

**IMPACT OF LAND USE LAND COVER CHANGES ON
GROUNDWATER – A CASE STUDY**

CHAPTER 1

1.0 INTRODUCTION

1.1 General

The escalating intrusion into forests because of increasing socio-economic pressures, combined with a dichotomy of scientific beliefs arising from the hydrological impacts of forest conversion, provides a clear need for an increased number of controlled experiments in the various sectors of forestry. Over the last few decades, dramatic land use (LU) and land cover (LC) changes (Drigo, 2006) have taken place in the humid tropics (Chang and Lau, 1993) which have resulted in rapid rates of deforestation. In response, Giambelluca (2002) remarked that hydrologists have traditionally focused on the hydrological impacts of forest conversion to cleared, actively used land, that is, at the respective extremes of this LC taxonomy (e.g. Bruijnzeel, 2004; Costa, 2004; Grip et al., 2004). The LC of the tropics is now becoming more fragmented and highly complex, and secondary forest is now emerging as the dominant forest type interspersed with remnants of old-growth forest and other intermediate LCs (Holscher et al., 2004; Cuo et al., 2008). These intermediate LCs include previously converted forest land now under various LUs as well as degraded forest (Scott et al., 2004; Safriel, 2007). The storm runoff hydrology of these intermediate LCs from multi-decades of human occupancy, and 'forestation' (afforestation–reforestation) of land in various states of degradation, have been much less studied across a range of soils and scales (van Dijk et al., 2007; Istedt et al., 2007; Malmer et al., 2010). The need for such attention is emphasized when one considers that globally an increasing proportion of the population in the humid tropics are becoming dependent on these intermediate LCs for their livelihoods and ecosystem services because of decreasing availability and access to less disturbed (or old-growth) tropical forest (Chazdon, 2008). For example within South and Southeast Asia, it was estimated that about 45% of the total land area has been affected by human-induced soil degradation (Eswaran et al., 2001). Fragmentation and a predictive frame-work for restoration scenarios.

The influence of forests on their surroundings forms part of a vast and complex relationship between environment and forest vegetation. Attempts have been made in the

past, to assess the influence of forests on various hydrological parameters and processes viz. Rainfall, interception, infiltration, soil moisture, evapotranspiration, ground water, water yield, flood and soil loss etc. However, studies pertaining to forest influences on ground water storage are quite limited. Though, the impact of forestry operations, such as logging and reforestation, on water supply has been the subject of many field investigations, other effects however, such as the influence of forests on soil water accumulation and redistribution and ground water recharge have so far received little attention from hydrologists. Some of the important hydrological processes involved in soil moisture redistribution and ground water recharge are discussed below.

1.1 WATER TRANSFER THROUGH THE UNSATURATED ZONE

Forest soils are noted for the proliferation of macro pores, especially in the surface layers, because of the high density of roots and soil fauna activity. Such macro pores allow the vertical by-passing of the unsaturated matrix and allow preferential flow to reach the saturated zone more quickly than through the unsaturated soil matrix (Beven and Germann, 1982; Germann, 1990). For example, the rapid rises and falls in water tables under eucalypt forest observed by Burch et al. (1987) were attributed to macro pore pathways for continuous preferential flow. In contrast, such path-ways appeared to be absent under forest converted to grassland. Consequently, the grassland catchment generated larger storm discharge volumes and higher peak flows, irrespective of antecedent soil moisture conditions. Although there is diversity of qualitative definitions of macro porosity, the preferential flow associated with macropores can occur in different forms and under different conditions of antecedent wetness. For example, downward movement of free water can be at least partially independent of hydraulic conditions in the smaller pores. Macro pores also dominate infiltration under ponded conditions, as was observed by Bonell and Williams (1986), and they even have a significant role after matrix ponding has occurred during flux infiltration (Smettem and Collis-George, 1985). Of particular interest to forest hydrology are the reports of preferential flow occurring through large pores in an unsaturated soil matrix, a process described as by-pass flow (Smettem and Trudgill, 1983) or short-circuiting (Bouma and Dekker, 1978).

Forests are also noted for larger macro pores, known as pipes, which can range from 10 mm to more than 2 m in diameter (Kirkby, 1988). There have been numerous studies

reporting the role of pipe flow in hill slope hydrology both in humid temperate (Kirkby, 1988; Burt, 1989) and tropical rainforest environments (Walsh, 1980; Elsenbeer and Cassel, 1990). Pipe systems, however, pose a major challenge to hill slope runoff modelling. Individually, they can discharge onto slopes, in the form of exfiltration (Bonell et al., 1984, Elsenbeer and Cassel, 1990), or discharge directly into streams volumes of water far in excess of that supplied by the adjoining soil matrix (Kirkby, 1988; Grayson et al., 1992). The connectivity of pipes is unknown in most catchment studies; this impedes any practical consideration of their role in hydrological modelling. Furthermore, Kirkby (1988) called into question whether pipes, especially by-pass pipes (Kirkby, 1988) just below the soil surface, can be treated as a Darcian flow system, because of reports of turbulent water flows (non-Darcy type) at velocities on a par with those in open channels. In the absence of such knowledge, field measurements should monitor larger areas, or volumes, following the concepts of a repetitive unit (Bear, 1979) or representative elementary volume (Bear, 1979) for processes on individual hill slopes (Bouma, 1983; Youngs, 1983; Jenssen, 1990, White et al., 1992). The hydrological literature has placed little emphasis on the effects of diurnal and seasonal change in root water content causing shrinkage and swelling, and therefore providing annular space for macro pore flow.

1.2 SATURATED, LATERAL SUBSURFACE STORM FLOW

A common assumption, both in the field (Dunne, 1978) and in modeling (O'Loughlin, 1986; Beven et al., 1984), is that down slope flow predominates, especially in the regolith, with the hydraulic gradient assumed to be parallel, and therefore sensitive to the topographic gradient. The work of Zaslaysky and Rogowski (1969) and Zaslaysky and Sinai (1981), for example, demonstrated the effects of soil anisotropy and soil layering in generating lateral sub-surface stormflow. In many humid temperate studies, the increase in clay content between the soil A and B horizons is considered as the throttle to vertical percolation, thus causing subsurface storm flow from the transient, perched water table developed in storms (Kirkby, 1978). Smettem et al. (1991) challenged this assumption in hill slope soils that do not have dispersible clay B horizons and that contain preferred pathway flow through macro-pores. These workers presented field evidence that the presence of fine fissures and infrequent cylindered macro pores allowed preferential flow through a medium clay B horizon of predominantly kaolinitic mineralogy. Lateral sub-

surface flow commenced only at the lower soil—rock interface, rather than at the boundary between the A and B horizons. Furthermore, Smettem et al. (1991) were able adequately to model the water tables during drainage after characterizing the macro pore—matrix dichotomy of soil hydraulic properties using in situ methods. Such findings are supported by results from a hydro-geochemical study in the tropical rainforest of north-east Queensland. The temporal variability of soil water deuterium concentrations suggests that, similarly, the medium to fine block structures of the kaolinitic-dominated clays allow vertical percolation to penetrate the deep B horizon and mix with the water table. Further mention of the isotopic work will be given below, but it is clear that some adjustments within topographically and physically based runoff models might prove necessary for the pedagogical conditions described. Other evidence, presented by McCord et al. (1991) and Jackson (1992), suggests that during rainfall, infiltration and percolation are nearly vertical in hill slopes with deep homogeneous soils. Lateral downslope flow in unlayered soils is suggested as being largely a drainage phenomenon arising from changes in the boundary condition at the soil surface. The quasi-analytical solution of Philip (1991a), was re-examined and used by Jackson (1992) to provide support for these findings. Most important, the results of McCord et al. (1991) and Jackson's (1992) simulations suggested that significant lateral downslope flow during wetting occurs only in soils with an extremely high constant anisotropy ratio (10 or greater).

The means by which subsurface storm flow is delivered to streams can be viewed as routing through the soil matrix (matrix flow), macro pore flow and pipe flow. The size of the voids and the scale of porous media control whether or not the lateral flow can be described as Darcian flow. Previous discussion has mentioned free water movement in macro pores within an unsaturated matrix. Preferential flow, however, becomes more prevalent under conditions of intense rainfalls and low matrix potentials (Germann, 1986; Burt, 1989), and can occur simultaneously with interstitial piston flow (the displacement of pre-existing water in the soil matrix) in heterogeneous soils (Foster and Smith-Carrington, 1980; Bonell et al., 1984a). Bonell et al. (1982, 1983a) described such mechanisms in detail in the tropical rainforest of north-east Queensland through the monitoring of subsoil water movement artificially tagged with treated water. As highlighted above, the connectivity of macro pores and pipes in the downslope direction

still remains unresolved (Kirkby, 1988); it is therefore difficult to apportion the volumes of water carried by such voids in their ability rapidly to conduct the water down the slope.

The role of matrix flow is more problematical. Hewlett and Hibbert (1967) originally envisaged that the side slope delivery of moisture to a water table at the foot of slopes was through the soil matrix by a piston-type flow (Goel et al., 1977) mechanism which they termed 'translatory flow' (Hewlett and Hibbert, 1967), based on the work of Horton and Hawkins (1965). It is now generally accepted that the occurrence of lateral subsurface storm flow via matrix flow is too slow to produce significant volumes of quick-flow (e.g. Kirkby, 1988) without the assistance of some other mechanism. To explain the apparent contributions of large volumes of 'pre-event' (defined by Rodhe, 1987) or 'old' water (defined by Obradovic and Sklash, 1986) to storm hydrographs, Sklash and Farvolden (1979) favored the 'groundwater ridging' mechanism of Ragan (1968), which was subsequently described under controlled laboratory conditions by Gillham (1984) and Abdul and Gillham (1984). This mechanism is associated with areas adjacent to streams, where the capillary fringe or tension-saturated zone above the water table is close to the surface. Such conditions should be more prevalent in fine-textured soils so that small amounts of rain will quickly convert small, negative matric potentials into positive pressures. A rapid rise in the water table then occurs; this in turn, steepens the hydraulic gradient so that significant volumes of subsurface storm flow (mostly pre-existing water) can be discharged through stream banks, provided the K^* of the soil is sufficiently large. Field evidence for the influence of the capillary fringe causing disproportionate, rapid water table rises (Novakowski and Gillham, 1988), and the important role of the water table ridging mechanism in the processes of stream flow generation were presented by Blowes and Gillham (1988) and Abdul and Gillham (1989) at various locations in Ontario, Canada. None of these investigations were connected with forested environments. Instead, the study sites were concerned with mining tailings (Blowes and Gillham, 1988) or a man-made channel (Abdul and Gillham, 1989), both of which were grass-covered, of low relief and connected with sandy aquifers. Despite such evidence, it is clear that further experimentation is necessary to verify the generality of this process.

One of the major issues in of land use and land cover change is that it profoundly transform terrestrial hydrological budgets and processes. Although the effects occur at multiple spatial scales from local (small basins) to global, the scale at which local communities and land-use managers are affected is of special concern as decision making on ecosystem services. One of the important paradigms that was dominant for much of the 20th century in local scale terrestrial hydrology, and supported by observed and experimental data, is the relationship between accumulation of forest biomass and decrease in stream flow as a result of increased evapotranspiration, or vice versa, (Bosch and Hewlett, 1982; Brown et al., 2005). However, based on emerging evidence to the contrary, especially from the tropics, Bruijnzeel (1989, 2004) proposed the “infiltration- evapotranspiration trade-off hypothesis”. Part of this hypothesis states that under certain conditions of land-cover and land-use change in the seasonal tropics, a degraded forest’s ability to allow sufficient infiltration may be impaired to such an extent that the effects on delayed flow or dry-season flow would be detrimental, even after accounting for gains from reduced evapotranspiration. Recent work in the Andes mountains of Columbia by Roa- Garcia et al. (2011) put forward some of the first evidence in support of the Infiltration- Evapotranspiration ‘trade-off’ hypothesis based on a comparative basin study (0.6–1.7 km²), albeit involving volcanic ash deposits i.e., Andisols, that are vastly different than the soils in the Western Ghats. Roa-García et al. (2011) noted in particular that their stream flow frequency–duration curves (FDCs) highlighted that the basin with highest forest cover (68%) showed the smallest reduction in flow during the dry season. Moreover the highest low flows were maintained during the dry season from this forest- dominated basin in contrast to a grassland dominated basin. In addition, soil moisture release curves undertaken in that study showed that the natural forests has a larger capacity to store and release soil moisture in comparison to the grassland. These writers thus concluded that the preceding two findings support the “infiltration- evapotranspiration trade-off” hypothesis for tropical environments (for), soils that are subject to compaction (such as highly grazed grasslands) have a reduced rainfall infiltration, which impairs the maintenance of base flows” (Roa-García et al., 2011).

In formerly forested regions in the humid tropics, notably in the more densely populated regions of south and south–east Asia such as the Western Ghats of India, major land- cover changes have occurred at a century time scale. The latter have included permanent

deforestation and conversion to a variety of agro-forestry and agro-ecosystems, re-growth as well as reforestation. Consequently there is a particular need for decision makers and policy makers to have information from hydrological studies that address the fundamental processes associated with such land cover changes. Over 100 million people depend on surface water sources in streams and rivers that emanate from the Western Ghats. Further this region is a major repository of carbon in its forests and soils (Seen et al., 2010) and is a global biodiversity hotspot (Das et al., 2006). In an era where various ecosystem services are being recognized and valued, it is essential for ecological economists, policy and decision makers to be aware of the synergies and trade-offs between various regulatory and provisioning services (Elmqvist et al., 2010). Thus an investigation of the hydrological effects of specific land-cover changes is a high priority (De Fries and Eshleman, 2004).

Earlier studies carried out in North Kanara district of Karnataka, India by NIH, Belgaum established that the soil hydraulic properties (notably field saturated hydraulic conductivity), Kfs, in the tropical, humid Western Ghats can be significantly altered from land-cover change up to a century time scale from forest conversion or degradation. The enhanced occurrence of infiltration-excess overland flow (IOF) was inferred (and thus reduced vertical percolation and groundwater recharge) when comparing selected rainfall intensity-duration-frequency with Kfs across both land covers and soil types. Such changes are sufficient to allow the hill slope hydrology aspects of the infiltration-evapotranspiration trade-off hypothesis to be realized (Bonell et al., 2010).

Later work using experimental catchments also showed how land-cover change from native forest to heavily used forest and its subsequent reforestation have major effects on the rainfall-runoff process in the wet-season (Krishnaswamy et al., 2012). They showed the highest proportions of rain converted to runoff being associated with the degraded forests whereas the natural forests showed the lowest runoff yields. Using stream hydrograph separation, they also reported much higher quick flow volumes from degraded forest and reforested, former degraded land in the form of *Acacia auriculiformis* plantations when compared to the less disturbed natural forest. Furthermore, time series analysis showed much shorter rainfall-runoff time lags for the degraded forest and *Acacia auriculiformis* plantations when compared to natural forest. This characteristic of faster rainfall-runoff responsiveness supports the notion of the frequent occurrence of IOF

within the former two, more human-impacted land covers. Pertinent to the current work, the data in Krishnaswamy et al., 2012, clearly indicates that even assuming the maximum measured annual actual Evapotranspiration (AET) for humid forests globally (1500 mm, Kume et al., 2011), the estimated water available for recharge from natural forest catchments annually after accounting for both measured runoff and AET was 259 mm (rainfall of 2252 mm) and 978 mm (rainfall of 4016 mm). Thus we concluded from the earlier work that (i) a significant amount of rainfall was potentially available for recharge to groundwater and for downstream base flow and dry-season flow, (ii) deeper subsurface water or groundwater of possible large capacity, had a significant role in the storm runoff generation process and (iii) the continuation of a secondary, longer rainfall-runoff time lag in the intensely, disturbed land covers indicated that there was a retention of 'memory' of the previous natural forest response. The escalating intrusion into forests because of increasing socio-economic pressures, combined with a dichotomy of scientific beliefs arising from the hydrological impacts of forest conversion, provides a clear need for an increased number of controlled experiments in the various sectors of forestry. The influence of forests on their environment forms part of a vast and complex relationship between environment and forest vegetation. Attempts have been made in the past, to assess the influence of forests on various hydrological parameters and processes viz. Rainfall, interception, infiltration, soil moisture, evapotranspiration, ground water, water yield, flood and soil loss etc. However, studies pertaining to forest influences on ground water storage are quite limited. Though, the impact of forestry operations, such as logging and reforestation, on water supply has been the subject of many field investigations, other effects however, such as the influence of forests on soil water accumulation and redistribution and ground water recharge have so far received little attention from hydrologists.

1.3 GROUND WATER

Groundwater is one of the major components of the hydrological cycle. One of the predominant factors, which affect the movement of water over and into the ground surface, is the vegetation cover of the watershed. There could be several types of covers or the land uses on the soil surface, for example forests, grass, agriculture, barren land etc. Different land use will have different kinds of effect on movement of water over and under the ground surface. In the presence of forest, water movement and water action are

different because of the canopy, forest floor and distinctive soils. Due to forest deep rooting system and added contribution to organic matter content of the soil have been generally found to improve the soil structure resulting in better surface recharge conditions. On the other hand, the evapotranspiration requirements of the forest have been found relatively higher than other land uses. Therefore, the net effect of forest on ground water regime becomes an important issue for investigation by hydrologist which in turn will be useful for water resources planner and environmentalist.

Groundwater recharge is the process by which water moves from the earth's surface in to the groundwater system. It is the ultimate source of renewable groundwater and is fundamentally critical parameter for water resources investigations. A tremendous volume of technical literature on groundwater recharge has been published over past 30 yrs with numerous dedicated books on the subject (Simmers 1998, 1997, Sharma 1989, Lerner et al 1990). Ground water is the largest source of fresh water on the planet excluding polar icecaps and glaciers. The amount of ground water within 800m from the ground surface is over 30 times the amount in all fresh water lakes and reservoirs, and about 3000 times the amount in stream channels, at any one time. The average annual rainfall of India is around 114cm. Based on this Dr K L Rao has estimated that the total annual rainfall over the entire country is of the order of 370M ha-m and one third of this is lost in evaporation. Of the remaining 247M ha-m of water, 167M ha-m goes as runoff and the rest of the 80M ha-m goes as subsoil water. Out of this 80 M ha-m goes as subsoil water that seeps down annually in to the soil, about 43Mha-m gets absorbed in the top layer, thereby contributing to the soil moisture; the balance of 37 M ha-m is the contribution to ground water from rainfall. The average annual ground water recharge from rainfall and seepage from canals and irrigation systems is of the order of 67M ha-m. Human beings have exerted large-scale changes on the terrestrial biosphere, primarily through agricultural practices. However, the impacts of such changes on the hydrologic cycle are poorly understood. Therefore, it is necessary to understand the hydrological processes involved in ground water recharge.

1.4 INFILTRATION PROCESS

Water that infiltrates the soil surface either enters the soil or runs off as overland flow. Infiltration is a complex phenomenon because infiltration rates and capacity vary with

time. Water entering the soil can bring about physical changes in the soil that can also reduce the rate of infiltration, such changes may include swelling of colloidal matter and in wash of fine particles in to pore spaces and destruction of soil structure by the impact of rain drops. Infiltration and overland flow are two sides of same coin, since what does not infiltrate the soil runs off the surface as overland flow. There is no doubt that infiltration rates are influenced by diverse factors that include pedagogical and slope conditions and the effects of forest cover. The resulting spatial variations together with temporal variations of infiltration make comparison of results obtained in different forested tropical basins difficult. Klinge et al (1981) found that high vertical permeability of soils in one of the three watersheds studied in the Amazon basin in French Guiana resulted in high infiltration rates and hence low overland flow. In contrast, the other two catchments in the same area had low subsoil permeability's, which resulted in low infiltration rates and transformed 60-70% of the incidental rainfall in to runoff. Some of the catchment characteristics in parts of Malaprabha catchment are shown in figures 1.1 to 1.5



Figure 1.1 : A View of Forests in Malaprabha catchment at Gangavli



Figure 1.2: A View of Acacia Plantation in Malaprabha catchment at Gangavli



Figure 1.3 Afforested with native species in Malaprabha catchment



Figure 1.4 Grassland in parts of Malaprabha catchment



Figure 1.5 Degraded land with shrubs and Grassland

The changes in land use have mostly occurred locally, regionally and globally over the last few decades and will carry on in the future as well. The increase in imperviousness has a major impact on groundwater and is of major concern over the past years to those who are involved in groundwater studies. The increase in urbanization results in reduction in infiltration, which affects the groundwater recharge and storage. The increase in population leads to increase in food, fodder and fuel demands with rapid change in land use patterns. From the time when the human civilization started, mankind interdependence on environment is greater, excess hunt of progress, comfort and security has resulted in augmented stress on the environment. Proper planning and management for development of natural resources without jeopardizing the environment is a vital concern to be sorted out for the world community. Quality inputs on the rate and pattern of land use change is essential for proper planning and management. Land use change pattern reflects the rate of change of groundwater recharge. It is necessary to detect the land use change in the past and present existing land use, and its spatial distribution and potential changes are essential prerequisites for planning and management. Proper land use planning and management is Groundwater is a major source of drinking water across the world and plays a vital role in maintaining the ecological value of many areas (IPCC, 2001) However, the quantity and quality of groundwater are changing due to human activity (Gehrels et al., 2001) jeopardizing the suitability of the groundwater system as a source of drinking water and affecting natural reserves. Assessing the impact on the groundwater system and predicting the magnitude of change in the future is therefore a major scientific challenge (Tang, 2005). Land-use and land-cover changes are one of the main human induced activities altering the groundwater system (Calder, 1993). Nevertheless, the impact of future land-use changes in the groundwater system has not been investigated extensively. Throughout the entire history of mankind, intense human utilization of land resources has resulted in significant changes of the land-use and land-cover (Bronstert, 2004). Since the era of industrialization and rapid population growth, land-use change phenomena have strongly accelerated in many regions. A Land-use change directly impact the hydrology of the catchment area (e.g. Bhaduri et al., 2000; Fohrer et al., 2001; Tang et al., 2005). The research on the impact of land-use changes on surface hydrology has therefore received considerable attention from both field observations and model simulations.

Therefore, in the present study an attempt is made to determine the magnitudes of differences among soil physical properties under land uses such as forest, degraded, grassland, agriculture and acacia plantation and across two parent materials, basalts and sedimentary formations. Particle size distribution, saturated hydraulic conductivity, bulk density, total porosity, and volumetric moisture content were determined for selected sites from one geologic unit and associated with land-use class. Variability in soil physical properties due to differences in land use were expected to have resulted from two mechanisms: (1) direct compaction by heavy equipment and/or livestock associated with non-forest land uses, and (2) variation in macropore development, organic matter, and soil structure associated with different vegetation types and associated fauna. Thus it was expected that non-forest land use would be associated with increased bulk density and reduced saturated hydraulic conductivity, porosity, and volumetric moisture content, and that soils underlying managed land use would demonstrate greater contrast to forest soils than would degraded soils. Understanding such differences is necessary for the development of a full understanding of how land-use change in this region is affecting watershed hydrologic processes, and is additionally necessary for providing data for use in regional hydrologic modeling to forecast hydrologic response to land-use change.

The fragmented LCs of the Karnataka State part of the Western Ghats in India are typical of those commonly found in the more highly elevated and densely populated parts of the humid tropics. Further in this area, a mix of State Government and community-based forestation programmes have been implemented for more than two decades within degraded forests and severely degraded, former forest-covered land (Pomeroy et al., 2003; Ramachandra et al., 2004). Consequently this area offered an opportunity to make a preliminary assessment of first, the impacts of long-term, land-forest degradation at multi-decadal to century time scales on both soil permeability and inferred runoff generation processes (Blanchart and Julka, 1997; Menon and Bawa, 1998; Pomeroy et al., 2003; Pontius and Pacheco, 2004; Seen et al., 2010). The study has been carried out in Malaprabha representative basin, a tributary of river Krishna (up to Khanapur in Belgaum district) with the following objectives:

1.5 STATEMENT OF THE PROBLEM

As a result of degradation of forests over multi-decadal to century time scales, the land cover is complex (Blanchart and Julka, 1997; Menon and Bawa, 1998; Pomeroy et al., 2003; Pontius and Pacheco, 2004; Seen et al., 2010). Patches of remnant forest, which are less disturbed and less used by people are at one end of the disturbance gradient and at the other end are a heterogeneous category of disturbed and heavily used forest which consist of open forest, grassland and savannah woodlands. Livestock grazing, fuel wood and fodder extraction, fire as well as extraction of leaf-manure and cropland are major land- uses in these highly disturbed or degraded sites which provide local communities with substantial “provisioning” ecosystem services (Millennium Ecosystem Assessment,2005) and sustain many livelihoods (Lele, 1993; Rai, 2004). However the trade-offs of these provisioning services with respect to hydrologic functions and services (Elmqvist et al., 2010) is relatively unknown. Further within the humid tropics, Rai (1999) estimated that nearly 80% of forestation using both native and exotic species was taking place in India and the Karnataka State portion of the Western Ghats has taken a lead in such forest restoration. Many degraded patches of land cover have been reforested with *Tectonagrandis* plantations, pre-1980 (from here on referred to as ‘Teak’), exotic *Acacia auriculiformes* plantations, post-1980 (‘Acacia’) and more locally, *Casuarina equisetifolia* plantations, post-1980 (‘Casuarina’) (Pomeroy et al., 2003; Pontius and Pacheco, 2004; Ramachandra et al., 2004). Consequently the Western Ghats (Karnataka State) offers an opportunity to evaluate LC impacts on permeability at contrasting time scales namely the impacts on soil permeability of: (i) forest land use and degradation, (ii) forestation over previously degraded land, relative to less used native forest. Both these land cover scenarios are in line with the storm runoff generation issues. In this connection, it is highly essential to understand the impact of forest degradation on soil hydraulic properties as well as on groundwater recharge on a catchment scale. Therefore, Malaprabha catchment (from Kankumbi to Khanapur) has been selected as it undergoes fast degradation due to man made changes.

1.6 THE OBJECTIVES OF THE STUDY

1. Measure and model hydraulic conductivity as a function of water content.
2. Study the impact of soil hydraulic properties under different land use/land cover

changes.

3. Monitoring soil moisture variations in selected locations based on land use/land cover changes.
4. Estimation of ground water recharge under different land covers using soil moisture and hydraulic conductivity.
5. Ground water modelling using PM WIN under varied flow conditions

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Numerous studies have been conducted in the past to examine the impact of forest degradation on the soil hydrological regime. There is a commonly held belief that degraded land have much reduced vertical percolation to the water table and in turn, much increased storm runoff, erosion and nutrient loss at the surface, Consequently dry season base flow in streams essential for water supply in agriculture and domestic use would be substantially reduced. Further, one would expect to find a depletion of available soil moisture and nutrient status for plant grown. Such claims have not been scientifically quantified, possibly due to the limited duration and nature of earlier studies. In recent years, number of studies has been carried out in the area of forest hydrology. However, the studies conducted to define the effect of vegetation on the groundwater regime, is still appears to be in controversy and need detailed investigations for drawing definite conclusions.

