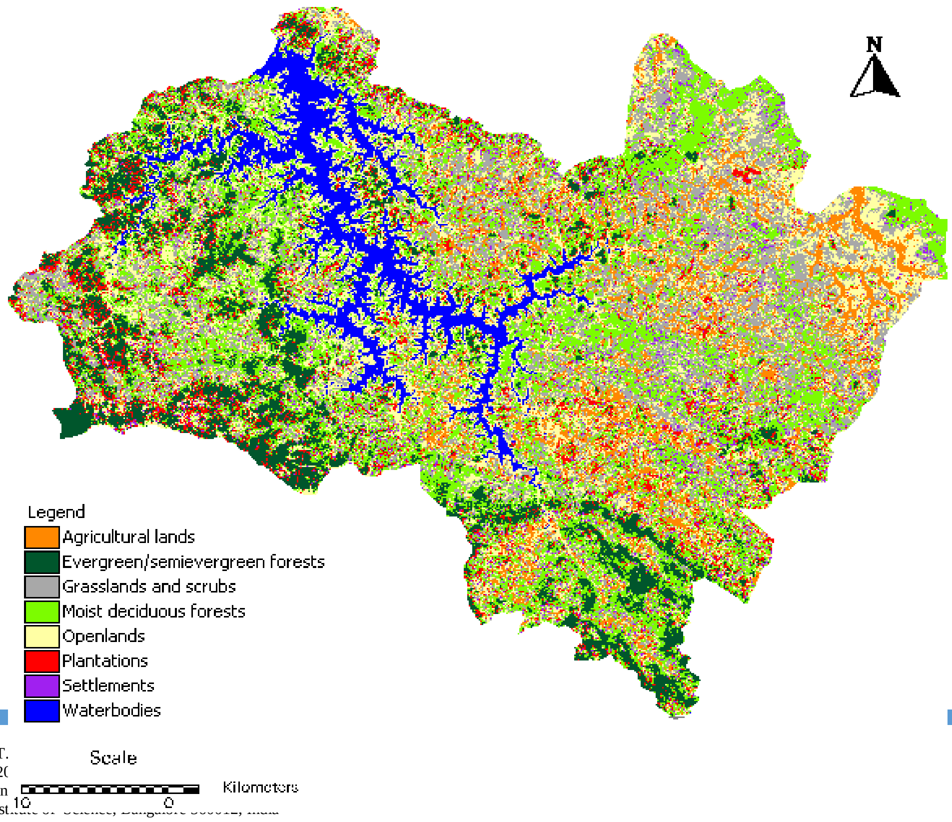


Figure 5.3: Land use Classification (IRS LISS III, 1999)



Results of Error Matrix (Landsat TM, 1989)

Table 5.2: Error Matrix (Landsat TM, 1989)

	Evg/SE	MD	Plant	Grass	Agri	Open	Sett	Water	Total
Evg/SE	4125	0	0	0	0	0	0	0	4125
MD	208	319	2	0	0	0	0	0	529
Plant	2	1	85	0	0	0	0	0	88
Grass	0	0	0	17	0	0	0	0	17
Agri	0	0	0	0	326	0	0	0	326
Open	0	0	0	1	1	62	0	0	64
Sett	0	0	0	0	0	9	8	0	17
Water	0	0	0	0	0	0	0	1211	1211
Total	4333	320	87	18	327	71	8	1211	6377

Note: Evg/SE - evergreen/semievergreen forests; MD – moist deciduous forests; Plant – plantations; Grass – grasslands and scrubs; Agri – agricultural lands; Open – open fields; Sett- settlements

Overall accuracy = 96.4%

Results of Error Matrix (IRS LISS III, 1999)

Table 5.3: Error Matrix (IRS LISS III, 1999)

	Evg/SE	MD	Plant	Grass	Agri	Open	Sett	Water	Total
Evg/SE	553	0	19	0	0	0	0	0	572
MD	0	586	0	0	0	1	0	0	587
Plant	17	0	101	0	0	0	0	0	118
Grass	0	0	0	191	0	0	0	0	191
Agri	0	0	0	1	168	0	0	0	169
Open	0	0	0	0	0	278	0	48	326
Sett	0	14	0	0	0	0	7	0	21
Water	0	0	0	0	0	0	0	981	981
Total	570	600	120	192	168	279	7	981	2965

Note: Evg/SE - evergreen/semievergreen forests; MD – moist deciduous forests; Plant – plantations; Grass – grasslands and scrubs; Agri – agricultural lands; Open – open fields; Sett- settlements

Overall accuracy = 97.6%

Low accuracy for settlements from both the imageries is partly due to spectral signature overlap with vegetation as most of the houses are surrounded by vegetation inside and outside the compound. Townships are few and houses are sparsely distributed separated by hundreds of meters. Since the building material is also different as almost all houses have tiled roof than concrete, overlap also occurred between open fields. Overlap of spectral signatures was also observed between evergreen/semievergreen forest and moist deciduous forests in full leaf.

Table 5.4 compares the percentage change in the land use in Sharavathi upstream river basin.

Table 5.4: Changes in Land use in Upstream (1989-1999)

Land use/Land cover	1989 (km^2)	1990 (km^2)	Change in %
Evergreen/semievergreen forests	272.67	209.39	- 23.2
Moist deciduous forests	539.26	512.25	- 5
Plantations	122.09	143.29	+17.3
Grasslands and scrubs	433.98	310.6	- 28.4
Agricultural lands	102.77	157.36	+ 53.1
Open fields/Barren lands	247.96	430.29	+ 73.5
Settlements	52.63	78.48	+ 49.1
Water bodies	218.01	147.31	-32.4

From Table 5.4, it is seen that natural forests such as evergreen/semi-evergreen and moist deciduous forests have decreased by 28.2% whereas monoculture plantations (due to afforestation work of the forest department) have increased by 17.3%. Grasslands and scrubs have decreased by 28.4% in 1999 but this can be attributed to the season as in summer, grasses dry out leaving only the scrubs. The main anthropogenic activity apart from plantation is paddy cultivation, which has increased by 5% in 1999. Paddy cultivation is the most common agricultural activity in the basin and is usually grown in valleys. Shimoga ranks first among the other districts of the state as far as paddy is concerned (KSG, 1975).

Human population has also increased in the basin and has been reported that there has been immigration of people from adjoining districts of Karnataka and also from neighbouring States (KSG, 1975). In recent years, few people from drought affected districts of Gulbarga and Bidar to Shimoga district to work on daily wages. A large number of seasonal in-migrants visit the villages at different seasons of the year. They arrive in large numbers in October-November and continue to stay there upto the end of about February-March. Some factory workers from Bhadravati town also come to villages to work on the agricultural lands during peak harvesting season.

Another major activity that has been beneficial to the villages in Sharavathi and also adjoining districts is the setting up of the Linganamakki Dam across the Sharavathi River. The Sharavathi Hydroelectric Project formerly known as Honnemaradu Project was taken up by the State Government in 1956, to utilize the potential of the river. It has been one of the important undertakings of the state in the field of economic development (KSG, 1975). A dam of nearly 2.4 kms long has been put across this river at Linganamakki in Sagar taluk of Shimoga district. It was so designed as to impound 4368 million cubic meter of water in an area of around 300 km^2, submerging 50.62 km^2 of wetland, 7 km^2 of dry land and 3.9 km^2, the remaining being forest land and wasteland.

Although the dam has provided electricity, water and other benefits to the surrounding areas, it has proved to be at the cost of the valuable ecosystem. Evergreen forests are being cleared to yield timber, which are used for electric transmission poles and railway sleepers. The felled areas are sometimes tended for getting the natural regeneration of valuable species. Deciduous forests supply timber, firewood, charcoal, bamboo, matchwood and plywood. Plantations of teak, silver oak (*Gravillea robusta*), matchwood etc are sometimes replaced for clear felled forests.

Table 5.5 and Table 5.6 give the sub-basin wise area under different land uses. Table 5.7 gives the overall change in 1999.

Note: Evg/SE - evergreen/semievergreen forests; MD – moist deciduous forests; Plant – plantations; Grass – grasslands and scrubs; Agri – agricultural lands; Open – open fields; Sett- settlements

Table 5.5: Area of Land use in Sub Basins (sq.km) 1989

Sub Basins	Evg/SE	MD	Plant	Grass	Agri	Open	Sett
Yenneholé	50.78	59.21	12.87	34.51	3.86	26.66	4.01
Nagodiholé	25.13	19.26	6.62	7.59	0.07	4.67	0.61
Hurliholé	24.88	31.73	8.3	17.55	1.52	9.95	1.47
Linganamakki	88.25	187.76	43.31	149.01	42.32	89.83	20.73
Hilkunji	24.59	25.41	5.1	14.35	4.041	10.69	1.84
Sharavathi	21.67	34.32	9.9	39.47	6.94	22.81	4.25
Mavinaholé	10.75	38.09	7.17	23.39	3.84	10.05	1.57
Haridravathi	15.85	74.47	16.79	101.21	28.36	48.32	12.68
Nandiholé	10.37	67.96	11.54	46.33	10.97	24.5	5.33

Table 5.6 Area of Land use in Sub Basins (sq.km)
1999

Sub Basins	Evg/SE	MD	Plant	Grass	Agri	Open	Sett
Yenneholé	54.22	45.52	29.27	22.82	2.07	38.5	6.05
Nagodiholé	26.17	15.21	8.87	3.09	.03	8.42	2.81
Hurliholé	22.14	30.45	7.99	13.37	1.24	18.26	3.08
Linganamakki	50.47	202.38	55.41	13.37	50.47	194.91	25.72
Hilkunji	25.79	30.02	5.57	6.53	4.94	9.9	3.67
Sharavathi	16.29	40.66	14.16	16.35	19.37	27.31	7.06
Mavinaholé	2.36	33.9	4.87	20.47	10.3	18.08	6.62
Haridravathi	3.87	64.87	11.65	79.9	49.93	73.39	14.34
Nandiholé	2.22	48.48	5.19	52.71	18.71	41.03	8.96

Table 5.7: Changes in Land use in Sub Basins sq.km
1999

Sub Basins	Evg/SE	MD	Plant	Grass	Agri	Open	Sett
Yenneholé	3.44	-13.69	16.4	-11.69	-1.79	11.84	2.04
Nagodiholé	1.04	-4.05	2.25	-4.5	-0.04	3.75	2.2
Hurliholé	-2.74	-1.28	-0.31	-4.18	-0.28	8.31	1.61
Linganamakki	-37.78	14.62	12.1	-135.64	8.15	105.08	4.99
Hilkunji	1.2	4.61	0.47	-7.82	0.89	-0.79	1.83
Sharavathi	-5.38	6.34	4.26	-23.12	12.43	4.5	2.81
Mavinaholé	-8.39	-4.19	-2.3	-2.92	6.46	8.03	5.05
Haridravathi	-11.98	-9.6	-5.14	-21.31	21.57	25.07	1.66
Nandiholé	-8.15	-19.48	-6.35	6.38	7.74	16.53	3.63

5.2 Rainfall

i) Talukwise rainfall analysis

Yearly data for hundred years were available for 7 taluks in and around the river basin viz. Hosanagara, Sagara, Soraba and Tirthahalli (Shimoga district) and Honnavar, Kumta and Siddapur (Uttara Kannada district). Since these are the taluks surrounding the river basin, rainfall analysis is done to study any variation in rainfall for 100 years. The rainfall periods were divided into 1901-1964 and 1964-2001, which represents respectively the periods before construction and after construction of Linganamakki dam.

The graphs depict the rainfall variation in all taluks for the 2 periods. The highest rainfalls in Hosanagara occured in 1961 and 1994 with 5175 mm and 5110 mm respectively. Sagara experienced high rainfall of 4826 mm in 1962 and low rainfall of 993m in 1976. Low rainfall was also recorded in Soraba consecutively for 4 years during 1979-1982 with the lowest recorded in 2001. Tirthahalli recorded maximum rainfalls of 6400 and 6115 during the first period (1901-1963) and a maximum rainfall of 4044 during the second period (1965-2001).

Analysis of 100 years rainfall in the various taluks in and around the river basin were done to study any discrepancies in the rainfall for two periods viz. 1901-1964 (before construction of dam) and 1964-2001 (after construction of dam).

Figure 5.4: Annual rainfall (Hosanagara)

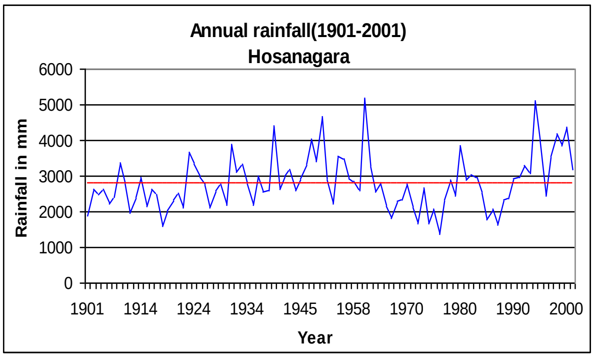


Figure 5.5: Annual rainfall (Sagara)

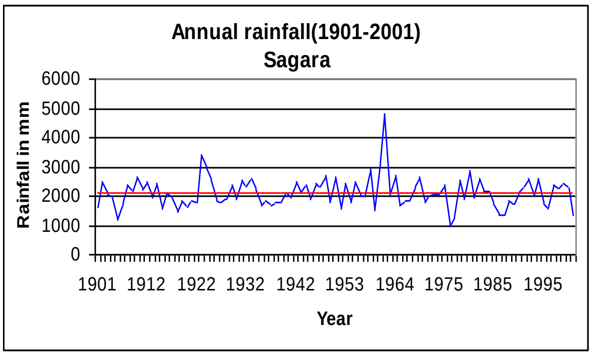


Figure 5.6: Annual rainfall (Soraba)

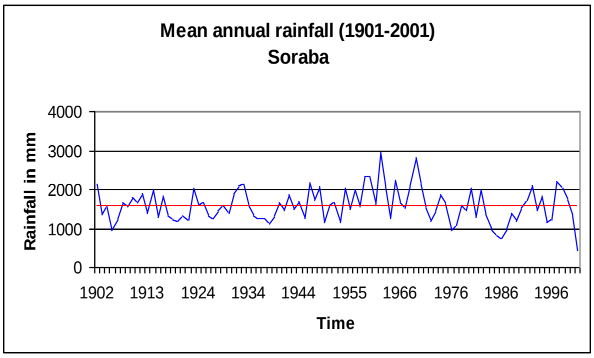


Figure 5.7: Annual rainfall (Tirthahalli)

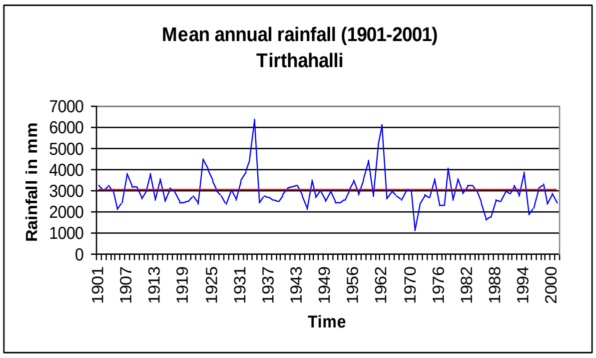


Figure5.8: Annual rainfall (Honnavar)

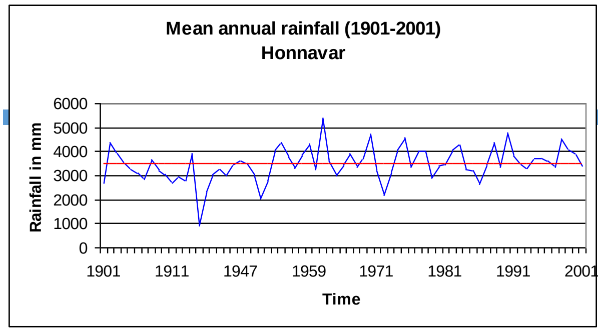


Figure5.9: Annual rainfall (Kumta)

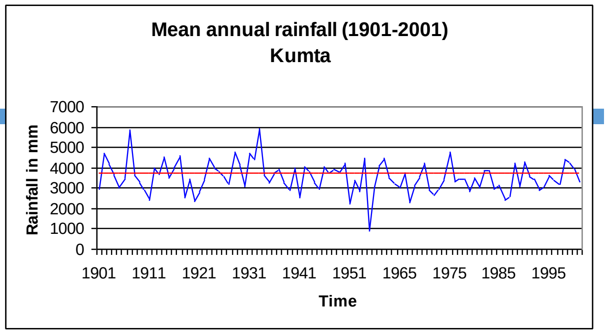


Figure 5.10: Annual rainfall (Siddapur)

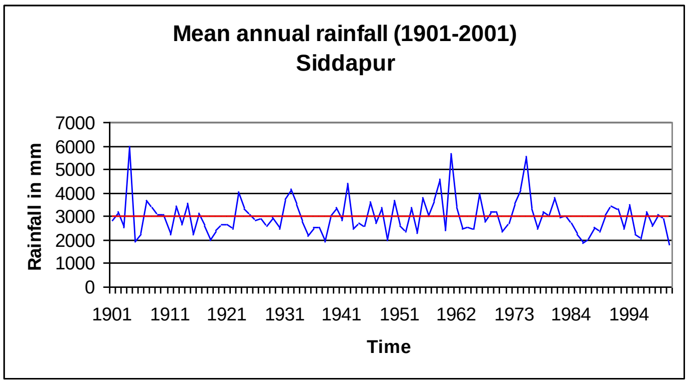


Figure 5.11: Mean annual rainfall (1901-1964) (Hosanagara)

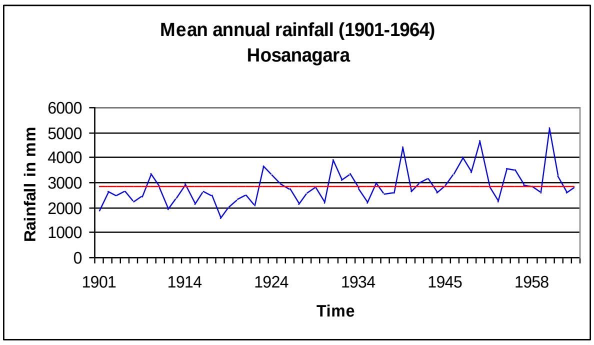


Figure 5.12: Mean annual rainfall (1965-2001) (Hosanagara)

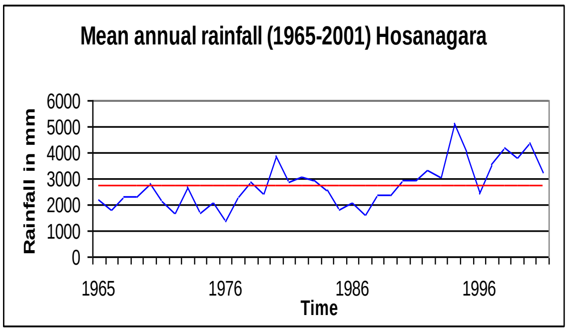


Figure 5.13: Mean annual rainfall (1901-1964) (Sagara)

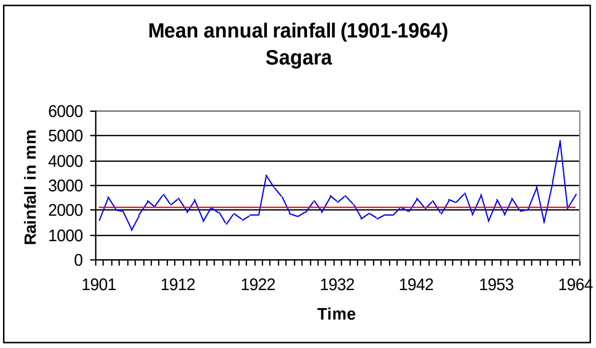


Figure 5.14: Mean annual rainfall (1964-2001) (Sagara)

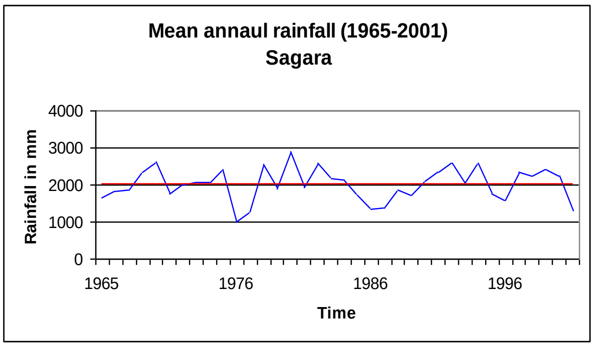


Figure 5.15: Mean annual rainfall (1901-1964) (Soraba)

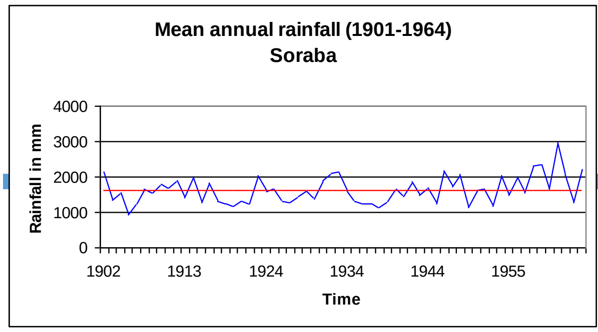


Figure 5.16: Mean annual rainfall (1964-2001) (Soraba)

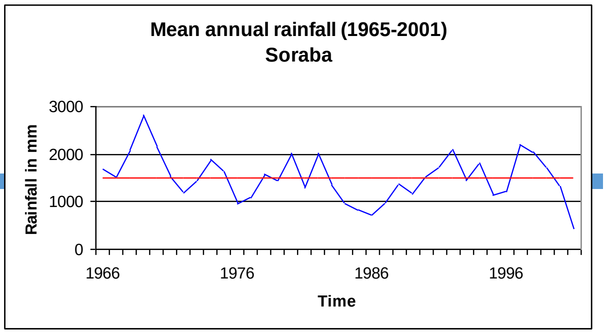


Figure 5.17: Mean annual rainfall (1901-1963) (Tirthahalli)

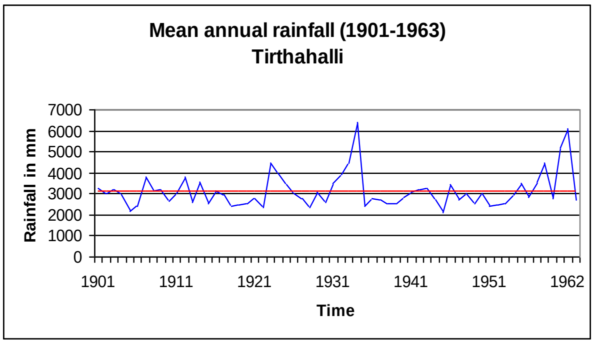


Figure 5.18: Mean annual rainfall (1965-2001) (Tirthahalli)

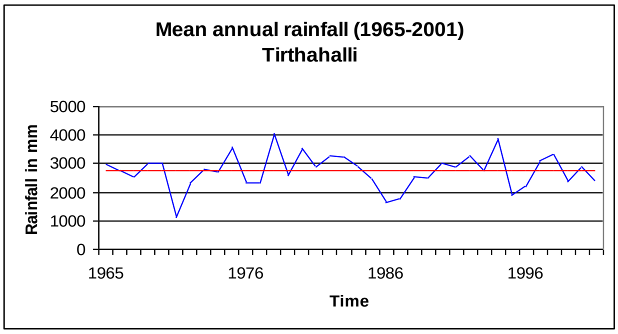


Figure 5.19: Mean annual rainfall (1901-1963)(Honnavar)

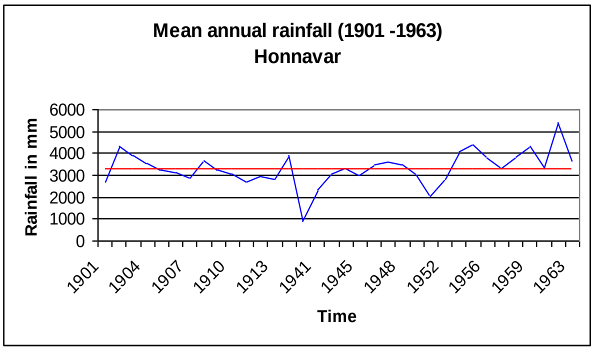


Figure 5.20: Mean annual rainfall (1965-2001)(Honnavar)