The effect of vegetation on groundwater is not unique and it varies widely with the change in hydrological environment. The impact of forest cover on groundwater storage can be inferred from change in evapotranspiration, soil moisture and discharge relationships. It depends on the depth and the proliferation of rooting system and on growing season length. Not many studies have been reported to find effects of forests on ground water regime. It is reported by earlier workers that wherever the groundwater is not deep, the water table is always shallow on open, treeless terrain than in forest. The water table is reported sinking rapidly with the age of the plantation due to the fact that tree roots remove large quantities of groundwater and soil moisture by suction (Vysotskii, 1930). There have been opinions that the roots of forest trees exhibit a sponge effect that soak up water in the wet periods and let it release slowly and evenly in the dry season to keep water supplies adequately restored. But such opinions are difficult to believe due to the fact that forest cutting experiments in small watersheds have universally given increased total water yield over the years Hamilton & King, 1980, Borsch & Hewlett, 1982 and Boughton, (1970). The studies conducted in Shipov forest, Russia, Morozov (1900) concluded that water table lies at a greater depth under forest than under field. Higher

position of the water table under forest was confirmed by the researches of Ribbentrop in India and Hermann in the mountainous districts of Bavaria, (Tkechenko, 1932). Berg (1938), within the regions of plains in Russia, the influence of forest upon ground water is more or less similar to that of meadow and fields. The groundwater under the forest in Hungary, lies below the water table under meadow, (Iijacz, 1939), in Hungarian low land, the groundwater table under acacia plantations is at a higher level in spring, but same as in open terrain during the summer and autumn (Iijacz, 1939). Boscov (1948) showed that there is no progressive sinking of the ground water under forest strips as foreseen by Ototskii's theory, in fact the water table has risen by 1.7 m during the last 54 years.

Eitingen (1945) observed a periodic fluctuation of the water table in connection with changes of precipitation within the zone of mixed forest. Yakovlev (1925) reported that the seasonal fluctuations of water table are not simultaneous in forest and on fields. In August, it sinks under forest while there is a rise under field. The reverse occurs in October. In December, the level of ground water is again the same under forest and field.

In the opinion of Tkechenko (1943), the summer lowering of the water table due to transpiration is not the same in different forests, because various arboreal species do not expend the same amounts on transpiration. Hence, it may be concluded that the fluctuation of water table depend upon the composition of the forest. Raj et al. (1986) reported that the water table under blue gum and under grass cover rose to maximum level in July/ August due to monsoon rains and fell to lowest in the month of May/June. They observed that there was a fall of 29 cm in the water table in grassland and 70 cm in blue gum. A survey conducted by Gujarat State Forest Department in April 1984, showed that, out of 143 tube wells in eucalyptus plantations of six districts, there was no drop of water table in four districts where as in two districts the drop in level was less than that of control wells located outside the plantation area (1984).

Aside from cloud forest, increasing heights of water table have usually followed cutting of forest in area where permanent water table are found (Wicht, 1949). Gilmour (1977) observed an approximate 10 % increase in ground water storage after logging in a tropical rain forest situation. Murray,(1973) observed that grazing of forest land leads to reduction in infiltration capacity. Further, burning of forest cause reduction in canopy cover permitting greater through fall and reduced evapotranspiration losses, which could

account for increased accessions component of the hydrograph (Megahan, 1981 and Boughton, 1981) Surface sealing of soil has occurred after fire in the Philippines and it reduced infiltration and percolation to ground water aquifers. Boughton (1970) reviewed Australian experience in converting forest to grass land by cutting, burning and ring barking. He found an increase in ground water level when trees were replaced with shallower rooted native grasses. Meltzer (1962) reported water rise of 33 feet following conversion to grassland. Murray et al (1975) reported low infiltration rate under artificially established grassland (20-25% less than under the forest). In Fiji infiltration rates for grassland were substantially less than under forest, and runoff was almost 100% (Cochrane, 1969). Reforestation of open land usually leads decreased water table, with effects most pronounced in the dry season. The additional evapotranspiration amount of soil moisture available for groundwater recharges (Holmes and Wronski, 1982). Whereas the reforestation of upland watershed may induce dry season streams flow, rise of groundwater levels and also restore the reliability of spring (World Bank, 1978). The leader of Chipko movement in the country also claims that tree plantation, particularly the broad leaved varieties, creased water in sol (World Water, 1981). In Southern Australia, Cassells (as cites in Hamilton and King, 1983) reported that in some areas under grass, about 10% of the annual 632 mm rainfall reached the ground water aquifer, but under nearby plantations, no recharge occurred at all Singhal (undated) reviewed Indian experiments of effects of eucalyptus plantation on ground water table. He concluded that the top root of eucalyptus is not a major absorber of water from the water table in the low lying area, however, where the superficial root system is in contact with the capillary fringe water tables direct absorption could be significantly. In a study carried out by Ram Prasad et al (1984) (stated by Davidson, 1985) found that in the case of eucalyptus camaldulensis of 5 and 15 years age , root depth was less than 3m and lateral spread is up to 9 m and 20 m, respectively. This indicates that most of the water demand is met from the surface layers rather than form the permanent ground table (Anon, 1984). Increase in the water table due to afforestation and other soil conservation measure in a watershed has been evidence in CR halli, Chitradurga (Anon. 1983). In the semi-arid areas of Gujarat, the water levels of the wells of eucalyptus hybrid plantation did not go deeper than in a surrounding well during period of 7 years.

Zhou et al. (2001) presented data from experimental first-order basins (up to 6.4 ha) in monsoonal southern China to study the impacts of rehabilitation of barren degraded land using eucalyptus (*Eucalyptus* etc) as a plantation and separately, by under planting this eucalyptus with indigenous species. Within a 10-year period subsequent to 16 years of forestation, Zhou et al. (2001) noted that there was a progressive reduction in quick flow largely attributed to increasing macro porosity associated with the incorporation of biological matter. Although no soil hydraulic conductivity or hill slope hydrology data were presented, these writers remarked that the quick flow response was the highest from the degraded catchment due to surface soil crusting and showed no trend over the 10-year period, except being sensitive to rainfall variability. Similarly, work in very small basins (0.13–0.25 ha) over karst in Leyte, the Philippines (Chandler and Walter, 1998. Chandler, 2006) suggests that that pasture–fallow sites produced high volumes of infiltration-excess overland flow, IOF (70–80% of annual rainfall) compared with the minimal volumes of basin stream flow (3% mostly from subsurface storm flow, SSF) from forest.

The Asian studies are for the most part dealing with multi- decadal to century time scale, human impacted landscapes. In contrast there has been a concentrated effort on the impacts of forest conversion to pasture in the Amazon basin where such land cover changes are more recent. Whilst most of the work (reviewed in Bonell (2010)) has focused on point-scale, field saturated hydraulic conductivity (Kfs; Bower, 1966; Talsma and Hallam, 1980; Talsma, 1987) measurements; the work of de Moraes et al. (2006) was one of the first to present comparative hydrometric evidence (e.g. runoff plots, storm hydrograph response characteristics) from a forested (0.33 ha) and pasture basin (0.72 ha). Forest conversion to pasture 30 years ago had now clearly enhanced the occurrence of saturation-excess overland flow, SOF and further introduced IOF leading to higher proportions of total flow volumes as quick flow (2.7% forest viz 17% pasture). A reduction in macro porosity beneath the pasture when compared with the forest, and a corresponding decrease in Kfs in the surface pasture soil, were the causal factors (de Moraes et al., 2006). Similar conclusions from a 3.9 ha basin in Rondonia which drained a cattle pasture were reported by Biggs et al. (2006). They noted quickflow was 16% of rainfall for a 10 rainstorm sample and 50% of this quickflow resulted from IOF. Later Chaves et al. (2008) and Germer et al. (2010) reported on a combined hydrology– hydrochemistry study for respectively a forest (1.37 ha) and pasture (20 years old, 0.73

ha) basin. These writers reported that overland flow (mostly SOF) dominated stream flow from the pasture in contrast to SSF in the forest supported by varying proportions of groundwater and soil water. Further evidence at larger scales in the Amazon basin that infer similar changes in the dominant storm flow pathway have also been presented (e.g., Costa et al., 2003; D'Almeida et al., 2007; Rodriguez et al., 2010).

2.2 HILL SLOPE HYDROLOGY STUDIES IN TROPICAL FORESTS

In comparison with humid temperate areas, only a limited number of field experiments have been undertaken in the humid tropics (Walsh, 1980; Dunne, 1983; Bruijnzeel, 1990, pp. 12-13; Bonell with Balek, 1993). Also, the intensity of investigation and the experimental methods used in deducing the runoff process by and large have been less rigorous than in equivalent studies in humid temperate regions. Bonell with Balek (1993) provided a detailed review of hill slope hydrology studies in the humid tropics and their use in interpretation of land-use impacts and water yield changes after forest conversion. Consequently, only a summary of the more pertinent points will be included here. Reference will be made, however, to more recent literature not cited in that review (Bonell with Balek, 1993), by Malmer (1993), supplemented by brief mention of processes in the tropical, semi-arid environments of north-east Australia.

When dealing with the humid and semi-arid tropics, some differences in the runoff generation process from that observed in humid temperate forests might be expected, on the basis of the higher rainfall intensities experienced in the former areas. For example, the rainfall intensity—frequency—duration curves presented for north-east Queensland study sites (Bonell, 1988; Prove, 1991) show rainfall amounts up to 10 times higher in magnitude for particular frequencies and durations compared with those in the humid temperate studies cited above. Bonell et al. (1991) emphasized that the link between soil hydraulic properties and topography should be extended to include synoptic climatology—rainfall intensity characteristics in partly explaining the various hill slope hydrology responses across the tropics. North-east Queensland tropical rainforest provides an interesting seasonal change in the dominant pathways for hill slope runoff because rainfall intensities range from an extremely wet 'monsoon' regime where daily 24 h totals commonly exceed 250 mm in the 'summer' months, to rainfall characteristics more identified with humid temperate latitudes during the 'winter' months, separated by

transitional seasons (Gilmour et al., 1980; Bonell, 1988, 1991b; Bonell et al., 1991). Consequently, on a more global scale, the nature of different tropical meteorological systems and their corresponding rainfall characteristics have to be recognized within the context of the hill slope hydrology. The non-cyclonic, equatorial areas are associated with short-duration convection storms whereas in the monsoon regions of the outer tropics more well-organized rain-producing systems (cyclonic) of long duration occur during the summer seasons, which thus provide the highest 24 h totals (Jackson, 1988a; Bonell, 1991b; Bonell with Balek, 1993; Manton and Bonell, 1993). Jackson's (1986, 1988b) analyses, however, showed that oro-graphic effects, among other factors, can distort this simplified picture.

Infiltration-excess (Hortonian) overland flow has been reported from studies in some West African tropical rainforests (e.g. Dubreuil, 1985; Wierda et al., 1989); this was attributed more to low surface infiltration rates than to high short-term rain intensities. Elsewhere, in the tropical rainforest of Sabah, Malaysia, Malmer (1993) reported that 2.9% of rainfall occurred as overland flow over clays. This flow vector was restricted to the occasional high-magnitude storms, and Malmer reasoned it to be infiltration-excess (Hortonian) overland flow. It is possible; however, that some of this overland flow is of the saturation-excess type. The surface K^* of 154 mm h^{-1} showed a decline of two orders of magnitude at both 0.2 m depth ($K^* = 0.68 \text{ mm h}^{-1}$) and 0.4 m ($K^* = 0.16 \text{ mm h}^{-1}$) (Malmer and Grip, 1990). Rain intensities for less than 1 h were not quoted, but Malmer mentioned that over periods of 5-10 min they were higher than the actual maximum hourly intensities, which were still less than 30 mm h^{-1} . From other evidence, Malmer (1993) reasoned that shallow subsurface storm flow was the dominant flow path, in which case saturation overland flow is also likely.

Examples of widespread overland flow on hill slopes (not only valley bottoms), in conjunction with subsurface storm flow, have been presented for forested environments where an impeding soil layer occurs at shallow depth below highly transmissive surface layers (Bonell et al. (1981) and Herwitz (1986) for north-east Queensland; Elsenbeer and Cassel (1990) for western Amazonia; Dietrich et al. (1982) for Panama; Nortcliff et al. (1990) and Ross et al. (1990) for northern Roraima, Brazil). Herwitz's (1986) stem flow study is of particular interest because he reported localized stemflow fluxes as high as 314

mm min⁻¹, when the rain intensity was 2 mm min⁻¹, so that 'local' infiltration-excess overland flow occurred. This flow type added to the prevailing saturation overland flow.

In a series of papers which were summarized by Bonell et al. (1991) for paired north-east Queensland tropical rainforest catchments, near Babinda, it has been argued that the characteristics of the prevailing high rainfalls, i.e. amount, intensity and duration, are the most critical variables. These inputs exceed the capacity of the impeding subsoil layer below 0.1 m depth to transmit considerable volumes of water; consequently, under monsoon rainfalls saturation overland flow and subsurface storm flow can occur over large areas of the catchments based on simulations using TOPOG (O'Loughlin, 1986) during the summer wet season. Support for the storm runoff response being highly sensitive to rainfall intensity during the summer wet season was presented from a preliminary statistical analysis for the undisturbed forested catchment (Bonell and Gilmour, 1978; Bonell et al., 1981). Work has just been completed (Bonell, Howard, Cassel's and Gilmour, unpublished data, 1993) on analysis of a much larger sample of storms on the lines of Hewlett et al. (1977, 1984), including their stratification into 'meteorological' seasons (Bonell et al., 1991). The results confirm the significance of rain intensity for quickflow volumes exceeding 10 mm for both undisturbed and disturbed catchments. For the largest storms (more than 100 mm quickflow), total rain is statistically the most significant variable because the upper soils' storage capacity is full so that most rain is discharged immediately as saturation-excess overland flow. The significance of the synoptic climatology—rain intensity relationship is emphasized by the contraction in volumes and occurrence of saturation overland flow on progressing towards the winter season, when ultimately this flow vector becomes innocuous (Gilmour et al., 1980). Subsequent work by Elsenbeer and Cassel (1990), however, reported similar runoff processes in western Amazonia, where rainfall characteristics are very weak by Babinda standards. A comparison of the two studies (Bonell with Balek, 1993, pp. 216- 218), shows that the K^* of the subsoil impeding layer in Elsenbeer and Cassel's (1990) study is an order of magnitude lower than at Babinda; this compensates for the much lower prevailing rainfalls. Therefore, the earlier view of Walsh (1980, p. 181), (previously supported by Bonell et al. (1986) and Bonell (1988)) that, of all the tropical rainforest areas then investigated, the Babinda catchments had 'the only distinctively

tropical runoff process pattern', owing to the anomalously high cyclonic rainfalls, is not completely correct.

It becomes clear that any shift in the delicate balance of rainfall intensity soil hydraulics properties—topography can provide both similar as well as different runoff responses, both within and between various tropical forests. Most studies in tropical rainforests have reported a lack of occurrence of overland flow; this has been attributed to more permeable subsoil. The delivery mechanisms to stream flow during storms are envisaged to be similar to those described in humid temperate studies (Walsh, 1980; Bruijnzeel, 1990; Lesack, 1993). More important, most of these studies were located in the equatorial regions, where annual rainfalls are moderate (by humid tropical standards), short-duration convective storms prevail, and there were no shallow impeding layers (e.g. Lesack, 1993). Consequently, the influence of different rainfall characteristics across the humid tropics was not highlighted by previous reviewers (Walsh, 1980; Bruijnzeel, 1990) as one of the underlying criteria responsible for the spectrum of hill slope responses.

Forest conversion on storm flow is a controversial land management issue in the tropics. A common perception is that removal of forests increases the frequency and magnitude of floods. Several workers have presented scientific evidence to counter the 'myths' surrounding this controversial issue (e.g. Gilmour et al., 1987; Hamilton, 1988, 1990; Bruijnzeel with Bremmer, 1989). Work in north-east Queensland (Herwitz, 1986; Bonell et al., 1991) demonstrated that floods can emanate from forests and they do not act as infinite 'sponges' (part of the 'myth') because of the high prevailing rainfalls. For example, total storm discharge was 2096 mm from North Creek (disturbed) and 1880 mm from South Creek (undisturbed), respectively, in the Babinda catchments over a 14 day period in January 1981 from 2602 mm of rain. The quickflow to gross rainfall response ratio reached 74% for individual events over this period, but 45% is commonly exceeded at other times (Bonell et al., 1991). In contrast, Lesack (1993) recorded the same ratio as ranging only between 0.5 and 4.0% for a 23.4 ha undisturbed terra firma rainforest in the central Amazon basin because of the previously mentioned differences in rainfall climatology and more permeable subsoil (geometric mean, 54 mm h⁻¹, for piezometer depths of 1, 2 and 4 m; Lesack (1993)).

The few controlled experiments in the tropics have suggested that the bulk of the changes in water yield arising from forest conversion occur in the delayed flow component (Bonell with Balek, 1993, pp. 224-227). Malmer's (1993) Sabah study may be one of the exceptions. The areal coverage of new tractor tracks was 24% in the mechanically extracted timber catchment trial, which reduced the mean value of steady-state infiltrability (approximately K^*) from 154 mm h⁻¹ in forest to 0.28 mm h⁻¹ on new tractor tracks over clays (Malmer and Grip, 1990). Similar figures for the sandy soil in the catchment were, respectively, 48.7 mm h⁻¹ declining to 1.26 mm h⁻¹. Even 6-year-old tractor tracks on clays had hardly recovered ($K^* = 1.26 \text{ mmh}^{-1}$). Thus the impeding layer has been transferred from the subsoil at 0.2 m depth to the surface in these disturbed areas; this causes a change in preferred subsurface pathway (subsurface storm flow) to infiltration-excess (Hortonian) overland flow, and in turn, increases the quickflow component of the hydrograph.

The most dramatic changes in the runoff process after land use change may occur, however, in tropical forest environments where the soils are highly permeable and any impeding layers are located at depths of 1 m or more. Disturbance might cause a dramatic location of the impeding layer to the surface from a considerable depth (Bonell, 1991). The deep, upper trans-missive layer previously acting as a buffer to the occurrence of overland flow would be lost. Consequently, the delivery mechanism of storm flow would dramatically change from deep, lateral subsurface flow to infiltration-excess overland flow, with obviously much faster velocities and shorter concentration times in terms of the flood hydrograph. No in situ soil hydraulic properties have been measured to confirm this concept, but visible observations at the Reserva Ducke site near Manaus suggest that the surface fabric collapses easily on disturbance, and semi-permanent depression storage is a feature of hollows. A schematic diagram presented by Bonell with Balek (1993) summarized these ideas, on the basis of the assumption of typical maximum 1 min rainfalls for storms being about 60 mm h⁻¹ (no detailed rainfall intensity—frequency—duration data are available for the Reserva Ducke), and is reproduced .

As one progresses into the tropical, semi-arid areas of north-east Queensland, which have a more distinct wet season, the open eucalypt woodlands present a more random mosaic of bare soil and grass tussocks at the surface. These low-relief environments are very similar to the African Sahel (Williams et al., 1985), and are very vulnerable to

erosion from grazing disturbance connected with the beef cattle industry. Infiltration-excess (Hortonian) over-land flow prevails within the short-duration, summer convective storms. Although considerable volumes of overland flow were measured, considerable redistribution also occurred, along a 100 m transect, i.e. rainfall-runoff, so that net discharge downslope was normally 1 mm or less (Bonell and Williams, 19861), 1987; Williams and Bonell, 1987, 1988). A simple model for estimating cumulative infiltration—time plots from a new cascade system of troughs confirmed the existence of 'profile at infinity' conditions of Philip (1969) and the dominance of K^* in ponded infiltration. It became clear that the bare soil areas dominated the runoff process, with the higher K^* associated with the grass tussocks acting as 'vents' for infiltrating water to their roots and the remainder of the soil profile (Williams and Bonell, 1988).

When discussing the management of these fragile landscapes, the point was made that the surface hydraulic properties are in a state of equilibrium with the high short-term intensities (Bonell and Williams, 1989). Any disruption to the surface soil fabric immediately places these systems in a state of vulnerary and disequilibrium, arising from increased overland flow and erosion. It is also significant that, in this study, the throttle (impeding) layer was at the surface, induced by raindrop compaction. The remaining part of this gradational profile (red earth, Stace et al., 1968), has a much higher K^* (Bonell, 1991). As with the in situ infiltration study (Bonell and Williams, 1986a), the surface IC^* for the large, unbounded runoff plots showed considerable temporal as well as spatial variability, caused by biological activity, raindrop compaction and desiccation cracks emerging in the associated thin surface seal (Williams and Bonell, 1988). The 'scale' of measurement and comparisons between infiltration variables determined from the in situ infiltrometers and runoff plots were also discussed (Williams and Bonell, 1988).

Forest conversion, degradation and reforestation affect both infiltration and evapotranspiration, and there can be a trade-off between the two. These components are encapsulated in the 'infiltration trade-off' hypothesis of Bruijnzeel (1989, 2004). In the context of this study, this hypothesis suggests that the ability of a degraded forest to allow sufficient infiltration (and thus groundwater recharge via vertical percolation) in the wet-season maybe impaired to such an extent, that the short and long-term effects on delayed flow after storms as well as on dry season flow would be detrimental, even after accounting for 'gains' from reduced evapotranspiration.

Further such reductions in infiltration have the ability to change the dominant storm flow pathways (Chappell et al., 2007) on hill slopes from subsurface storm flow (SSF) to infiltration-excess overland flow (IOF). Under certain conditions and at 'local' scales, there is now emerging evidence in support of this hypothesis when concerning these changes in the storm runoff generation component. Through the use of a Comparative Catchment approach (Blackie and Robinson, 2007), this work will present rainfall–stream flow data from 11 basins (645 ha) in the monsoonal tropics to test hypotheses from an earlier survey of field, saturated hydraulic conductivity, K_{fs} in the Uttar Kannada district (Karnataka State), of the Western Ghats of India (Bonell et al., 2010). The locations of the experimental basins were guided by the landscape groupings of Gunnell and Radhakrishna (2001). Consequently three of the basins were located on the Coastal block and the remainder in the higher interior known as the Up-Ghat block or Malnaad.

The rainfall–stream flow data analysed in this work was collected over a 2–3 year period (2003–2005) at a daily time resolution which was supplemented by 36 min data in the case of the Coastal basins. As a result of degradation of forests over multi-decadal to century time scales, the land cover is complex in Uttar Kannada in common with other parts of the Western Ghats (Menon and Bawa, 1998; Seen et al., 2010). Patches of remnant natural forest, which are less disturbed and less used by people are at one end of the disturbance gradient and whilst at the other end, are a heterogeneous category of disturbed and heavily used forest (known as degraded forest). In addition a mix of State Government and community based forestation programmes have been implemented for more than two decades within degraded forests and severely degraded, former forest- covered land (Pomeroy et al., 2003; Ramachandra et al., 2004). Consequently the Western Ghats (Karnataka State) provides a basis for evaluating land cover (LC) change impacts on stream flow hydrology at contrasting time scales linked with (i) forest land use and degradation, (ii) forestation over previously degraded land, relative to less used native forest and thus can address the hydrological knowledge gaps connected with these two scenarios (Ilstedt et al., 2007; Malmer et al., 2010).

The impacts on the storm runoff hydrology of three of the more common land cover types namely, less disturbed natural–tropical evergreen Forest (NF), heavily impacted, degraded forest (DF) and former degraded land that has undergone 'forestation' (Scott et al., 2004) byway of *Acacia auriculiformis* plantations (AC) will be evaluated. The DF

represents severely degraded, former evergreen forest, which has been converted floristically and architecturally into an open tree savannah. Bonell et al. (2010) had previously provided Kfs data for five LCs (natural forests, degraded forests, acacia and teak plantations) and three soil groups, and linked such data with rainfall characteristics (IDF, intensity–duration–frequency). For extreme rainfalls with return periods of 1 in 1 year upwards, these writers inferred that IOF was a more dominant storm flow pathway on hill slopes than previously thought when concerning many of the land covers and for many of the return periods of rainfall. Significantly such an inference included some (but not all) of the less disturbed natural forests. Otherwise it was suggested that subsurface storm flow (SSF), supplemented by saturation overland flow (SOF), was the most prevalent. One of the few other experimental basin studies previously undertaken in the Western Ghats was by Putty and Prasad (2000a), and later summarised in Putty (2006), based on first order basins (up to 8 ha in area) which were located south of Uttar Kannada within the Dakshina–Kannada district (near Talakaveri, annual rainfall, 6750 mm). Some of the conclusions of Bonell et al. (2010) aligned with the descriptions of Putty and Prasad (2000a). The latter, had noted the occurrence of IOF in the multi-decadal impacted, Kannike basin (2.8 ha) of mixed grassland and forestation where final soil infiltrability (Hillel, 1980) could be as low as 6 mmh^{-1} . However such IOF was supplemented SOF from riparian areas adjoining the stream (the Dunne mechanism, Dunne and Black, 1970) and more extensively on slopes, by an additional process termed pipe flow overland flow, POF (Putty and Prasad, 2000a). For the less disturbed, natural forest basin (8 ha), Putty and Prasad (2000a) noted that SOF is a significant contributor to stream discharge only during short duration events of higher rain intensity ($10\text{--}15 \text{ mmh}^{-1}$) and pipe-flow is the major mechanism generating stream-flow for the predominantly low rain intensity-longer storm durations. However these studies did not have detailed Kfs or stream hydrograph analyses and these aspects will be addressed in this study.

In the absence of detailed hill slope hydrology studies (a typical situation in most of the humid tropics), the work will analyse the rainfall–stream flow data using up to four analytical methods to assess if there is some coherence across the various interpretations of the results. These analyses will concurrently address the following questions:

- What are the impacts of the three land covers on the stream discharge hydrograph components, viz, total flow, quickflow, and delayed flow.

- What dominant storm flow pathways can be inferred from the storm hydrograph characteristics and is there any agreement with the storm flow pathways, as suggested from the earlier Kfs survey linked with rain IDF (intensity–duration–frequency) (Bonell et al., 2010)
- What is the impact of forestation on the recovery of the rain–stream flow responses towards those observed under the less disturbed, natural forest?

CHAPTER 3

STUDY AREA

3.1 GENERAL

The Malaprabha River is a right bank tributary of river Krishna. The Malaprabha sub-basin lies in the extreme western part of the Krishna basin. It extends between $74^{\circ} 20'$ and 75° E longitudes and $15^{\circ} 20'$ and $15^{\circ} 40'$ N latitude in Belgaum district of Karnataka. Catchment area of the river up to the reservoir is about 3000 km^2 . The Malaprabha originates from the Chorla ghats, a section of the western ghats at an elevation of about 792m about 35 km south-west of Belgaum district in Karnataka. The river flows east and the north-west and joins the Krishna at Kudalasangam in the Bagalkot district at an elevation of about 488 m. It traverses a length of 306 km before meeting the river Krishna. The Bennihala and the Hirehala are the principal tributaries of the river Malaprabha. To harness the waters of the Malaprabha river, a dam is constructed at Naviluteerth, Belgaum district to impound 1377 MCM water.

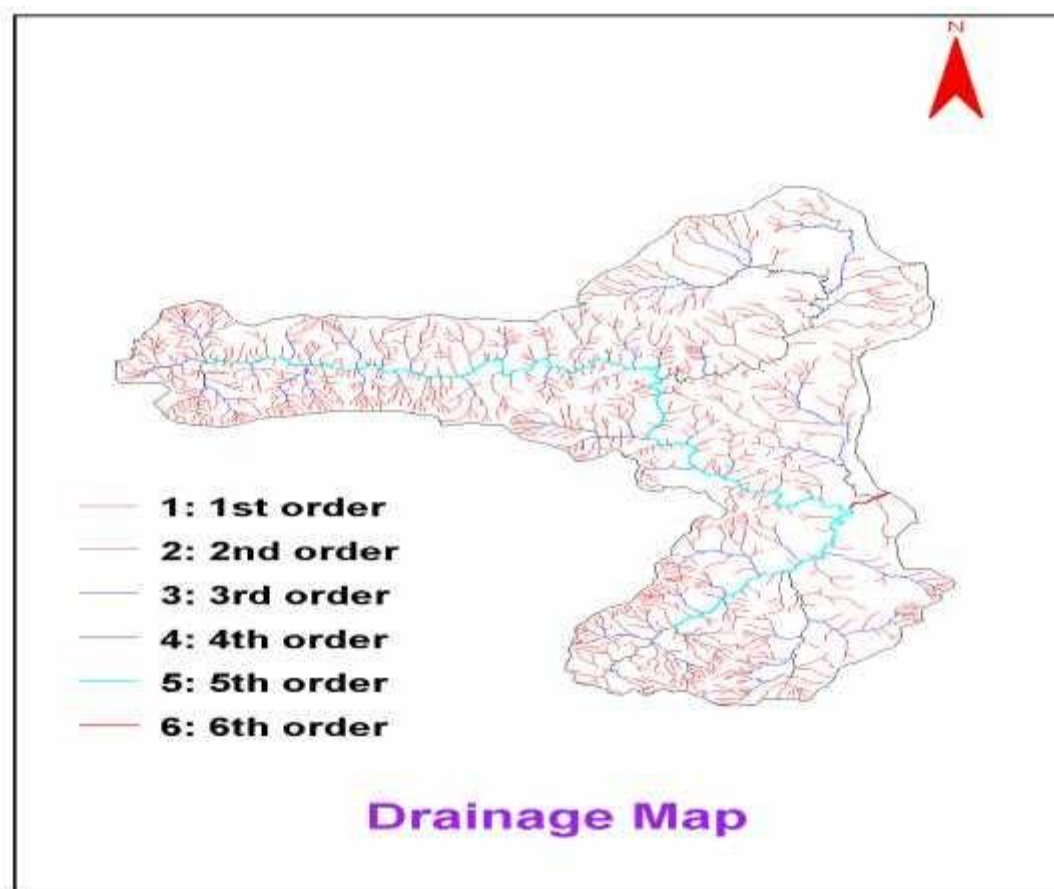


Figure 3.1 Drainage map of Malaprabha representative basin

3.2 PHYSIOGRAPHY AND GEOLOGY

The terrain is flat to gently undulating except for a few hillocks and valleys. The northern boundary is the common ridge between the Malaprabha and the Ghataprabha rivers. The eastern boundary is the common ridge between the Malaprabha, Krishna and the Tungabhadra rivers. The ridges in the southern and western boundaries are common between the Malaprabha and the west flowing rivers. The important rock formations in the sub-basin are (i) Sedimentary rock formations (Kaladgi group) comprising limestone, shale and quartzite's (ii) Schistose rock formations (Dhārwad super group) comprising granite, gneiss and crystalline rocks.

The relief of the Malaprabha representative basin varies between 668 and 1038 m from the mean sea level. The contour map depicts the morphological characteristics. The pattern closely spaced contours on the water divides indicates that the crest and mid-crest have convex-concave slope, and the broadly spaced contours in the valley bottom specify gentle and flat valley bottoms. Thus, the basin is divisible into three distinct morphological zones.

These are,

- * Convex hill summit (more than 900m)
- * Concave and gentle mid-crest and (800 - 900 m)
- * Flat valley bottom (less than 800 m)

This change in morphological character from hill crest to valley bottom of the basin is largely responsible in the change in behavior of water flow between hill-slope and foot slope. Further complete geomorphological studies are required to understand the change in behavior of the hydrological processes form hill slope to foot slope.

The 800 m contour line divides the area into the hill-slope. Above this contour line there is convex-concave hill-slope which has fully erosional environment. This is the zone of maximum overland flow and the minimum infiltration. The area below the 800 m contour line surrounding an area of 86.5% of the total basin, the gentle and flat slope has depositional environment. This is the maximum recharge zone of the basin as it comprises of colluvial materials.

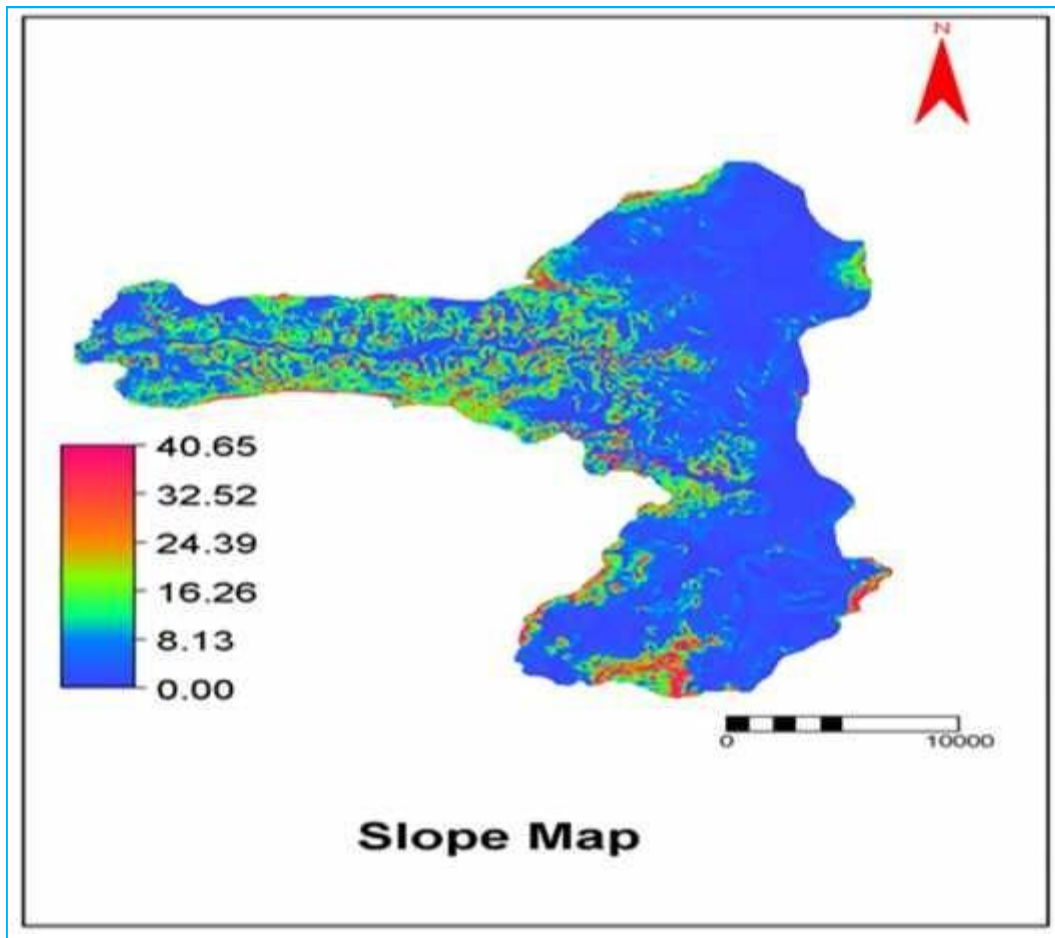


Figure 3.2 Slope map of Malaprabha representative basin

3.3 METEOROLOGY

There are three seasons prevailing in the catchment, the summer from March to April, the monsoon from May to November and the winter from December to February. The Malaprabha catchment mainly experiences the south-west monsoon. The rainfall in the non-monsoon period is insignificant. The average annual rainfall of the upper catchment (upto Khanapur) is around 2300 mm. The climate of the catchment is generally dry except for the monsoon months. The annual average maximum temperature is 32°C and minimum is 18°C. Evaporation is governed by temperature, relative humidity, atmospheric pressure and wind velocity. It influences transpiration from plants and loss of water from reservoirs, water conveyance systems and loss of moisture in the upper layer of soil. The mean relative humidity is high during the south-west monsoon season and comparatively low during the non-monsoon period. In summer, the weather is dry and the humidity is low. The catchment is influenced by the south-west or westerly winds during

the monsoon season. In the non-monsoon season winds from north-east and south-east are common. The sky is heavily clouded during the south-west monsoon. During the remaining part of the year, clear or lightly clouded sky prevails. The sunshine percentage in the catchment varies from 21 to 96. The rainfall drastically reduces (650-750 mm) as we move towards south-eastern region.

3.4 LAND USE PATTERN

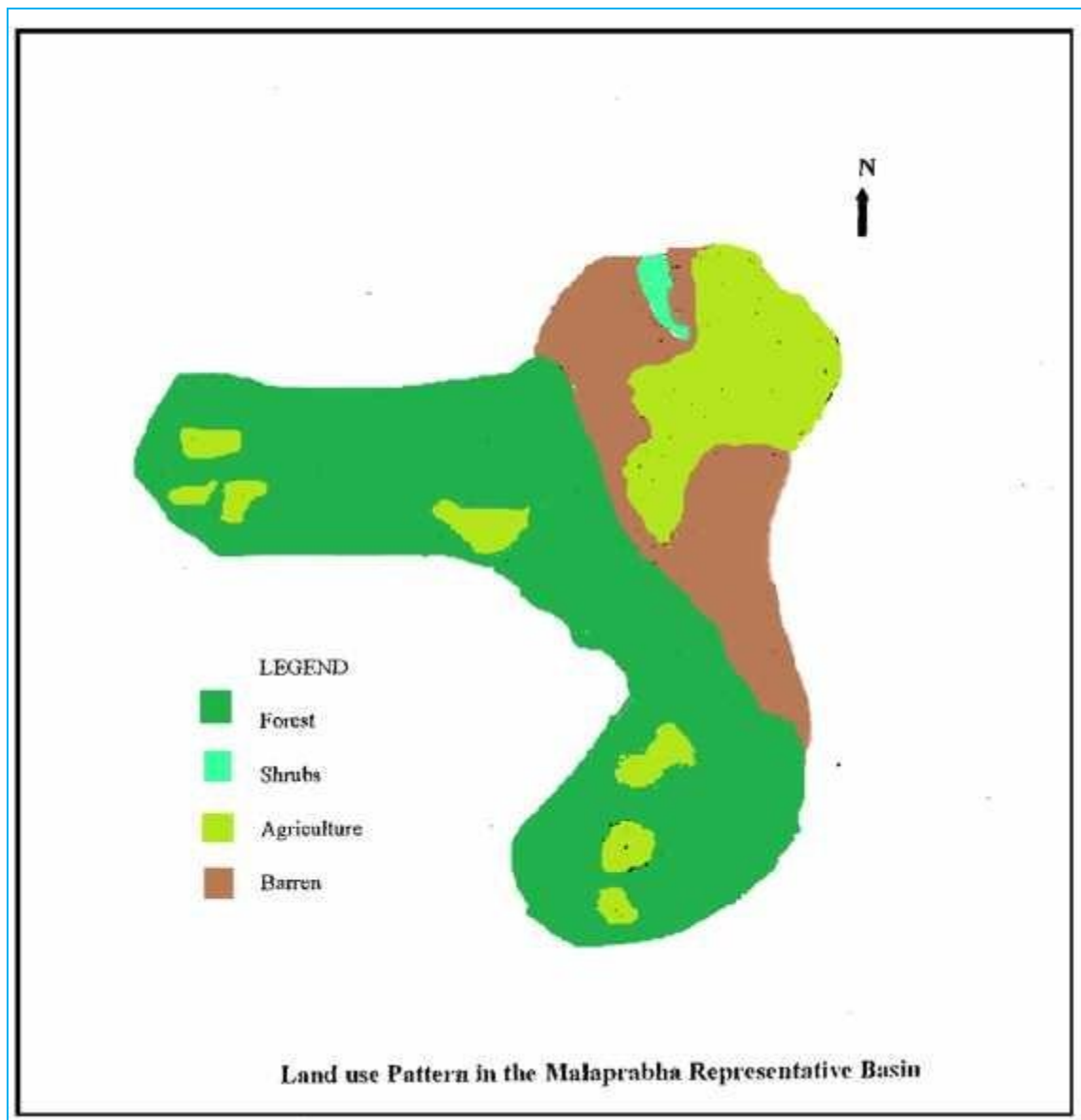


Figure 3.3 Land use pattern of Malaprabha representative basin

Land use pattern of the Malaprabha representative basin is very complex consisting of forest, agriculture, shrubs and barren land. A brief description of the different land use pattern is given below.

(i) Forests: About 62.65 per cent of the Malaprabha representative basin covering Kankumbi, Jamboti and Gunji areas are dominated by tropical forests. The foremost species covered are teak wood, rosewood, jack wood, Bamboo etc. The ground of this forest is covered by shrubs (2-4 m high) and grasses.

(ii) Shrubs: The eastern facing watersheds of the area having steep slope (20-30) are covered by shrubs and small trees and bushes (3-5 m high). The most important quality of this class of land is that these are relatively shallow soil areas. About 19.3 % area of the basin is covered by shrubs.

(iii) Agriculture Land: The gentle slopes and level valley bottom areas, where the most fertile soil is confined, have been occupied by man for the cultivation of various cereal (paddy, ragi etc.) and cash crops (cotton, sugarcane). About 16.85 % of the total basin area falls under agricultural land.

(iv) Barren Land: About 1.15 % of the area is in the form of small patches on steep slopes and on the gentle slopes having very thin layer of soil is in the form of barren land. This land is used for the grazing purpose of cattle.

3.5 TYPES OF SOILS

Red sandy soils occur on undulating lands on acidic rocks viz., granites and granite gneisses. These soils are deep to very deep, reddish brown to dark reddish brown, loamy sand to sandy loam or sandy clay loam on the surface with sandy clay to gravelly clay in the sub-surface horizon with well developed argillic (clay rich) horizon. They are neutral to acidic in reaction and low to medium in cation exchange capacity and base saturation with medium to high water holding capacity. The clay complex is dominated by kaolinites' and hydrous oxides of iron and alumina minerals. The soils are well drained with moderate permeability.

Red loamy soils occur on hilly to undulating land on granites, granitic gneisses and Dhār warschist's, occupying areas as long strip along the Western Ghats in the transitional tract

comprising the western ghats of Belgaum and Khanapur taluks in the dry agro climatic region. These soils are very deep, dark brown to dark red, sandy loam to clay loam on the surface and loam to clay loam and at places gravelly sandy clay in the sub-surface horizon, with distinct argillic (clay rich) horizon. They are neutral to weakly acidic in reaction, low in cation exchange capacity and medium to high in water holding capacity. The clay complex is dominated by kaolinitic and hydrous oxides of iron and alumina minerals. The soils are well drained with moderate permeability.

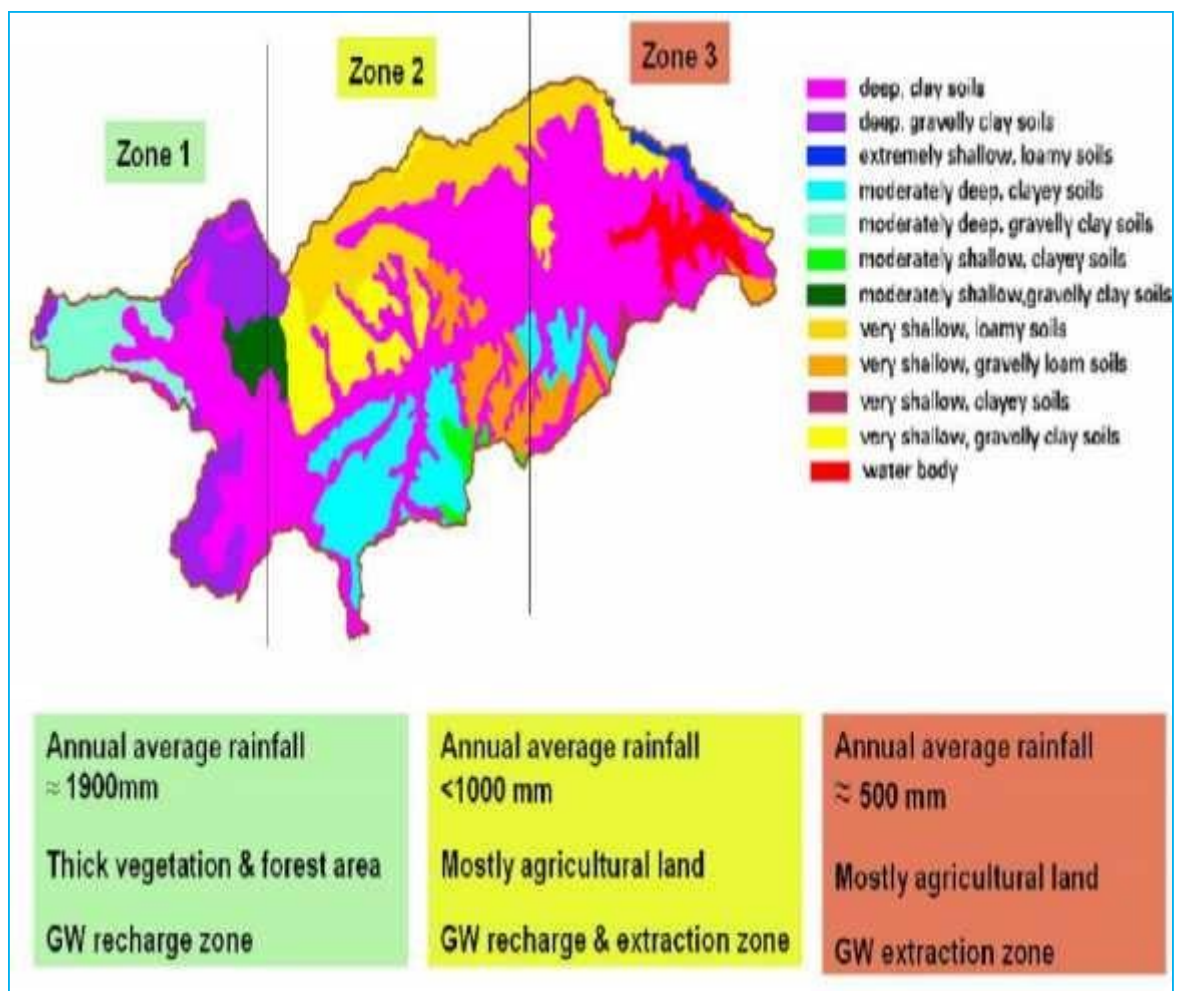


Figure 3.4 Soil Map of Malaprabha Representative Basin

CHAPTER4

METHODOLOGY

4.1 FIELD AND LABORATORY INVESTIGATIONS

4.1.1 Water Content (Gravimetric method)

Measurements of water content are needed in hydrological studies for direct knowledge of the quantity of the available soil water for interpretation of physical and chemical measurements, and for determination of water retention and hydraulic conductivity curves. Soil water content can be expressed as a dimensionless mass or volume ratio. The gravimetric content is mass ratio.

$$\Theta_m = M_w/M_s \quad (\text{Eq.4.1})$$

Where, Θ_m is gravimetric water content, M_w is water mass (mg) , and M_s is dry soil mass (mg) the volumetric water content is based on the volume ratio.

$$\Theta = V_w/V \quad (\text{Eq.4.2})$$

Where Θ is Volumetric water content, V_w is volume of water (cum) V is total soil volume.

Gravimetric and Volumetric soil water content are related to each other as

$$\Theta = r_s \Theta_m \quad (\text{Eq.4.3})$$

Where r_s is dry bulk density of the soil (mg/cu. m) soil water content can be measured by direct methods such as oven or microwave dry, or by indirect ones based on neutron thermalisation, gamma ray attenuation or electrical conductivity and capacitance.

4.2 DETERMINATION OF INFILTRATION CHARACTERISTICS

4.2.1 Disc Permeameter

The disc Permeameter has become a popular apparatus for measuring in situ sorptivity (S), and hydraulic conductivity, (K), of the soil at some prescribed potential. Measurements of sorptivity (S), and hydraulic conductivity (K), are important for predicting how water will enter, redistribute within, and drain from soils. Methods that can rapidly and accurately measure S and K are valuable. The disc Permeameter (Per

roux and White 1988) is a relatively new method that has gained popularity because of its simplicity, the speed at which measurements can be made, and because it does not greatly disturb the soil surface being measured (White and Sully 1987; White and Perroux 1987 and 1989; Smettem and Clothier 1989; Ankeny et al 1991). Different methods have been devised for calculating S and K are compared using same set of data. These methods are all based on the approximate, but usefully accurate, solution of flow from a disc source found by Wooding (1968). This linearized solution uses a hydraulic conductivity (K) function of the exponential form (Gardner 1958):

$$K = K_s \exp(\psi / \lambda_c) \quad (\text{Eq.4.4})$$

Where K_s is the saturated hydraulic conductivity (m s^{-1}), λ_c is the macroscopic capillary length scale (m) and ψ is the matric potential (m).

4.2.1 a Principles of Operation

When a source of water, such as a wet circular disc or shallow pond, is placed on the soil surface, the initial stages of flow into the soil are dominated by the soil's capillary properties. As time progresses, both the size and geometry of the water source and the force of gravity influence the water flow rate. For uniform soils a time is eventually reached where the flow rate from the source becomes steady. This steady state flow rate is governed by capillarity, gravity, the size of the disc and the pressure at which water is supplied to the soil surface.

In this technique we make use of both the initial and steady-state flow rates to separate the capillarity and gravity contributions to soil water flow. In addition, by selecting the water supply pressure we can dictate the sizes of pore sequences or fissures which participate in the flow process.

4.2.2 Hydraulic conductivity and Sorptivity

The method for determining soil hydraulic properties from disc Permeameter measurements in the field is based on an analysis of the three-dimensional flow from a shallow circular pond or surface disc.

For a pond or disc of radius r_0 , on a homogeneous soil, Wooding showed that when water is supplied at a potential of ψ_0 the steady state volumetric flow rate q is

$$q = \pi r_0^2 (K_0 - K_n) + 4r_0\phi \quad \text{(Eq.4.5)}$$

The first term on the right essentially represents the contribution of gravity to the total flow from the surface disc and the second term contains the contribution due to capillarity. In the gravity term K_0 is the hydraulic conductivity at the supply potential ψ_0 , and K_n is the hydraulic conductivity at the initial soil water potential ψ_n . For relatively dry materials K_n is much smaller than K_0 and we can safely ignore its effect. The capillarity term contains the matric flux potential, which is related to the conductivity by

$$\phi = K_0\lambda_c$$

The macroscopic capillary length (λ_c), is related to the sorptivity, S_0 , and the hydraulic conductivity (White and Sully, 1987),

$$\lambda_c = bS_0^2 / (\theta_0 - \theta_n) \quad \text{(Eq.4.6)}$$

is the initial moisture content at ψ_n is the moisture content at ψ_n , θ_0 is the moisture content at the supply potential, ψ_0 , S_0 is the sorptivity at ψ_n with supply potential ψ_0 and 'b' is a dimensionless constant whose value lies between 1/2 and $\pi/4$. For field soils a good mean value for b is 0.55. With simplification and, dividing by the area of the disc, we find the steady-state flow rate per unit area

$$q = K_0 + \frac{4bS_0^2}{\theta_0 - \theta_n} \quad \text{(Eq.4.7)}$$

Rearranging (Eq.6) to find the conductivity, we have

$$K_0 = q - \frac{4bS_0^2}{\theta_0 - \theta_n}$$

(Eq.4.8)

During the early stages of flow from the disc, capillarity dominates flows irrespective of the disc. At short infiltration times the system behaves as if it were one-dimensional. In this case the cumulative infiltration is given by (Philip, 1969). Where Q is the total volume of water infiltrated and t is time from the commencement of infiltration. Sorptivity then is the Slope of the cumulative infiltration vs. $t^{1/2}$ plot to calculate the hydraulic conductivity from (4), the measurements required are the sorptivity, the steady state flow rate, the initial volumetric moisture content at the supply potential.



Figure 4.1 Disc Permeameter experiment to measure the soil hydraulic properties

4.2.3 Guelph Permeameter apparatus

The Guelph Permeameter method (Reynolds et al. 1985) measure the steady state liquid recharge Q , necessary to maintain a constant depth of liquid (H), in an uncased cylindrical well of radius 'a' finished above the water table. Constant head level in the well hole is established and maintained by regulating the level of the bottom of the air tube which is located in the centre of the Permeameter. As the water level in the reservoir falls, a

vacuum is created in the air space above water. When the Permeameter is operating, equilibrium is established.

When a constant well height of water is established in a cored hole in a soil, a bulb of saturated soil with specific dimension is rather quickly established as shown in above figure. The bulb is very stable and its shape depends on the type of soil, the radius of the well and the head of water in the well. The shape of the bulb is numerically described by the C factor used in the calculations. Once the bulb shape is established, the outflow of water from the well reaches a steady state flow rate which can be measured. The rate of this constant outflow of water, together with the diameter of the well and height of water in the well can be used to determine the field saturated hydraulic conductivity of the soil.

The Richard analysis of steady state discharge from a cylindrical well in unsaturated soil, as measured by the Guelph Permeameter technique accounts for all the forces that contribute to three dimensional flow of water into soils, the hydraulic push of water into soil, the gravitational pull of liquid out through bottom of the well and the capillary pull of water out of the well into the surrounding soil. The Richard analysis is the basis for the calculation of field saturated hydraulic conductivity. The C factor is a numerically derived shape factor which is dependent on the well radius 'a' and head 'H' of water in the well.

4.2.3a Procedure for field use

Before making measurement with the Guelph Permeameter in the field, it is necessary to perform a site and soil evaluation, prepare a well hole assemble the Permeameter, fill the reservoir, and place Permeameter in the well hole.

(i) Well preparation

A borehole is drilled using soil and sizing auger. The soil auger is used to remove bulk amounts of soil and rock. The sizing auger is used as a finishing tool to produce a proper sized well hole of uniform geometry and to clean debris off the bottom of the well hole. The sizing auger is designed to produce a hole that is uniformly 6 cm in diameter with a flat bottom. Generally, the procedure is to use the soil auger to excavate the well hole up to a depth of about 60cm and then by using the sizing auger it will be shaped to produce a debris free well hole of uniform geometry.

In the moist soils or in medium to fine textured soils, the process of auguring a hole may create a smear layer which can block the natural flow of water out of the well into the surrounding soil. In order to obtain reliable and representative results using the Guelph Permeameter, the smear layer must be removed.

(ii) Permeameter placement

Simply centre the Tripod over the well hole and slowly lower the Permeameter so that the support tube enters into the well hole. The tripod is used to support the Permeameter in well down to approximately 38 cm in depth. For use in wells deeper than 38 cm, the tripod bushing alone provides the functions of centring and stabilising the Permeameter. After the Permeameter is placed, it can be easily filled with water. The following standard procedure should be followed for making measurements.

(iii) Verify that both the reservoirs are connected. The reservoirs are connected when the Notch on the reservoir valve is pointing up. Establish 5 cm well Head Height (H1). Slowly raise the air inlet tip to establish the 5 cm well head height. Raising the air tube too quickly can cause turbulence and erosion in the well.

Observe the rate of fall of the water level in the reservoir. If it is too slow, then turn the reservoir valve so that the notch is pointing down. Water will then be supplied, only from the small diameter inner reservoir which will result in a much greater drop in water level between readings. Measure Permeameter outflow. This is indicated by the rate of fall of water in the reservoir. Readings should be made at regular time intervals, usually 2 minute intervals are used. The difference of readings at consecutive interval divided by the time interval equals the rate of fall of water, R_1 in the reservoir. Continue monitoring the rate of fall of water in the reservoir until the rate of fall does not significantly change in three consecutive time intervals. This rate is called R_1 and is defined as the "Steady state rate of fall" of water in the reservoir at height H_1 which is the first well height established and is always 5 cm in the standardized procedure.