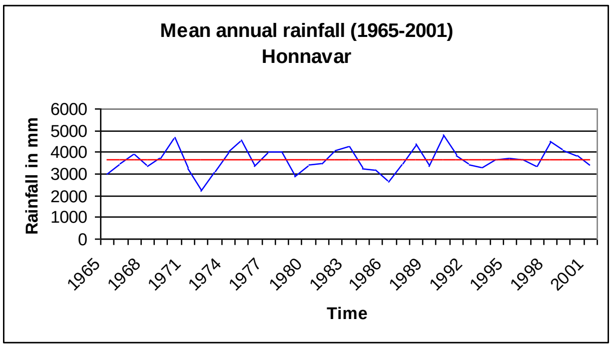


Figure 5.21: Mean annual rainfall (1901-1963) (Kumta)

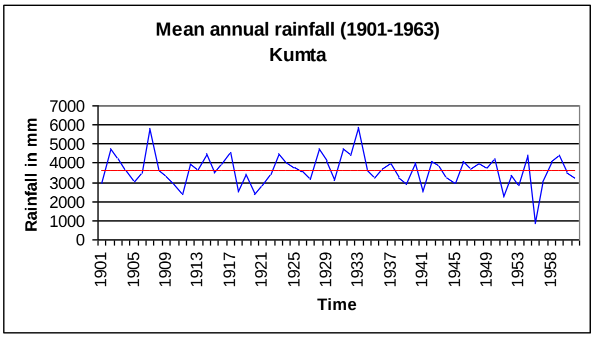


Figure 5.22: Mean annual rainfall (1965-2001) (Kumta)

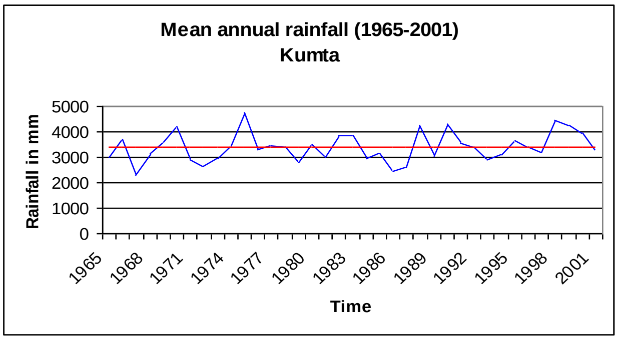


Figure 5.23: Mean annual rainfall (1901-1963) (Siddapur)

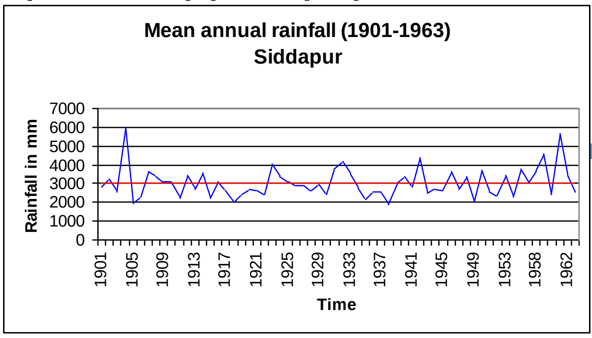


Figure 5.24: Mean annual rainfall (1963-2001) (Siddapur)

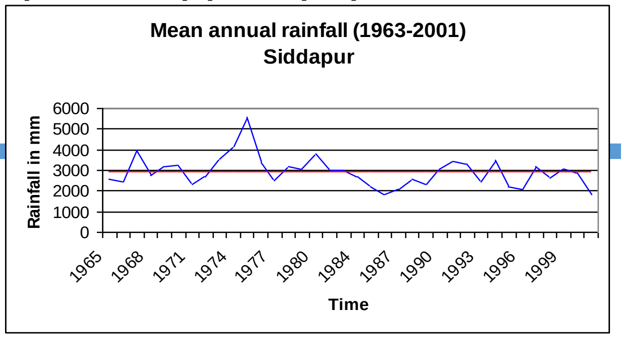


Table 5.8 gives the mean and standard deviation of rainfall in Shimoga district

Table 5.8: Variation of Rainfall in Shimoga

Taluk	1901-2001 (mm)	COV (%)	1901-1964 (mm)	COV (%)	1965-2001 (mm)	COV (%)	Change in rainfall (%)
Hosanagara	2813.9 ± 754.4	26.8	2854.2 ± 683.4	23.9	2752.8 ± 859.9	31.2	-3.55
Sagara	2098.1 ± 523.6	24.9	2144.5 ± 560.3	26.1	2018.4 ± 444.2	22	-5
Soraba	1583.8 ± 430.0	27.1	1627.3 ± 388.6	23.8	1511.4 ± 488.6	32.3	2.4
Tirthahalli	3051.8 ± 783.6	25.6	*3132.9 ± 841.4	26.8	2742.6 ± 607.0	22.1	-12.45

* 1901-1963

Table 5.9 gives the mean and standard deviation of rainfall in Uttara Kannada district

Table 5.9: Variation of Rainfall in Uttara Kannada

Taluk	1901-2001 (mm)	COV (%)	1901-1963 (mm)	COV (%)	1965-2001 (mm)	COV (%)	Change in rainfall (%)
Honnavar	3485.1 ± 687.8	19.7	3360.6 ± 775.4	23	3636.3 ± 565.5	15.55	8.2
Kumta	3755.9 ± 750.7	19.9	3633.8 ± 831.9	22.8	3391.1 ± 575.3	16.9	-6
Siddapur	2999.8 ± 769.9	25.6	3037 ± 793.2	26.1	2935.6 ± 734.4	25	-3.3

Hosanagara, Sagara, Tirthahalli and Siddapur taluks showed reduction in the mean annual rainfall with a significant reduction in Tirthahalli taluk. Sagara and Hosanagara were selected for further studies as these districts cover the study area. A student's t test was carried out to determine whether the changes in mean annual rainfall are significant for 2 periods viz. 1901-1964 and 1964-2001. The test produced the following results.

Table 5.10: t Test for Rainfall Variation

Taluks	T	Degrees of freedom (df)	$t_{0.95}$	$t_{0.99}$
Hosanagara	0.00062	91	1.662	2.368
Sagara	1.3	96	1.61	2.366

Null hypothesis H_0-no significant change in mean annual rainfall during the 2 periods
Alternative hypothesis H_1-significant change in mean annual rainfall during the 2 periods

Hosanagara
At df=91, $t_{0.05}$ = 1.662, i.e. 0.00062<1.662, null hypothesis is accepted
$t_{0.01}$ = 2.368, i.e. 0.00062<2.368, null hypothesis is accepted

Sagara
At df=96, $t_{0.05}$ = 1.61, i.e. 1.3 <1.662, null hypothesis is accepted
$t_{0.01}$ = 2.366, i.e. 1.3<2.368, null hypothesis is accepted

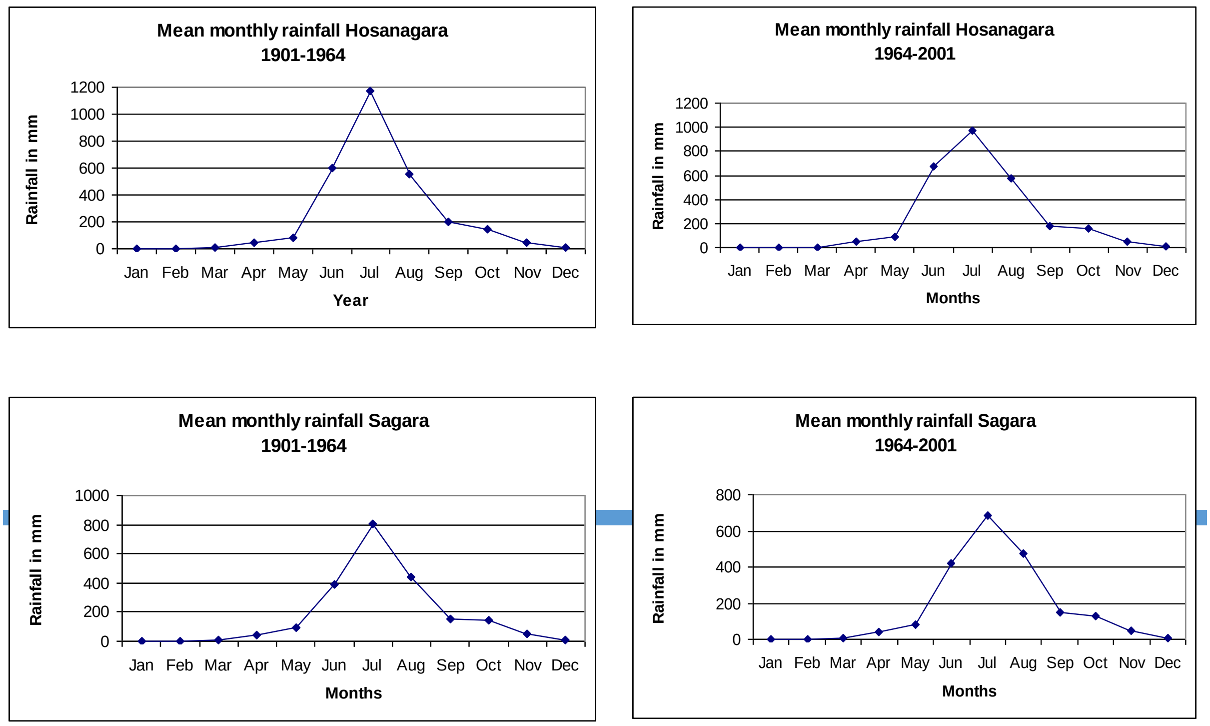
At 0.05% and 0.01% the null hypothesis is accepted for both the taluks.

Coefficient of variation was also calculated for all taluks. Coefficient of variation (COV) is the standard deviation divided by the mean. In practice, it "scales" the standard deviation by the size of the mean, making it possible to compare coefficients of variation across variables measured on different scales. Taluks in Shimoga district showed higher coefficient of variations as compared to Uttara Kannada with the exception of Siddapur. High CV shows that there is high rainfall variation from the mean rainfall. However, Hosanagara and Sagara showed the highest rainfall variation during 1965-2001.

Mean monthly rainfalls show a reduction of 200 mm and 100 mm in July (peak rainfall month) in Hosanagara and Sagara respectively.

ii) Mean monthly rainfall variation in Hosanagara and Sagara

Figure 5.25: Mean Monthly Rainfall of Sagara and Hosanagara



The mean monthly variation shows that the bulk of the rainfall occurs in the months of June, July and August. Rainfall peaks in the month of July and decreases then onwards with a slight increase in October (beginning of northeast monsoon). Both Hosanagara and Sagara show decrease in the peak rainfall month by 200 mm and 100 mm respectively during (1964-2001). Table 5.11 compares the change in monthly rainfall for the two taluks.

Table 5.11: Changes in Mean Monthly Rainfall (Hosanagara and Sagara)

Taluks	Mean rainfall in mm (June, July and August)		
	1901-1964	1965-2001	Change in %
Hosanagara	775.33	740.4	- 4.5%
Sagara	547.0	526.4	- 3.8%

iii) Sub-basin rainfall analysis

Rainfall data were available for 18 rain gauge stations from 1989-1999. Due to non-availability of data for certain months, analysis is done with respect to 5 months viz. June, July, August, September and October. Areal precipitation was determined for each sub basin and upstream. Figure 5.26 depicts the rain gauges in upstream river basin.

Figure 5.26: Rain Gauges of Upstream

Table 5.12 gives the mean areal rainfall for each sub basin.

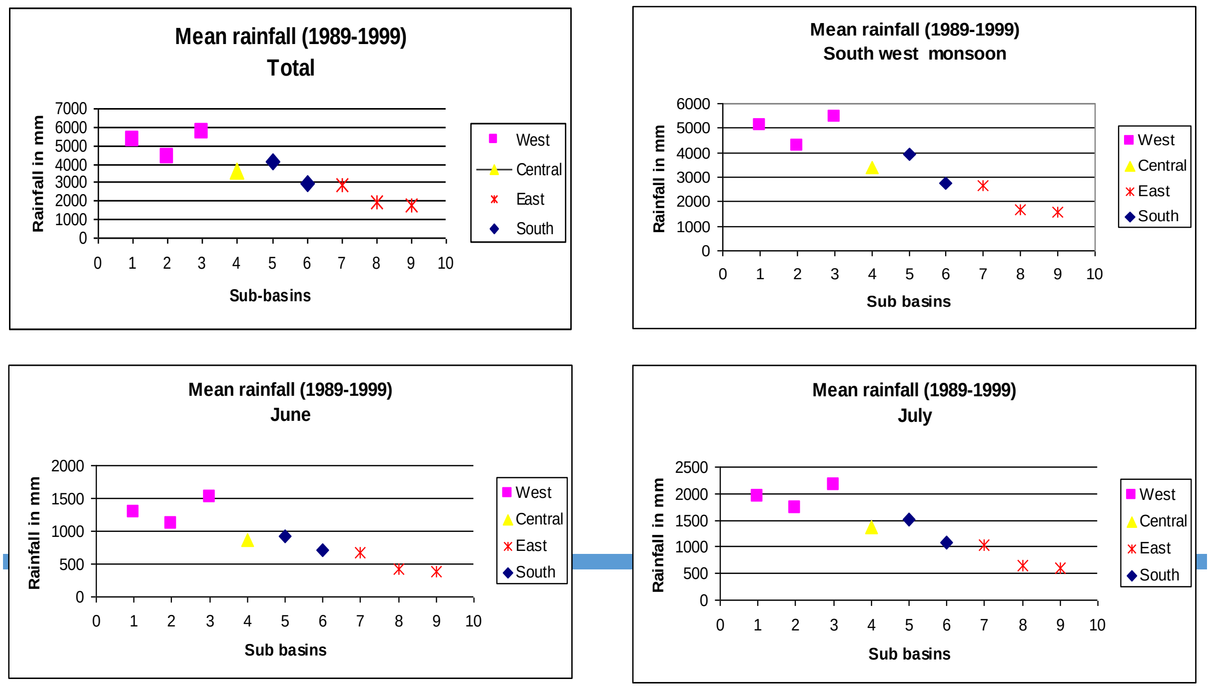
Table 5.12: Mean Rainfall for Sub Basins in mm (1989-1999)

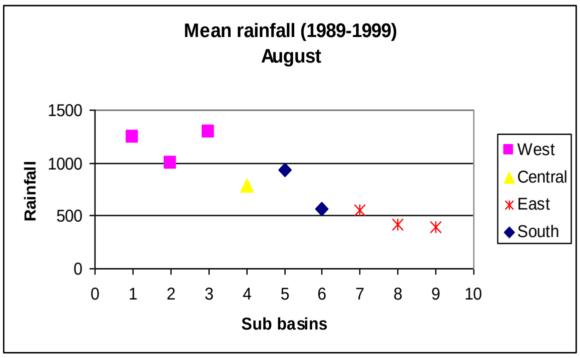
Sub basins	Total	SW	June	July	August	September	October
Yenneholé	5300.3	5113.1	1301.7	2115.1	1328.1	342.7	180
Nagodiholé	5740.1	5462.4	1515.5	2302.2	1311.6	332.9	311.9
Hurliholé	4410.1	4274.4	1117.9	1845.5	948.8	259.2	196.6
Linganamakki	3623.8	3400.7	866	1492.3	817.4	204.1	188.8
Hilkunji	4091	3940.9	1006.8	1687.2	967.9	252.9	173.2
Sharavathi	2930.3	2740.9	718.7	1211.2	587.2	165.5	193.5
Mavinaholé	2904.7	2670.3	695.6	1149.8	571.4	173.7	228.5
Haridravathi	1929.6	1688.4	420.7	689.7	432.2	141.6	227.2
Nandiholé	1792.7	1593.5	393.9	652.5	419.2	129.1	219.1
Upstream	3713.3	3438.8	892.9	1380.7	697.1	222.4	213.2

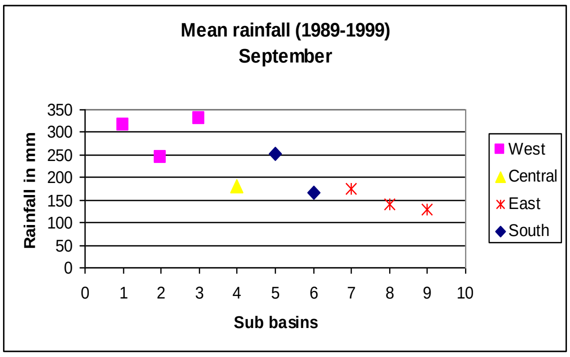
The sub-basins were further classified into clusters viz. west, east, south and central depending on their geographical locations. The mean rainfall (1989-1999) was determined for each sub basin in order to observe the rainfall variation and distribution within the river basin. They were classified as follows:

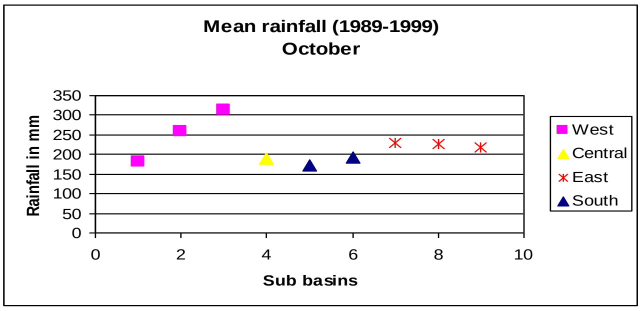
- West-Yenneholé, Nagodiholé and Hurliholé
- Central-Linganamakki
- East- Nandiholé, Haridravathi and Mavinaholé
- South- Sharavathi and Hilkunji

Figure 5.27: Rainfall Distribution for Sub Basins (1989-1999)







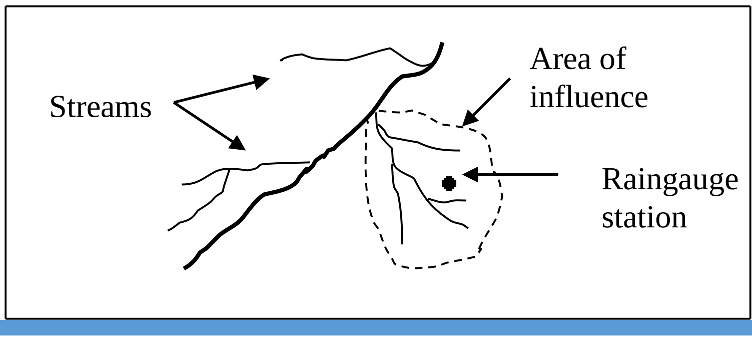


Rainfall is very heavy in the western region and there is striking variation as one proceeds from west to east. Total rainfall and southwest monsoon (June-Sept) showed similar pattern in rainfall distribution with the exception of October rainfall.

iv) Regression analysis

Regression analysis was carried out for each rain gauge station considering rainfall as dependent variable and latitude, longitude, altitude and land cover as independent variables. The area of influence of each rain gauge station was delineated with respect to contours and drainage as shown in Figure 5.28 and the land cover expressed as NDVI was determine using the imagery for each area around the gauge

Figure 5.28: Area of Influence of a Rain Gauge Station



Regression analysis showed rainfall having significant relationship with variables such as land cover, latitude, longitude, and altitude. At 5% level of significance rainfall showed good relationship between land cover, latitude, altitude and longitude. Therefore, the relationship can be expressed as:

R = f (land cover, latitude, altitude and longitude)

or

$$R = \pm a_1(\text{land cover}) \pm a_2(\text{latitude}) \pm a_3(\text{altitude}) \pm a_4(\text{longitude})$$

Table 5.13: Regression Relationships

X (independent)	Y (dependent)	R	R^2	p
Latitude	Rainfall	0.45	0.20	0.043
Land cover	Rainfall	0.71	0.5	0.0
Longitude, latitude	Rainfall	0.56	0.32	0.036
Longitude, land cover	Rainfall	0.71	0.5	0.002
Altitude, land cover	Rainfall	0.72	0.52	0.002
Land cover, latitude	Rainfall	0.74	0.55	0.001
Longitude, altitude, latitude	Rainfall	0.58	0.34	0.076
Longitude, latitude, land cover	Rainfall	0.75	0.57	0.003
Altitude, land cover, longitude	Rainfall	0.72	0.52	0.007
Land cover, altitude, latitude, longitude	Rainfall	0.77	0.6	0.005

The probable relationships are given in Table 5.14

Table 5.14: Probable Relationships of Rainfall

X (independent)	Y (dependent)	Probable relationships
Latitude	Rainfall	Rainfall = -6541.28 (latitude) +95120.76
Land cover	Rainfall	Rainfall = 1243.97 (land cover)-3679.31
Longitude, latitude	Rainfall	Rainfall =(1864.41(long) -8504.99(lat)+262543.8
Longitude, land cover	Rainfall	Rainfall = -234.71 (long) +1232.78 (land cover)+14011.74
Altitude, land cover	Rainfall	Rainfall = -4.33 (alt)+1273.63 (land)-1201.39
Land cover, latitude	Rainfall	Rainfall = -4.33 (alt)+1273.63 (land)-1201.39

Longitude, altitude, latitude	Rainfall	Rainfall = - 1868.78 (long)-8989.5 (lat) -4.97 (alt)+272688.8
Longitude, latitude, land cover	Rainfall	Rainfall = -926.48 (long) -4486.52 (lat) +997.16 (land)+130029.1
Altitude, land cover, longitude	Rainfall	Rainfall = - 4.2 (alt) +1264.58 (land) -171.13 (long)+11623.16
Land cover, altitude, latitude, longitude	Rainfall	Rainfall = 1016.06 (land) -6.07 (alt) -5002.23 (lat) -914.05 (long)+139910.8

From the regression relationship, rainfall shows increase with land cover (NDVI) and decrease with latitude, longitude and altitude. Rainfall decrease with altitude is contrary to the concept that rainfall increases with elevation (Davie, 2003). This may be due to the fact that the distribution of rain gauges is not sufficient to capture rainfall variation with elevation.

5.3 Interception: The mean monthly interception for each sub basin is given in Table 5.15. It is observed that interception is proportional to the amount and intensity of rainfall and vegetation. Thus, as rainfall and vegetation cover increases interception also increases and vice versa. As rainfall intensity decreases, interception also increases. Western and southern sub basins have higher interception than eastern sub basins due to high and low intensity rainfall and natural forest cover.

Table 5.15: Mean Monthly Interception (1989-1999)

Months / Sub basins	June (mm)	July (mm)	August (mm)	September (mm)	October (mm)	Total (mm)
Yenneholé	345.69	549.67	346.95	93.86	49.16	1385.33
Nagodiholé	424.16	639.78	366.59	97.05	92.08	1619.66
Hurliholé	303.12	491.94	255.27	73.58	54.94	1178.85
Linganamakki	228.59	364.17	201.46	55.42	53.55	903.19
Hilkunji	286.96	456.66	262.25	73.95	53.06	1132.88
Sharavathi	212.57	289.17	142.4	45.52	57.03	746.69
Mavinaholé	178.62	266.92	134.72	45.84	59.97	686.07
Haridravathi	102.26	142.47	90.65	34.92	50.75	421.05
Nandiholé	97.62	145.38	94.79	33.45	46.36	417.6
Upstream	226.34	376.93	215.26	62.2	54.39	935.12

Mean annual interception for the sub basins are given in Figure 5.29.