Establish 10cm well head height (H_2). Slowly raise the air inlet tip to establish the second well head height of 10 cm. Monitor the rate of fall of water, R_2 , in the reservoir until a stable value of R_2 is measured.

The field saturated hydraulic conductivity, K_{fs} can be calculated using the following equation:

$$K_{fs} = 0.0041 \cdot X \cdot R_2 - 0.005 \cdot X \cdot R_1$$

where,

X = Reservoir constant, equal to 35.39 when reservoir combination is used.

R_2 = Steady, rate of fall of water in the reservoir when second head H equal to 10 cm of water is established.

R_1 = Steady rate of fall of water in the reservoir when the first head equal to 5 cm of Water is established.

K_{fs} = Field saturated Hydraulic conductivity in cm/sec.



Figure 4.2. Guelph Permeameter apparatus for the estimation of saturated hydraulic conductivity

4.3 PRESSURE PLATE APPARATUS

This is a standard method for obtaining the soil moisture retention curve. Pressure plate apparatus consists of a pressure chamber in which a saturated soil sample is placed on a porous ceramic plate through which the soil solution passes but no soil particle or air can pass. The soil solution which passes through the membrane is in contact with atmospheric pressure. As soon as the air pressure inside chambers are raised above the atmospheric pressure. It takes excess water from the soil out of the chamber through the membrane outlet. Soil water will flow out from the soil sample until the metric potential of the unsaturated flow is same as the applied air pressure. The air pressure is then released and The moisture content of the soil is is gravimetrically determined.

During a run, soil moisture will flow from around from each of the soil particle and out through the ceramic plate until such time as the effective curvature of the water film throughout the soil are the same as at the pores in the plates. When this occurs an equilibrium is reached and the flow of moisture ceases. When air pressure in the chamber is increased, flow of water from the samples start again and continue until a new equilibrium is reached. A source of regulated gas pressure is required for all extraction work. Compressed air from a compressor is the most efficient source of supply.

The ceramic plates are available in different range. Each ceramic pressure plate cell consists of a porous ceramic plate, covered on one side by a thin neoprene diaphragm sealed to the edges of a Ceramic plate. An internal screen between the plate and diaphragm provides a passage for flow of water. An outlet stem running through the plates connects this passage to an outflow tube fitting which to the atmosphere outside of the extractor. To use the ceramic pressure plate Cell one or more soil samples are placed on the porous ceramic surface held in place by retaining rings of appropriate height. The soil samples together with the porous ceramic plate are then saturated with water. This is usually done by allowing an excess of water to stand on this surface of the cell for several hours. When the saturation is complete, the cell can be mounted into the pressure vessel

.air pressure is used to effect extraction of moisture from the soil samples under controlled conditions. The 1 bar ceramic plates are ideal for the routine determination of the 1/10 bar and 1/3 bar range of the soil suction. The 3 bar pressure plate cells are used

in the range of 0-3 bars. The 15 bar ceramic cells are commonly used for measurement of soil moisture suction in the range of 5-15 bars of soil suction.

The moisture retention curve of a soil sample can generally be determined by equilibrating a soil sample at a succession is known tension value and each time determining the amount of moisture. The graph is plotted between the tension and corresponding soil moisture value to obtain the soil moisture retention curve. Different types of soil yields different retention curves.

The runoff curve number (also called a curve number or simply CN) is an empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess. The curve number method was developed by the USDA Natural Resources Conservation Service, which was formerly called the Soil Conservation Service or SCS — the number is still popularly known as a "SCS runoff curve number" in the literature. The runoff curve number was developed from an empirical analysis of runoff from small catchments and hill slope plots monitored by the USDA. It is widely used and efficient method for determining the approximate amount of direct runoff from a rainfall event in a particular area (Wikipedia)

The runoff curve number is based on the area's hydrologic soil group, land use, treatment and hydrologic condition. References, such as from USDA indicate the runoff curve numbers for characteristic land cover descriptions and a hydrologic soil group

The basic assumption of the SCS curve number method is that, for a single storm, the ratio of actual soil retention after runoff begins to potential maximum retention is equal to the ratio of direct runoff to available rainfall. This relationship, after algebraic manipulation and inclusion of simplifying assumptions, results in the following equation found in Section 4 of the National Engineering Handbook (NEH-4) (USDA-SCS, 1985), where curve number (CN) represents a convenient representation of the potential maximum soil retention, S (Ponce and Hawkins, 1996)

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

where

Q is runoff ([L]; in)

P is rainfall ([L]; in)

S is the potential maximum soil moisture retention after runoff begins ([L]; in)

Ia is the initial abstraction ([L]; in), or the amount of water before runoff, such as infiltration, or rainfall interception by vegetation; and $I_a = 0.2S$ The runoff curve number, CN, is then related

$$S = \frac{1000}{CN} - 10$$

CN has a range from 30 to 100; lower numbers indicate low runoff potential while larger numbers are for increasing runoff potential. Values are tabulated in Chapter 9 of NEH-4 for various land covers and soil textures. These values were developed from annual flood rainfall-runoff data from the literature for a variety of watersheds generally less than one square mile in area (USDA-SCS, 1985).

4.3.1 Ground water Estimation Committee Methodology

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

Watershed may be used as the unit for groundwater resource assessment in hard rock areas, which occupies around 2/3rd part of the country. The size of the watershed as a hydrological unit could be of about 100 to 300 sq. km. area. The assessment made for

watershed as unit may be transferred to administrative unit such as block, for planning development programmes.

(b) For alluvial areas, the present practice of assessment based on block/taluka/mandal-wise basis is retained. The possibility of adopting doab as the unit of assessment in alluvial areas needs further detailed studies.

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(b) For alluvial areas, the present practice of assessment based on block/taluka/mandal-wise basis is retained. The possibility of adopting doab as the unit of assessment in alluvial areas needs further detailed studies.

(c) The total geographical area of the unit for resource assessment is to be divided into subareas such as hilly regions (slope > 20%), saline groundwater areas, canal command areas and non-command areas, and separate resource assessment may be made for these subareas. Variations in geomorphological and hydrogeological characteristics may be considered within the unit.

(d) For hard rock areas, the specific yield value may be estimated by applying the water level fluctuation method for the dry season data, and then using this specific yield value in the water level fluctuation method for the monsoon season to get recharge. For alluvial areas, specific yield values may be estimated from analysis of pumping tests. However, norms for specific yield values in different hydrogeological regions may still be necessary for use in situations where the above methods are not feasible due to inadequacy of data.

(e) There should be at least 3 spatially well-distributed observation wells in the unit, or one observation well per 100 sq. km. whichever is more.

(f) The problem of accounting for groundwater inflow/outflow and base flow from a region is difficult to solve. If watershed is used as a unit for resource assessment in hard

rock areas, the groundwater inflow/outflow may become negligible. The base flow can be estimated if one stream gauging station is located at the exit of the watershed.

Norms for return flow from groundwater and surface water irrigation are revised taking into account the source of water (groundwater/surface water), type of crop (paddy/non-paddy) and depth of groundwater level.

In subsequent section, the recommended GEC norms for estimation of various inflow/outflow components of the groundwater balance equation have been mentioned at appropriate places, along with other methodologies/formulae in use.

4.4 MODEL STUDY (PMWIN) PROCESSING MODFLOW

4.4.1 Creating Model in PMWIN:

Creating a groundwater flow modelling in PROCESSING MODFLOW includes these following steps:-

- (a) Creating a new model.
- (b) Defining model size.
- (c) Assigning model data.
- (d) Perform flow simulation.
- (e) Extract and view results.
- (f) Producing output from the results.
- (g) Presentation.

The detailed steps of the process are discussed below:

- a) **Creating a new model:** Open the PMWIN window, select FILE menu, click on the NEW MODEL option. A dialog box will open. Enter the name of the new model and click OK. A new model is created. The window will appear as shown in the picture below:

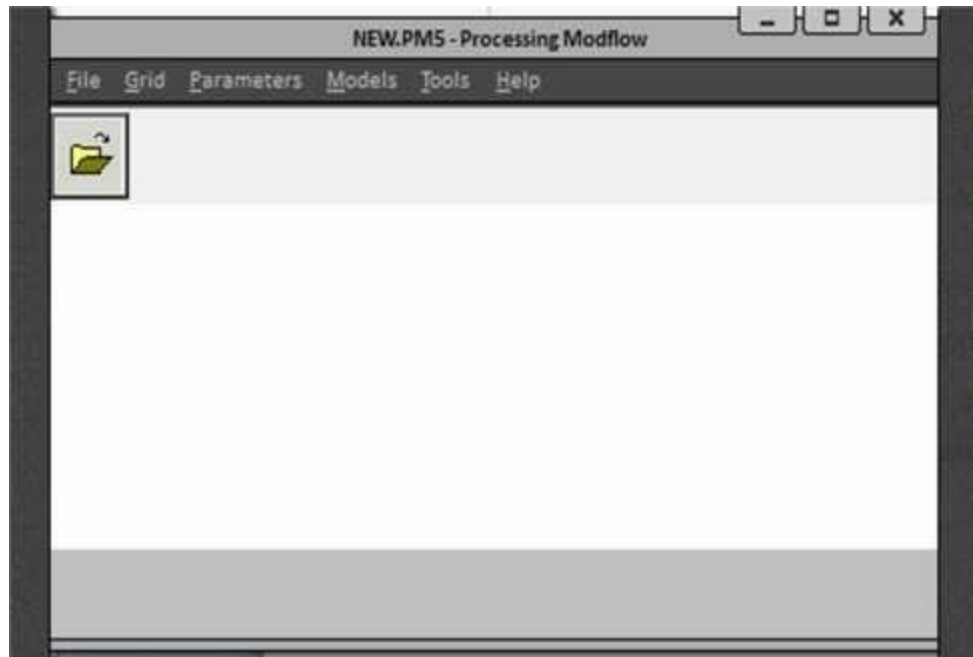


Figure 4.3 To Create Grid

- b) **Defining model size:** In PMWIN, the entire study area is divided into a grid containing various rows and columns. Our study area i.e. Malaprabha basin extends in a square area of 39 km by 39 km. So we require a grid of 39 km x 39 km.

For creating the grid, click on the GRID option on the menu bar. A drop down menu will appear, select MESH SIZE from the menu. In the dialog box, enter the number of layers as 1, number of rows and columns as 39 & 39 and enter the extent as 39000 m & 39000 m. Click on OK. This will create a square grid having 39 rows and 39 columns. The size of each cell will be 1 square kilometer.

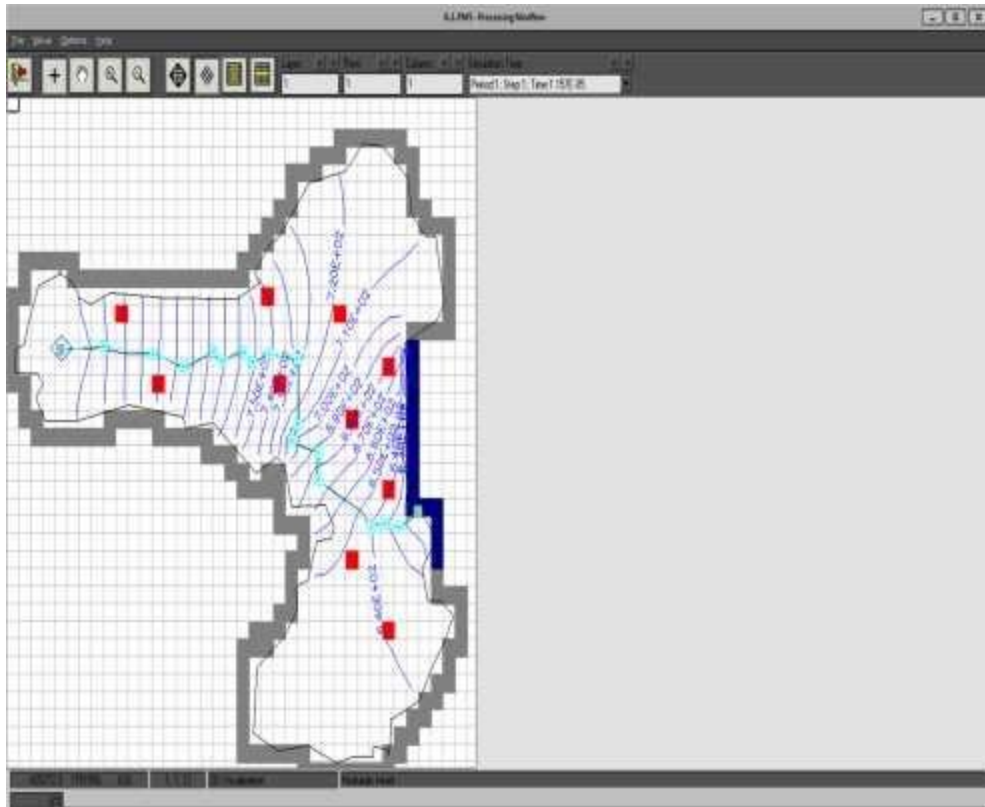


Figure 4.4 Two layered Grid Created

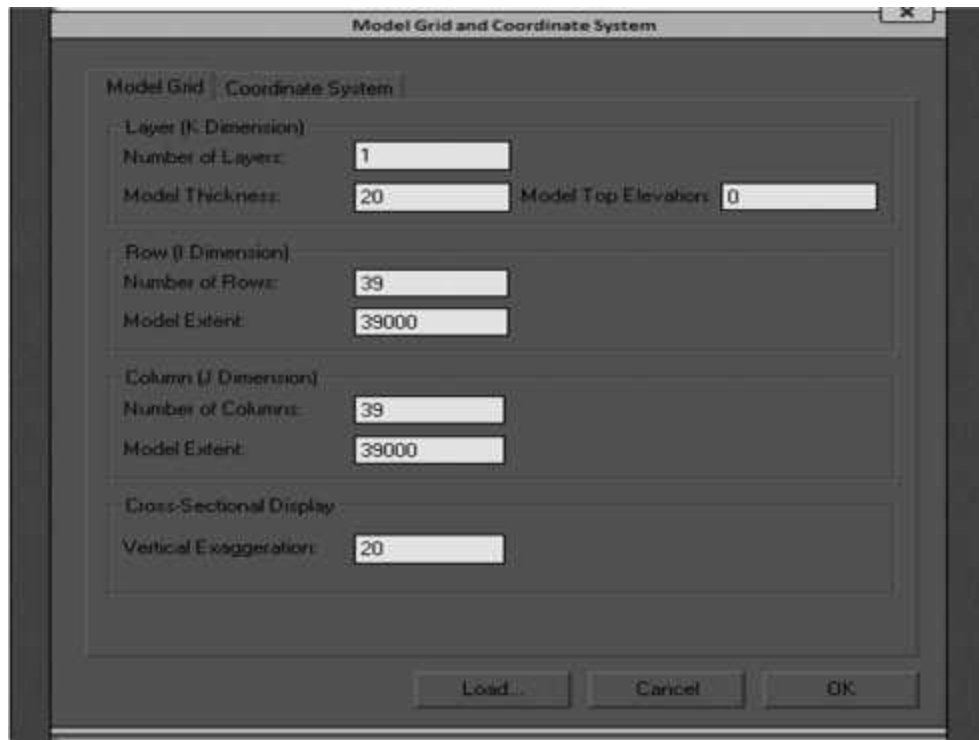


Figure 4.5 Grid Co-ordinate System

In order to accurately mark the boundary and the path of the river, we need to overlay a map of the basin on this grid. We have already created the base map of malaprabha basin in the AutoCAD (.dxf) format using ILWIS. To bring the map onto the grid, click on the OPTIONS menu and select MAPS. A dialog box will appear. In the dialog box, check the box beside the space for the DXF map to activate that particular map. In the first file name field of the DXF file, right click to bring the map files dialog box. Choose the dxf map of malaprabha which has been prepared using ILWIS. Click on the OK button.

In order to adjust and fit the map on the grid, click on the OPTIONS menu and select the ENVIRONMENT option. In the environment dialog box, click on the COORDINATE SYSTEM tab and enter the values of the extent of the window and the grid. These values are obtained using ILWIS. Click OK and the map will be displayed on the grid.

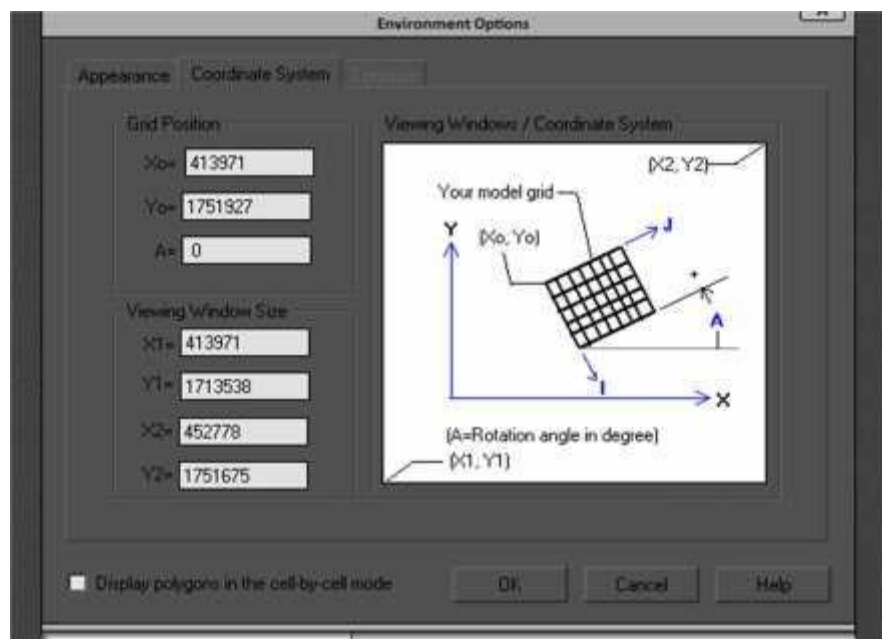


Figure 4.6 Environment option

- c) Assigning model data: The data required in PMWIN includes the layer type, soil hydraulic properties, boundary conditions and the river and well data. We will assign all these data in the following steps:-
- i) Layer type- Enter the layer type as unconfined.
 - ii) Cell Status- Provide no flow boundary and fixed head boundary along the basin.

- iii) Top of layer- Click on the value option, select “reset matrix” and enter the value as 640.
- iv) Bottom of layer- Go to the “reset matrix” option and enter the value as 600.
- v) Time- Go to the PARAMETERS option, click on TIME and change the simulation time unit to DAYS and simulation type as STEADY STATE.
- vi) Initial Hydraulic Heads- Provide initial hydraulic head as 610 m.
- vii) Horizontal Hydraulic Conductivity- Enter the value of the horizontal hydraulic conductivity as 2.88 m/day, which is around 120 mm/hour.
- viii) Effective Porosity- Provide the value of effective porosity as 0.35 and also the details of the recharge, river and the wells in the study area.
- ix) Recharge- Click on MODELS menu, select MODFLOW, then select FLOW PACKAGES and click on RECHARGE. Click on the “Polygon input” mode and three different polygons on the upper, middle and lower reaches of the basin. Enter the value of the recharge as 0.00164 m/day (600 mm/year), 0.00136 m/day (500 mm/year) and 0.0011 m/day (400 mm/year) respectively.
- x) River- Go to the RIVER package in the MODFLOW option. The grid will appear in the window with the base map. Click on the upstream point of the river and move the pointer along the river until the whole river is covered. Double click on the downstream end of the river to complete the path. Then click on the u/s and d/s points to enter the values of the river bed elevation, head in the river, river width and thickness of the river sediments. The values at the intermediate points are automatically calculated based on the inputs given on the extreme points.
- xi) Wells- Provide 10 wells in the entire study area with the pumping rate of each well defined as 100 m³/day.

The final appearance of our model grid after providing the inputs is shown below:

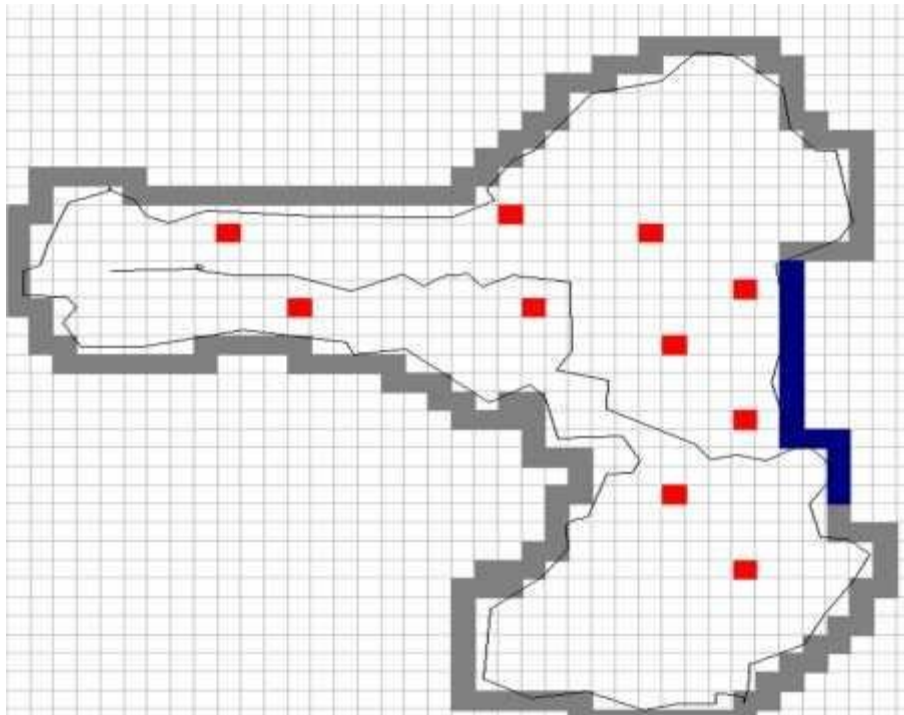


Figure 4.7 Flow simulation model

Thus all the necessary inputs required by PMWIN to run the flow simulation model have been provided.

- d) Perform flow simulation: To run the model, go to MODELS menu, select MODFLOW and then click RUN. A “run modflow” dialog box will appear. Check all the necessary tick boxes and click on OK. The model will perform the iterations required to complete the flow simulations and a DOS window will appear. Click any key to exit the window.

```

C:\Windows\system32\cmd.exe
uter Iter 11 Inner Iter 4: Max DH= -0.731E-05 Max Flow Residual= -0.104E-02
uter Iter 11 Inner Iter 5: Max DH= -0.540E-05 Max Flow Residual= -0.002E-03
Starting iteration 12 of time step 1 in stress period 1
uter Iter 12 Inner Iter 1: Max DH= -0.875E-05 Max Flow Residual= 0.104E-02
uter Iter 12 Inner Iter 2: Max DH= -0.892E-05 Max Flow Residual= -0.401E-03
Starting iteration 13 of time step 1 in stress period 1
uter Iter 13 Inner Iter 1: Max DH= 0.306E-05 Max Flow Residual= -0.449E-03

-----
PMWIN Message
MODFLOW run is complete. See the following file for full run details:
D:\STUDY MATERIAL\MODELS\MPE\MALAPRABHA BASIN\OUTPUT.DAT

In case of difficulties:
1. Read the OUTPUT.DAT file.
2. Check the version, path and file name of the Modflow program.
3. Let PM check the model data for you.
4. Regenerate all input files and run Modflow again.
5. Make sure that the packages used in your model are also supported by
your modflow program. To find out which packages are included in
Modflow, consult your Modflow document.
6. Set a higher convergence criterion or increase the allowed iteration
numbers, if the solution convergence is not achieved.
-----
End of PMWIN Message
Press any key to continue . . .
  
```

Figure 4.8 Run Flow Simulation

- e) Extract and view results: In order to view the results, click on the TOOLS menu and select the RESULTS EXTRACTOR option. Click on READ button to extract the results of the simulation. We can save the results by using the SAVE button.

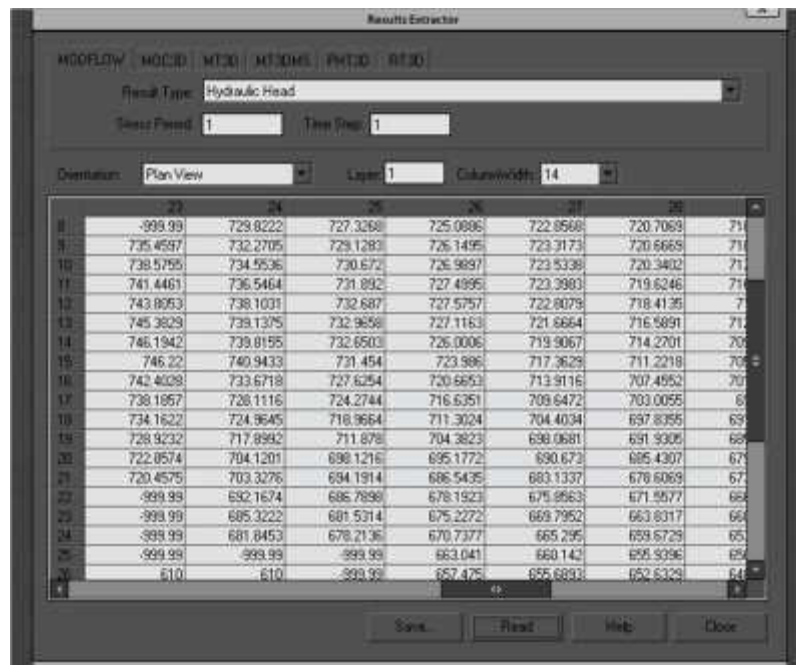


Figure 4.9 Result Extractor

- f) Produce output from the results: The results of the groundwater flow simulation can be represented in form of contours. To obtain the contours, go to the 2-D VISUALIZATION option in the TOOLS menu. Click on the ENVIRONMENT option in OPTIONS and go to the CONTOURS tab. Tick the “visible” option in the dialog box and click OK. The contours will be displayed on the screen.
- g) 3-D presentation: PMWIN allows us to present the model in three dimensional view with the help of another software package called SEER 3D. To open SEER 3D through PMWIN, go to the TOOLS menu and select 3-D VISUALIZATION. SEER 3D window will open.

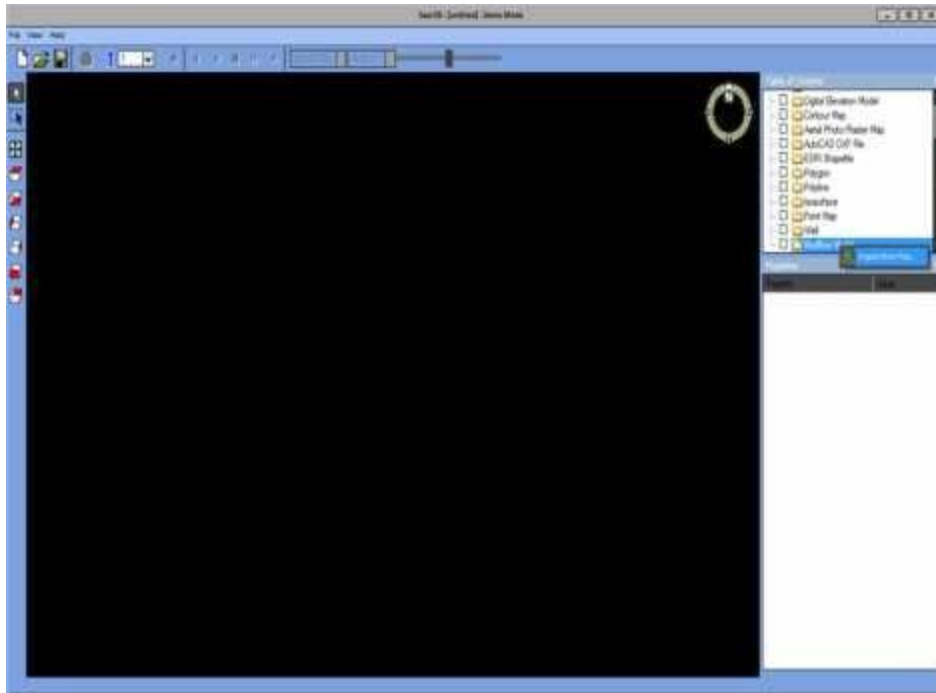


Figure 4.10 3D Visualization

On the right hand side of the window, we can see the TABLE OF CONTENTS. Go to the table and right click on the MODFLOW MODEL option to import our model into SEER 3D. Once the model is imported, right click on the HYDRAULIC HEAD CONTOURS and click on “create new object”. This will display the hydraulic head contours on the

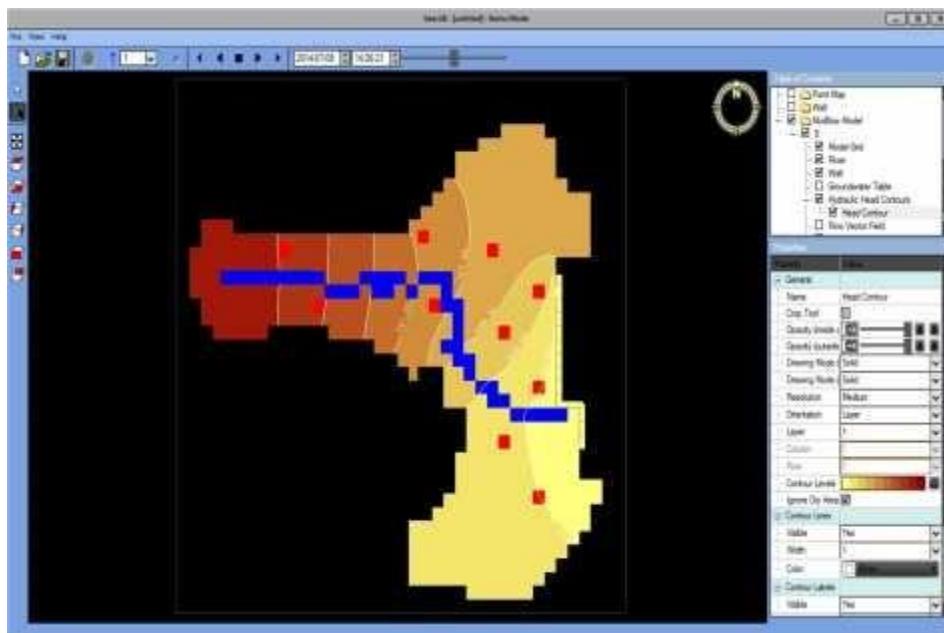


Figure 4.11 Hydraulic Head Contours

CHAPTER 5

ANALYSIS AND DISCUSSION

5.1 RAINFALL ANALYSIS

In order to analyse the spatial distribution of rainfall over the study area, the data for 22 years were considered. Monthly and annual average rainfall was computed for the basin. There are 7 rain gauge stations well spread over the catchment. Long term averages were calculated for each individual station. The highest rainfall exceeds 5000 mm in the western part of the catchment. This region is fully covered with the forest. The lowest rainfall is 1232 mm in the eastern part of the basin. The mean annual rainfall derived from these long term data for the shallow catchment is 2260 mm.

The monthly average rainfall and the coefficient of variation for all individual stations are shown in table 1. Out of the total rainfall, 90.46 % occurs during the monsoon season i.e., from June to September. July and August months are heavy rainfall months which contribute about 60.92 % of the total rainfall. The C.V. of the rainfall over the basin as a whole is 23.9 %, whereas the C.V. of the individual stations for their long term data varies from 82.7 % to 168.4%. This clearly indicates that the variations in rainfall over the basins is very much less than that of the point rainfall. Gauging records are available for the first gauging station on the river. Also a probability analysis of rainfall was carried out using the Gumbel and Pearson Type III to estimate the dependable rainfall. The analysis shows that the value of rainfall at 75 % dependability is 1983 mm by the method of plotting position, and 1650 mm by probability distribution. The value obtained by probability distribution is used to estimate the ground water recharge over the catchment

Table 5.1. Statistical Analysis of Rainfall

Station	Khanapur	Jamboti	S. Bastwad	K.Kumbi	Asoga	Gunji	Desur
Longitude	74 3	74 22	74 25	74 13	74 29	74 29	74 29
Latitude	15 38	15 04	15 46	15 42	15 36	15 32	15 44
Elevation	680	868	762	762	670	686	750
Jan	1.8	0	0.62	0	0	0	0
Feb	0.89	0	0.062	0	0	0.17	0
Mar	4.81	7.11	5.43	2.85	1.23	0	0.64
Apl	26.51	16.7	28.61	19.12	12.99	2.06	14.47
May	74.33	67.02	50.96	46.48	49.12	8.62	22.88
Jun	431.73	408.43	273.46	1237.31	371.96	264.59	245.5
Jul	672.24	836.83	400.01	1691.16	593.9	474.73	291.1
Aug	415.21	516.05	330.08	1511.4	379.43	424.73	291.1
Sep	131.75	149.64	139.43	352.22	115.79	138.11	149.9
Oct	91.82	77.62	84.46	187.45	53.81	70.94	100.1
Nov	44.01	28.10	15.01	34.93	11.97	7.75	23.72
Dec	3.10	4.72	1.5	0	1.62	0.38	0.24
Total	1898.34	2039.22	1330.15	5353.92	1591.33	1439.38	1232.2
CV	1.25	1.01	1.357	0.827	1.14	1.684	1.545

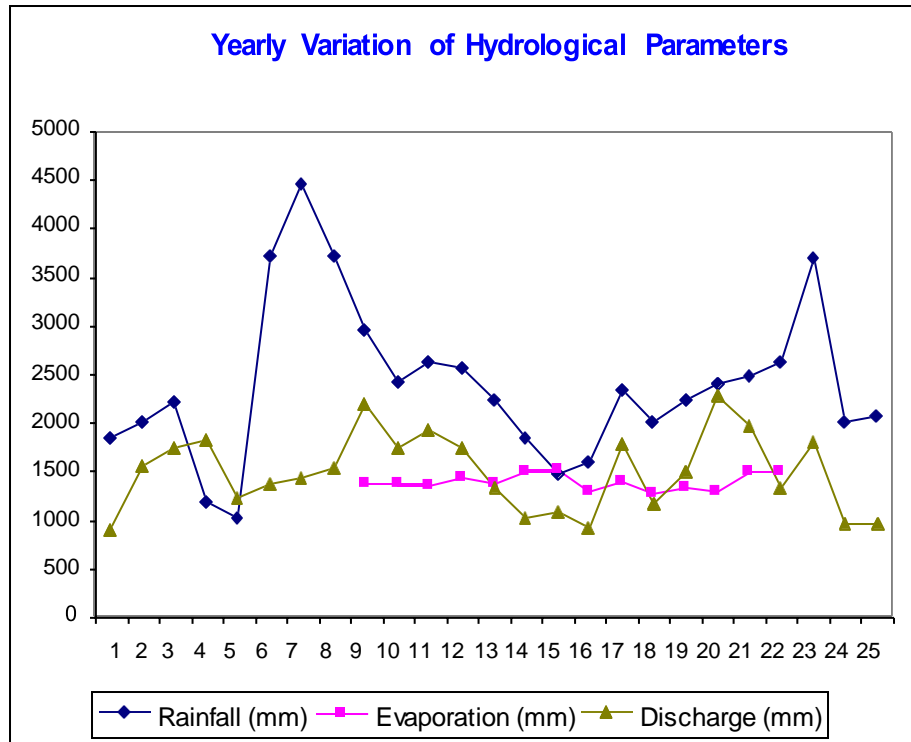


Figure 5.1 Yearly Variation of Hydraulic Parameters

5.2 INFILTRATION AND HYDRAULIC CONDUCTIVITY

Infiltration tests were carried out by using Disc Permeameter under different land use covers and the results are presented in table 5.2 .

The average rate of infiltration in the forest of Malaprabha representative basin varies between 3 cm/hr and 5 cm/hr. The rate of infiltration observed for scrubs varied from 2 cm/hr to 3 cm/hr. In the agriculture land, infiltration rate is minimum (1 cm/hr to 3 cm/hr). In the barren land, variation in infiltration is between 1 cm/hr and 3 cm/hr. In the case of Acacia plantation, the infiltration rate varied between 3 cm/hr to 5 cm/hr., which was same as that of forest land. However, in the case of Eucalyptus the rate of infiltration remained at 3 cm/hr, however, experiments were conducted only at a single plot which is not ideal for drawing definite conclusion. In the teak plantation the infiltration rate varied between 2 cm/hr. and 3 cm/hr which was relatively lower than other land types. In this case also, experiment is limited to a single plot.

The hydraulic conductivity depends mainly on soil properties and type of land covers. Various studies carried out in Malaprabha representative basin by Rawat et al (1992) Soni et al (1992) and Purandara et al (1995) also reported significant variation under different

land covers. From the present results it is evident that, the hydraulic conductivity also follows the same trend as that of infiltration indicating that the undisturbed forests show maximum conductivity value followed by Acacia plantation, eucalyptus, scrubs, teak and agriculture land respectively.

Table 5.2. Range of Hydraulic Properties under different land covers

Sl. No	Land use pattern	Type of soil	Soil texture	Range of Hyd. cond	Range of infiltration
1	Forest	Black and Grey	Light loam to heavy loam	3 - 4	3-5
2	Scrubs	Black, grey & Red	Medium to heavy loam	1-2	2-3
3	Agriculture	Black, Grey & Red	Medium to heavy loam	1- 2	1 - 3
4	Barren	- do-	Light loam to clay loam	2 -3	1- 3
5	Acacia plantation	Red and Black	Medium loam to heavy loam	4 - 5	3- 5
6	Eucalyptus	Red	Light loam	2	3
7	Teak	Grey	Medium loam	1- 2	2 - 3

5.3 SOIL MOISTURE ANALYSIS BASED ON LAND USE

Infiltration event is followed by redistribution of soil water within the soil profile. There is a continued downward redistribution of the infiltrated water, together with an evaporative loss from the soil surface, and extraction of water from the depth of soil which is exploited by the roots of transpiring vegetation. Therefore, the redistribution of soil moisture is a very complicated process and need a systematic study. Even in uniform, non-swelling soil the water movement process is complicated by severe non-linearity and hysteresis phenomenon.

In the present study, Soil moisture percentage in different land covers is estimated by gravimetric method. Monitoring of soil moisture is done once in two months and in most of the cases soil samples were collected only up to depth of 5 to 6 ft. The moisture content observed and corresponding rainfall pattern for available stations.

The results indicate that soil moisture variation is quite varied and depend upon various factors such as land use, soil type, type of plantation, rainfall intensity and duration. Further results indicate that there is no marked variation in soil moisture distribution if the region falls under the same agro-climatic conditions. Along the Gunji- Khanapur belt the moisture observation showed almost a similar trend irrespective of the land use and plantation. However, it is noted that the moisture content remains for longer duration under forest and plantation covers when compared to degraded lands. Similar observations were also made for Jamboti- Khanapur belt and Belgaum – Jamboti belt. It is also noted that along Belgaum – Jamboti belt the moisture distribution is higher than in other two zones. This is mainly because of the red loamy soil and comparatively higher thickness of the soil layer.

5.3.1 Gangavali Forest

Figure 5.2) shows the variation of moisture content with depth under forest cover. Steady increase of moisture was observed from June to October at 0.5m depth. In the deeper layers (1 m and 1.5m, the higher moisture was observed only during August, i.e during heavy rainfall period and decreased steadily. The observations on the bottom soil layer and below 1m depth there is no significant variation in moisture content. This could be due to the deeper roots present in the forests, which draws water from deeper layers without affecting the top layers.

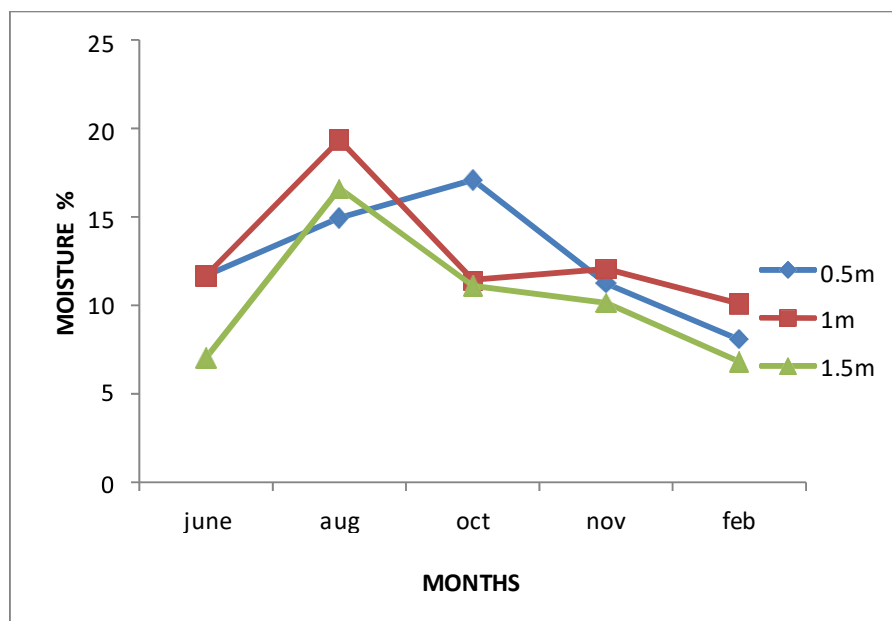


Figure 5.2 Distribution of Moisture with depth under forest cover at Gangavali

Figure 5.3 shows the variation of soil moisture at Kankumbi (forest) i.e. at the upper most part of the catchment at this location the distribution of soil moisture showed significant variation from the one which was observed at Gangavali. Very high moisture content was observed as compared to November months. The drastic change in moisture percentage is due to the higher rainfall (more than 5000 mm) occurring in and around Kankumbi. The relatively higher forest cover observed in this part of the study area may lead to increased interception and stemflow. This kind of dissipation of rainfall energy influences soil moisture redistribution after the process of infiltration. This also demonstrated the fact that the distribution of moisture content not only depends on the land use/land cover changes but also on the rainfall pattern and intensity.

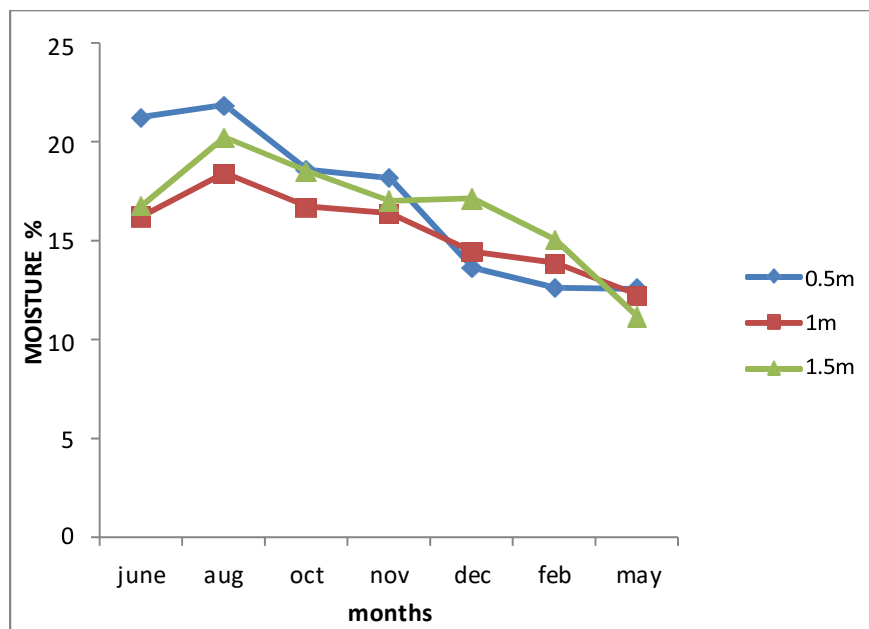


Figure 5.3 Distribution of soil moisture at Kankumbi (forest)

5.3.2 Degraded Forest:

Figure 5.4 and 5.5 shows the variation of moisture content with depth in degraded forest in Kankumbi (a high rainfall region) and a moderate rainfall area (between Jamboti and Khanapur). Degraded forests in Kankumbi in spite of having high rainfall (more than 5000mm) showed comparatively lower moisture content than in forest cover. Variation of moisture in a degraded land Jamboti and Khanapur also showed similar trend. This clearly indicated that, irrespective of the rainfall pattern, the moisture content varies considerably in the degraded forests, which could be attributed to higher runoff and lower recharge taking place in the scrubs.

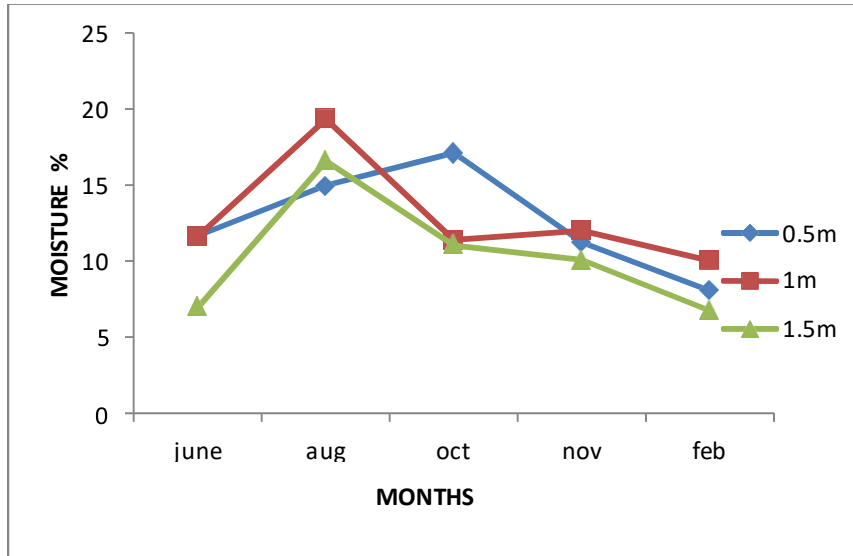


Figure 5.4 Distribution of moisture with depth under degraded forest(Kankumbi)

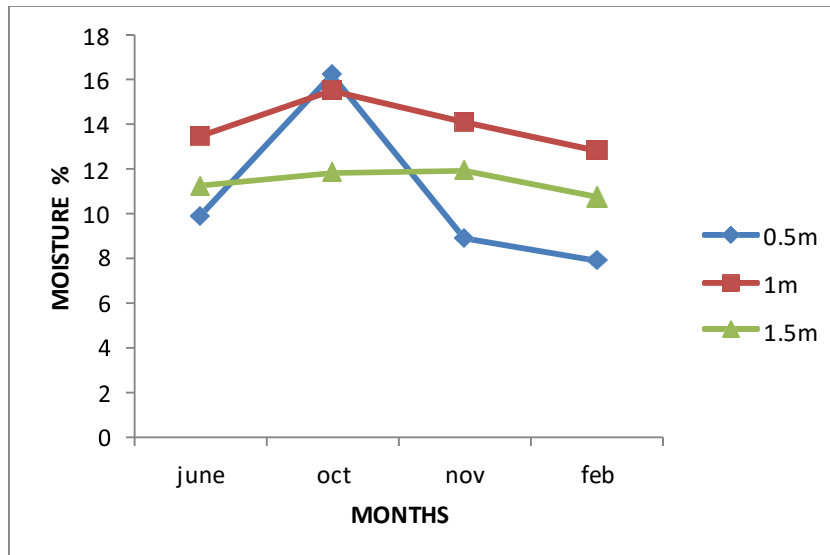


Figure 5.5 Distribution of moisture with depth under degraded forest(Kankumbi)

5.3.3 Barren land

In the case of barren land it is found that the average moisture content is much higher than the forest and scrubs. The maximum percentage varies from 20% to 35% at Kankumbi and 11 to 18% at Santibastwad. This could be attributed to change in rainfall pattern. Kankumbi receives very high rainfall whereas Santibastwad, receive less than 50% of Kankumbi. The higher moisture content observed in the barren land could be attributed to low rate of evapotranspiration. In addition, the type of soil and its physical and chemical characteristics play a significant role in deciding the moisture holding capacity. Figure 5.6 shows the distribution of moisture with depth in a barren land at Kankumbi.

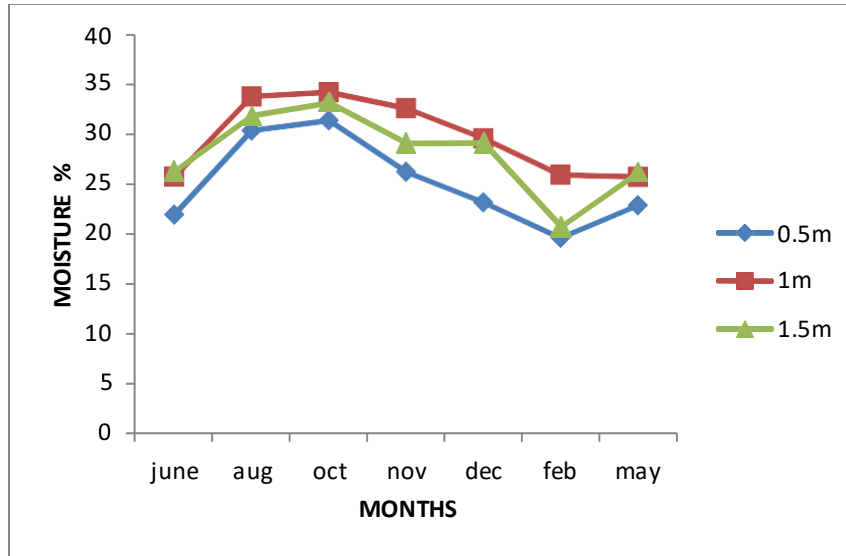


Figure 5.6 Distribution of Moisture with depth in a barren land(Kankumbi)

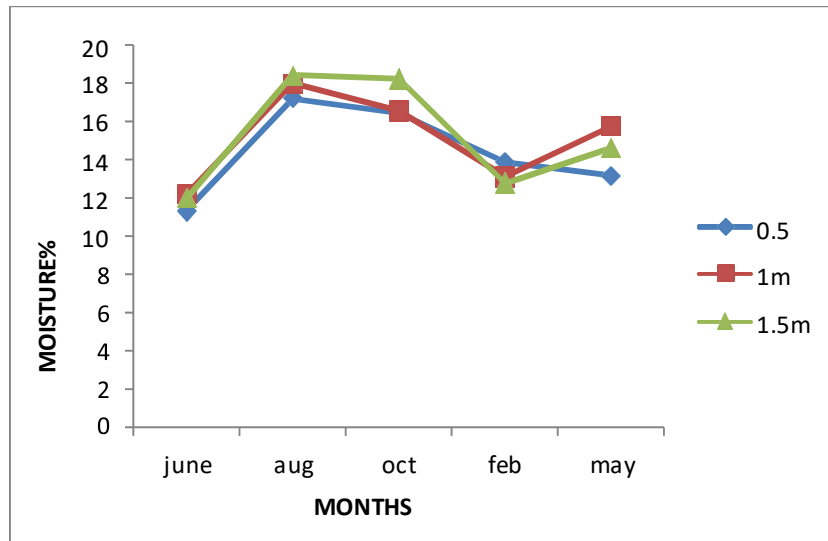


Figure 5.7 Distribution of Moisture with depth in a barren land(Jamboti)

5.3.4 Acacia plantations

Figure 5.8 shows the variation of moisture content with change in type of acacia plantation. It is noticed that the moisture content is significantly high in acacia plantation as compared to eucalyptus. This is true as reported by number of earlier researchers. In eucalyptus plantation, the maximum moisture content is less than 18% whereas in the acacia, it is more than 30%. This variation could be explained based on the horizontal growth of roots observed in acacia. Due to the spreading of surficial roots horizontally, acacia plantation does not draw much water from deeper layers. In the case of eucalyptus, it is noticed that the roots are deeper and draws much more water than acacia.

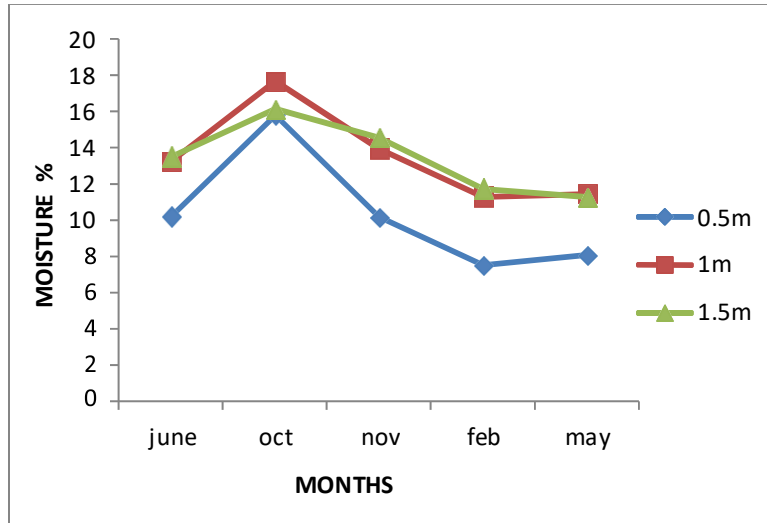


Figure 5.8 Soil moisture distribution in an Eucalyptus plantation

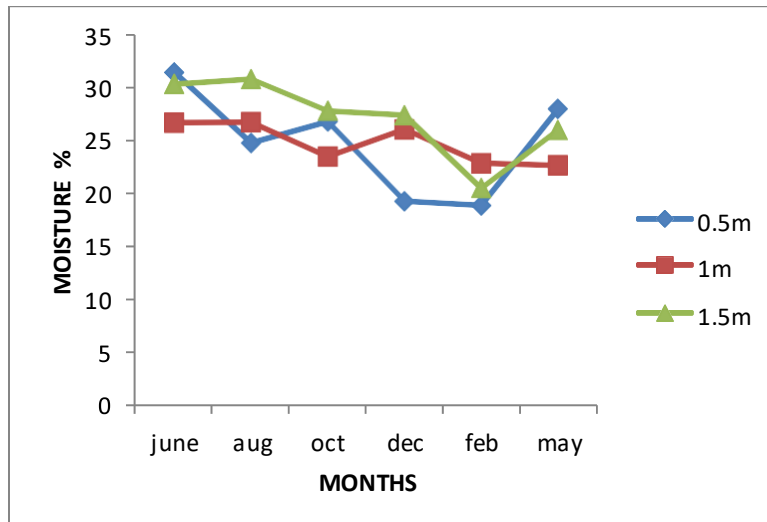


Figure 5.9 Soil moisture distribution in an Acacia auriculiformis plantation

5.3.5 Teak plantations

One of the interesting observation made in the present study is with regard to the distribution of moisture in teak plantation. Teak plantation showed minimum rate of infiltration as compared to other afforested areas. However, distribution of moisture under two different land covers showed a reasonably good match with that of forest. This could be attributed to the deep roots present in the teak which draws water from deeper layers without affecting the surface layers. Further, the leaf litter present in the teak plantation give rise to high organic matter which acts as sponge and slowly transmits water to soil layers. Apart from the said reason, wider leaves and comparatively higher interception,

moisture can be held for longer time. In order to conclude, it is essential to have a detailed analysis of soil moisture, ecology and hydrological processes. Figure 5.10 and 5.11 indicates the variation of moisture content in two teak plantations one at high rainfall region and another at relatively lower rainfall area.