Figure 5.29: Mean Annual Interception

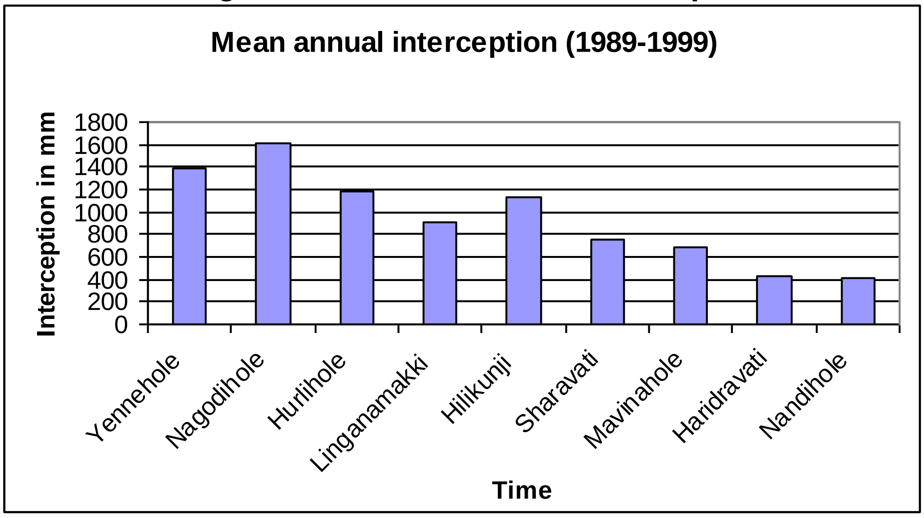


Table 5.16: Mean Monthly Interception for Different Vegetation Types (1989-1999)

Vegetation Type \ Months	June (mm)	July (mm)	August (mm)	Sept (mm)	Oct (mm)
Evergreen/semievergreen Forests	329.11	533.38	306.97	83.88	68.11
Moist deciduous forests	252.32	416.52	235.49	66.5	68.04
Plantations	199.83	325.71	189.33	53.18	46.09
Grasslands and scrubs	142.64	234.79	132.56	39.06	23.79
Paddy	-	112.74	64.31	33.42	-

Mean monthly interception of each vegetation in the study area is given in Table. 5.16 From the data, evergreen/semi-evergreen forests have higher interception as compared to other vegetation types. Similar conclusion have been drawn from other studies that in wet conditions, interception losses will be higher from forests than shorter crops primarily because of increased atmospheric transport of water vapour from their aerodynamically rough surfaces.

Evergreen forests are multilayered and are replete with climbers: lianas and epiphytes. Orchids in particular are plentiful. They also have a thick canopy, which can attribute to higher interception in evergreen forests. It is followed by moist deciduous forest which even though have large leaves are more open compared to evergreen/semi-evergreen forests. The structure and composition is also different. There is no layering but the amount of under brush is high as compared to evergreen forests due to better light penetration. Evergreen/semi-evergreen forests are almost bare of ground vegetation and plants grow only if sufficient light penetrates through gaps in the canopies. Plantations (acacia) show low values due to the smaller leaf size, which reduces the overall canopy interception. Acacia and areca constitutes a major portion of the plantation trees and have long narrow, vertically aligned leaves. Vertically aligned leaves intercepts lesser rainfall (Valente, et al., 1997) as compared to broad leaves. Areca plantations do have some understorey – small shrubs that yields fruit and sometimes mulching with green leaves is practiced to prevent soil erosion during high intensity precipitation. Paddy intercepts the least rainfall, which shows that interception is highest in trees than in crops or grasses. Interception is highest during July as it receives the highest rainfall and lowest during September and October as these months receive the lowest rainfall in the basin.

Figure 5.30: Mean Interception for Different Vegetation Types

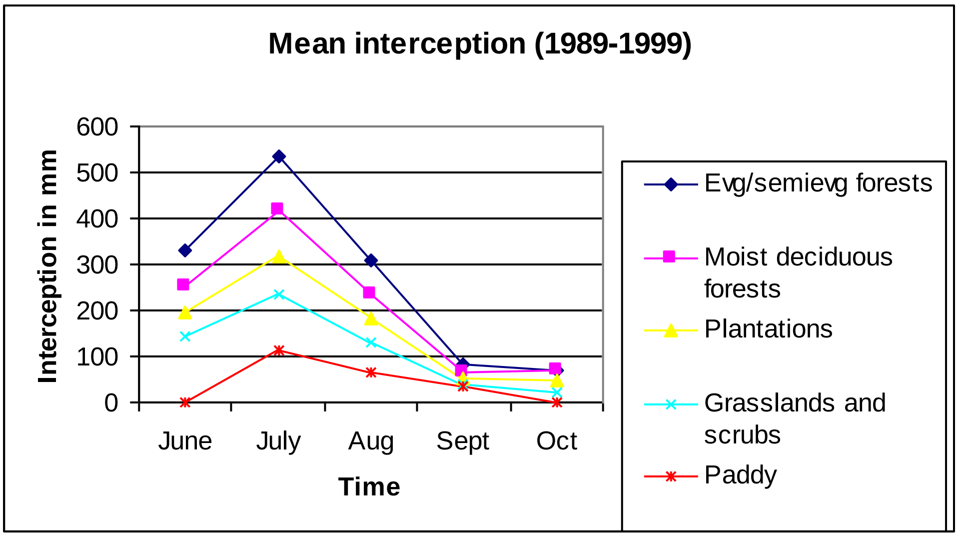


Table 5.17 clearly shows the increase in interception with vegetation and rainfall. High interception in western sub basins is due to good vegetation cover such as evergreen/semievergreen forest and moist deciduous forests whereas the vegetation cover such as natural forests is lesser in eastern sub basins. Plantations and agricultural activities are higher in the eastern and southern basins.

Table 5.17: Percentage of Interception w.r.t Rainfall

Sub basins	Interception (%)
Yenneholé	26.13
Nagodiholé	28.21
Hurliholé	26.73
Linganamakki	24.92
Hilkunji	27.69
Sharavathi	25.48
Mavinaholé	23.61
Haridravathi	21.82
Nandiholé	23.29

5.4 Runoff

The most common drainage pattern found in upstream river basin is dendritic. However, the drainage density differs from west to east of the basin i.e. it decreases from west to east. Higher densities are found in sub basins such as Yenneholé, Hurliholé, Nagodiholé and Hilkunji. Lower drainage densities are found in Linganamakki, Sharavathi, Mavinaholé, Haridravathi and Nandiholé. High drainage densities usually reduce the discharge in any single stream, more evenly distributing runoff and speeding runoff into secondary and tertiary streams. Where drainage density is very low, intense rainfall events are more likely to result in high discharge to a few streams and therefore a greater likelihood of "flashy" discharge and flooding in humid areas and suggests resistant bedrock.

Table 5.18 lists the drainage densities and sediment yields in the sub basins.

Table 5.18: Drainage Density and Sediment Yield

Sub basins	Drainage density (km/km^2)	Sediment yield (x 10^6 m^3/year)
Yenneholé	2.43	0.016
Nagodiholé	2.8	0.040
Hurliholé	2.6	0.019
Linganamakki	0.9	0.354
Hilkunji	2.16	0.057
Sharavathi	1.64	0.087
Mavinaholé	1.42	0.057
Haridravathi	1.01	0.176
Nandiholé	0.74	0.11

High drainage densities and sediment yields are seen to decrease from west to east of the basin. Western sub basins, which are highly vegetated show the highest values even though studies show that highest values of drainage density may be found in the areas of poor vegetation cover and its value diminishing with increasing share of surface covered with plants (Melton 1957). The reasons for high drainage density can be due to steep slopes and clayey soil texture.

Local variability in drainage density may also be ascribed to the set of topographical and lithological factors (Gregory and Gardiner 1975). Particularly important factors of lithology are rock permeability and resistance to weathering and erosion. Granites and greywackes occurring in the sub basin are of low permeability i.e. 3.1m/day to 3.4 m/day respectively. Another factor affecting drainage density is weathering of rocks. Carlston (1963) stated that under identical conditions of relative relief and climate, higher drainage density occurs on less resistant lithology. Eastern sub basins such as Nandiholé and Haridravathi are characterized by flat lands with coarse textured soil, which would have resulted in low drainage density.

Sediment yields in Table 5.18 show increase from west to east of the river basin. Though western sub basins have steeper slopes compared to eastern sub basins e.g. Nandiholé, good vegetation cover in the former impedes much of the sediment load and thus erosion during high rainfall events.

Surface Runoff

Table 5.19 and 5.20 gives the mean monthly surface runoff from each sub basin and the surface runoff generated from each land cover.

Table 5.19: Mean Monthly Surface Runoff (1989-1999)

Months / Sub basins	June (mm)	July (mm)	August (mm)	September (mm)	October (mm)	Total (mm)
Yenneholé	311.05	499.64	309.65	79.89	48.06	1241.96
Nagodiholé	398.42	603.27	343.27	86.37	96.16	1496.39
Hurliholé	305.97	499.79	256.57	69.39	54.67	1180.72
Linganamakki	324.11	530.22	290.1	71.36	81.74	1287.72
Hilkunji	257.06	408.14	232.17	59.98	47.94	1000.1
Sharavathi	262	364.06	176.1	48.39	76.35	914.29
Mavinaholé	218.79	356.71	176.64	52.68	80.48	871.5
Haridravathi	262	364.06	176.1	48.39	76.35	702.28
Nandiholé	141.28	217.82	139.67	42.08	95.44	623.9
Upstream	266.42	421.37	236.88	62.71	82.12	1058.05

Table 5.20: Mean Monthly Surface Runoff from Different Land covers

Vegetation Type \ Months	June (mm)	July (mm)	August (mm)	Sept (mm)	Oct (mm)
Evergreen/semievergreen Forests	125.02	203.38	113.65	30.03	28.35
Moist deciduous forests	125.73	205.5	115.15	30.39	24.45
Plantations	149.98	247.93	140.4	36.03	32.28
Grasslands and scrubs	189.11	315.05	175.33	47.56	99.26
Paddy	388	393.06	221.39	55.62	126.71
Open fields	475.48	795.39	448.45	119.62	126.08
Settlements	627.2	1038.43	583.81	158.37	172.16

Surface runoff progressively increases from evergreen/semievergreen forests to settlements as seen in Figure 5.31, indicating that where there is good vegetation cover, surface runoff is less. Forests usually have thick leaf litter and a spongy humic horizon, both of which retard surface runoff or overland flow. Among the forest types, plantation forests showed higher runoff. Certain species such as Tectona Grandis, which are majorly found in the eastern sub basins, may cause severe erosion (Calder, 2002). This is due to the large leaves, which produce big raindrops that roll of the leaves, and causes splash and subsequently rill erosion if not protected by underbrush.

Figure5.31: Mean Monthly Surface Runoff from Different Land covers

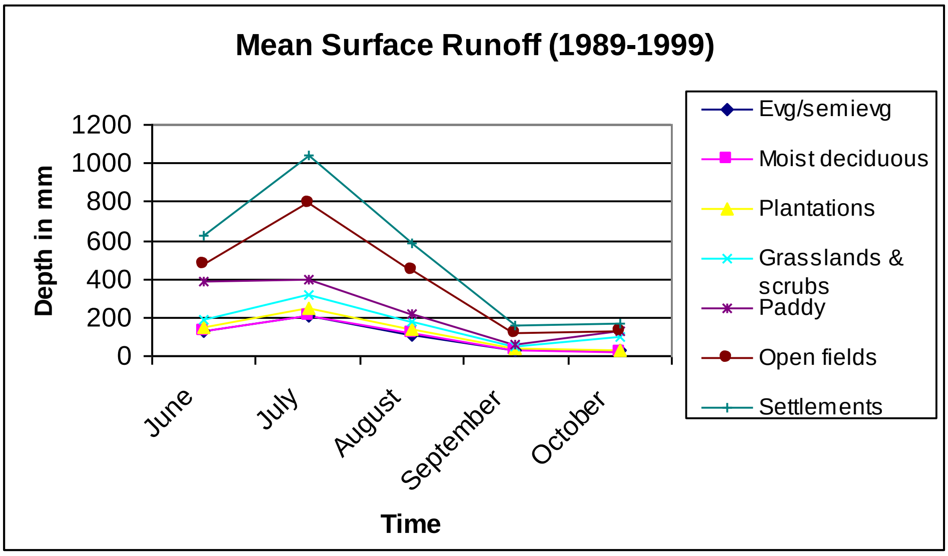


Figure 5.32 shows the variation in surface runoff generation from western sub basins to eastern sub basins portion with respect to rainfall. Table 5.21 shows the values the percentage variation of runoff w.r.t. rainfall.

Figure 5.32: Rainfall-Surface Runoff Generation (1989-1999)

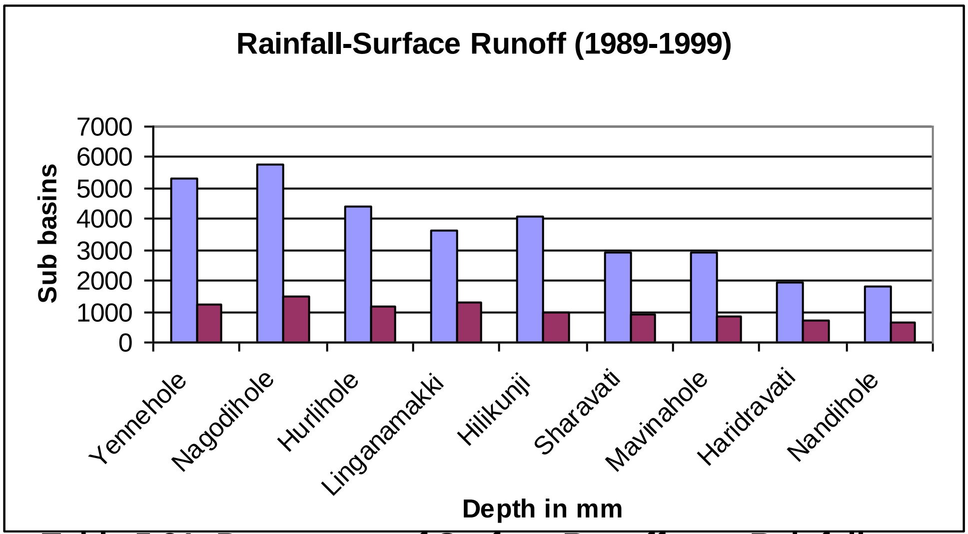


Table 5.21: Percentage of Surface Runoff w.r.t Rainfall

Sub basins	Runoff (%)
Yenneholé	23.43
Nagodiholé	26.06
Hurliholé	26.77
Linganamakki	35.52
Hilkunji	24.44
Sharavathi	31.2
Mavinaholé	30
Haridravathi	36.39
Nandiholé	34.8

Low runoff generation in western (Yenneholé, Nagodiholé and Hurliholé) can be due to good vegetation cover and lower anthropogenic activities as compared to eastern sub basins (Mavinaholé, Haridravathi and Nandiholé). There is also high percentage of forest cover in the western clusters, which intercepts 20-30% of the rainfall before it reaches the ground. Natural forests are effective at retarding overland flow preventing flash floods downstream. Agricultural activities and open fields are higher in Haridravathi and Nandiholé resulting in higher runoff.

Sub Surface Runoff or Pipeflow

Table 5.22 gives the mean total sub-surface generation different sub basins. Pipes are abundant in the Western Ghats and are a general feature in undisturbed evergreen/semievergreen forests and moist deciduous forests. While a part of the pipe outflow is from storage build up during previous rainfall evens, some part would presumably for current rainfall also (Putty and Prasad, 2000). Pipe outflow was not significant in the forested catchments and as observed by Putty and Prasad, 2000, may be due to the high infiltration capacity of the soil that pipe outflow does not create saturation of the soil.

Table 5.22: Mean Total Sub Surface Flow Generation

Sub basins	Mean total pipeflow (1989-1999) (mm)
Yenneholé	173.56
Nagodiholé	193.83
Hurliholé	142.51
Hilkunji	135.27
Sharavathi	90.57
Mavinaholé	257.07
Upstream	158.3

Here pipe flow increases from west to south of the basin. These are the areas of abundant vegetation consisting of evergreen/semievergreen and moist deciduous forests. However, Mavinaholé shows the highest total pipe flow as it has the lowest relief ratio. Table 5.23 shows the percentage of pipe flow w.r.t rainfall which is a very small component.

Table 5.23 Percentage of Pipeflow w.r.t Rainfall

Sub basins	Pipe flow (%)
Yenneholé	3.27
Nagodiholé	3.37
Hurliholé	3.23
Hilkunji	3.3
Sharavathi	3.03
Mavinaholé	8.85

5.5 Evapotranspiration

Table 5.24 shows the mean monthly transpiration for different vegetation types in the study area calculated by Turc's equation, which makes use of albedo. Albedo is observed to increase from evergreen forests to crops with respect to openness and height of vegetation. Tall forests with close canopy have lesser albedo than tall forests with more open canopy. Grasses and crops are short vegetation resulting in higher albedo.

From the graph, it is observed that transpiration from evergreen/semievergreen forests is higher compared to other vegetations. This is attributed to the albedo. Albedo from tall forests with thick canopy is less i.e. the amount of energy reflected (α) is less due to internal reflections. Lesser albedo indicates that the energy that is absorbed by the vegetation ($1-\alpha$) is high. It is the absorbed energy, which is responsible for phase change i.e. from liquid water to water vapour. Turc's equation is radiation based and is not limited by the absence of water. Moist deciduous forests and plantations are more open, which results in higher albedo and that means lesser energy available for conversion of liquid water to water vapour. The mean annual transpiration decreases from evergreen/semievergreen forests to paddy crop.

Transpiration values peak during summer when plants use up most of the water but varies with the type of vegetation. Three factors may be playing a role in transpiration during summer i.e. a) solar energy or insolation, b) soil moisture, c) rooting depth.

During summer, there is greater energy available for plant absorption. Absorption of this energy by the leaf raises its temperature and its water vapour pressure. The result is that transpiration increases along with insolation.

Transpiration is dependent on the soil moisture. The soil moisture regime in the basin is ustic i.e it is moist for 90 or 180 days (during monsoon months) and dry during the remaining period. However, in evergreen/semievergreen forests the soil moisture is conserved due to thick leaf litter and since light penetration is very low, evaporation from the soil is also minimal. Thus, during summer, soil moisture pool under an evergreen/semievergreen forests is quite high as compared to moist deciduous or plantations, facilitating in higher transpiration.

Another factor that affects plant water uptake, in other words transpiration is the rooting depth of plant species. Calder, 2002 indicates that studies of transpiration in dry (drought) conditions show that the transpiration from forests is likely to be higher because of the generally increased rooting depth of trees as compared with shorter crops such as grass and paddy and their consequent greater access to soil water.

Evergreen, deciduous and plantation tree species mostly have taproots that are deep, but in mature evergreen trees, shallow-rooting is usually indicated by a more swollen tree base. They also have low root:shoot ratio i.e. the biomass in shoots are higher than roots. Buttressing indicates a very shallow root system and are a feature of many trees in the forests of upstream river basin. It also provides support for large trees. Since trees with buttress roots have shallow root system, it can only survive where there is sufficient soil moisture storage in the upper soil, especially during the lean season. But as the moisture regime in the basin is ustic, it can be assumed that evergreen trees with non-buttressed roots may have deeper taproots to tap moisture during summer.

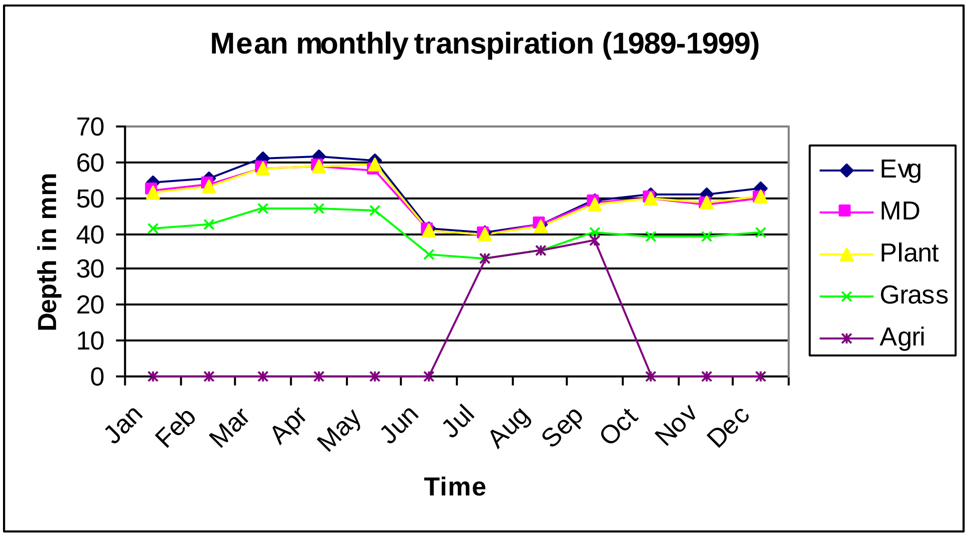
Deciduous trees also have deep taproots but conserve water during summer by leaf shedding. Leaves appear in May after a bout of convective rains in April, thus moistening the soil. Certain plantation species such as *Eucalyptus sp*. is known to tap water deep from the soil creating severe soil moisture deficit (Scott and Lesch, 1997). Such trees are known to survive in dry areas where surface soil moisture is quite low. Grasses and crops have fibrous roots with high root:shoot ratio i.e. the biomass of roots are higher than shoots but are shallow and therefore cannot tap water deep from the soil. Grasses wither during dry season leaving the scrubs in the basin. Transpiration due to crops such as paddy is the least and zero during summer as it is grown only during rainy season. Thus, higher transpiration is observed in trees during summer than during the monsoon and winter season.

It is also observed that transpiration is small during the monsoon period. The reason maybe due to high vapour pressure gradient, which occurs when the vapour pressure of the air becomes high due to high relative humidity. As a result, little transpiration occurs. Even if the rainfall event continues over several days, transpiration cannot occur because of the high gradient.
Note: Evg/SE- evergreen/semievergreen forests; MD – moist deciduous forests
Plant- plantations; Grass- grasslands and scrubs; Agri – agricultural lands

Table 5.24: Mean Monthly Transpiration for Different Vegetation Types

	Transpiration in mm					
Months	**Evg/SE**	**MD**	**Plant**	**Grass**	**Agri**	**Total**
Jan	54.06	52.01	51.63	41.5	-	199.3
Feb	55.5	53.7	53.05	42.7	-	204.95
Mar	61	58.22	58.21	46.8	-	224.2
Apr	61.4	58.8	58.6	47.1	-	225.9
May	60.7	57.6	59.5	46.5	-	224.3
June	41.3	40.8	40.7	34	-	156.8
July	40.2	39.9	39.6	33.1	33.19	185.99
Aug	42.8	42.3	42.1	35.2	35.24	198.64
Sept	49.2	48.5	48.4	40.3	38.11	224.51
Oct	50.8	49.8	49.9	39.2	-	189.7
Nov	50.7	48.4	48.5	39.1	-	186.7
Dec	52.5	50	50.2	40.4	-	193.1

Figure 5.33: Mean Monthly Transpiration for Different Vegetation Types



The decrease in mean annual transpiration for each vegetation type is as shown in Figure 5.33. Table 5.25 shows the mean annual transpiration of vegetation types in the basin.

Table 5.25: Mean Annual Transpiration for Different Vegetation Types

Vegetation type	Mean annual transpiration (1989-1999) (mm)
Evergreen/semievergreen forests	620.7
Moist deciduous forests	600.76
Plantations	598.32
Grasslands and scrubs	486.76
Paddy (3 months)	106.55

Table 5.26 gives the monthly evaporation for bare soil, settlements and water bodies. Evaporation from open water is found lower compared to bare soil and settlements. Waterbodies have very low albedo resulting in greater absorption of energy. Large and deep water bodies such as Linganamakki reservoir also have high heat storage capacity and thermal inertia. Solar energy penetrates to greater depth in water which results in slow heating. This results in lesser evaporation. Since solar radiation can only penetrate a few centimeters of soil due to its chemical composition and the structure, the air above the soil warms up much more rapidly due to the low heat capacity of air. This results in high evaporation from soil. However, bare soil evaporation also depends on moisture content of the soil. Wetter the soil, lower the evaporation and vice versa. Bare soil evaporation during wet season is low as greater energy is required to overcome the attractive forces of water and soil particles. Table 5.27 shows the annual evaporation for each cover type.