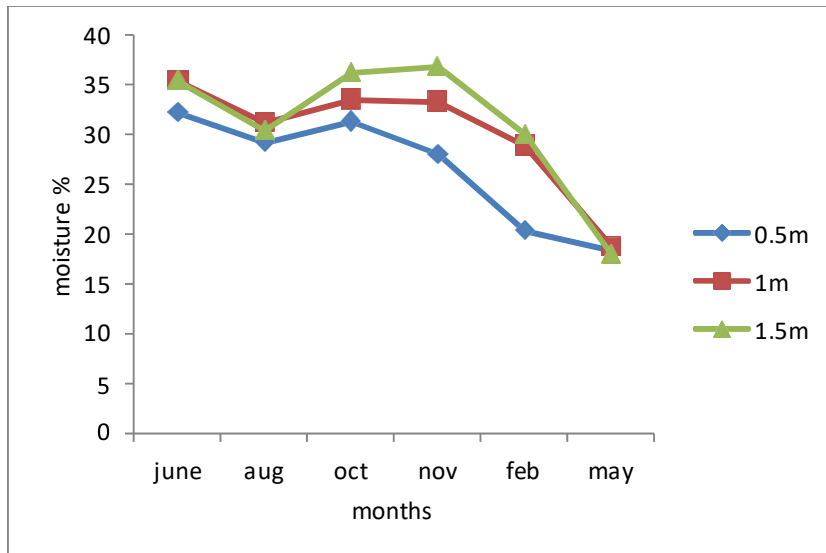


Figure 5.10 Soil moisture distribution in teak plantation at Jamboti

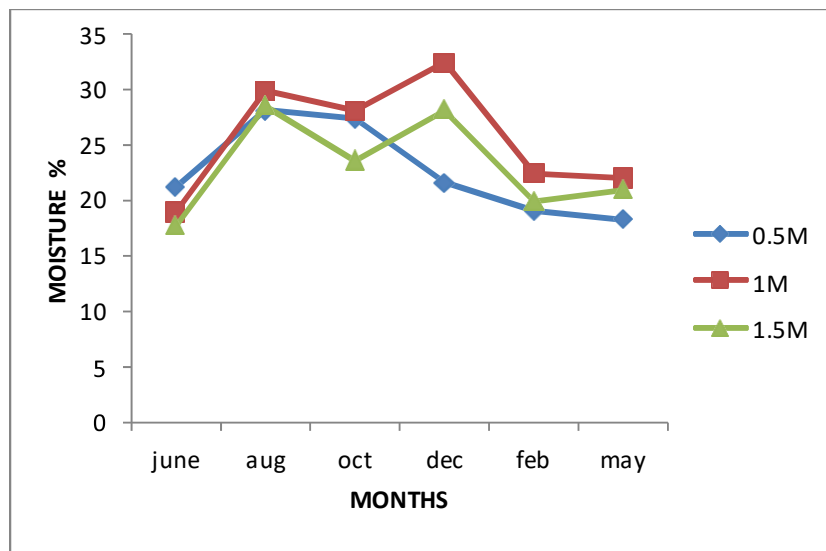


Figure 5.11 Soil moisture distribution in teak plantation at Khanapur

5.3.6 Agriculture Land

Figure 5.12 and 5.13 shows the variation of moisture content in two locations. In the agriculture land the role of moisture plays a significant role as it may help to grow more crops. Therefore, in agriculture land the conservation of moisture is the priority. The

observations made in two agriculture sites(5.12&5.13) shows two different kinds of scenario. In the first case moisture varies between 10 and 15% (except in the month of May) whereas in the second case, moisture varies from 20% to 25%. The variation in the moisture distribution could be attributed to the following reasons.

1. Impact of agriculture activity on soil hydraulic properties
2. Type of crops plays a significant role in moisture redistribution
3. Rainfall intensity, erosivity and type of activity.

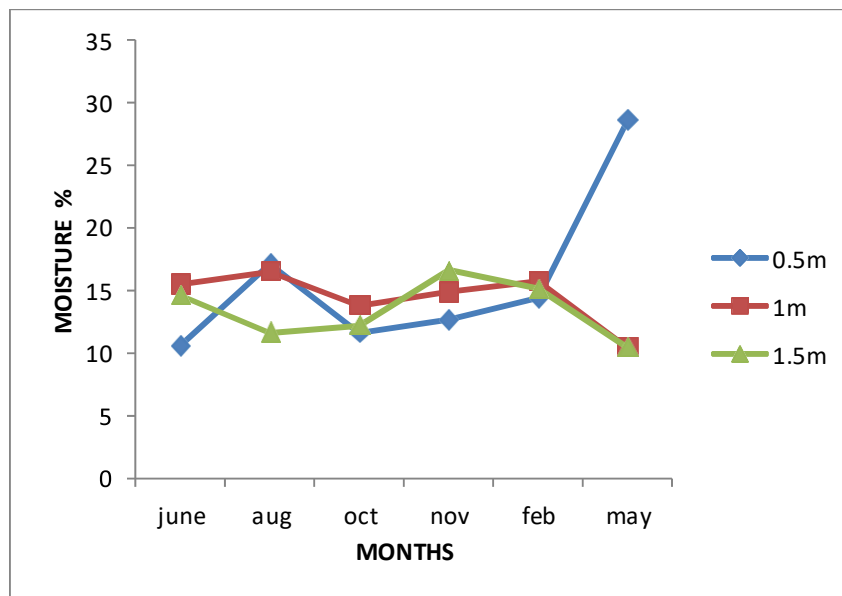


Figure 5.12 Soil moisture distribution in Agricultural land

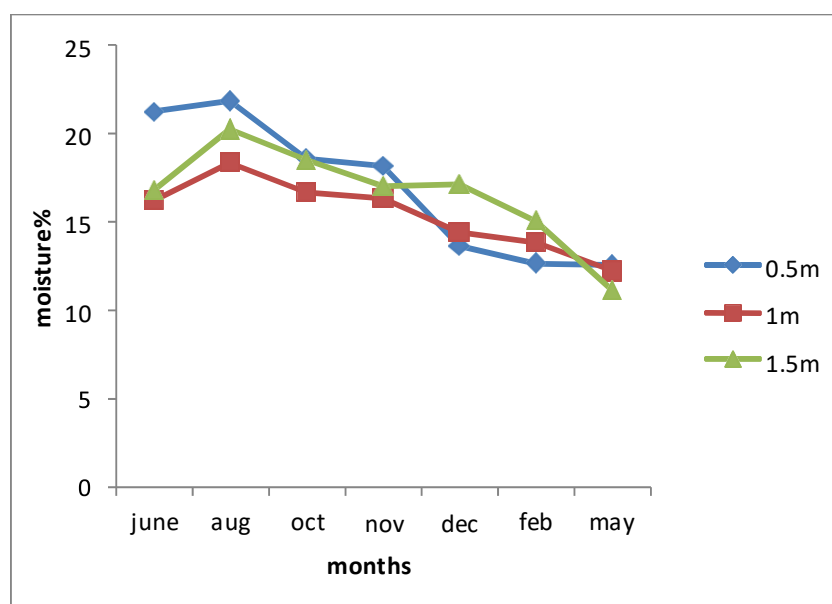


Figure 5.13 Soil moisture distribution in Agricultural land

5.4 MOISTURE RETENTION CHARACTERISTICS

Table 5.3 Shows the moisture retention characteristics of soils in Malaprabha representative basin under different land covers.

Land use/Land covers	Pressure in bars							
	0.33	1	3	5	7	10	12	15
	Variation of Moisture content with pressure							
Degraded	0.28	0.24	0.22	0.19	0.15	0.13	0.12	0.09
Degraded	0.21	0.18	0.14	0.13	0.12	0.1	0.09	0.07
Agriculture	0.48	0.44	0.42	0.39	0.37	0.35	0.33	0.32
Agriculture	0.25	0.24	0.23	0.21	0.2	0.18	0.17	0.16
Forest	0.3	0.21	0.19	0.17	0.14	0.12	0.11	0.07
Forest	0.34	0.32	0.3	0.27	0.24	0.22	0.19	0.17
Grassland	0.25	0.24	0.23	0.21	0.2	0.18	0.17	0.16
Grassland	0.28	0.26	0.22	0.21	0.19	0.15	0.13	0.1
Teak	0.2	0.16	0.15	0.13	0.13	0.12	0.1	0.07
Teak	0.26	0.24	0.22	0.21	0.18	0.15	0.12	0.1

From the above results it is understood that for a given land, the parameters show significant variations for each of the soil samples (taken at different times); implying temporal variability in soil water retention characteristics. The higher water content at saturation and lower residual water content of these soils suggest that soils are wholly underdeveloped and contain some coarse fragments (i.e. higher % sand).

5.4.1 Gangavali Forest:

The slope of the curve (figure 5.14) is sharp indicating greater mixing of soil due to changes brought by human interference. In the case of natural disturbed forest (figure 5.15), there is a drastic reduction in the moisture content which could be due to the constant disturbance by human and live stock population.

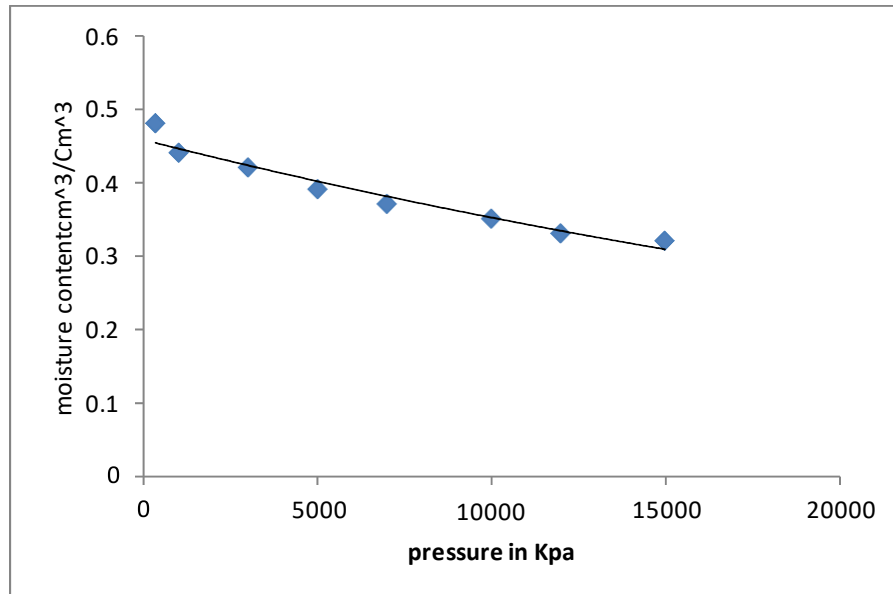


Figure 5.14 Relation between Pressure & Soil Moisture (Old Growth forest)

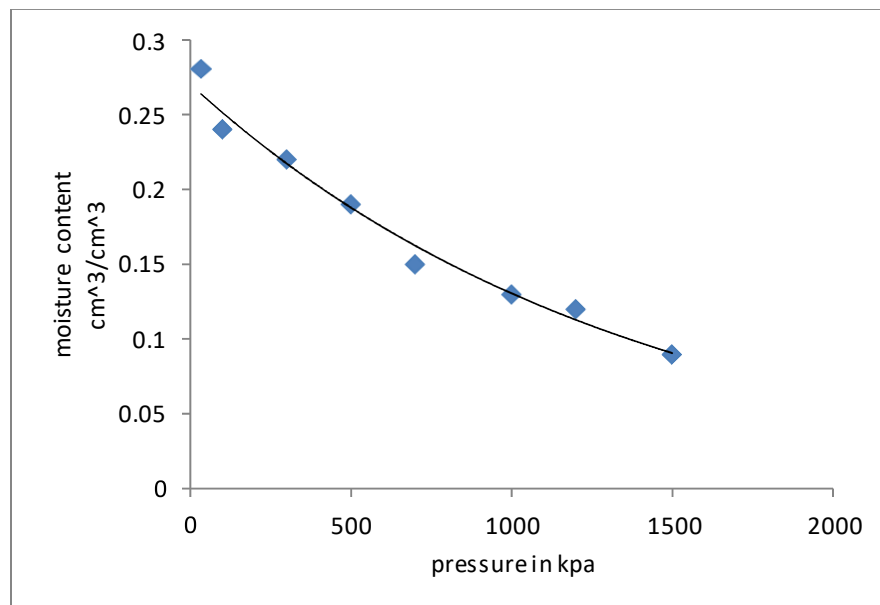


Figure 5.15 Relation between Pressure & Soil Moisture (natural disturbed forest)

5.4.2 Acacia Plantation:

Slope in this case gradual and the moisture content vary between 18% and 7% . However, higher moisture content was noticed at Santibastwad which indicates that the soils in Jamboti (figure 5.16) are more stressed than in Santibastwad (figure 5.17).

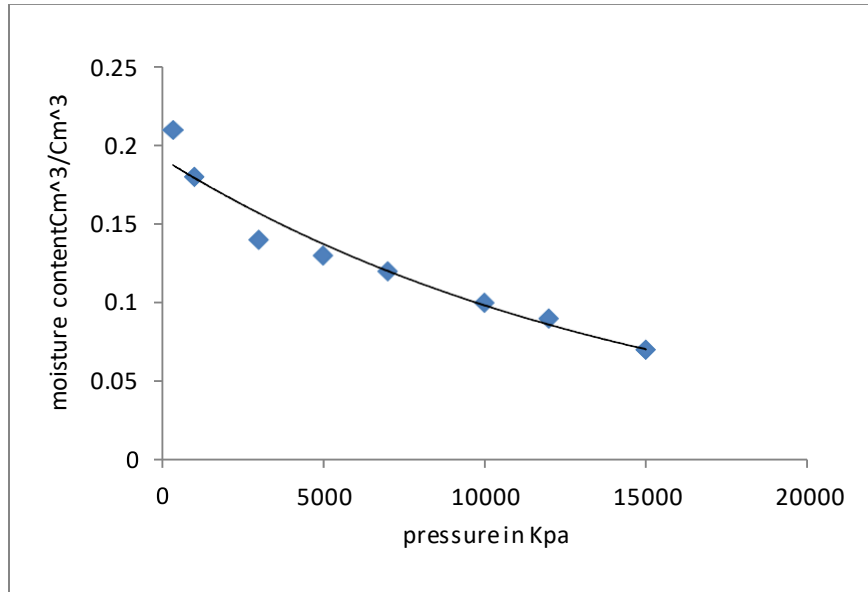


Figure 5.16 Relation between Pressure & Soil Moisture (Jamoboti)

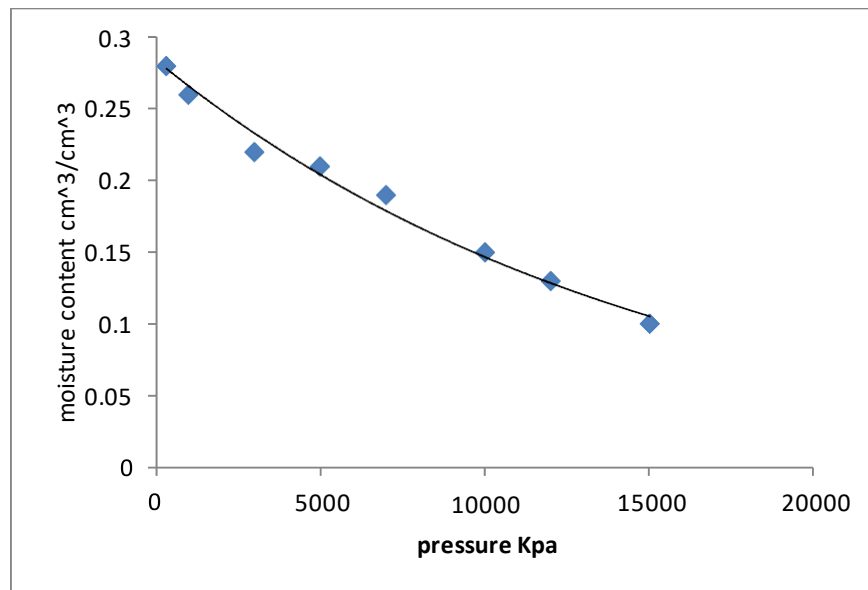


Figure 5.17 Relation between Pressure & Soil Moisture (Santibastwad)

5.4.3 Eucalyptus Plantation:

Slope of the curve is smooth and gradual (figure 5.19). It is noticed that field capacity and wilting point are comparatively higher in the eucalyptus plantation.

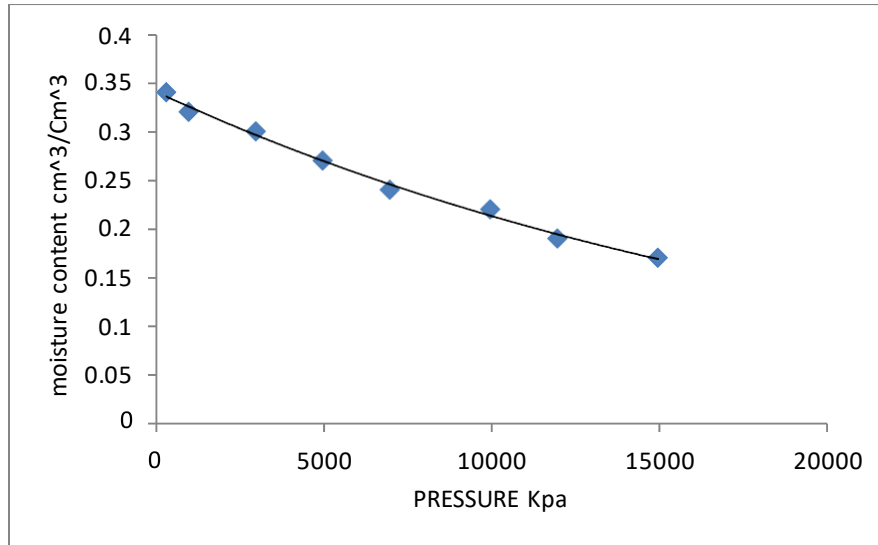


Figure 5.18 Relation between Pressure & Soil Moisture

5.4.4 Teak Plantation:

Soils shows higher retention capacity in-spite of coarser grain size (figure 5.19). This could be attributed to higher organic matter content present in the soils of Teak plantation.

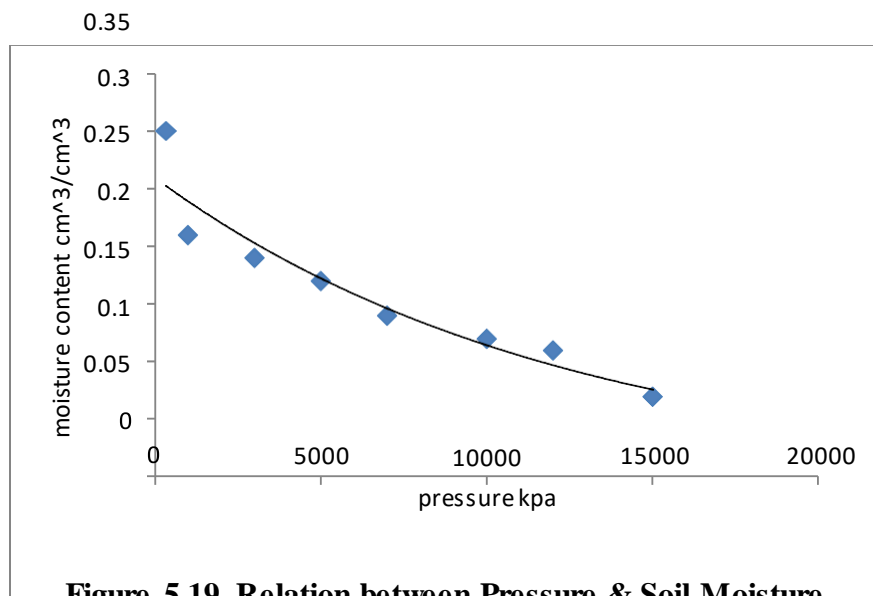


Figure 5.19 Relation between Pressure & Soil Moisture

5.4.5 Degraded land:

Slope is quite sharp (figure 5.20). Moisture content is very high indicating higher field capacity and wilting point. This is due to the mixed clay nature of the soil.

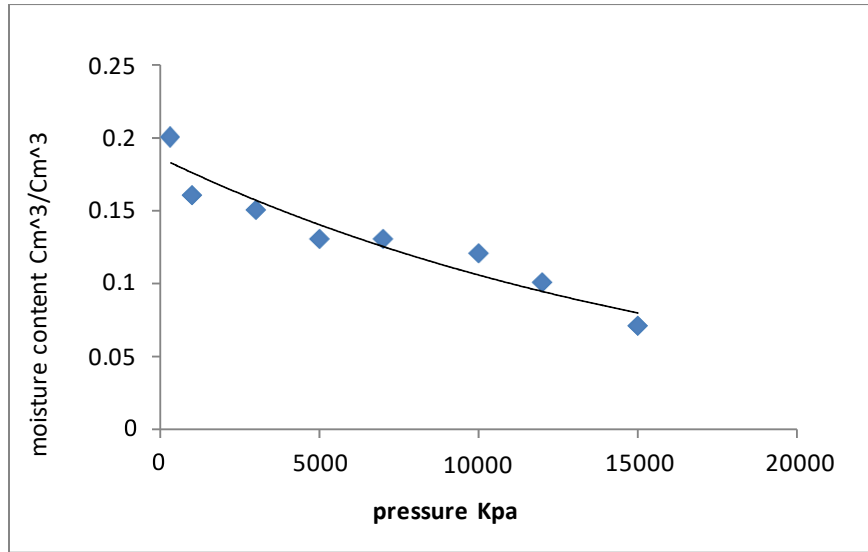


Figure 5.20 Relation between Pressure & Soil Moisture

5.4.6 Agricultural land:

In the agriculture land, it is found that the moisture holding capacity of the soil is much lower than the degraded land. In spite of finer size of the particles, moisture is less which is attributed to the continuous disturbances due to agriculture activity (figure 5.21).

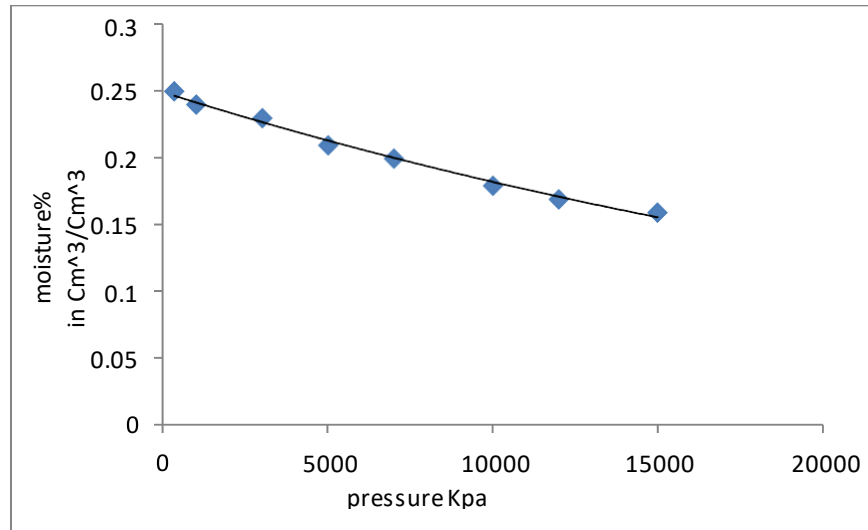


Figure 5.21 Relation between Pressure & Soil Moisture

5.4.7 Barren land:

The slope of the curve is gradual (figure 5.22). There is wide variation between field capacity and wilting point. The curve clearly indicates the influence of human activity in the area. Figure 5.23 shows the retention characteristics of the soil in a red soil where the texture of the soil was uniform.

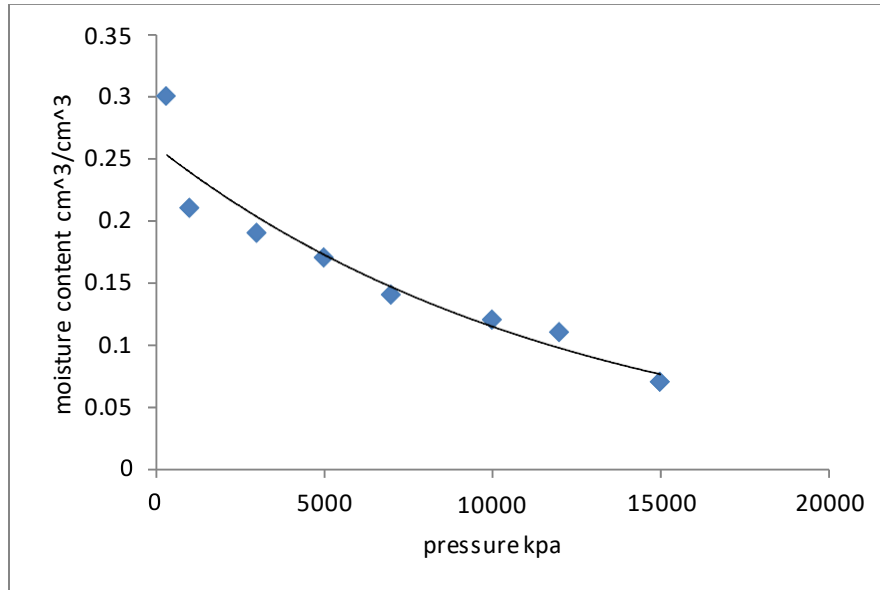


Figure 5.22 Relation between Pressure & Soil Moisture

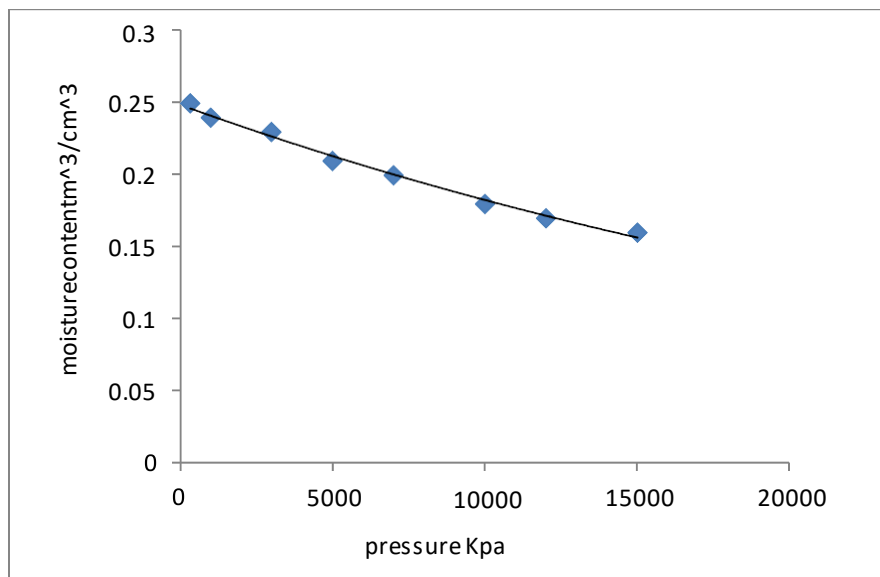


Figure 5.23 Relation between Pressure & Soil Moisture

Maeda et al. (2006) have reported similar observations for the soils of Satoyama catchment in Toyota, Japan. However, it is quite difficult relate the soil moisture retention characteristics with land use/land cover changes because there are no significant changes in the parameter values across the land cover types. This suggests that soil water retention characteristics are not significantly influenced by land cover. To support this inference, differences in water retention and the water contents at 33 kPa to 1500 kPa pressures between natural forest, acacia plantation and degraded watersheds were statistically tested using the Mann-Whitney U test. The average total available water content is higher in

forested watershed at 0.5 m and 1.0 m compared to other two land cover. However, the difference is quite high in the forested watershed.

5.5 ESTIMATION OF UNSATURATED HYDRAULIC CONDUCTIVITY USING DISC PERMEAMETER

5.5.1 Forest

Experiments conducted in forested watersheds by using disc permeameter for varying heads (0, 10, 20, 30 and 40 mm) shows that there is a gradual decline in hydraulic conductivity with matric potential. The R^2 value between the two parameters is 0.957. Similar relationship (R^2 more than 0.9) is obtained between infiltration and sorptivity. It is also noticed that hydraulic conductivity is directly proportional to infiltration and sorptivity. Figure (5.24 to 5.27) shows the relationship between head and hydraulic conductivity, infiltration and sorptivity.

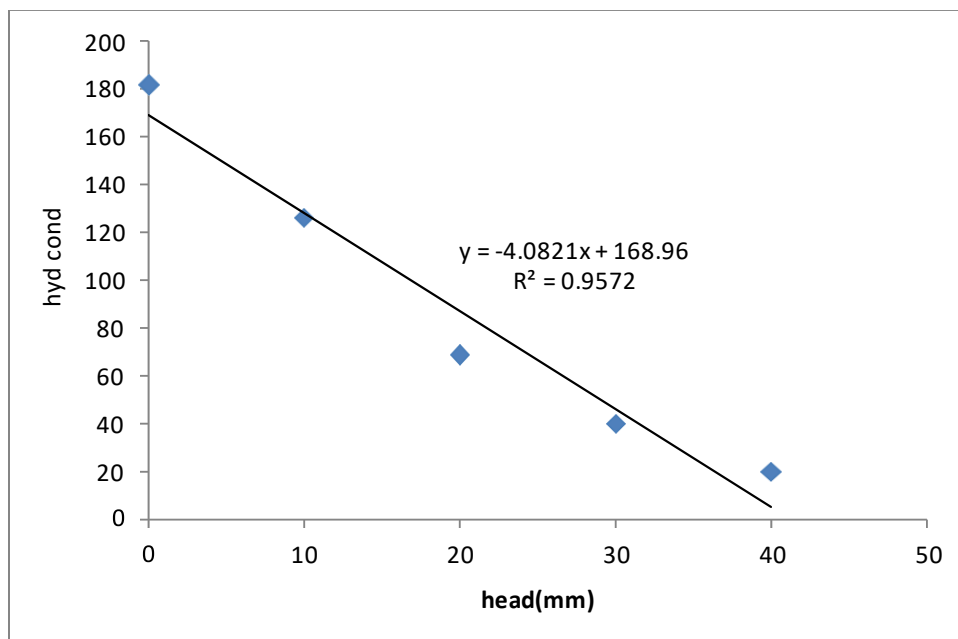


Figure 5.24 Variation of hydraulic conductivity with head (mm)

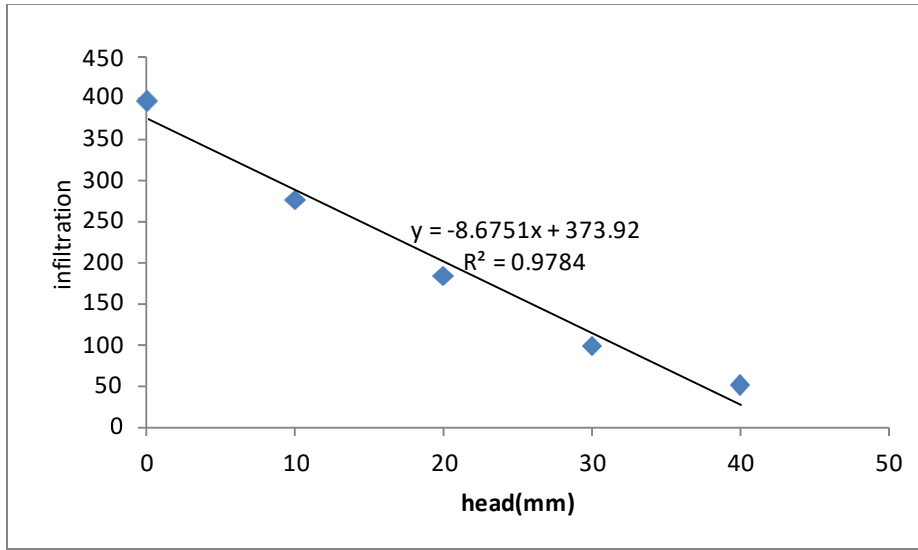


Figure 5.25 Variation of infiltration with head (mm)

Figure 5.26 shows the variation of rate of infiltration with hydraulic conductivity. It is found that infiltration is directly proportional to hydraulic conductivity ($R^2 = 0.99$). Figure 5.27 shows the variation of sorptivity with head. In the case of sorptivity wider variation is noticed indicating the anthropogenic disturbances in the study area.

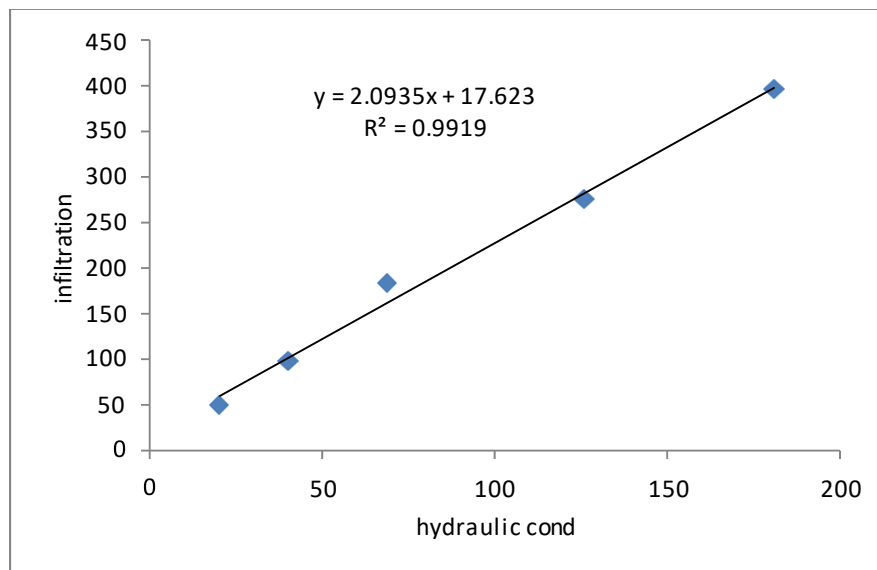


Figure 5.26 Variation of rate of infiltration with hydraulic conductivity

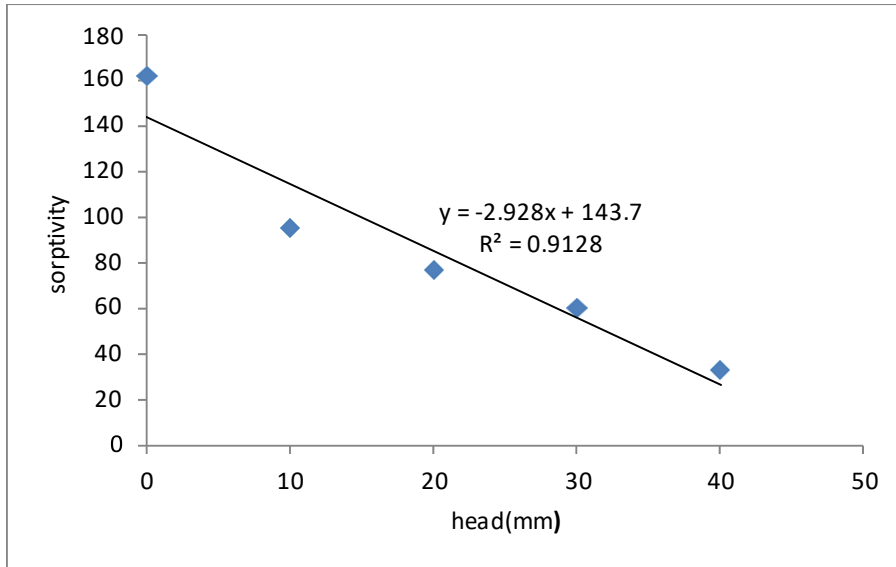


Figure 5.27 Variation of Head with Sorptivity

Figure 5.28 indicates the relationship between sorptivity and hydraulic conductivity ($R^2 = 0.945$).

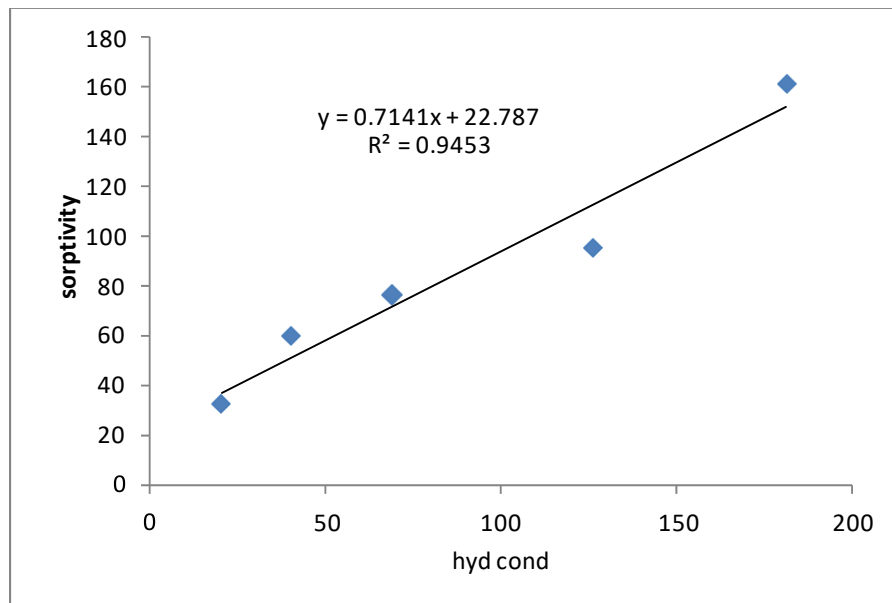


Figure 5.28 Variation of Sorptivity with Hydraulic conductivity (mm)

5.5.2 Agricultural Land:

In the agriculture land, it is observed that, though there is a positive correlation between hydraulic conductivity with head, the R^2 shows a lesser value which could be attributed to the variation occurring in hydraulic properties due to management activities such as ploughing, seeding, land erosion and other activities. It is also noticed that drastic change

in the relationship between infiltration and head difference ($R^2 = 0.768$). This clearly indicates the impact of agriculture activity on the infiltration and groundwater recharge. Figure 5.29 to 5.33 shows the variation of various soil hydraulic parameters with head.

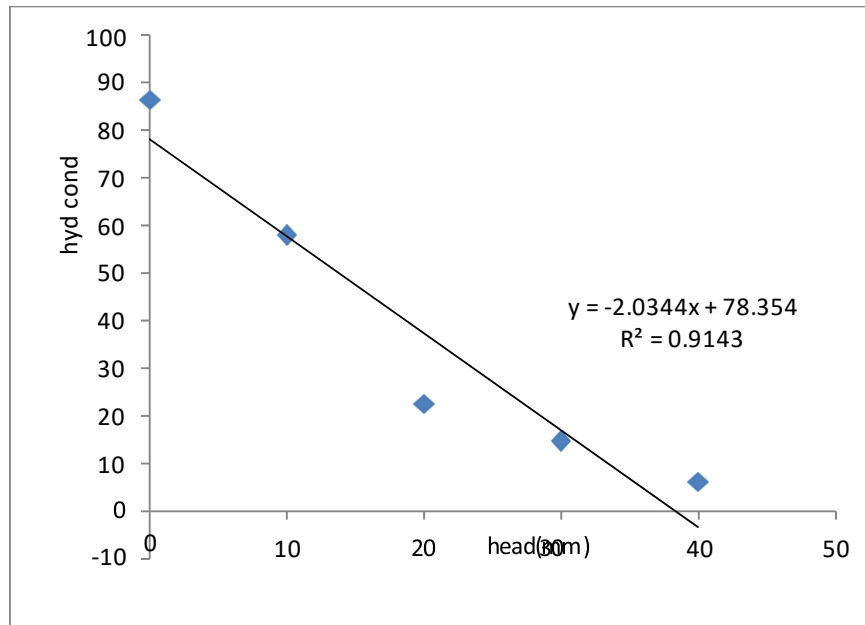


Figure 5.29 Variation of Hydraulic conductivity with Head

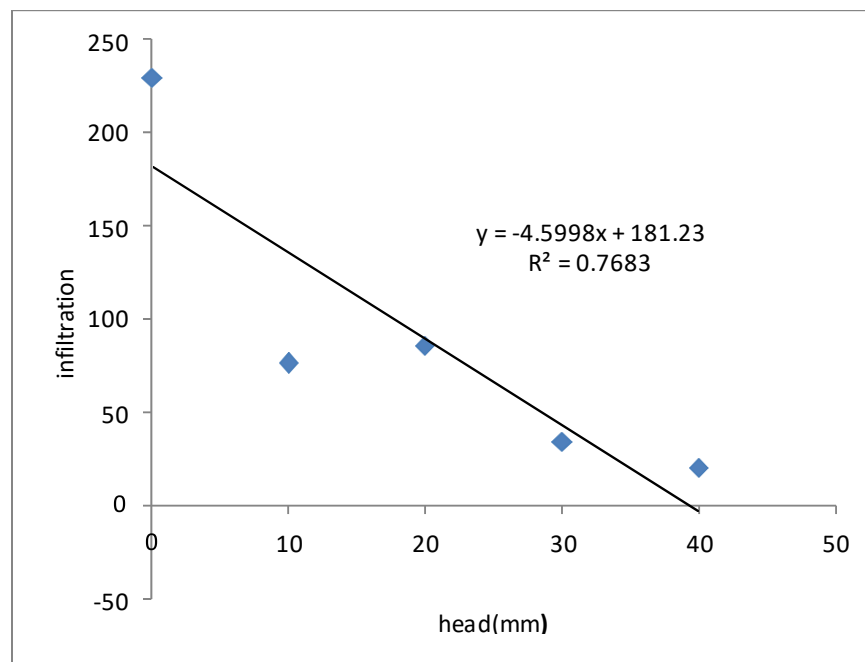


Figure 5.30 Variation of Infiltration with Head (mm)

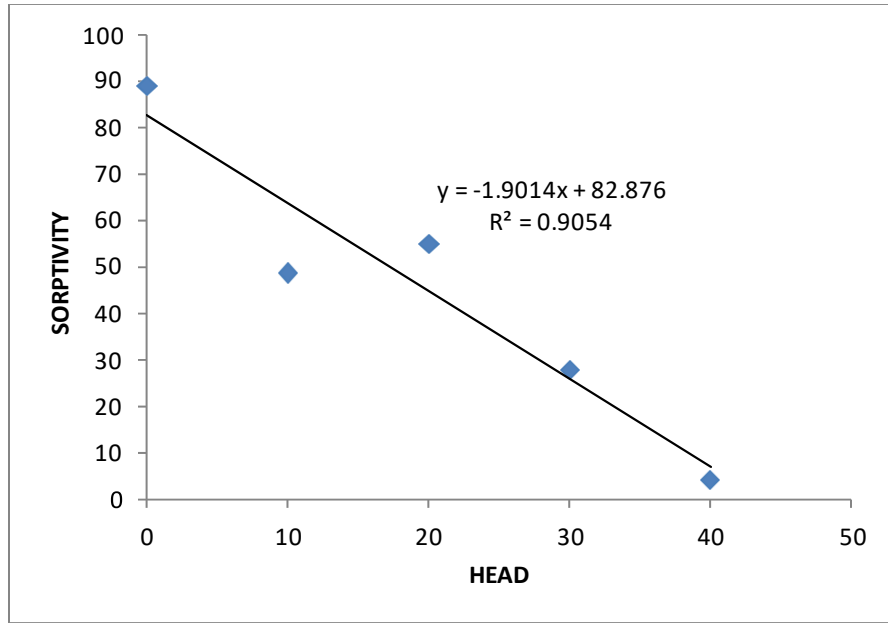


Figure 5.31 Variation of Sorptivity with Head

From the figure (5.29) it is noticed that hydraulic conductivity shows moderately high to high correlation with infiltration and sorptivity.

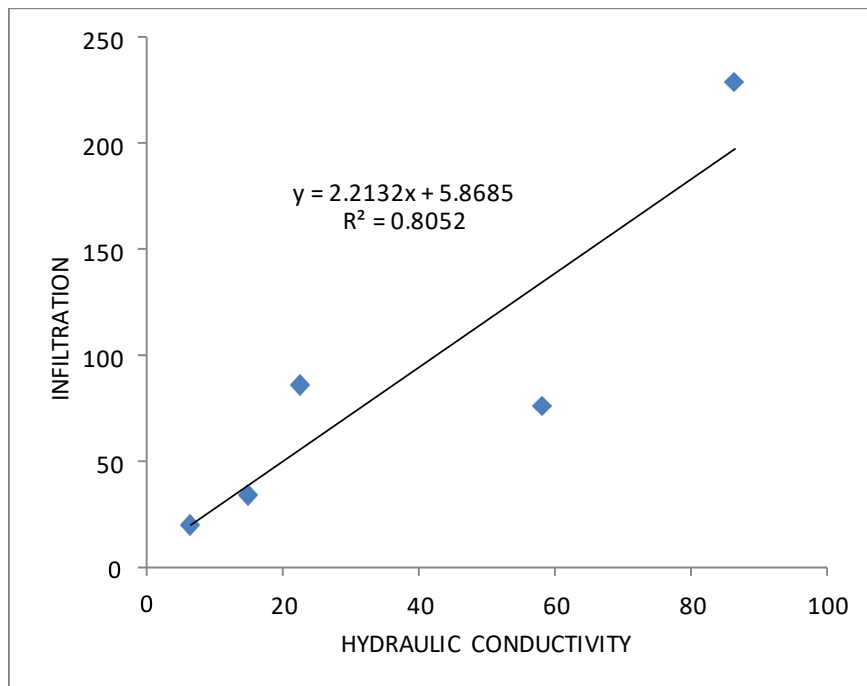


Figure 5.32 Variation of hydraulic conductivity with infiltration

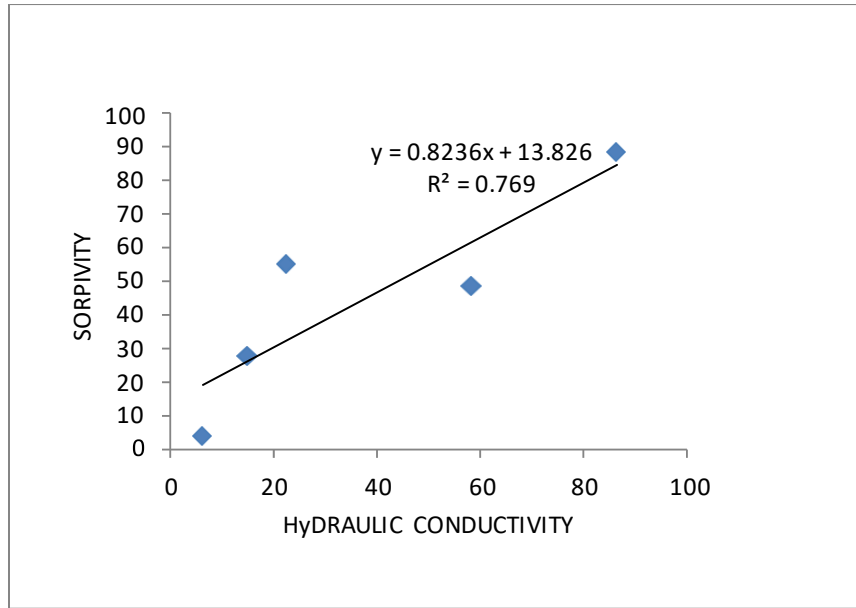


Figure 5.33 Variation of Hydraulic conductivity with Sorptivity

5.5.3 Degraded Land:

In the case of degraded lands, maximum hydraulic conductivity was 35 mm/ hr and gradually decreases with head. Minimum hydraulic conductivity was 3mm/hr. The relationship between the two parameters is highly correlated and the with R^2 value 0.861. The relationship between infiltration rate and head showed higher R^2 value than with the hydraulic conductivity. This could be due to lesser interference in the top soil characteristics. Figure(5.34) shows the variation of hydraulic conductivity with head.

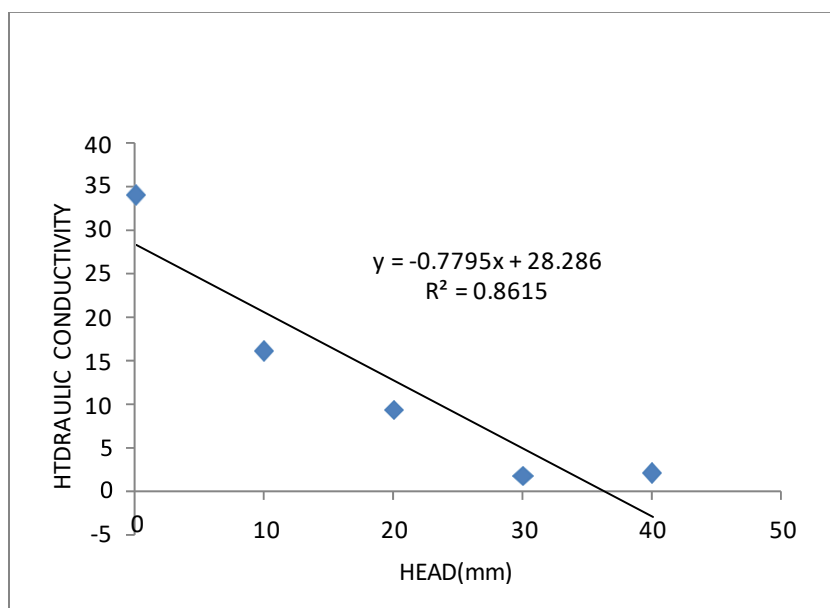


Figure 5.34 Variation of Head with Hydraulic conductivity

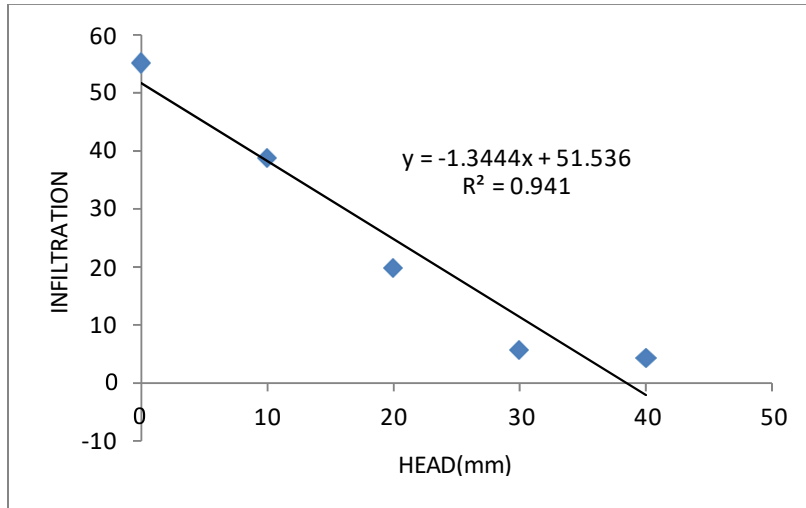


Figure 5.35 Variation of Infiltration with Head(mm)

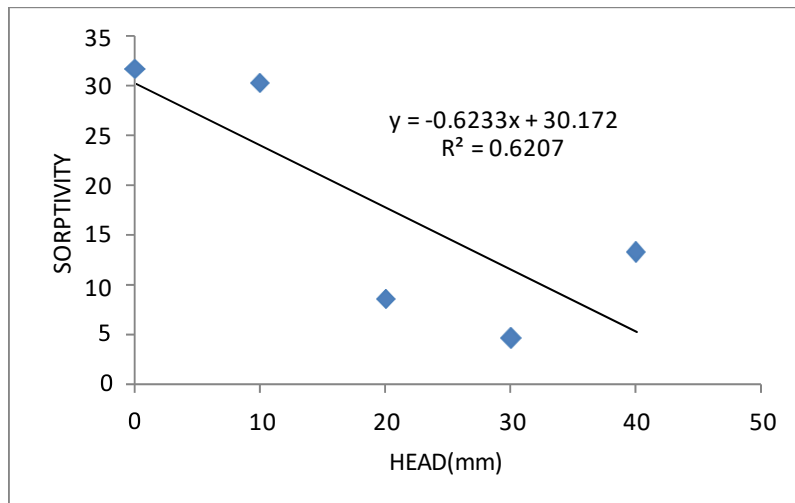


Figure 5.36 Variation of Sorptivity with head(mm)

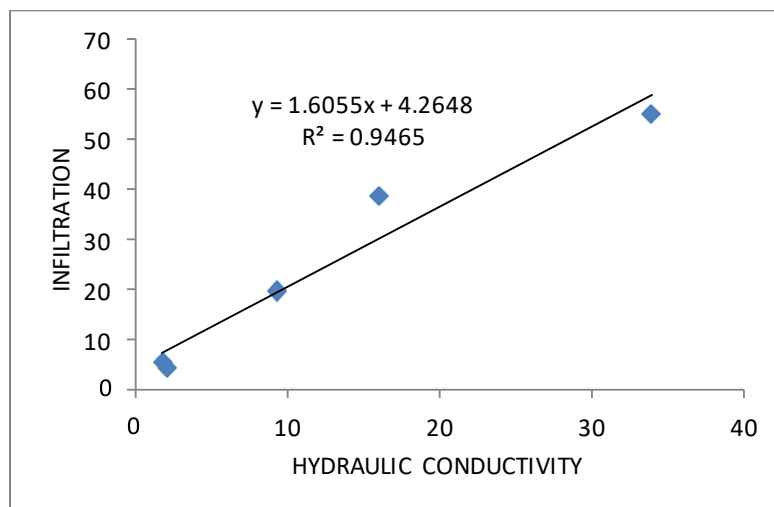


Figure 5.37 Variation of Infiltration with Hydraulic conductivity

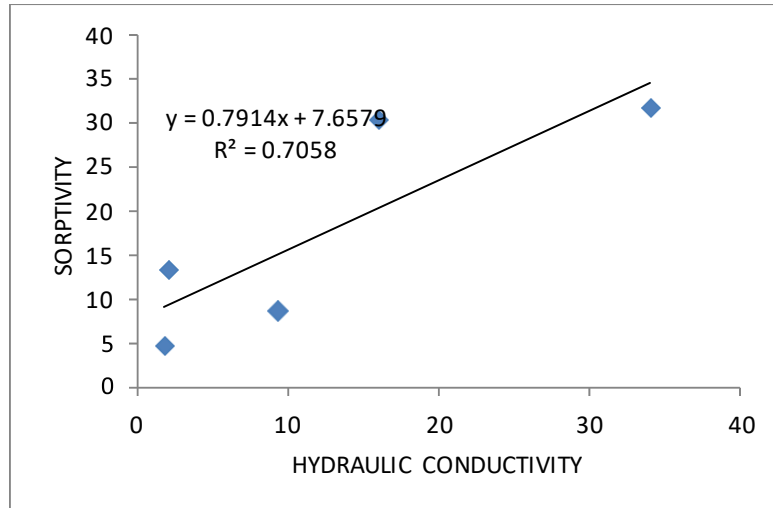


Figure 5.38 Variation of Sorptivity with Hydraulic conductivity

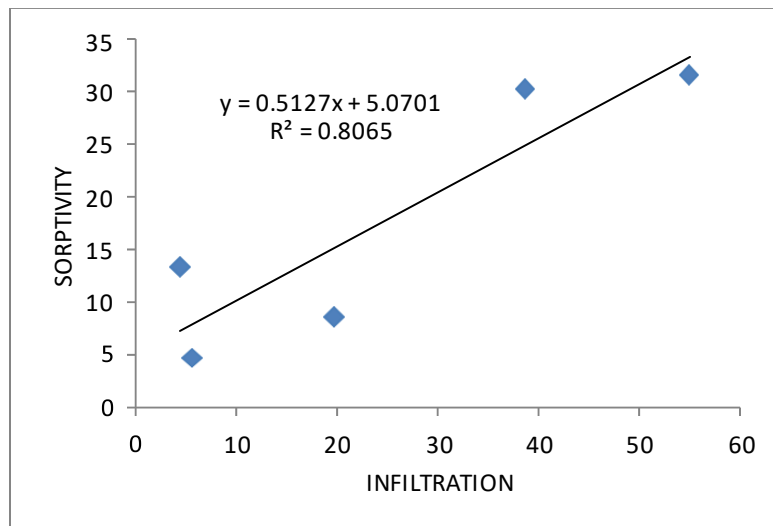


Figure 5.39 Variation of Sorptivity with Infiltration

5.5.4 Grassland:

In the grassland hydraulic conductivity shows a good correlation with head ($R^2 = 0.961$). However, it is noticed that the maximum hydraulic conductivity is 5.2 mm/hr and the minimum is 1 mm/hr. Figure (5.39) shows the variation of hydraulic conductivity with head. Figure (5.38) shows the relationship between infiltration and head. The maximum infiltration rate was observed is 8.8 mm/hr and minimum was 2.5 mm/hr. Very high correlation is exhibited between infiltration and head. In the case of sorptivity, the correlation ($R^2 = 0.505$) is only moderate. This could be due to the soil physical and chemical characteristics.