Table 5.26: Mean Monthly Evaporation for Other Land covers

Months	Open water (mm)	Open fields (bare soil) (mm) / Settlements (mm)	Total (mm)
Jan	38.66	47.14	85.8
Feb	39.64	48.44	88.08
Mar	43.96	52.98	96.94
Apr	44.2	53.4	97.6
May	43.77	52.74	96.51
June	26.7	46.35	73.05
July	26.06	45.12	73.05
Aug	28.1	48	71.18
Sept	34.14	55.23	89.37
Oct	35.21	56.97	92.18
Nov	35.58	44.5	80.08
Dec	37.73	45.9	83.63

Figure 5.34: Mean Monthly Evaporation for Other Land covers

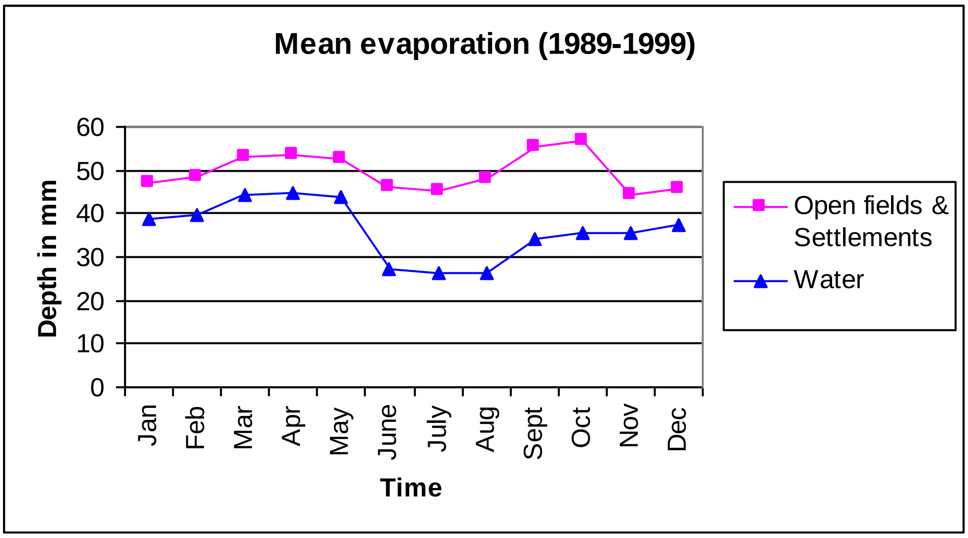


Table 5.27: Mean Annual Evaporation for Other Land covers

Cover type	Mean annual evaporation (1989-1999) (mm)
Open fields	596.81
Settlements	596.81
Water bodies	436.72

5.6 Groundwater Recharge/Discharge

Groundwater recharge analysis results are given in Table 5.28. The rate of replenishment or recharge is dependent on the soil moisture status, which in turn is dependent on soil texture. Soil texture in the study area varies from loamy sand to clay loam. From soil studies, sand is an important constituent in the basin and is responsible for high infiltration rates. Average recharge in the basin is 30.3% of the rainfall.

Total mean monthly recharge is observed to vary from west to east with the eastern sub basins receiving the least recharge.

Table 5.28: Mean Monthly Recharge (1989-1999)

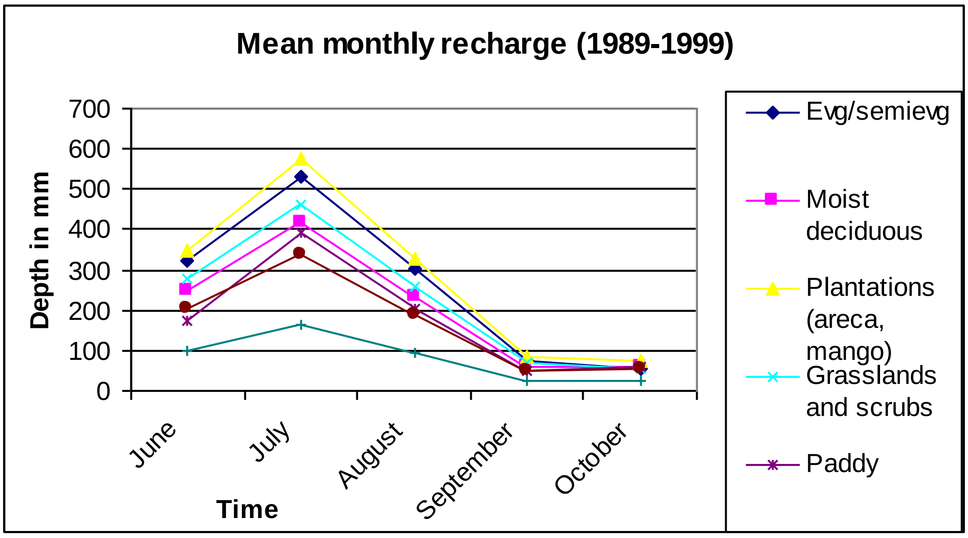
Months / Sub basins	June (mm)	July (mm)	August (mm)	September (mm)	October (mm)	Total (mm)
Yenneholé	373.61	620.46	380.94	98.59	46.94	1513.76
Nagodiholé	506.22	770.94	438.34	109.72	65.5	1883.3
Hurliholé	329.02	546.28	280.09	75.23	58.44	1282.99
Linganamakki	280.83	495.75	270.88	66.03	58.7	1164.7
Hilkunji	294.71	503.31	286.14	73.55	45.44	1198.12
Sharavathi	212.25	338.87	163.59	44.53	52.81	803.28
Mavinaholé	178.7	291.96	144.72	42.68	65.12	712.04
Haridravati	125.9	217.48	135.84	42.98	63.57	576.13
Nandiholé	119.75	205.33	131.17	39.17	56.17	544.55
Upstream	220.16	360.62	200.06	55.44	59.33	886.71

Table 5.29: Mean Monthly Recharge Under Different Land use

Months / Vegetation Type	June (mm)	July (mm)	August (mm)	Sept (mm)	Oct (mm)
Evergreen/semievergreen Forests	325.13	532.15	302.78	76.81	54.19
Moist deciduous forests	248.75	419.05	213.68	60.71	59.57
Plantations (areca, mango)	347.1	573.58	325.21	83.42	74.3
Grasslands and scrubs	277.98	463.39	258.34	70.06	56.56
Paddy	175.68	394.35	203.52	51.75	57.46
Open fields	201.37	337.17	190.28	50.72	53.55
Settlements	98.4	163.16	91.91	24.91	27.09

Mean monthly recharge under different land use is shown in Table 5.29. From Figure 5.35, it is clearly observed that recharge under vegetation is higher as compared to other land cover types. Among different vegetation types, recharge under plantation was slightly higher as compared to natural forests (evergreen/semievergreen forests and moist deciduous forests). Plantation trees include areca and mango. Areca plantations are a common feature in the river basin and are extensively grown in river valleys. Lesser recharge in natural forests may be due interception (20-30%) and diversion of infiltration water by sub surface flow (10-30%). Sub surface flow phenomenon is not observed under plantations. Paddy, open fields and settlements show the least recharge. It is observed from the graph that recharge peaks during July and tapers off with decreasing rainfall.

Figure 5.35: Mean Monthly Recharge Under Different Land use



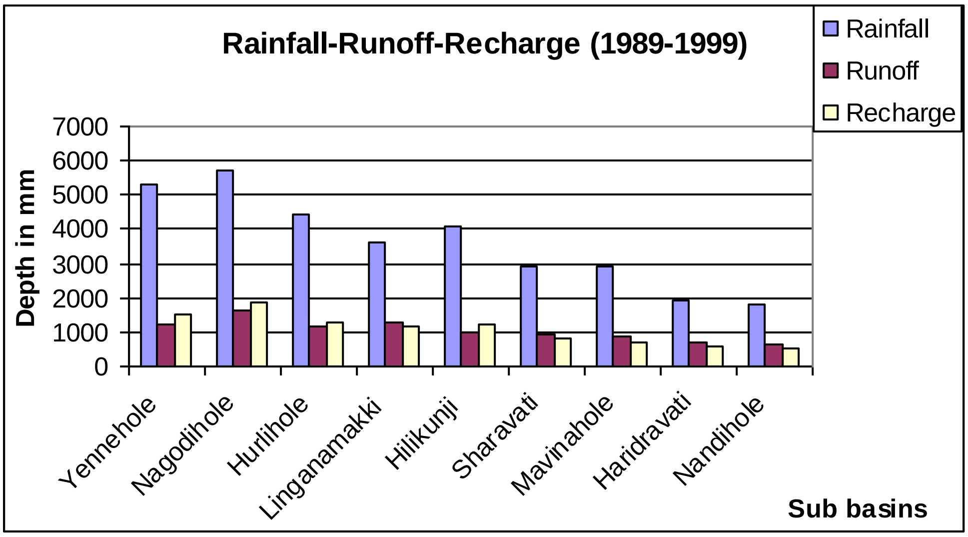
Total recharge in each sub basin was compared with total rainfall and total surface runoff to determine any variation. Table 5.30 gives the variation in each sub basin.

Table 5.30: Rainfall-Runoff-Recharge Variation

Sub basin	Rainfall (mm)	Recharge (mm)	Runoff (mm)
Yenneholé	5300.3	1513.76	1241.96
Nagodiholé	5740.1	1883.3	1496.39
Hurliholé	4410.1	1282.99	1180.72
Linganamakki	3623.8	1164.7	1287.72
Hilkunji	4091	1198.12	1000.1
Sharavathi	2930.3	803.28	914.29
Mavinaholé	2904.7	712.04	871.5
Haridravati	1929.6	576.13	702.28
Nandiholé	1792.7	544.55	623.9

Figure 5.36 clearly shows the variation of recharge and runoff w.r.t rainfall. It is interesting to note that sub basins with larger vegetation covers have higher recharge. Vegetation such as forests not only provide shade to the ground that prevent soil water from evaporating, it provides organic matter to the soil in the form of forest litter sand, other microorganisms etc. Decomposition of this layer results in an organic rich top layer called humus, which enhances infiltration rates and replenishes the aquifers. Due to higher concentration of anthropogenic activities in the eastern basins, recharge is considerably reduced as forests are cleared for agricultural and other purposes. Recharge is an extremely important component as it is responsible for providing flow in rivers during dry seasons from the aquifers.

Figure 5.36: Rainfall-Runoff-Recharge (1989-1999)



Groundwater Discharge/Baseflow Analysis

The determination of groundwater volumes and flow rates requires a thorough knowledge of the geology of the groundwater basin (Viessman, 1989). The geologic structure of a groundwater basin governs the occurrence and movement of the groundwater beneath it. Base flow contribution to stream flow varies widely according to the geologic nature of the aquifer.

The two major rock types occurring in the basin are gneisses /granites and greywackes. Gneisses and granites have the lowest specific yield (3%) and occurs in the eastern portion of the study area such as Mavinaholé, Haridravati and Nandiholé. Hence, streams here are ephemeral indicating baseflow only during monsoon season. Western sub basins have perennial streams, which is an indication of the rock types present in the area. The region consists of greywackes, which has higher specific yield of 27%. Discharge for each sub basin is given in Table 5.31.

Table 5.31: Mean Total Discharge (1989-1999)

Sub basins	Mean total discharge (1989-1999) (mm)
Yenneholé	225.98
Nagodiholé	463.95
Hurliholé	192.44
Linganamakki	174.7
Hilkunji	179.71
Sharavathi	120.49
Mavinaholé	21.36
Haridravati	17.28
Nandiholé	16.33
Upstream	92.05

Another important reason for better discharge in western sub basins is the good vegetation cover. Natural forests retard much of the overland flow facilitating in enhanced infiltration and thus recharge. In other words, regardless of the geology the amount of water entering an aquifer is dependent first on the vegetation and soil present in the area. Forestlands cleared for agriculture or other purposes increases overland flow thus decreasing recharge and subsequent discharge into the streams.

Well Behavioral Analysis

Water table levels of ten wells were available to observe groundwater fluctuations and behavior in the basin. These wells were mainly located in eastern portion and southern portion of the study area. Well data for western sub basins were not available. Table 5.32 gives the long term trend and amplitude in each well.

Table 5.32: Long Term Trend and Amplitude in Selected Wells in Upstream

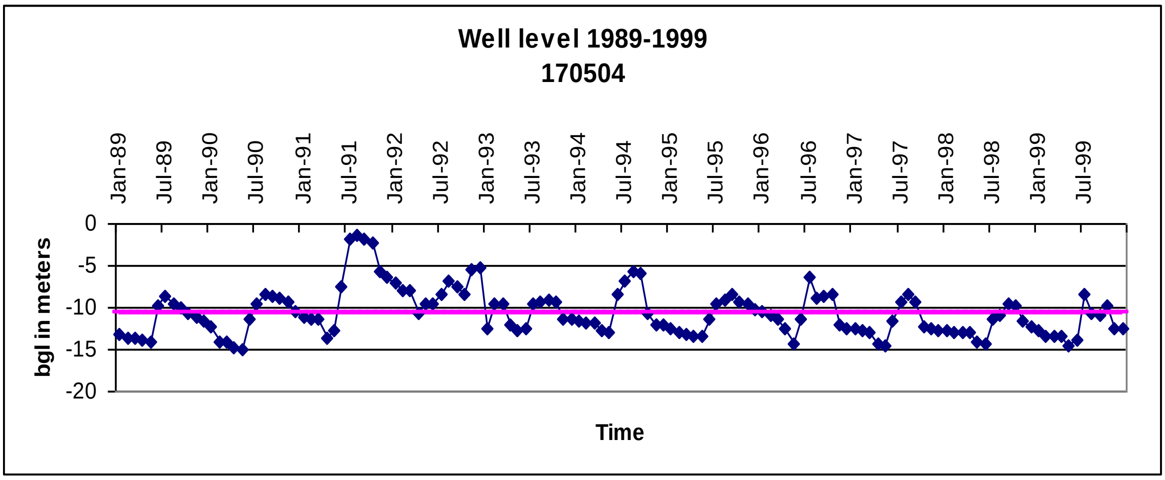
Well Nos.	Amplitude	Depth to Water Table
170504	Strong dampening	Increasing
170511	Slight dampening	Increasing
170510	Strong dampening	Increasing
170502	Strong dampening	Increasing
170410	Strong dampening	Decreasing
170402	Strong dampening	Decreasing
170406	Slight dampening	Increasing
170401	Strong dampening	Increasing
170404	Strong dampening	Decreasing
170903	Strong dampening	Increasing

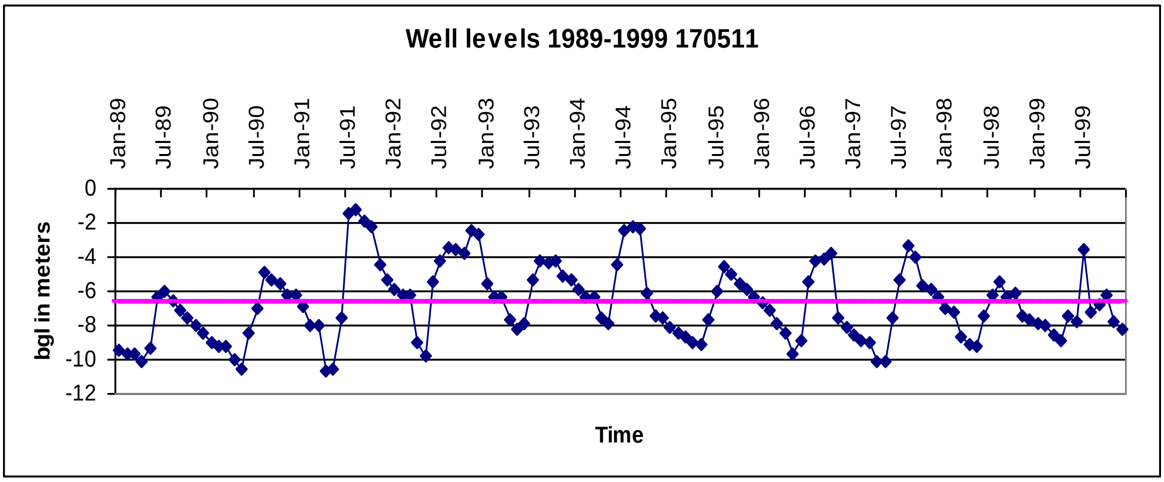
It is interesting to note that wells showing increase in water depth had dampening effect with some showing strong effects. Dampening indicates reduction in amplitude, which may be due to groundwater overexploitation occurring during the rainy season (June-August) with the result that well levels are unable to rise even during heavy rainfall. Other reasons may include groundwater irrigation and the type of irrigation practiced or the downstream overexploitation of ground water, which has affected well levels upstream. The dampening effect is seen beginning from 1994-1999 in all wells.

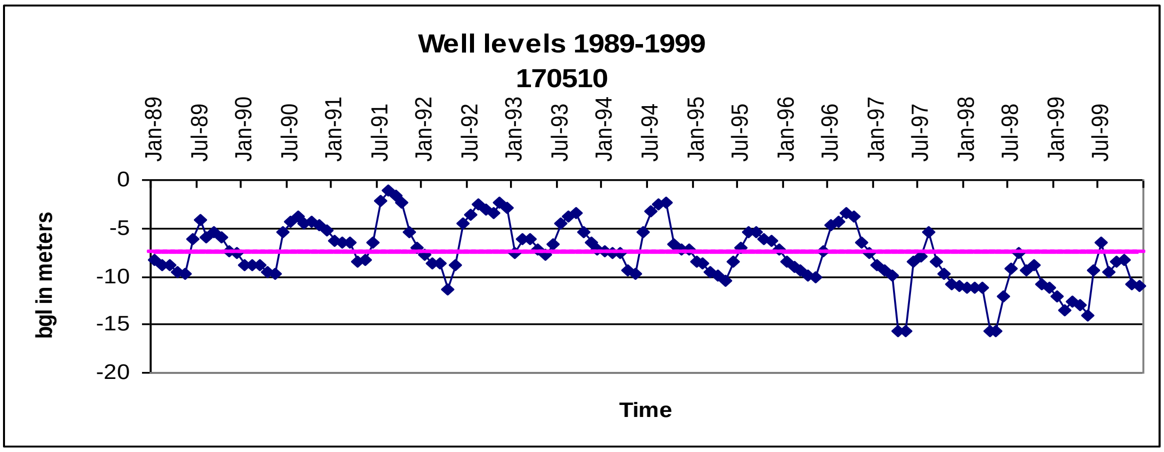
Well no. 170404 showed decrease in the depth to water table with strong dampening. The reason may be due to the fact that water logging by damming Linganamakki reservoir would have increased recharge or downstream pumping may have changed the geometry of the basin. Also, as it is along the ridgeline there is quicker drainage of water, which would have increased the water levels. Well nos 170410 and 170402 are located in Haridravati and Nandiholé sub basin respectively. Both these wells showed decrease in depth to water table i.e. the water table must be rising in these regions but shows strong dampening effect due to over extraction of groundwater.

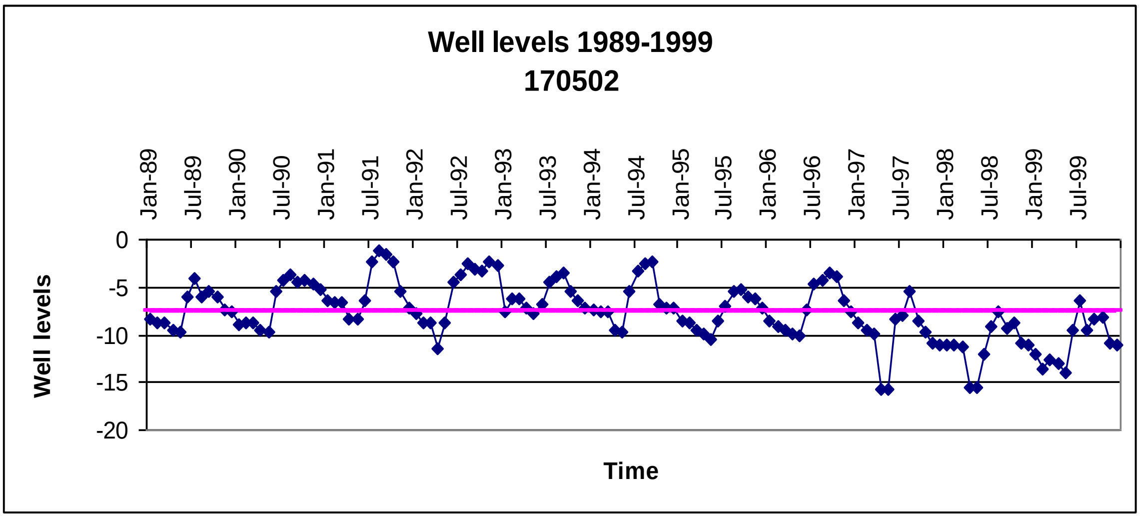
Figure 5.37 depict the water table depths in well. Negative values actually indicate the water levels below ground. Zero is considered the ground level or reference level.

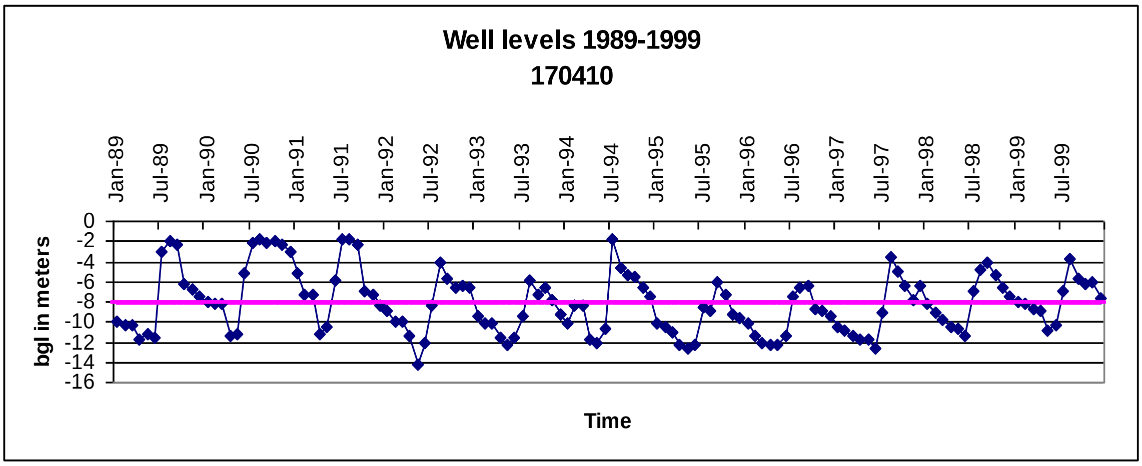
Figure 5.37 Water Table Depths (bgl) in Selected Wells Upstream (1989-1999)

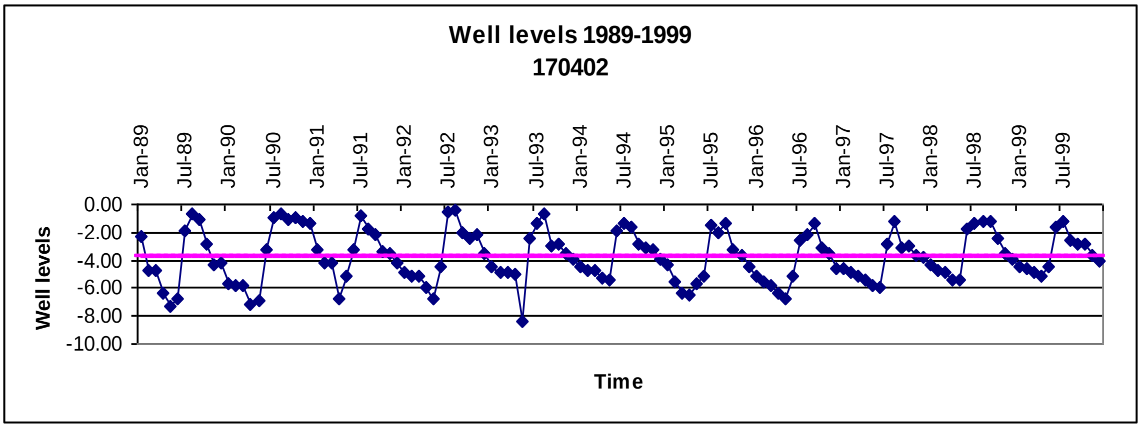


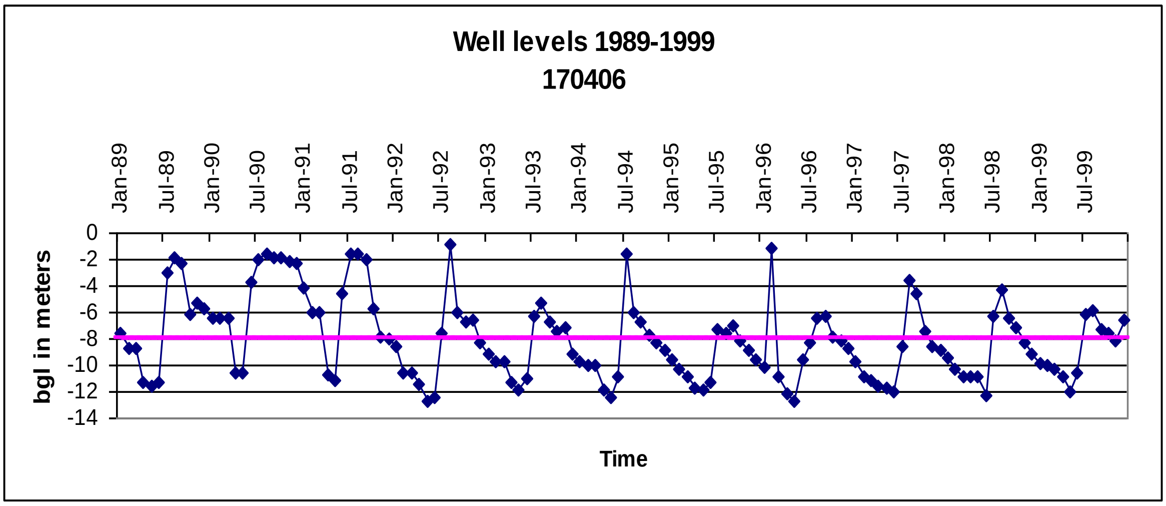


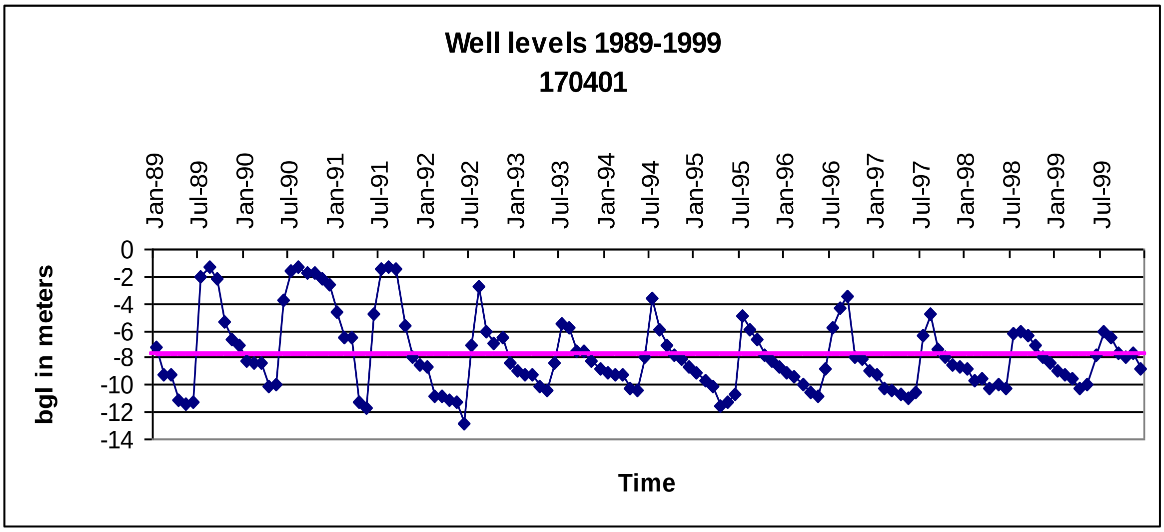


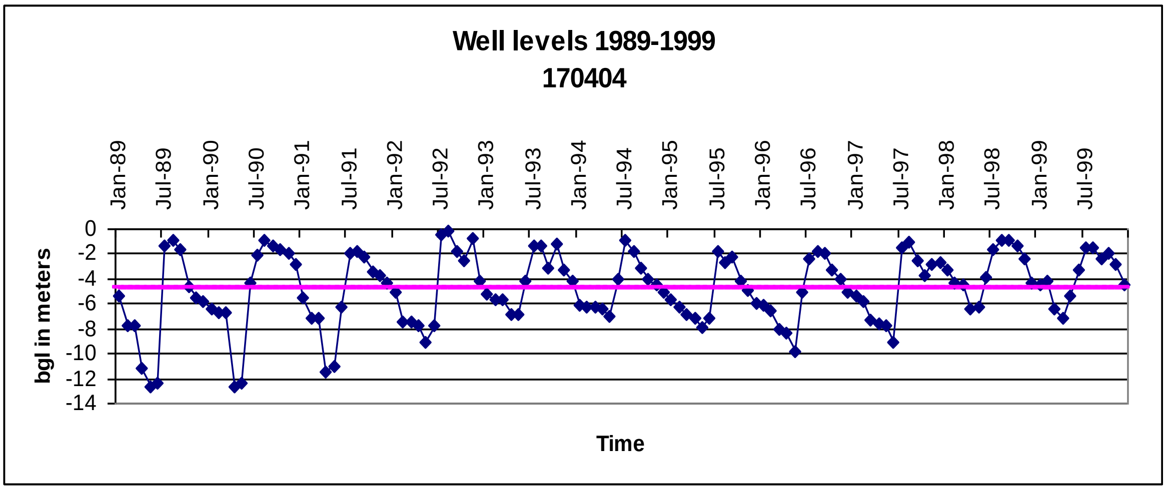

Well levels 1989-1999
170502
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
0
-5
-10
-15
-20
Well levels
Time

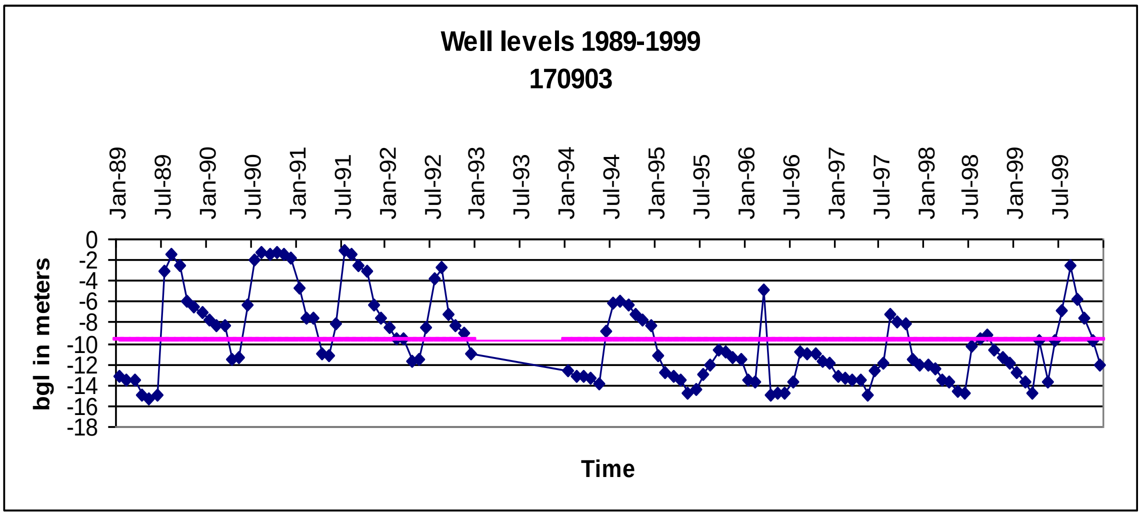

Well levels 1989-1999
170410
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
0
-2
-4
-6
-8
-10
-12
-14
-16
bgl in meters
Time


Well levels 1989-1999
170402
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
Well levels
Time


Well levels 1989-1999
170406
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
0
-2
-4
-6
-8
-10
-12
-14
bgl in meters
Time


Well levels 1989-1999
170401
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
0
-2
-4
-6
-8
-10
-12
-14
bgl in meters
Time


Well levels 1989-1999
170404
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
0
-2
-4
-6
-8
-10
-12
-14
bgl in meters
Time



Mean monthly water table levels showed similar seasonal fluctuations i.e. water table rises during monsoon season and thereafter decreases. Water table is almost steady during August to September and decreases with the maximum decline in the month of May. Decrease in water levels is partly due to natural discharge or baseflow and partly due to artificial extraction of groundwater. Streams located south of the basin receive substantial baseflow during non-monsoon season. The amount of baseflow decreases from south to east such as Nandiholé and Haridravati. It is observed that wells in the region have reported decrease in water levels and as such fail to provide baseflow during the lean season. Streams in these sub basins are ephemeral.

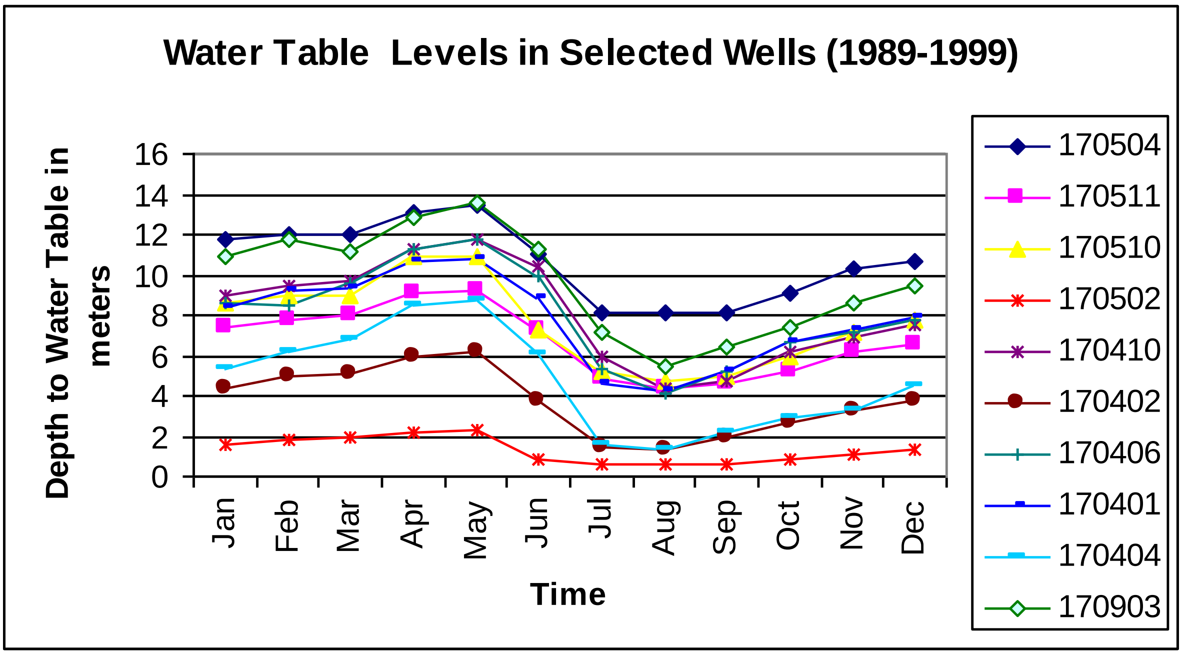
Variation of water table levels is also seen within a sub basin. For example, well no. 170502 located in Nandiholé sub basin showed increase in water table levels whereas well no. 170504 located in the same sub basin showed decrease in water table levels. Well no. 170903 also showed decrease in well levels even though it is located near Hilkunji, which has higher rainfall than Nandiholé and Haridravati. Natural and artificial factors such as soil texture, the hydraulic characteristics such as specific yield of aquifers, the amount of recharge, distribution of vegetation types, topography and climate and artificial factors may be showing a combined effect in influencing well levels in the region.

Table 5.33 gives the mean monthly water table levels in selected well. Figure 5.38 gives the graphical representation of well levels. It is seen that well levels increases during the monsoon season and thereafter decreases.

Table 5.33: Mean Monthly Water Table Levels in Selected Wells (1989-1999)

	170504	170511	170510	170502	170410	170402	170406	170401	170404	170903
Jan	11.71	7.33	8.63	1.6	8.94	4.33	8.55	8.35	5.33	10.95
Feb	11.96	7.76	8.94	1.78	9.49	4.96	8.53	9.23	6.2	11.75
Mar	12.03	8.05	9.03	1.88	9.72	5.12	9.58	9.35	6.73	11.15
Apr	13.14	9.14	10.88	2.22	11.31	5.93	11.29	10.64	8.45	12.79
May	13.46	9.25	10.89	2.31	11.8	6.17	11.76	10.74	8.73	13.57
June	11.06	7.21	7.3	0.87	10.42	3.8	9.96	8.82	6.1	11.29
Jul	8.16	4.82	5.19	0.6	5.95	1.47	5.29	4.58	1.55	7.16
Aug	8.1	4.3	4.73	0.57	4.32	1.36	4.08	4.18	1.36	5.5
Sept	8.16	4.62	5.02	0.56	4.75	1.99	5.19	5.24	2.13	6.43
Oct	9.08	5.17	5.87	0.89	6.14	2.71	6.69	6.7	2.89	7.35
Nov	10.29	6.2	7.14	1.14	6.87	3.27	7.2	7.25	3.32	8.66
Dec	10.66	6.56	7.73	1.37	7.49	3.79	7.73	7.93	4.43	9.47

Figure 5.38: Mean Monthly Water Table Levels in Selected Wells (1989-1999)



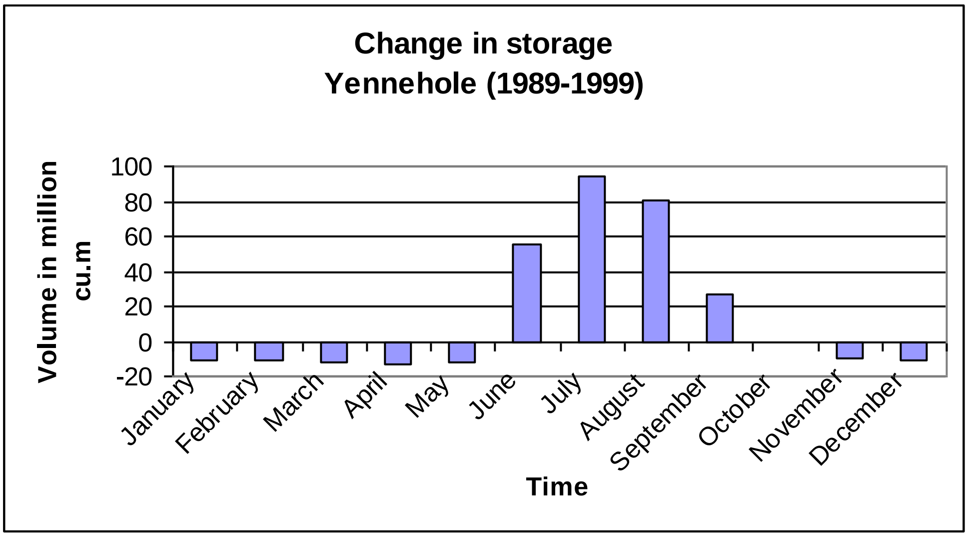
5.7 Water Budget

Water budgeting was done sub-basinwise in the river basin. For example, water budget for Yenneholé was estimated for each month in Table 5.34. Change in storage in Yenneholé sub basin is given in Figure 5.39.

Table 5.34: Water Budget -Yenneholé

MEAN MONTHLY WATER BUDGET (x 10^6 m^3) – YENNEHOLÉ (1989-1999)									
Month	**R**	**I**	**T**	**E**	**SR**	**P**	**GR**	**GD**	**Change in storage**
January			6.93	2.06				0.0095	-11.03
February			7.12	2.07				0.002	-11.36
March			7.82	2.23				0.0004	-12.39
April			7.88	2.29				0.0001	-12.6
May			7.87	2.28					-12.56
June	243.62	47.09	5.42	2.06	62.37		69.38		55.09
July	395.86	76.87	5.40	1.87	100.32		115.12		94.28
August	248.56	48.52	5.74	1.96	62.26		70.74	20.93	80.27
September	64.14	13.12	6.59	2.22	16.06	0.674	18.30	4.26	26.44
October	31.41	6.35	6.60	2.36	8.96	0.0044	8.23	0.92	-0.01
November			6.52	1.97				0.29	-9.65
December			6.75	1.95				0.0442	-10.47

Figure 5.39: Water Budget -Yenneholé



Similar analyses were done for the other sub basins (except Linganamakki). Monthly change in storage for each sub basin is graphically represented as follows.

Figure 5.40: Water Budget -Nagodiholé

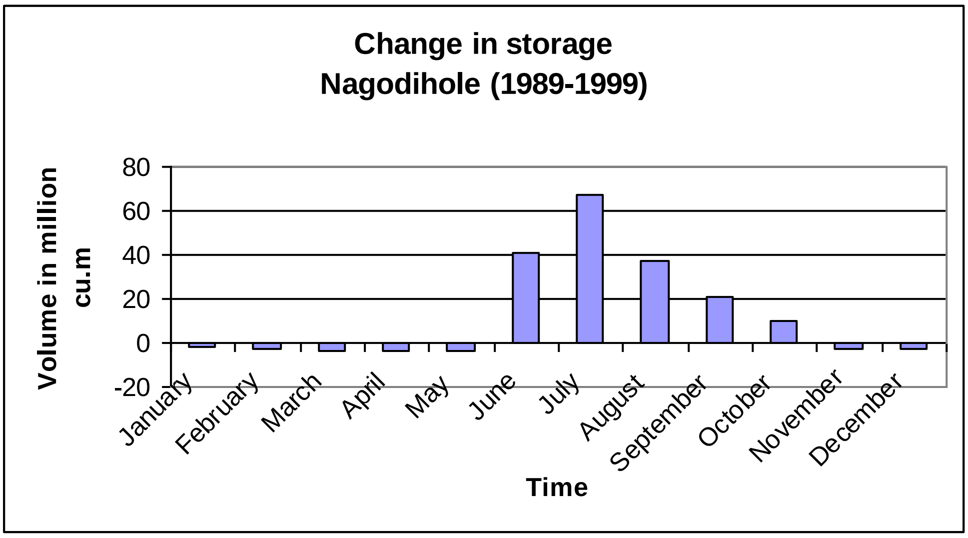


Figure 5.41: Water Budget -Hurliholé

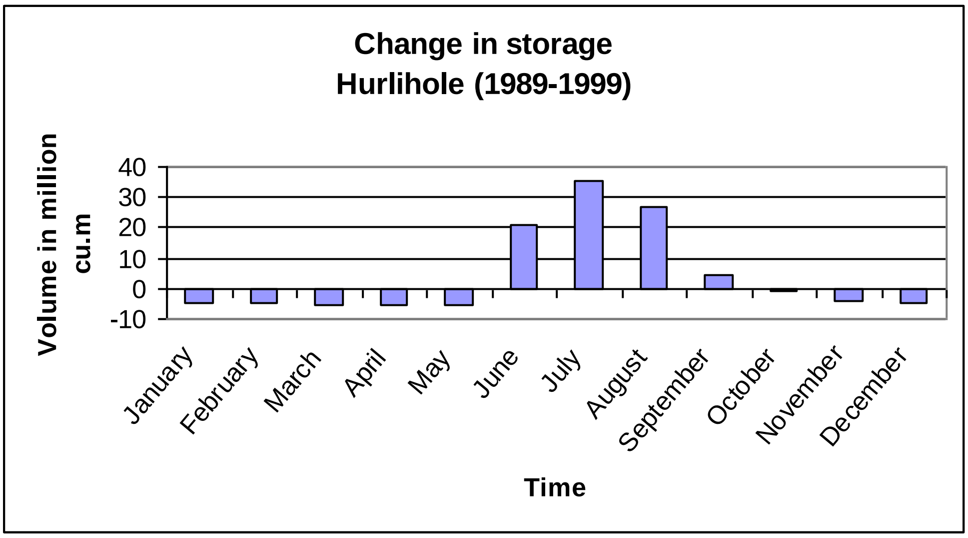


Figure 5.42 Water Budget - Hilkunji

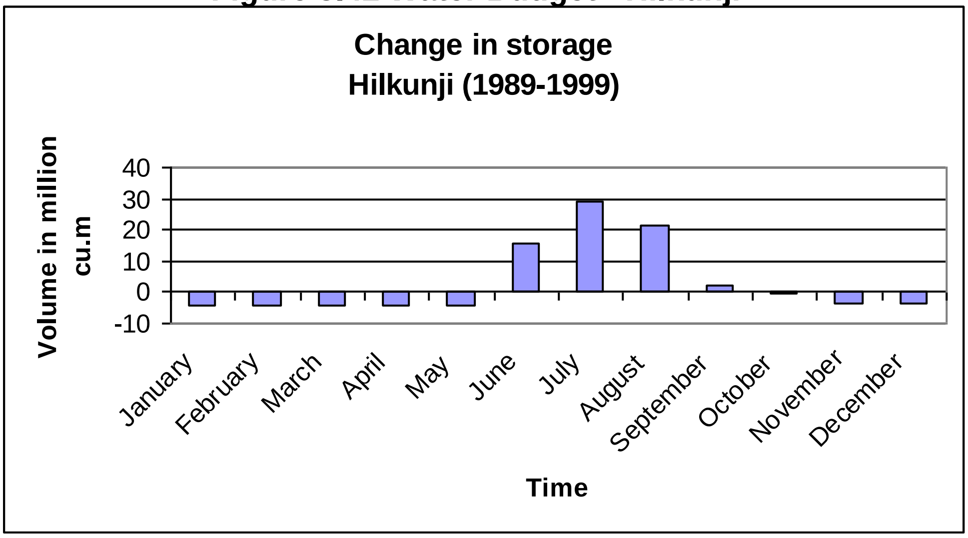


Figure 5.43: Water Budget - Sharavathi

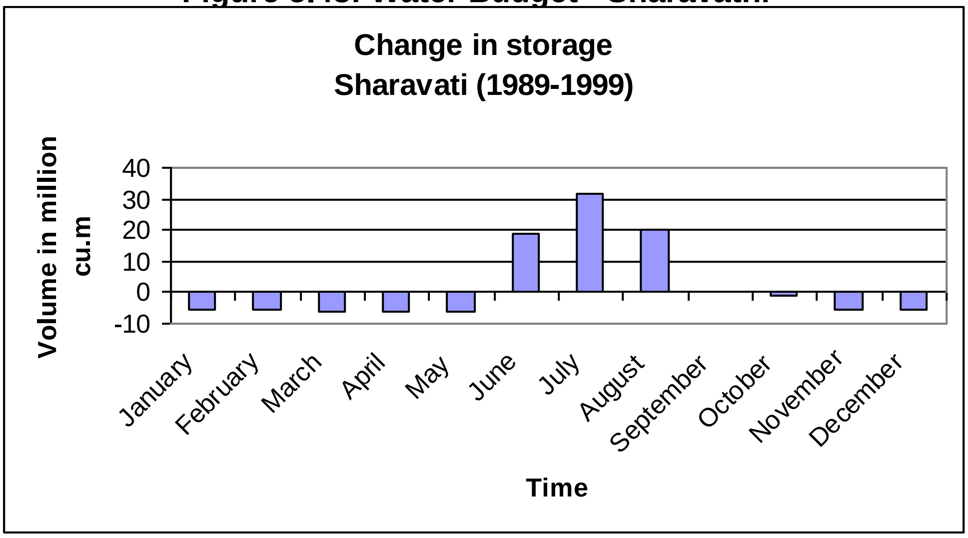


Figure 5.44: Water Budget - Mavinaholé

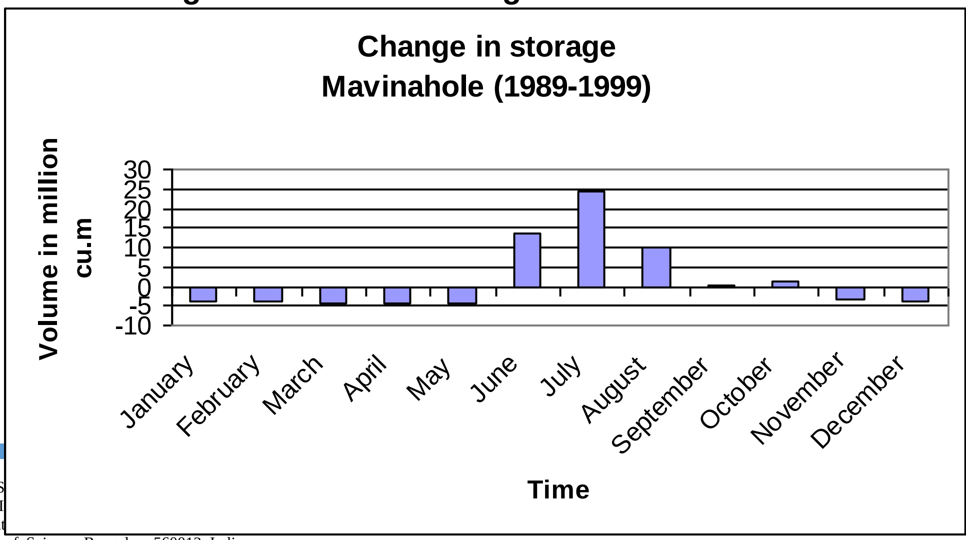


Figure 5.45: Water Budget - Haridravathi

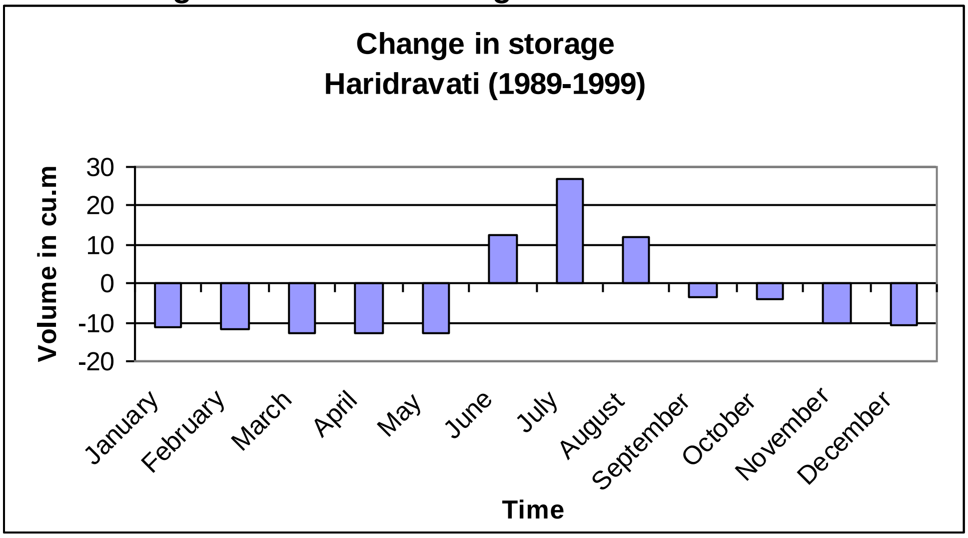


Figure 5.46: Water Budget - Nandiholé

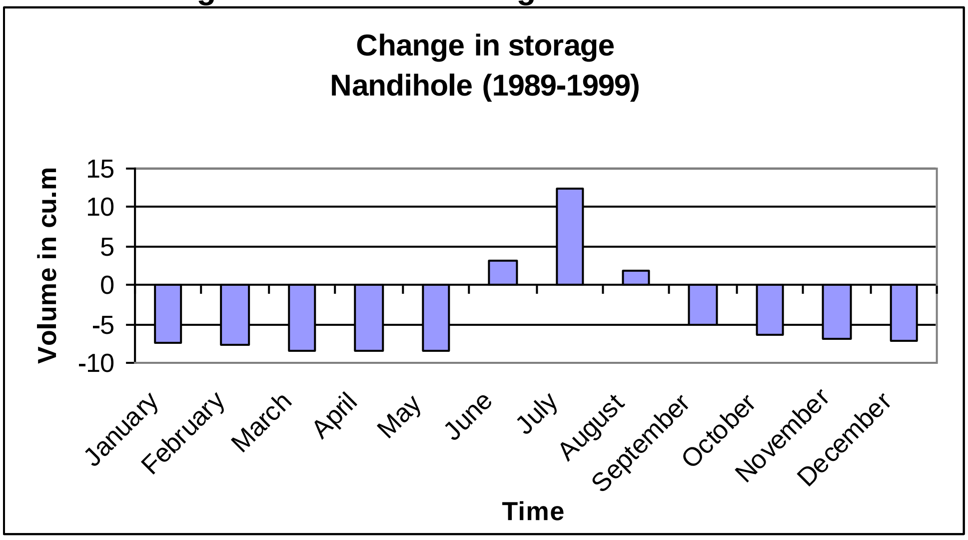
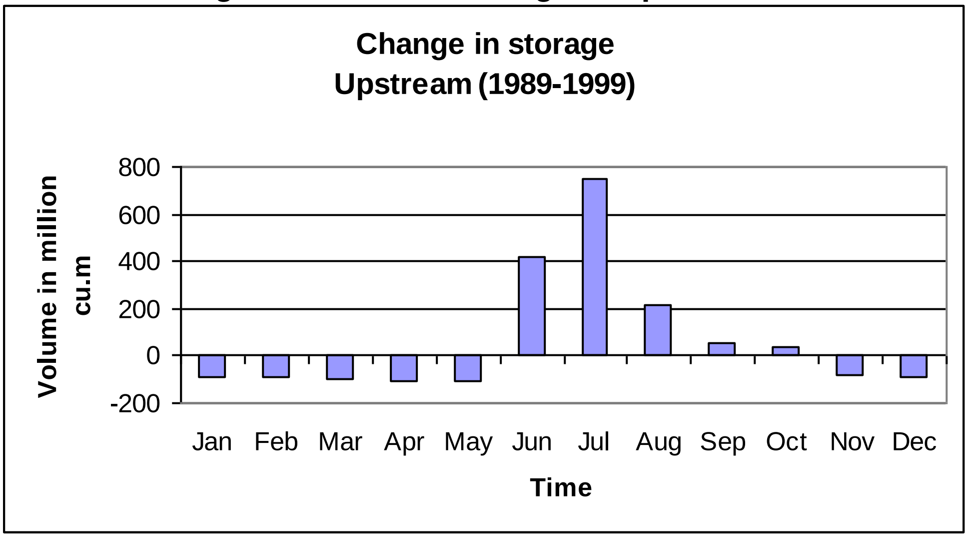


Figure 5.47: Water Budget – Upstream



The total change in storage for each sub basin is given in Table 5.35. Storage consists of the water contained in soil and the underlying rock. Higher storage in western sub basins are responsible for the lush vegetation present in these areas. During summer, the plants can extract sufficient moisture from the soil for its physiological processes.

Table 5.35: Total Storage in Sub Basins

Sub basins	Mean Total Storage (x 10^6 M cu.m) (June-Oct)
Yenneholé	233.09
Nagodiholé	171.56
Hurliholé	86.80
Linganamakki	834.69
Hilkunji	68.55
Sharavathi	70.54
Mavinaholé	48.03
Haridravathi	51.21
Nandiholé	17.6

Mean annual volumes of hydrological components in each sub basin are given in Table 5.36.

Table 5.36: Mean Annual Volumes of Hydrological Component (x 10^6 m^3) (1989-1999)

Sub basins	R	I	T	E	SR	P	GR	GD
Yenneholé	983.6	191.96	80.7	25.37	281.78	0.67	286.79	26.47
Nagodiholé	374.68	86.63	32.22	6.7	88.91	0.79	115.75	16.98
Hurliholé	413.69	85.32	42.13	12.74	111.88	0.62	200.72	11.55
Linganamakki	2915.53	379.06	265.12	228.73	815.2	-	749.01	78.05
Hilkunji	337.85	77.31	39.45	7.72	83.03	0.8	99.38	9.23
Sharavathi	358.68	61.53	50.4	17.89	119.0	0.26	105.46	9.46
Mavinaholé	254.41	42.71	33.16	13.58	78.81	0.3	64.97	1.17
Haridravathi	555.82	77.56	90.3	51.25	188.13	-	184.79	3.25
Nandiholé	31.08	49.84	61.24	29.67	125.3	-	97.37	1.86

Table 5.37: Mean Monthly Stream flow Contribution in Sub Basins (x 10^6 m^3) (1989-1999)

Sub basin	Yenne	Nagod	Hurli	Lingan	Hili	Shara	Mavin	Hari	Nandi
Jan	0.0095	0.029	0.008	0.039	0.002	0.002	0.002	0.002	0.002
Feb	0.0021	0.006	0.001	0.008	0.0006	0.0005	0.0004	0.0003	0.0002
Mar	0.0004	0.001	0.0004	0.001	0.00018	0.00016	0.00015	0.0001	0.0001
Apr	0.0001	0.0002	0.0002	0.0004	-	-	-	-	-
May	-	0.0001	-	0.0002	-	-	-	-	-
Jun	69.38	35.34	28.87	204.14	21.25	33.85	19.63	35.47	28.87
Jul	115.11	20.11	47.16	333.96	33.74	47.07	32.01	70.35	47.16
Aug	91.67	19.84	33.36	237.84	27.24	30.3	15.85	44.01	33.63
Sept	23.25	19.29	9.03	62.97	6.44	7.79	5.96	16.63	9.03
Oct	9.16	2.75	5.49	53.21	4.29	9.62	6.77	24.77	5.49
Nov	0.29	0.59	0.09	0.87	0.09	0.065	0.04	0.12	0.09
Dec	0.044	0.13	0.01	0.19	0.01	0.01	0.009	0.019	0.01

The mean monthly stream flow contribution for all sub basins is given in Table 5.37. It is the sum of surface runoff, sub surface runoff (pipeflow) and groundwater discharge. Natural and artificial forces operating over a watershed or a basin ultimately impacts its stream flow regime. Perenniality of streams is dependent on factors such as geology, type and distribution of vegetation, soil, climate and topography. Western clusters enjoys the benefit of good rainfall, vegetation and geology to give rise to stream flow even during the lean season. A contrast is seen on the eastern side as volume of stream progressively decreases from Hilkunji to Nandiholé sub basins. Modification of land by agriculture and other uses, unfavourable geology, clearcutting of natural forests and poor rainfall have resulted in decline in baseflow during the non-monsoon months and significant decrease during summer (Mar-May).

The evergreen forests have high humidity thereby are the major driving forces in determining the amount of rainfall in these regions. Thus in the upstream, heavy rainfall occurs along Nagodi, Kogar and Aralagodu raingauge stations. Forest cover in these regions is also high (land cover analysis, land use analysis) indicating the close relationships between rainfall in Western Ghats regions with the type (evergreen, semi-evergreen) and spatial extent of vegetation cover (Table 5.38). Within the catchment area of Linganamakki, the areas surrounded by rich vegetation like Nagara, Karimane, Byakodu receive high rainfall compared to fragmented, poorly vegetated eastern regions like Ulluru, Anandapura and Ripponpet.

It is found that western side sub-basins (Nagodihole, Hurulihole, Yennehole) have rain fall ranges from 4500-6500 mm and their stream flow is quite high having grade of A (perennial streams). Sub-basinwise stream flow is given in Table 5.39. South east region (Sharavathi, Hilkunji) has rain fall of around 5000mm with stream flow moderate to high having grading of B-C (stream flow for 6-9 months). Finally sub-basins of eastern side (Nandihole, Haridravathi and Mavinahole) have rain fall of 1400-3000 mm which is very less and their stream flow is also quite low, graded C-D (4-6 months: mostly during monsoon).

Table 5.38: Land-use pattern (%) and associated annual rainfall in the sub-basins of Sharavathi river upstream

Locality	Annual rainfall (mm)	Forests EVG/SE	MD	Plantation	Grassland	Agri	Open	Sett
Nandihole	1715.20	1.25	27.34	2.93	29.73	10.55	23.14	5.05
Haridravathi	1776.49	1.3	21.77	3.91	26.82	16.76	24.63	4.81
Mavinahole	2157.88	2.44	35.09	5.04	21.19	10.66	18.72	6.85
Sharavathi	3382.40	11.54	28.80	10.03	11.58	13.72	19.34	5.00
Hilkunji	4801.25	29.84	34.74	6.45	7.56	5.72	11.46	4.25
Hurulihole	4410.05	22.94	31.54	8.28	13.85	1.28	18.92	3.19
Nagodi	5597.50	40.51	23.54	13.73	4.78	0.05	13.03	4.35
Yennehole	4933.01	27.32	22.94	14.75	11.50	1.04	19.40	3.05
Linganamakki	3423.25	8.51	34.14	9.35	2.26	8.51	32.88	4.34

* Water body constitutes 15.8% of the region, Note: EVG/SE: Evergreen/semi evergreen; MD: Moist deciduous; Agri: Agriculture; open: open area; sett: settlements

Table 5.39: Stream flow data for major tributaries of streams in the Linganamakki catchment

Stream	Location	Stream flow measurement (Discharge m^3/sec) Oct.	Nov.	Dec.	Jan	Stream Grading*
Nandihole	Northeast	1.23	3.68	0.09	0.000	D
Haridravathi	East	16.23	3.02	0.46	0.000	D
Mavinahole	East	5.93	3.00	0.44	0.000	D
Sharavathi	Southeast	26.73	5.83	1.08	0.964	C
Hilkunji	Southeast	46.27	10.64	2.64	1.670	B
Nagodihole	West	22.56	4.84	1.90	1.420	A
Hurlihole	West	6.30	1.37	0.78	0.661	A
Yennehole	West	NM	13.40	1.81	1.680	A

* Based on numbers of months with flow a: 12 months, B: 9 months; C: 6 months and D: 4 months

6.0 Conclusions

This study explored and quantified the altered hydrological parameters due to large scale land use and land cover changes. In this regard, satellite data has offered excellent inputs to monitor dynamic changes through repetitive, synoptic and accurate information of the changes in a river basin. It also provided a means of observing hydrological state variables over large areas, which was useful in parameter estimation of hydrologic models. GIS offered means for merging various spatial themes (data layers) that was useful in interpretation, analysis and change detection of spatial structures and objects. Studies reveal the linkages among variables such as land use, hydrology and ecology. Following are the conclusions drawn from the hydrological studies of upstream, river basin.

Rainfall analysis based on one hundred years data for Sagara and Hosanagara show reduction of –3.55% and 5% respectively in the Sharavathi upstream river basin Regression analysis was carried out for each rain gauge station considering rainfall as dependent variable and latitude, longitude, altitude and land cover as independent variables. Regression analysis showed rainfall having significant relationship (5% level of significance) between land cover, latitude, longitude, and altitude.

Interception was comparatively high in evergreen/semievergreen forests due to thicker and multilayered canopies. It was followed by moist deciduous forests, plantations, scrub savanna and paddy. Interception was the highest during peak rainfall months and showed least values for shorter crops.

Transpiration also decreased from evergreen/semi-evergreen forests to paddy due to lower albedo in the former. Lower albedo corresponds to higher latent energy, which converts liquid water to water vapour. Transpiration peaks during summer and is the lowest during the monsoon season. Low transpiration during wet months is because most of the energy available for evaporation is consumed by the interception process, which precedes transpiration and because solar radiation is inhibited by clouds in the wet months (Shuttleworth, 1993).

Catchments with good forest (evergreen/semi-evergreen and moist deciduous forests) cover showed reduced runoff as compared to catchments with poor forest covers. The results are similar to conclusions drawn by Bosch and Hewlett, 1982 from various catchment experiments that forested areas have reduced runoff as compared with those under shorter vegetation. Runoff and thus erosion from plantation forests was higher from that of natural forests. Erosion rates in undisturbed natural forest could be considered to represent a natural baseline or background erosion rates against which the erosion rates from all other land uses.

Sub-surface flow caused by pipes in the Western Ghats appears at valley bottoms of forested slopes. The macropore flow collects in the pipes and flows through them into the stream. Recharge in the sub basins varied with respect to vegetal cover and soil texture. Higher recharge was observed in sub basins with good forest cover.

Sub basins with good forest cover showed good amount of dry season flow for all 12 months with the flow decreasing as we move towards east. Decrease of low flows in eastern sub basins can be partly attributed to eucalyptus plantations. Eucalyptus trees have deep roots that tap water deep in the soil mantle creating severe soil moisture deficits. It may take many years of rainfall before field capacity conditions can be established and recharge of the groundwater aquifer and perennial flows can take place. Another reason is the low specific yield of the underlying rock.

This highlights the impacts of tropical forests on dry season flows as the infiltration properties of the forest are critical on the available water partitioned between runoff and recharge (leading to increased dry season flows).

In short, sub basins with good vegetation cover i.e. natural forests and low anthropogenic activities especially in the western sub basins had high interception, transpiration, recharge and discharge and low surface runoff. On the other hand, eastern sub basins with less natural forest cover had low interception, transpiration, recharge and discharge and high surface runoff.

The anthropogenic influences on the land cover are related to the land use for agriculture, plantation forestry and urbanisation. It was obvious from the present study that land use has an implication on the hydrological components operating in the river basin. However, further research may be necessary to understand the scale of study, low flow mechanism in rivers, sub surface flow distribution under forests in Western Ghats etc.

Some studies that need to be considered in the future analysis are discussed below.

a) The scale of study is important as macro level understanding of the hydrology of a river basin may not be enough to capture the dynamics as some changes are relevant only at micro scale. For example, clearing a few hectares of forest may not influence the regional or global hydrological cycle but it can have implications on the local water cycle. Impact on the local water cycle can affect the micro ecosystem, which may harbour flora and fauna that are adapted to that type of an environment. A water balance study should thus link the ecology and hydrology of a river basin so as to understand the complexities of a region.

   Ecohydrology describes species diversity, growth forms of vegetation, biomass estimates etc and fuses it with hydrology. Another important area of study is the geology, which is helpful in understanding the occurrence and distribution of ground water and thus the low flow regime of a river. It is important to have a holistic approach when dealing with river basins rather than a pure engineering or ecological approach.

b) Interception analysis in the present study takes into account only the storage capacity and its associated evaporative fraction, intensity of rainfall and seasonality of vegetation. Interception is also dependent on leaf thickness, leaf and stem roughness and leaf orientation, which varies with species. Components such as stemflow and throughfall have not been considered and have to be included in future analysis.

c) Field studies of soil are required to determine the soil infiltration rates. In the present study, infiltration is the difference of net rainfall and surface runoff and the actual values may differ. Studies have proved that infiltration under forested areas in Western Ghats is high.

d) Sub surface flow distribution through pipes in Western Ghats has only been studied in the past few years. Pipeflow have been observed to contribute to flow in streams and in Western Ghats, many dug wells are known to derive their water from large diameter pipes. In regions where Hortonian flow cannot occur, it is observed that pipe overland flow which is new mechanism of runoff generation occurs. This has not been quantified in the studies and needs to be included in future analysis. Studies are also needed to understand the extent and distribution of pipes under forested slopes.

e) Low flow contribution to stream flow in the study area takes into consideration only the natural factors and not artificial factors such as pumping. The effects of groundwater pumping near the head of a perennial river may result in groundwater table depletion through tapping of recharge water. This can result in substantial environmental degradation of the river habitats, loss of naturally sustained fisheries, reduction in the general amenity value of the river. Monitoring of wells in the western sub basins are needed to obtain a more realistic picture in the analysis.

f) The use of remote sensing data should be maximized in watershed studies. It is particularly useful to study the spatial and temporal dynamics in tropical forested watershed as field studies may prove to be difficult depending on the region. However, training site strategies and choice of classification methods have to be considered in order to classify the vegetation in these regions accurately due to its diversity.

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Landscape dynamics on hydrologic regime in Aghnashini river basin

Landscape composition has a central role in water cycling and managing the quality and availability of water in the region. However, in recent decades, human activities have significantly altered the landscape composition; major reason being the disturbance and fragmentation of landscape which are the outcomes of unplanned development and the growing demand of the burgeoning population. This has resulted in decline in both quality as well as quantity of the pristine forest which has led to the changes in regional hydrology, raising the concern to understand the impact of landscape degradation on the hydrological regime. Thus the need to understand the coupled interaction between land use and water resources, which is essential to enhance the sustainability of water resources in a region, is of paramount importance. In this context, present study has been carried out to explore and quantify the hydrological components of the Aghanashini River Basin of Karnataka, India and determine the consequences of the land use changes, at the sub-basin level, on the water availability of the region. Global availability of temporal remote sensing data has helped in analyzing the land use condition of the region at different epochs. The result of the investigation suggests groundwater recharge to be a function of the structure of landscape in the region. It also underscores that the sub surface flow which is responsible for the low flows in the river, is a function of vegetation cover in the region.

Key Words: Land Use, Hydrological Cycle, Fragmentation, Interior forest, Groundwater Recharge and Water Yield

1. Introduction

Landscape is any heterogeneous area comprising of different interacting ecosystems that are repeated in a similar fashion (**Forman & Godron, 1986**). Landscape is seen as a spatial expression of the ecosystem (**Burel, 2004**).Different units or different elements like patch of forest and stream corridor present in a landscape constitute landscape structure. The interactions between these different elements results in flow of nutrients, energy, water, etc between the different ecosystems, which constitute the landscape function. These interactions maintain the dynamisms in the ecosystems. Changes in any of the landscape structure caused either due to natural disturbances (floods, volcanic eruptions, etc) or anthropogenic factors result in the changes in the functioning of the landscape and vice-versa.

Human activities have caused explicit changes in the landscape on a global scale. Human led deforestation, urbanization and increase in other land use activities are important contributors to the myriad of changes in landscape pattern and processes (**Turner et al., 2001**).The causes of these changes are multifaceted but are driven by population growth, politics and pattern of economic development (**Paulson, 1994; Gretchen, C D 1995 and Ruder & Roper, 1996**). These factors have resulted in the fragmentation of the landscape (**Forman & Godron, 1986**).

Fragmentation is regarded as the breaking of a landscape into small parcels of land which is mostly human guided, like encroaching of forest area for agriculture or plantation, building of roads and impoundments, coming up of urban areas in undisturbed forest area, etc. Thus, fragmentation is considered as the dissection of the earth's surface into spatially isolated parts; rearranges the structure of the ecosystem and shapes their function worldwide (**Hobbs et al., 2008**). Hence it has emerged as a central force in driving global change

Fragmented landscapes, now common in existence, consist of remnant forest patches and various human-disturbed land covers, which are degraded both ecologically and physically (**Ziegler et al., 2004**). This structural degradation has influenced the functioning of landscape on a global scale.

One of the major functions of the landscape is the cycling of water between terrestrial ecosystem, aquatic ecosystem and the atmosphere which is essential for the sustenance of life on Earth. Evaluating the impact of land use change on water and matter fluxes is a major challenge in hydrological research (**Breuer et al., 2009**).

A hydrologic cycle is an assemblage of various components that include precipitation, evaporation, runoff, subsurface flow and ground water flow. Although the concept is simple, but the phenomenon is enormously complex and intricate as it is influenced by various meteorological phenomenon (like intensity of rainfall) as well as physical factors like topography, geology and vegetation. Apart from this, in recent decades human activities have significantly altered the dynamic equilibrium of hydrological cycle as these responses are highly sensitive to land use changes. Hence manifestation of land use and its management may have significant hydrological impacts by either enhancing or retarding infiltration, thereby reducing or enhancing the stream flows (**Schulze, 2000**). Thus, understanding the consequences of land-use change for hydrological processes and integrating this understanding into planning is an emerging focus of land-change science (**Turner et al., 2003**). These consequences include changes in water demand from changed land-use practices, changes in water supply from altered hydrological processes like infiltration, groundwater recharge, stream flow, etc and changes in water quality from agricultural runoff and suburban development (**DeFries, 2004**).

Various studies (**Sikka et al., 1998; Van Lill et al., 1980 and Scott & Lesch, 1997**) provide evidence to support the assumption that conversion of natural forests to other land use practices (agriculture, pasture land & horticulture) have led to soil compaction, reduced infiltration, groundwater recharge & discharge and rapid & excessive runoff which ultimately affect the flow of water from the landscape. **Bruijnzeel (1989)** establishes that, following clearance of tropical forest land, there is an increase in annual runoff. The actual increase depends on numerous factors such as forest types, rainfall regime, soil type, soil depth and topography (**Bosch & Hewlett, 1982**). Thus concerns about the impact on water resources on changing patterns of land-use associated with deforestation and agricultural transformation have created social and political tensions from local to national level (**Rattanaviwatpong et al., 2005**). **Schulze (2000)** found out that intensification of LU, like conversion of natural grass cover to exotic plantation may increase the canopy interception, enhances the infiltration and consequently higher transpiration, resulting in lesser storm runoff generation as well as lesser water percolating the ground zone to feed the base flow store, which ultimately results in lesser flows in the stream. On the other hand, degradation of vegetation in the land reduces the infiltration capacity of the region which may increase the risk of flash flood in the catchment with enhanced peak discharges and sediment yield. **James et al.,** (**1987**), also found out that the sediment yield from the exploited basins is much more than the basins that have dense forest cover. Thus forest and water are intrinsically intertwined (**Bruijnzeel, 2001**) and forest removal produces wide range of hydrological responses (**Hibbert, 1967; Dunne & Leopold, 1978; Bosh & Hewlett, 1982 and Bruijnzeel, 2001**).

Despite of these studies, realm of hydrological consequences associated with the degradation of forest or conversion of forests to other land use categories and fragmentation is not clearly understood (**Ziegler et al., 2004**) and still a cause of controversy and debate. In addition, there is worldwide concern about the detrimental effect associated with the exotic monoculture plantations, which are often done on the degraded and open land in forests, with the focus on the changes in the water yield that these monoculture species cause in the catchment (**Purandara et al., 2010**).With this intent, the objective of the present study is to focus on the influence of land use on amount of water available in various sub systems of hydrological cycle.

Analysis of the hydrological impacts of land use change has been made feasible by observing land-cover changes through the availability of satellite data which was not possible a decade ago. Information of land-use over larger areas allows new kind of investigations, such as, the effects of spatial patterns of land-use within a watershed on hydrological processes and also mapping and modeling of large drainage basins (**DeFries, 2004**). Satellite remote sensing now has a potential of providing extensive coverage of key variables such as precipitation **(Smith et al., 1996; Sturdevant-Rees et al., 2001**), soil moisture (**Sano et al., 1998**), flooding (**Townsend & Foster, 2002**), imperviousness (**Slonecker et al., 2001**), etc which can be used as input to various hydrological models. Thus, recent studies also focus on the potential of an integrated modeling approach to evaluate the impact of land use changes on water resources (**Lin et al., 2007 and Bithell & Brasington, 2009**). Further, with the aid of Geographic Information System (GIS) it is possible to combine all the spatial layers and bring them in one domain for holistic analysis.

2. Material

2.1 Study Area: The study has been conducted for Aghanashini River, which is one of the westwards flowing rivers in Western Ghats, in Uttara Kannada district of Karnataka, India; lying between 14.39° to 14.58°N latitude and 74.30° to 74.51°E longitude. The Western Ghats form an area of hectic activity as far as water resources development is concerned (**Putty & Prasad, 2000**). This signifies the importance of simulating various components of hydrological cycle (as affected from land use) in this catchment.

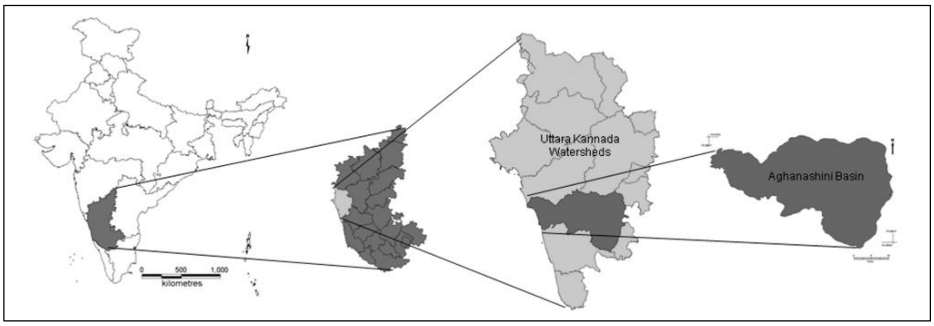

Fig. 1: Study region, Aghanashini river basin in Uttara Kannada District, Western Ghats, Karnataka, India

Aghanashini River originates in Sirsi taluk of Uttara Kannada district at an elevation of about 1800ft above the sea level and it encompasses a catchment area of 1370sq.km. with a length of 121km (Fig. 2a). During its course, it forms beautiful falls like Lushington (or Unchalli) falls and Burude falls and flows thorough three major taluks of the district namely Kumta, Sirsi and Siddapur. After making a 13km long estuarine expanse in the coastal zone of Kumta taluk, it finally discharges into the Arabian Sea. Since the River has a large catchment area, hence for the analysis purpose it was divided into seven sub catchments, where each sub catchment was considered as a hydrological response unit (HRU), assumed to be homogenous in hydrologic response to land cover change (Fig. 2b).

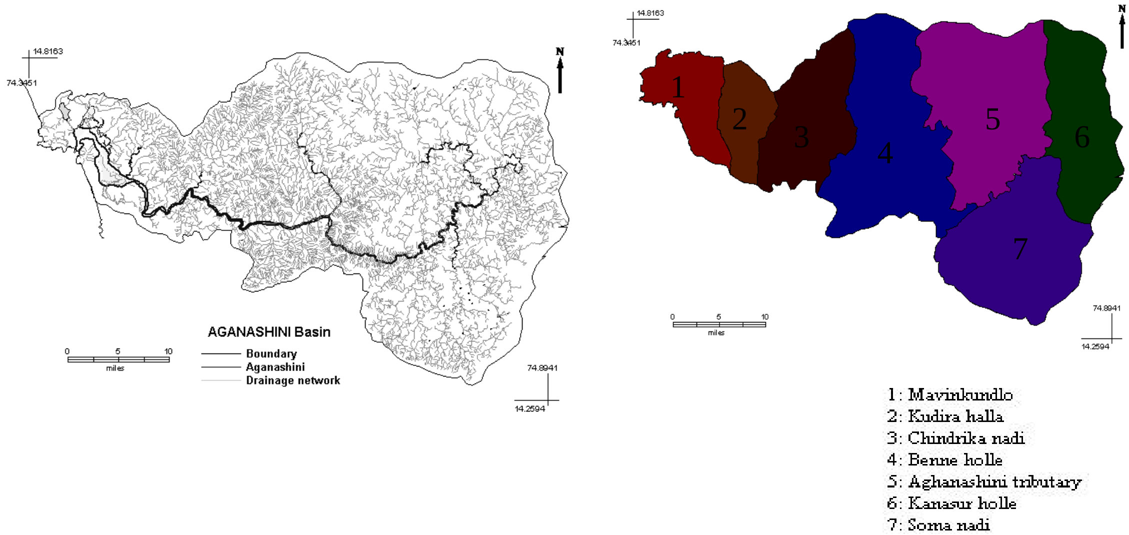

Fig. 2: Drainage network (a) and sub-basins (b) of the Aghanashini River basin

2.2 Data collection: Daily series of rainfall data since 1901 was procured from Indian Meteorological Department (IMD) and Directorate of Economics and Statistics, and was analyzed for annual and monthly variation. Detailed information about the landscape was obtained from the temporal satellite images (Table 1), procured from the Global Land Cover Facility (GLCF) and United States Geological Survey (USGS) Earth Explorer.

Table 1: Data Source Information

Satellite/Sensor	Date of Imagery	Path/Row	Resolution
Landsat MSS	December, 1972	157/49 157/50	60m
Landsat TM	November, 1989	146/50	30m
Landsat ETM+	December, 2006	146/50	30m
Landsat ETM+	January, 2010	146/50	30m
Shuttle Radar Topography Mission (SRTM)		51/10	90m

Topographic information about the region was obtained from the Shuttle Radar Topography Mission (SRTM) data from the CGIAR Consortium for Spatial Information (CGIAR-CSI) at 90m spatial resolution. Digital Elevation Model (Fig. 3a) and Slope Map (Fig. 3b) was generated from this data.

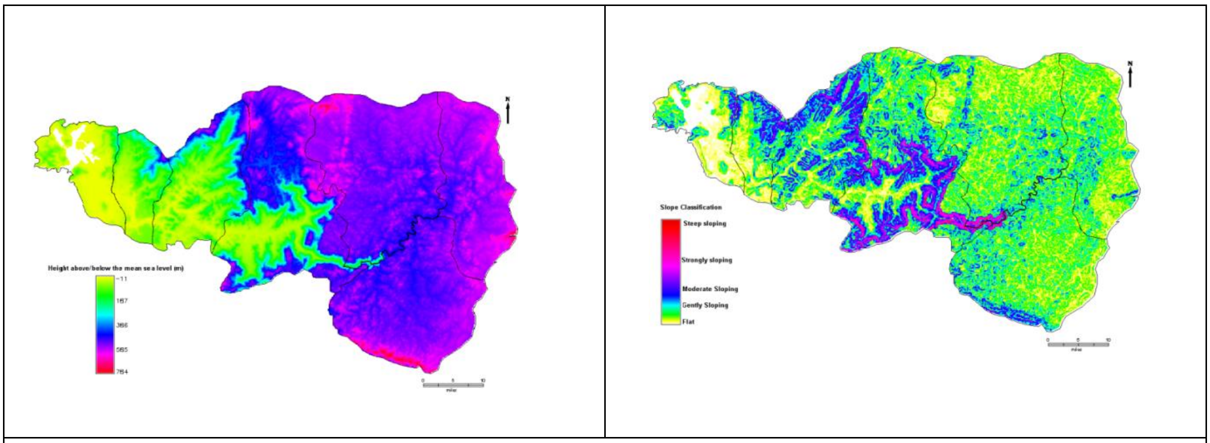

Fig. 3: Digital Elevation Model (a) and Slope Map (b) of the Aghanashini river Basin

Other ancillary data include Geology/soil texture map (Fig. 4a) and Lithology/ Rock type map (Fig. 4b) of the region obtained at 1:250,000 scale from French Institute.

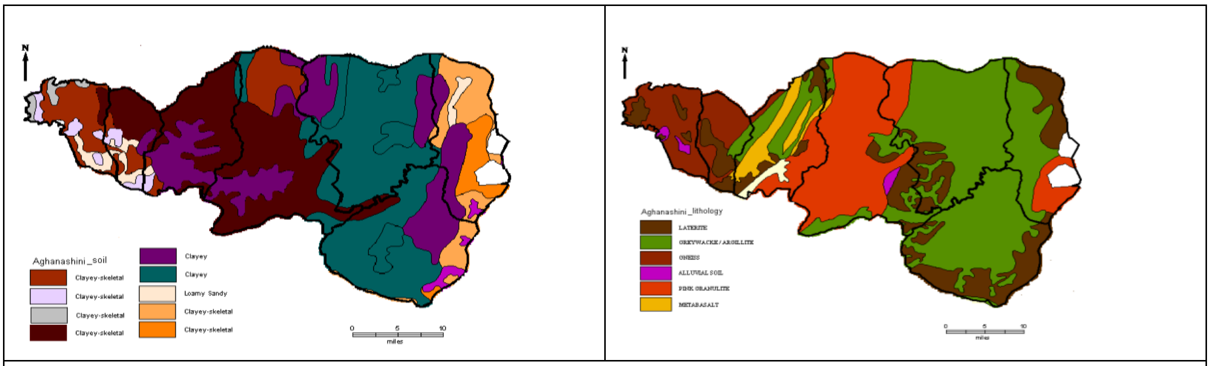

Fig. 4: Soil Texture Map (a) and Rock type Map (b) of the Aghanashini River Basin

3. Methodology

The overall methodology is shown in Figure 5 and briefly described in the following section.

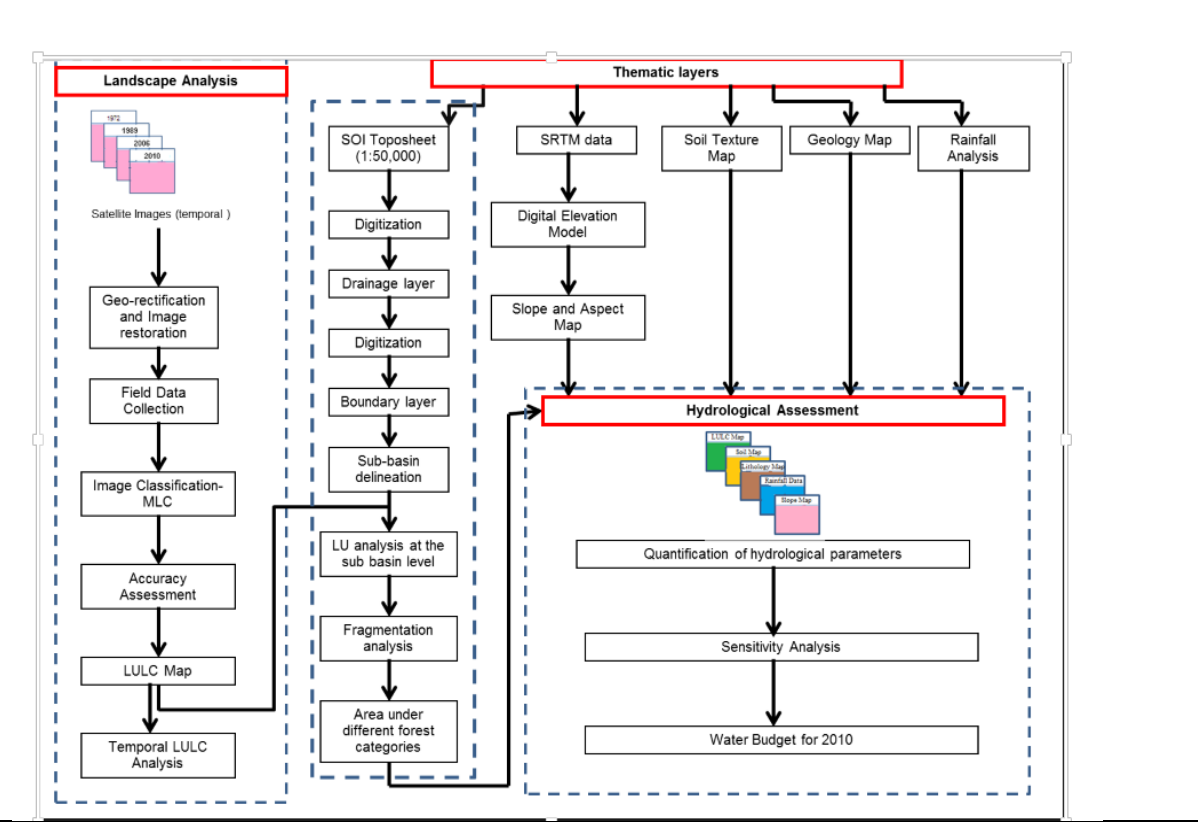

Fig. 5: Methodology adopted in the study

Obtained satellite images were first processed, wherein all the acquired data sets were georectified, resampled and then cropped using the delineated watershed boundary. For land cover analysis, Normalized Difference Vegetation Index (NDVI) of the region was generated using NIR and Red band, which gives the information about the vegetated and non-vegetated (crop land, barren land, water body, etc) areas.

Supervised classified of the images (corresponding to the watershed area) was done through maximum likelihood classifier (MLC) for Land Use (LU) analysis. Obtained LU maps were assessed for their accuracy through generation of error/confusion matrix, referring to the data collected from the field, which was selected in such a way that they are uniformly distributed over the region and can be easily identified on the satellite imagery.

LU maps indicate only the location and type of forest, and further analysis is required to quantify the forest fragmentation (**Ramachandra et al., 2009**). Thus, for the fragmentation analysis of the region, model developed by **Ritters et al., (2000)** was considered, whose details are specified elsewhere (**Hurd et al., 2001 & 2002**). The model calculates Pf (Proportion of forest) and Pff (Connectivity of the forest) values in the region based on a moving window analysis which helps in characterizing the forest pixel located at the centre of the window. It allows easy visualization of the extent of forest fragmentation and also tracks the changes in the fragmentation over time.

Based on Pf and Pff values, forest area is classified into six different categories (**Ritters et al., 2000**) namely, Interior forest (Pf=1, where all the pixels surrounding the centre pixel are forest); Edge forest (Pf>0.6 and Pf-Pff<0); Perforated forest (Pf>0.6 and Pf-Pff>0); Transition forest 0.4<Pf<0.6); Patch forest (Pf<0.4) and Undetermined forest (Pf>0.6 and Pf-Pff=0). Hydrological phenomenon vary in all the three space dimensions and thus explicit accounting of all the variables makes modeling a cumbersome approach. Hence empirical method is considered, where a real world situation is represented through some mathematical equations and statistical analysis is done to find relationship between different variables.

In general, water cycle is guided by the law of conservation of mass in which no water is gained or lost, but the amount of water available to the user may fluctuate, due to variation in the source or in delivering system (**Raghunath, 1985**) and is given by:

$$I = O + \Delta S \quad (1)$$

Where I= inflow, O= outflow and ΔS is the change in the storage.

The output from a watershed system includes various abstractions like Interception (amount of rainfall held by the vegetation canopy); Evaporation (loss of water from the free water and soil surface); Transpiration (loss of water from plant leaves); Evapo-transpiration (from irrigated or cropped land); Infiltration loss (entry of surface water into the soil and held within the soil pores); Surface Runoff (Infiltration excess rainfall that flows over the surface) and Sub surface flow (interflow which is flow of water from the vadose/unsaturated zone to the stream and baseflow which is groundwater flow to the stream), that are deducted from the precipitation (input) to compute the net storage amount. Equations used to compute various hydrological parameters are enlisted in table 2 along with the values (table 3-5).

Table 2: Hydrologic parameters and the equations to compute them

Parameter	Equation	Source
Interception	**$I = C + \alpha P$** Where, C: canopy storage capacity; α: evaporative fraction (vegetated area/total area); P: total amount of precipitation	Singh, 1992
Surface Runoff/ Yield	**C*A*P** Where, C: runoff coefficient; A: area of catchment; P: amount of precipitation	Raghunath, 1985
Evapo-transpiration	$E_{rc} = 0.4[\frac{T}{T+15}(Sn + 50)]$ Where, T: mean air temperature (°C); $S_n = S_t(1-\alpha)$ where, α is the albedo and $S_t = \left(0.25 + 0.5\frac{n}{N}\right) So$ Where, n: number of sunshine hours (hr); N: maximum possible sunshine hours in a day; S_o: extra terrestrial radiation (MJ/m^2/day) $E_{forest} = k\ E_{rc}$ Where, k: crop factor	Turc, 1961
Infiltration loss	**I= AWC coefficient * [(1-C)*A*P]** Where, AWC: Available Water Capacity; C: runoff coefficient; A: area of catchment; P: amount of precipitation	
Interflow	**Interflow = Pipeflow coefficient * $\frac{FC}{AWC}$ *Percolated rate** Where, AWC: Available Water Capacity; FC: Field Capacity	Modified from Guoqing & Hui, 2005
Baseflow	**Baseflow = S_y * Ground Water** Where, S_y: specific Yield	Singh, 1992

Table 3: Values considered for the computation of hydrological parameters for different land use types

Landuse/ Landcover	Canopy Storage Capacity, C (mm) (Putty & Prasad, 2000)	Runoff Coefficient, C (Singh, 1992)	Albedo range (α) (Shuttleworth, 1993)	Crop Factor (k) (Putty &Prasad, 2000)
Evergreen/ semi evergreen	4.5-5.5	0.2	0.11-0.16	1.20
Moist Deciduous	4-5	0.2	0.11-0.16	1.00
Plantations	4-5	0.2	0.11-0.16	1.00
Grasslands	1.8-2.0	0.3	0.20-0.26	0.85
Scrub	2.5-3.5	0.3	0.20-0.26	0.85
Agriculture land (paddy)	1.8-2	0.6	0.20-0.26	1.10

Table 4: Values for Field Capacity (FC) and Available Water Capacity (AWC) for different soil types

Soil texture	FC (FAO)	AWC (%) (USDA)
Loamy Sand	0.15	9
Sandy Clay Loam	0.30	10
Clay loam with sand	0.35	10
Clay with sand	0.40	15

FAO: Food and Agriculture Organization; USDA: United States Department of Agriculture

Table 5: Different coefficient values based on characteristics of the sub-basins

Sub-basin	Relief Ratio (%)	Pipeflow coefficient	Rock type (French Institute Soil Map)	Average Specific Yield (Ministry of Water Resources, 1997)
1	1.68	0.2	Gneisses	0.03
2	3.47	0.1	Gneisses	0.03
3	1.93	0.25	Greywacke/Basaltic rock	0.1
4	2.29	0.3	Granite	0.03
5	2.12	0.25	Greywacke	0.27
6	2.05	0.25	Greywacke/Granite/Laterite	0.15
7	3.69	0.1	Greywacke/Laterite	0.15

4. Results and Discussion

4.1 Land Cover Analyses:

Land Cover analysis of the year 2010 (Fig.6) shows that 65.76% (997.61 sq.km.) of the entire catchment area is vegetated (forest and plantations) while the remaining 34.24% is non-vegetated (crop land, barren land, water body, aquaculture, etc).

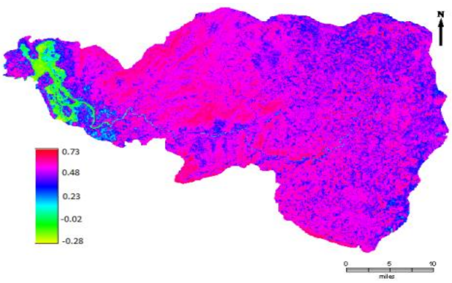

Fig. 6: Land Cover Analysis of the Aghanashini river basin

4.2 Land Use Analyses

LU details of each sub-basin of the region since 1971 are shown in Fig 7. The change in area of each class for the entire watershed (Table 6) shows that evergreen forest decreased drastically (29.82%) in all the sub-basins during the period of 1972-1989, but remained almost stagnant after that. While deciduous forest initially increased by 21% but thereafter no significant change was observed. Areca plantations have increased manifold by 2010 due to their great economic value.

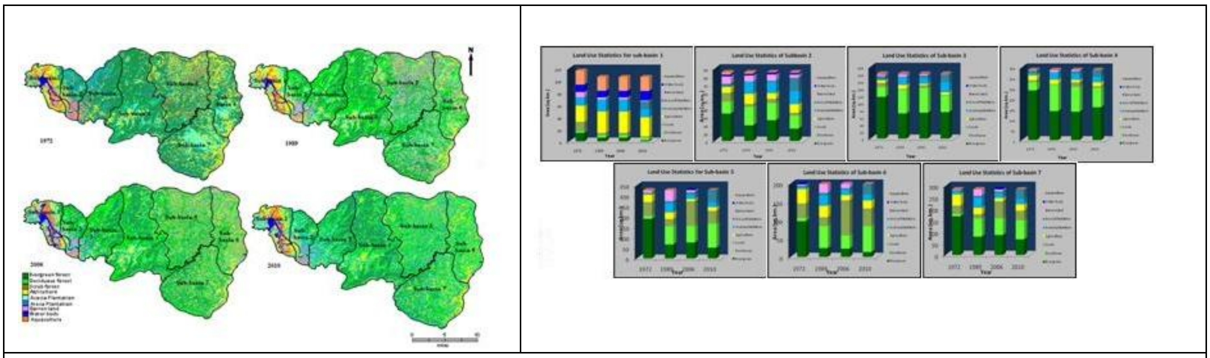

Fig. 7: Land Use Analysis of the Aghanashini river basin

Table 6: Change in land use classes

Class	1972-1989		1989-2006		2006-2010	
	Change in Area (sq.km.)	Change (%)	Change in Area (sq.km.)	Change (%)	Change in Area (sq.km.)	Change (%)
Evergreen	-452.52	-29.82	26.44	1.74	-50.37	-3.32
Deciduous	329.60	21.72	-46.33	-3.05	29.2	1.92
Scrub	-99.51	-6.56	236.96	15.62	-161.16	-10.62
Agriculture	-17.74	-1.17	-89.96	-5.93	53.66	3.54
Acacia plantation	167.25	11.02	-66.18	-4.36	9.17	0.60
Areca plantation	-10.29	-0.68	13.53	0.89	165.37	10.90
Barren land	89.61	5.90	-71.43	-4.71	-50.01	-3.30
Water body	-1.92	-0.13	6.67	0.44	-1.27	-0.08
Aquaculture	-4.51	-0.30	-9.67	-0.64	4.91	0.32

4.3 Fragmentation Analyses

Temporal fragmentation index maps obtained after computing Pf and Pff for all the sub-basins has been shown in figure 8 which qualitatively shows the status of forests in the region.

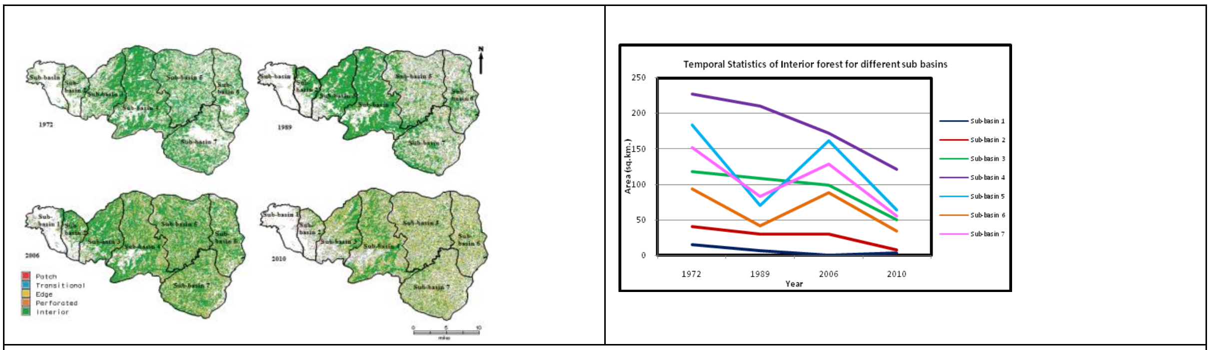

Fig. 8: Fragmentation Analysis of the Aghanashini River Basin

Results showed that the sub-basins like sub-basin 1 (which is near the coast) and sub-basin 6 and 7 (which include densely populated taluks like Sirsi and Siddapur) have witnessed significant decline in interior forest and increase in patch and edge forest due to greater human exploitation in these areas. Whereas sub basins 3 and 4 which have steep slopes and difficult terrain (evident from figure 3b) and thus less exposed to anthropogenic activities, still have 40% of the area under interior forest.

4.4 Hydrological Investigation

For the hydrological assessment, rainfall of the taluks Kumta, Sirsi and Siddapur were analyzed for annual as well as monthly variation (Fig. 9). Annual rainfall analysis shows that the rainfall in the region follows a periodic pattern within a time span of 5-10 years.

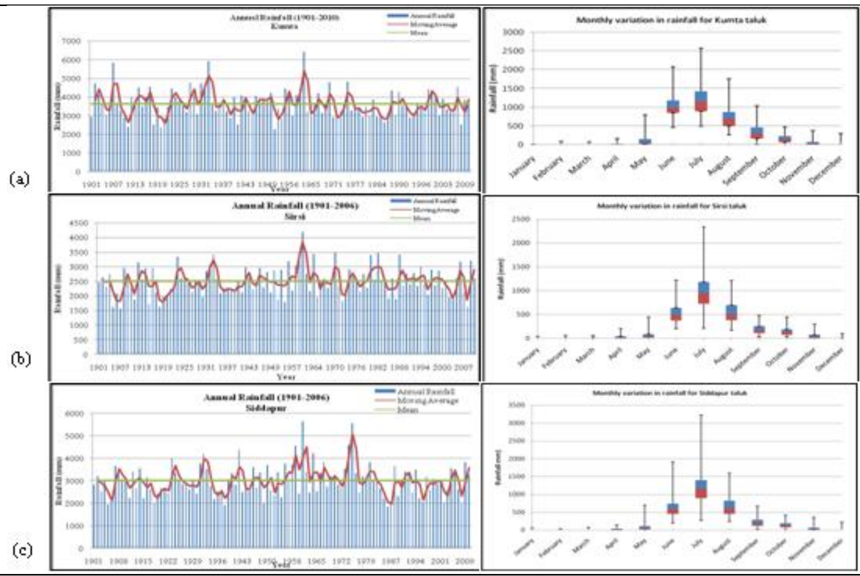

Fig. 9: Annual (left) and monthly (right) variation in the rainfall of Kumta (a), Sirsi (b) and Siddapur (c) Taluks

Monthly rainfall analysis of the taluks shows that the region receives quantifiable amount of rainfall (input) during the period of June-Oct and for the rest of the months there is only withdrawal (output). Hence only these months were considered for the computation of different parameters.

Subtracting the different abstractions (interception, evapotranspiration, surface runoff, sub surface flow, infiltration loss), determined by various equations specified in the methodology section, from the rainfall gives the net amount of recharge. Figure 10 shows the spatial distribution of rainfall and recharge over the entire region for the time periods corresponding to the available land use data.

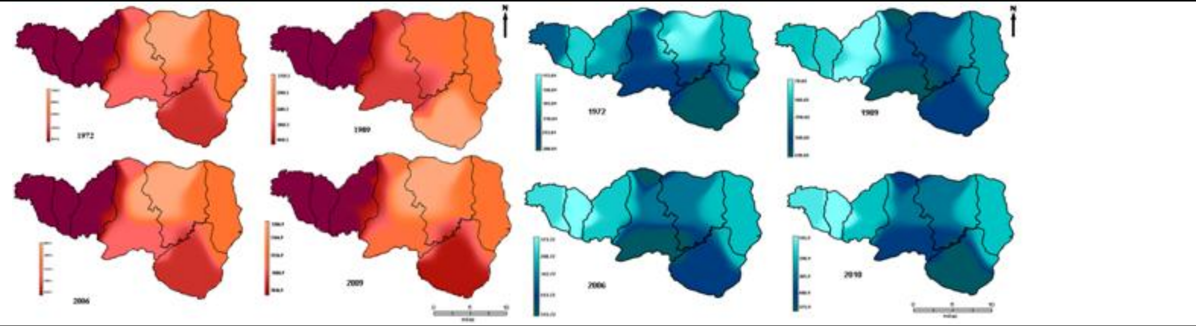

Fig 10: Spatial distribution of Rainfall (left) and Recharge (right)

It can be seen in figure 10 that sub-basin 4 having greater area under evergreen forest has comparatively higher recharge for all the years while sub-basin 1 which has least percentage of area under evergreen forest has lowest recharge among all the sub-basins for all the years.

Following this, statistical analysis was done to understand the relationship between various independent parameters. Paired t-test analysis conducted at 5% significance level (95% confidence level) showed that the rainfall and interior forests (considered to be independent parameters) have significantly changed over the time period in the region. Further the link between various hydrological parameters and land use (primarily interior forest and plantation) has been estimated by generating the correlation matrix (Table 7).

1972	Rainfall	Interior forest	Plantations	Runoff	Infiltration	Recharge	Water Yield
Rainfall	1	0.31	**0.04**	0.78	0.26	**0.005**	**0.03**
Interior forest	0.45	1	0.32	0.41	0.5	0.79	0.45
Plantations	**0.78**	0.44	1	0.43	**0.01**	0.08	**0.01**
Runoff	0.13	**-0.37**	**0.36**	1	0.11	0.73	0.26
Infiltration	0.49	0.31	**0.86**	0.66	1	0.45	**0.012**
Recharge	**0.91**	0.12	0.69	0.16	0.34	1	0.15
Water Yield	**0.78**	0.34	**0.87**	0.49	0.86	0.60	1

1989	Rainfall	Interior forest	Plantations	Runoff	Infiltration	Recharge	Water Yield
Rainfall	1	**0.004**	**0.03**	0.72	0.12	0.39	0.068
Interior forest	**0.91**	1	0.19	0.32	0.36	0.93	**0.039**
Plantations	**0.79**	0.56	1	0.59	0.27	**0.037**	0.50
Runoff	-0.1	**-0.44**	**0.25**	1	0.43	0.073	0.85
Infiltration	0.64	0.41	0.5	0.36	1	0.17	0.20
Recharge	0.39	0.041	**0.78**	0.71	0.58	1	0.99
Water Yield	0.72	**0.78**	0.31	-0.088	0.55	0.004	1

2006	Rainfall	Interior forest	Plantations	Runoff	Infiltration	Recharge	Water Yield
Rainfall	1	**0.00**	**0.00**	0.82	0.42	**0.004**	**0.02**
Interior forest	**0.96**	1	**0.02**	0.74	0.72	**0.03**	**0.01**
Plantations	**0.89**	0.84	1	0.79	0.59	**0.009**	0.12
Runoff	0.11	**-0.15**	**0.13**	1	**0.01**	0.37	0.72
Infiltration	0.37	0.17	0.25	0.87	1	0. 15	0.89
Recharge	**0.91**	**0.8**	**0.88**	0.4	0.60	1	0.15
Water Yield	**0.81**	**0.84**	**0.64**	-0.17	0.07	0.53	1

2010	Rainfall	Interior forest	Plantations	Runoff	Infiltration	Recharge	Water Yield
Rainfall	1	**0.00**	**0.01**	0.63	0.34	**0.003**	**0.04**
Interior forest	**0.89**	1	0.086	0.24	**0.04**	**0.03**	0.18
Plantations	**0.86**	0.69	1	0.78	0.75	0.11	**0.002**
Runoff	0.23	**0.52**	**-0.13**	1	0.006	0.63	0.83
Infiltration	0.43	**0.76**	0.15	0.90	1	0.41	0.88
Recharge	**0.92**	**0.79**	0.65	0.23	0.37	1	0.23
Water Yield	**0.78**	0.57	**0.94**	-0.10	0.07	0.52	1

Table 7: Correlation matrices of different parameters for different years
***Water Yield is sum of surface runoff, interflow and baseflow**

In the correlation matrices, values on the right above the diagonal values show the p-value (significance level) for the null hypothesis stated as the variable are not inter-related. The values on the left below the diagonal values show the correlation coefficient. The highlighted values are those that have p-value below 0.05 (5% significance level) for which null hypothesis can be rejected and the alternate hypothesis stating that the variables are significantly correlated can be accepted.

From the matrices it can be inferred that interior forests, plantations are strongly positively correlated to the rainfall. Thus it verifies the rarely documented but often stated fact (**LØrup et. al., 1998**) that "forests attract rainfall". Recharge is also strongly positively related to rainfall throughout; giving the evidence that groundwater recharge is always dependent on the amount of rainfall that a region receives. Also there is strong positive relation between interior forests and infiltration and consequently with recharge for 2006 and 2010 implying that core/pristine forests promote percolation of water into sub surface system and thus ground water recharge. Plantations also have shown positive correlation with the recharge throughout the time period. In addition, for all the years, runoff has shown negative correlation with the interior forests and positive with plantations inferring that the deep roots of the forests prevent surface runoff while plantations having shallow rooting system lack that capability. As a consequence, plantations were found to have strong positive relation with the water yield (dominated by runoff) obtained from the system.

On plotting land use with individual hydrological parameter (figure 11), it was observed that the sub-basins having greater proportion of area under Interior forest have higher rainfall, lesser runoff but higher interflow which contribute to greater water yield (sum of surface runoff, interflow and baseflow) from such sub-basins. Baseflow was found to be higher for the sub-basin 5 in comparison to other sub-basins due to higher specific yield of the Greywacke rock type.

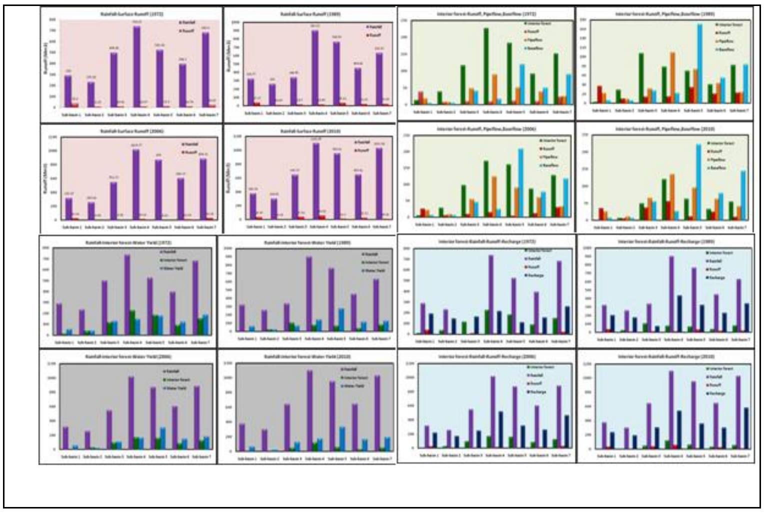

Fig. 11: Relationship between Rainfall and Runoff (a); Interior forest, Runoff, Interflow and Base flow (b); Rainfall, Interior forest and Water Yield (c) and Interior forest, Rainfall, Runoff and Recharge (d)

4.5 Water Balance Analysis

Water balance is analysis done with respect to the demand and supply of water to understand the deficit and surplus water. The main stakeholders considered for this analysis are population of the region, livestock, agriculture area to be irrigated and areca plantations (Fig. 12 and Fig. 13). Table 8 shows that, for the entire watershed area, available water was surplus in 2010.

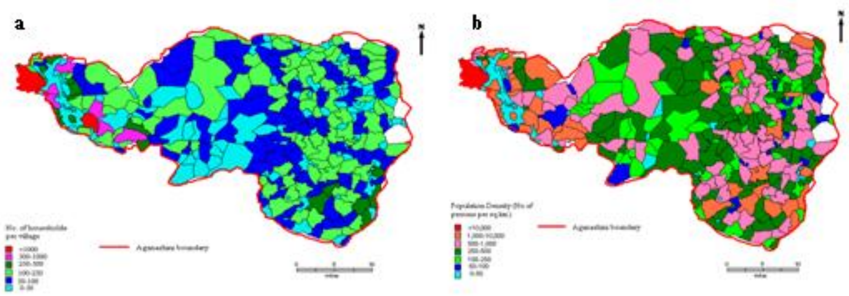

Fig. 12(a) Number of household in a village, (b) Population density of each village

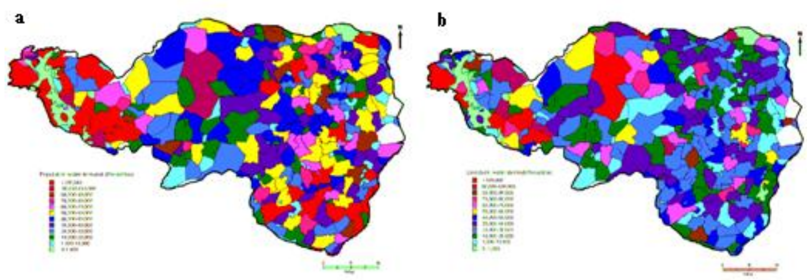

Fig. 13 (a) Water requirement of (a) human population, (b) livestock

Table 8: Water Balance for the year 2010

Total Water Yield for the year 2010 (Mm^3)	Water requirement by the stakeholder								Net water requirement in the region (Mm3)	Net water balance (Mm3)
	Human beings		Livestock		Arecanut Plantation		Paddy			
	Total No.	Water requirement (Mm^3/yr)	Total No.	Water Requirement (Mm^3/yr)	Area (m^2)	Water requirement (Mm^3)	Rice production (kg)	Water requirement (Mm3)		
1112.4	308,362	11.26	262,330	6.70	209280000	251.136	132600000	99.45	368.456	743.944

4.6 Sustainability of the catchment yield

Irrigation water requirement for the non-monsoon season was computed for each sub-basin for the year 2010 and compared with the water yield (only interflow and baseflow, as they are responsible for the non-monsoon flow in the stream) in the sub-basin. Figure 14 shows that the sub-basin 4 and 5 having greater proportion of area under interior forest have very high water yield in comparison to the irrigation requirement, while sub-basin 1 and 2 having negligible area under interior forest has very less water yield. Due to excessive water yield in the sub-basins 4 and 5, the streams are perennial here while the streams of sub-basins 1 and 2 get dry after the cessation of monsoon, which has been verified through field visits as well.

Table 9: Irrigation requirement at the sub-basin level in 2010

Sub-basin	Arecanut			Paddy			Interior forest	Net Irrigation Requirement	Water Yield
	Area (sq.km.)	Area (sq.m.)	Water requirement (Mm^3)	Area (sq.km.)	Area (sq.m.)	Water requirement (Mm^3)	Area (sq.km.)	(Mm^3)	Pre and Post Monsoon (Interflow and Baseflow) (Mm^3)
Sub basin1	13.13	13130000	15.756	30.92	30920000	23.19	0.71	38.946	23.14
Sub basin2	16.59	16590000	19.908	10.54	10540000	7.905	7.90	27.813	44.71
Sub basin3	21.60	21600000	25.92	5.98	5980000	4.485	50.31	30.405	158.91
Sub basin4	31.49	31490000	37.788	18.00	18000000	13.5	121.14	51.288	207.32
Sub basin5	57.37	57370000	68.844	18.18	18180000	13.635	63.54	82.479	304.98
Sub basin6	28.57	28570000	34.284	21.64	21640000	16.23	34.09	50.514	176.14
Sub basin7	40.55	40550000	48.66	27.33	27330000	20.4975	55.74	69.1575	260.49

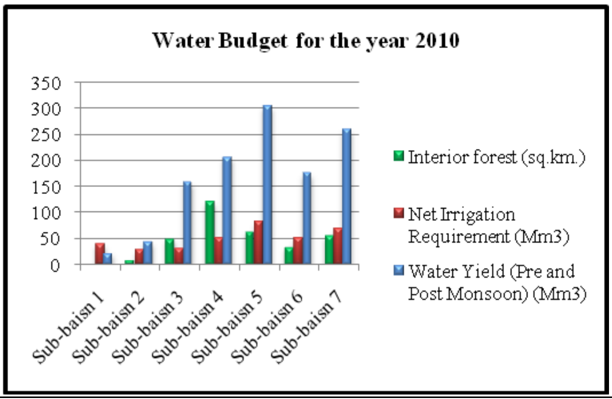

Fig. 14: Water Budget at the sub-basin level for 2010

5. Conclusion

From the analysis, done to assess the effect of land use on water resources in the region in non-experimental (empirical) way, it can be concluded that the status of landscape has significant effect on controlling the water availability in the region. The results obtained show that, whilst the overall percentage of interior forest in the catchment has shrunk since 1972, still the sub-basins having relatively greater proportion of area under interior forest have greater water yield in comparison to sub basins with fragmented forest. Furthermore, from the correlation analysis it was established that pristine forests have lesser surface runoff and higher groundwater recharge that result in higher low flows. As a consequence, the streams are perennial in such regions. In addition, water balance analysis shows that catchment yield of only those sub-basins is sustainable that have greater proportion of area under interior forest. Thus landscape structure has much important role in determining the water resources in the region, rather than just acting as a driver of hydrological cycle.

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Appendix I - Vegetation Characteristics of Western Ghats

Type of vegetation	Species	Type of roots	Root depth (m)	Description of roots	Crown shape	Leaf / leaflet/ shape
Evergreen	Mangifera indica	Shallow to deep tap root	5.5 (Stephens, 1949) 1.2 (Musahibuddin, 1960)	Almost the level of water table in Queensland (Australia)	Spherical/ broad	Oblong
	Cocos nucifera	Fibrous roots	4-6 (Ramadasan and Rajagopal, 1987)		Palm, upright	Linear lanceolate
	Tamarindus indica L.	Moderately deep taproot	1.5 (minimum) http://plants.usda.gov/cgi_bin/char_sciname.cgi		Spherical	Ovate lanceolate
	Delonix regia (Gulmohar tree)	Moderately deep taproot	1.5 (minimum) http://plants.usda.gov/cgi_bin/char_sciname.cgi		Spreading, vase shape, Flat crowned (umbrella shaped)	Oblong
	Michelia champaca	Deep tap root		Requires moist deep soil ($Troup_a$, 1986)	Rounded	Ovate lanceolate
	Polyalthia fragrans	Buttress roots		($Troup_a$, 1986)	Conical	Lanceolate ovate
	Mesua ferrea	Taproot		Seedling roots: primary root moderately long, lateral roots numerous, long, fibrous and	Rounded	Elliptical lanceolate

				branched (Troup$_a$, 1986)		
	Dipterocarpus indicus	Buttress roots		Seedling roots: primary root long, lateral roots short and distributed down main root (Troup$_a$, 1986)	Rounded	Ovate
	Pterospermum acerifolium	Taproot		Seedling root: Primary root long, lateral roots numerous, fine and distributed down main root (Troup$_a$, 1986)	Conical	Ovate
	Azadirachta indica	Taproot		Seedling root: Primary root moderately long (Troup$_a$, 1986)	Spreading, rounded	Ovate lanceolate
	Hardiwickia pinnata	Taproot		Seedling root: primary root long, lateral roots few to moderate in number (Troup$_b$, 1986)	Rounded	Oblong
	Santalum album	Taproot		Seedling root: primary root long, flexuous, whitish delicate, lateral roots moderate in number, distributed down main root. Roots at an early stage show		Elliptical

				nodular growths, the first signs of haustoria. (Troup$_c$ 1986)		
Deciduous	Terminalia catappa	Shallow taproot	0.82 (minimum) http://plants.usda.gov/cgi_bin/char_sciname.cgi		Broad, flat	Obovate oblanceolate
	Albizzia lebbek	Shallow to moderately deep tap root	0-1.4 1.4-2.05 >2.05 (Muthana et al. 1984)	Sand to loamy sand, loose friable Gravelly loamy sand, somewhat compact Hard compact zone, rich in lime	Moderately spreading, feathery	Oblong
	Dalbergia sisoo	Shallow tap root	1 (Chaulya et al. 2000)			Obovate/orbicular
	Terminalia tomentosa	Deep tap root	3.6 Champion and Trevor, (1938)	Attained 3.6 m in two growing seasons		Oblong
	Bombax malabaricum	Buttress roots		Seedling root: Primary root long, lateral roots few or moderately numerous (Troup$_a$, 1986)	Elliptical, elongated	Ovate or cordate
	Aegle marmelos	Tap root		Seedling root: Primary root long, lateral roots few or moderate in number and distributed down the main root.	Round	Elliptical lanceolate

				Root system is superficial. Lateral roots spreads to some distance (Troup$_a$, 1986)		
	Acrocarpus fraxinifolius	Large buttress roots		Seedling roots: Primary root moderately long, lateral root moderate in number and length (Troup$_a$, 1986)	Rounded	Elliptical lanceolate
	Cassia fistula	Tap root		Seedling roots: primary root long, lateral roots numerous, fibrous, distributed down main root (Troup$_b$, 1986)	Open crown	Ovate oblong
	Xylia xylocarpa	Tap root		Seedling roots: primary root long, lateral roots fairly numerous, long and distributed down main roots (Troup$_b$, 1986)	Elliptical	

	Anogeissus latifolia	Tap root		Seedling roots: Primary root long, lateral roots few to moderate in number, short, fibrous and distributed down main root (Troup$_c$, 1986)	Feathery and rounded	
Plantations	Acacia catechu	Deep tap root	2 (http://www.deh.gov.au/biodiversity/invasive/publications/a-catechu.html)		Rounded	
	Eucalyptus globulus	Deep tap root	2.8 Samraj et al. (1977)		Elongated	Lanceolate
	Eucalyptus hybrid	Shallow to moderately deep taproot	1.5-2 >2 Rajan, (1980)	Nandi Hills		Lanceolate
	Tectona grandis	Shallow taproot	0.3-0.4 Singh et al (1984) < 0.5 http://library.wur.nl/prosrom/tectona.html	The primary root is long, but gradually disappears after lateral roots have developed	Spreading, conical	Obovate

	Casuarina equisetifolia	Shallow taproot	0.6 minimum (http://plants.usda.gov/cgi_bin/char_sciname.cgi)		Elongated	Narrowly angular
	Hevea brasliensis	Very deep tap root	> 10 (Moraes, 1977)	In shallow alluvial soils, tap roots are confined to the top zone of A horizon but are compensated by profuse growth of lateral roots	Foliose crown (flat and thin)	Ovate