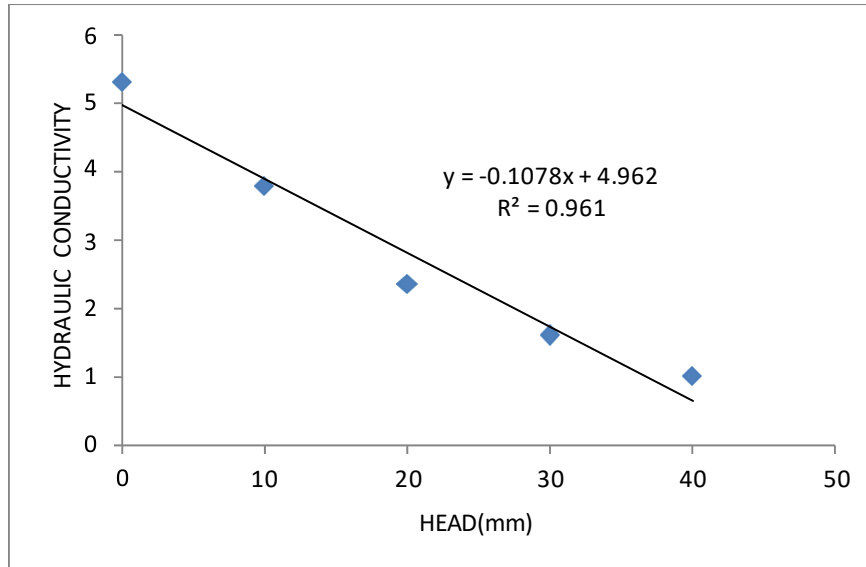


Figure 5.40 Variation of Hydraulic conductivity with Head(mm)

Figure 5.41 shows the relationship between infiltration and head. The maximum infiltration rate was observed is 8.8 mm/hr and minimum was 2.5 mm/hr. Very high correlation is exhibited between infiltration and head. In the case of sorptivity, the correlation ($R^2 = 0.505$) is only moderate. This could be due to the soil physical and chemical characteristics.

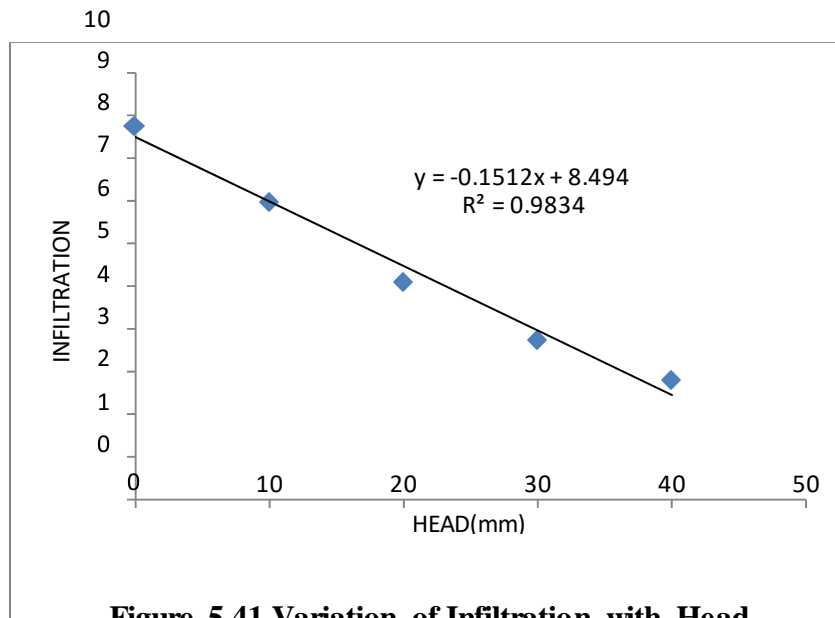


Figure 5.41 Variation of Infiltration with Head

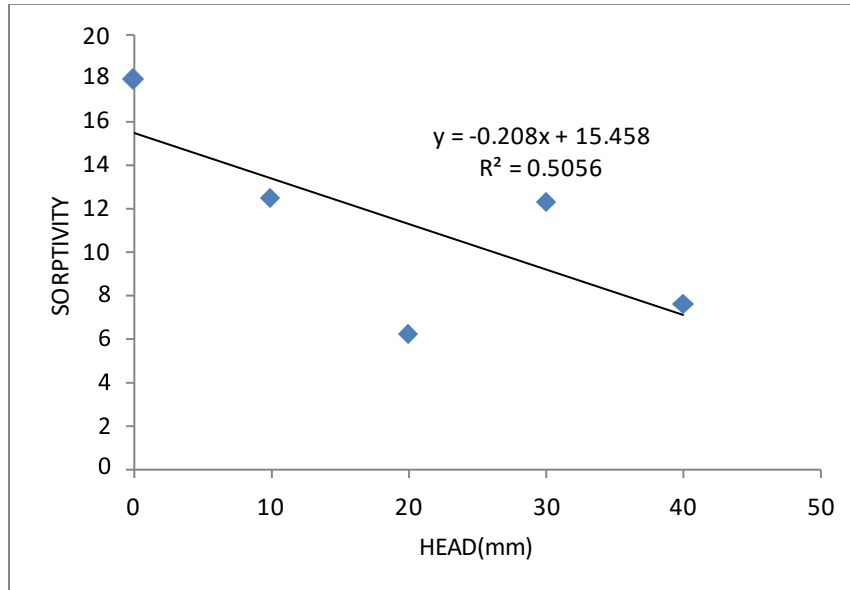


Figure 5.42 Variation of Sorptivity with head(mm)

Figures (5.39) it is evident that hydraulic properties such as infiltration, hydraulic conductivity and sorptivity are mutually related. However, the change in land use/ land cover changes may result in lower correlation. The relationship between hydraulic conductivity and infiltration rate shows a very high correlation (0.995) and between sorptivity and hydraulic conductivity it is moderately correlated ($R^2 = 0.625$). Sorptivity and infiltration rate also showed lower correlation which could be attributed to the soil disturbance and Physical-chemical characteristics of the soil.

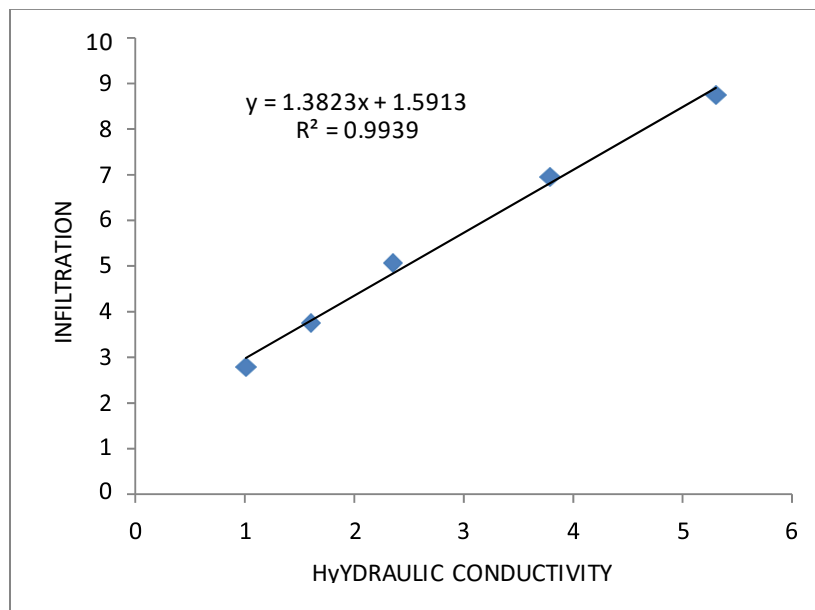


Figure 5.43 Variation of Infiltration with Hydraulic conductivity

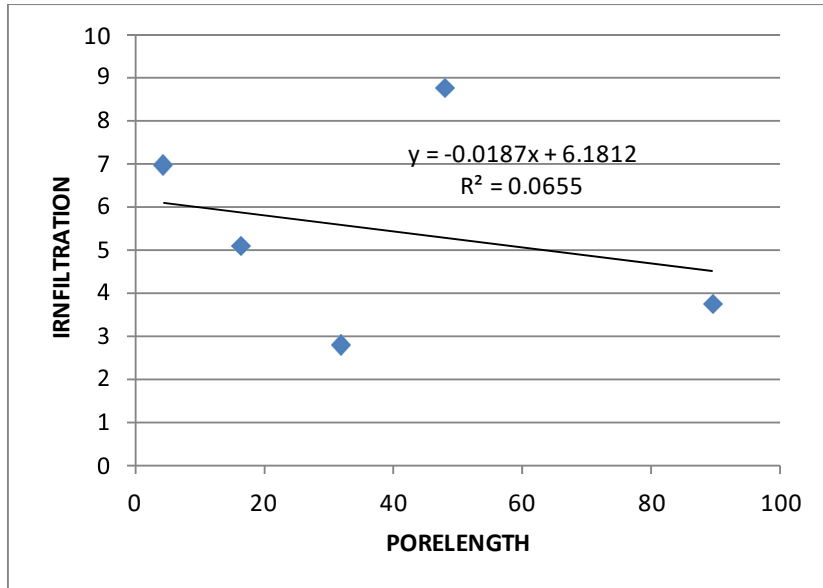


Figure 5.44 Variation of Infiltration with porelength

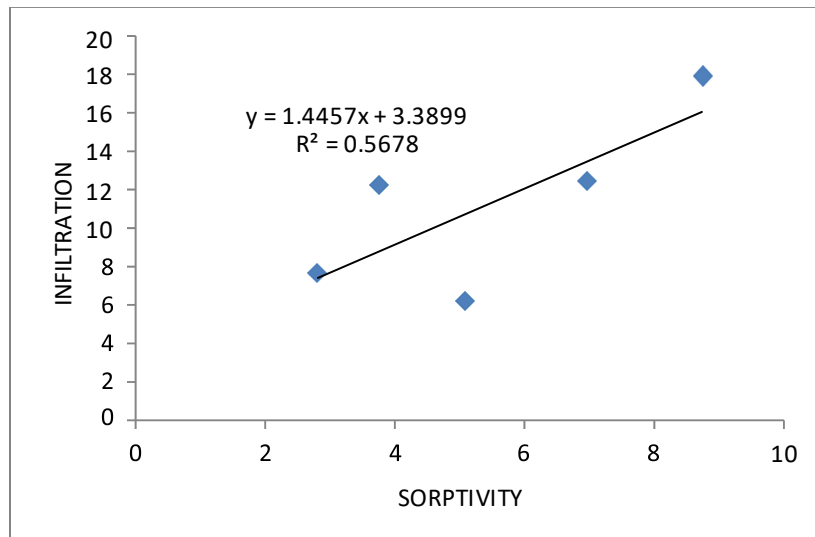


Figure 5.45 Variation of Infiltration with Sorptivity

5.5.5 Acacia Plantations

Figure (5.46) shows the variation of hydraulic conductivity with head in acacia plantation. The maximum hydraulic conductivity observed is 50 mm/hr and minimum is 5 mm/hr. The R^2 value observed between the two parameters is 0.974. This could be attributed to the larger number of pores present in the soil take part in the transmission of water.

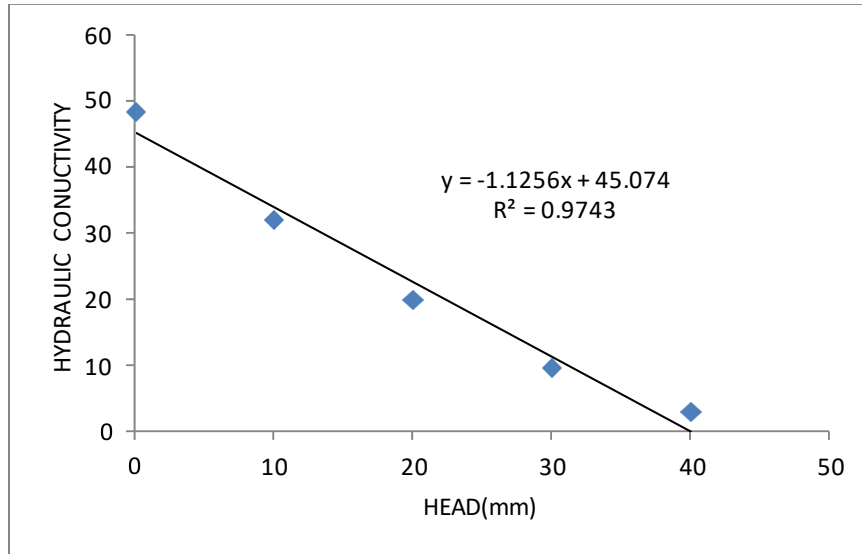


Figure 5.46 Variation of Hydraulic conductivity with head

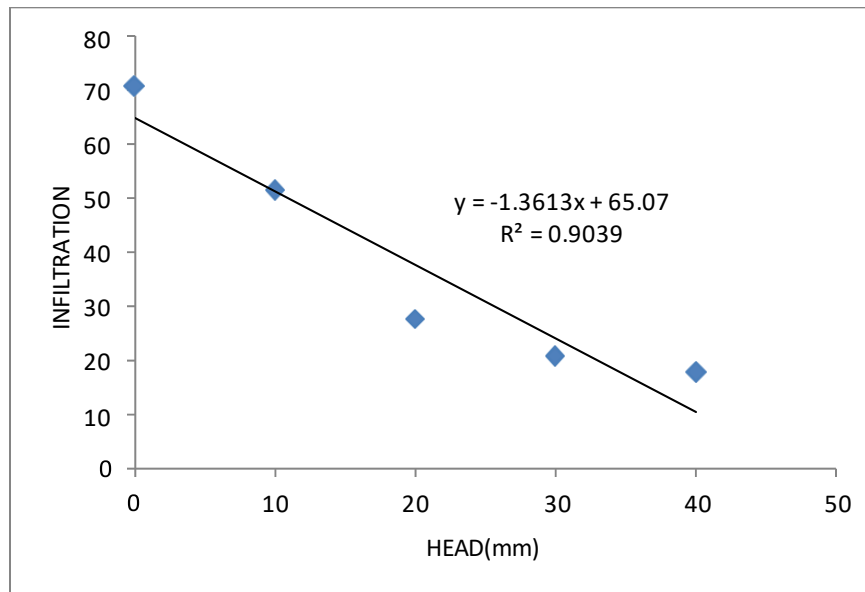


Figure 5.47 Variation of infiltration with Head

Figure 5.47 indicate the linear relationship between infiltration and head. Infiltration rate shows relatively lower R^2 value in comparison hydraulic conductivity. This can be explained based on the anthropogenic disturbance taking place in the upper layer of the soil. Sorptivity and head shows relatively lower correlation ($R^2 = 0.807$). In the present case, it is attributed to soil disturbance and textural variation of soil particles.

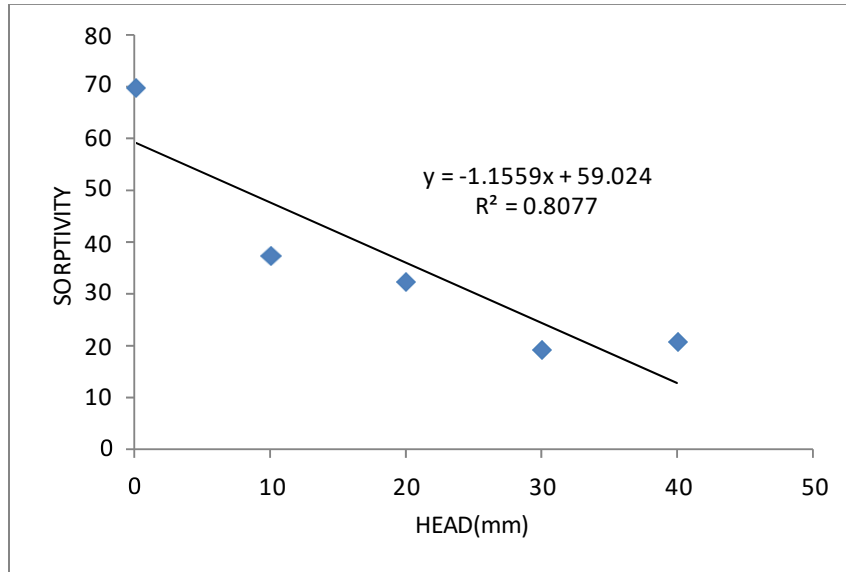


Figure 5.48 Variation of Sorptivity with Head

Plots show variation of hydraulic conductivity with infiltration. The correlation between the parameter is very high ($R^2 = 0.966$). This indicates that the hydraulic conductivity is directly proportional to infiltration. Similar kind of relationship is observed with sorptivity(both infiltration and hydraulic conductivity).

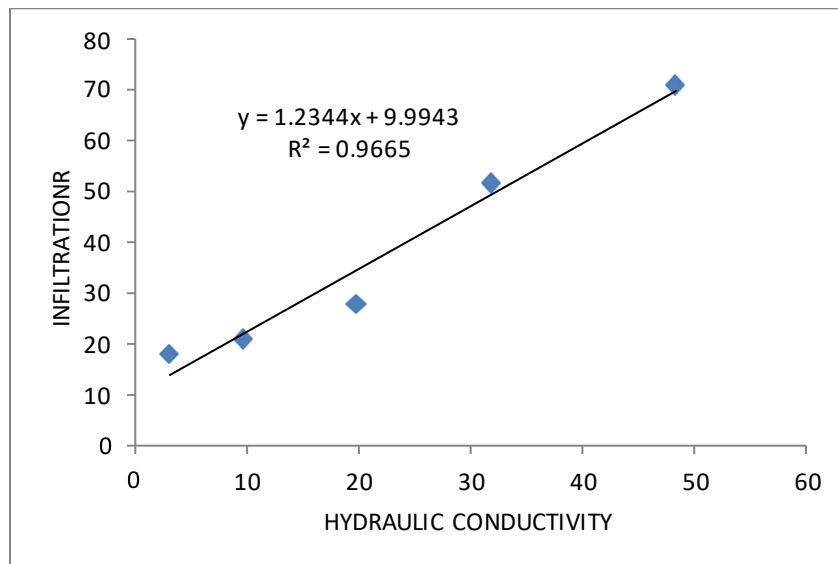


Figure 5.49 Variation of Hydraulic conductivity with Infiltration rate

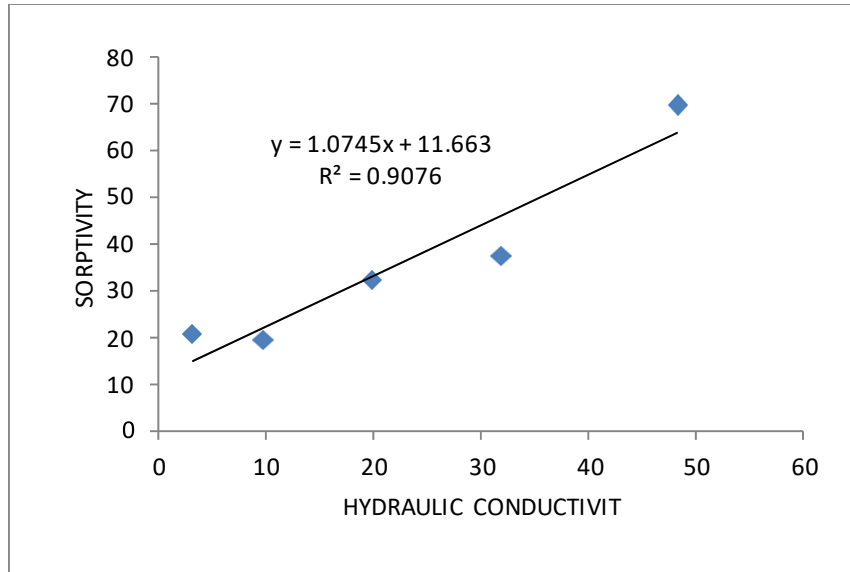


Figure 5.50 Variation of Hydraulic conductivity with Sorptivity

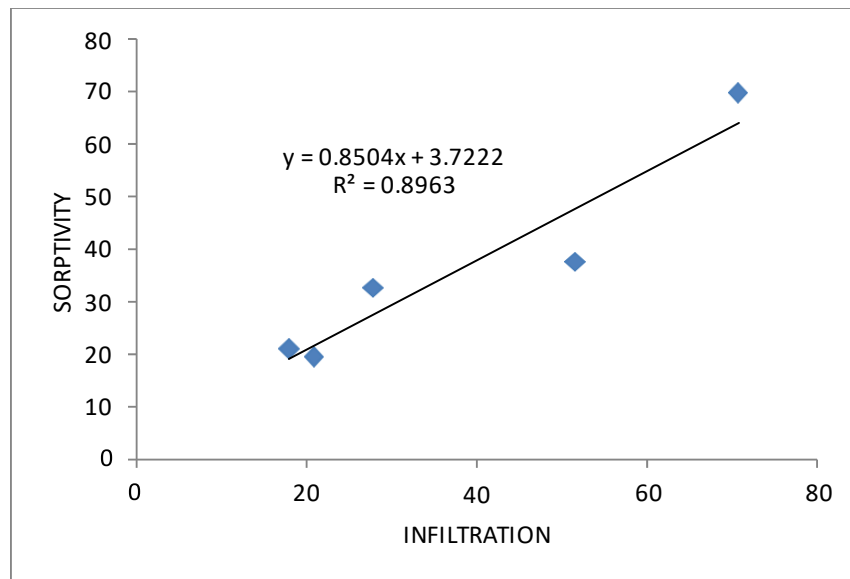


Figure 5.51 Variation of Infiltration rate with Sorptivity

In the acacia plantation, unlike in other land covers, the relationship between pore length and pore diameter is quite high ($R^2 = 0.939$). This is attributed to the improvement in the soil structure and texture due to the growth of acacia plants.

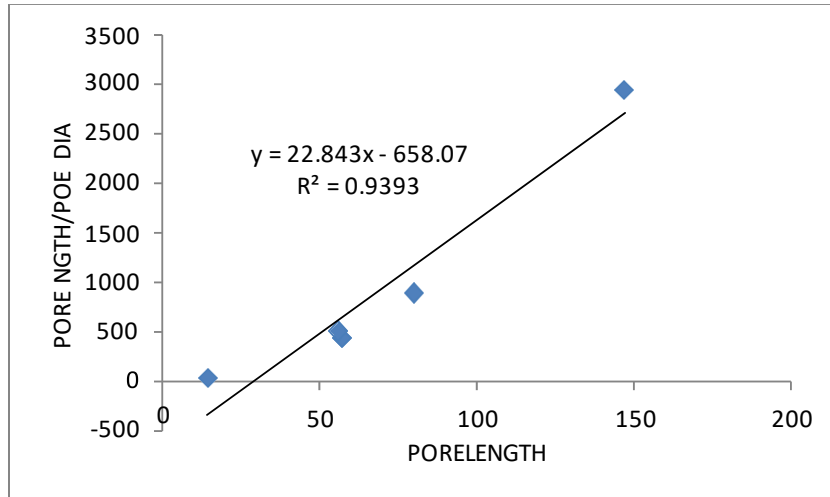


Figure 5.52 Variation of Pore length with pore diameter

5. 5.6 Teak Plantations

Analysis of the hydraulic properties under teak plantation shows significant variation from that observed in the other land use/land covers. Maximum hydraulic conductivity observed is 15 mm/hr and minimum is 1.5 mm/hr at 30 mm head. Soil remained impermeable above 30 mm head. Figure 5.53 indicates the relation between hydraulic conductivity and head ($R^2 = 0.699$). This could be due to the low hydraulic conductivity and higher runoff characteristics of the region. In the case of infiltration rate versus head (figure 5.54) very high correlation which could be related to the grain size characteristics of the soil due to which comparatively higher infiltration rate is reported. Sorptivity also showed a moderately high correlation with head (figure 5.55). However, this could be due to soil thickness and structure which significantly influence the sorptivity of the media.

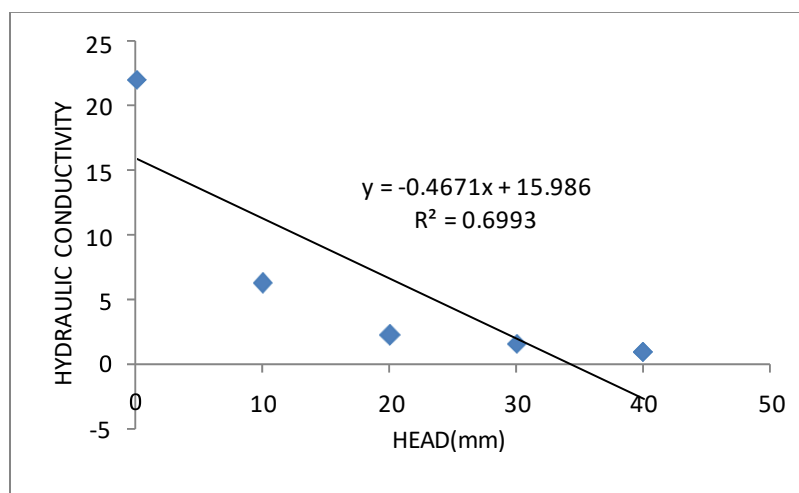


Figure 5.53 Variation of hydraulic conductivity with Head(mm)

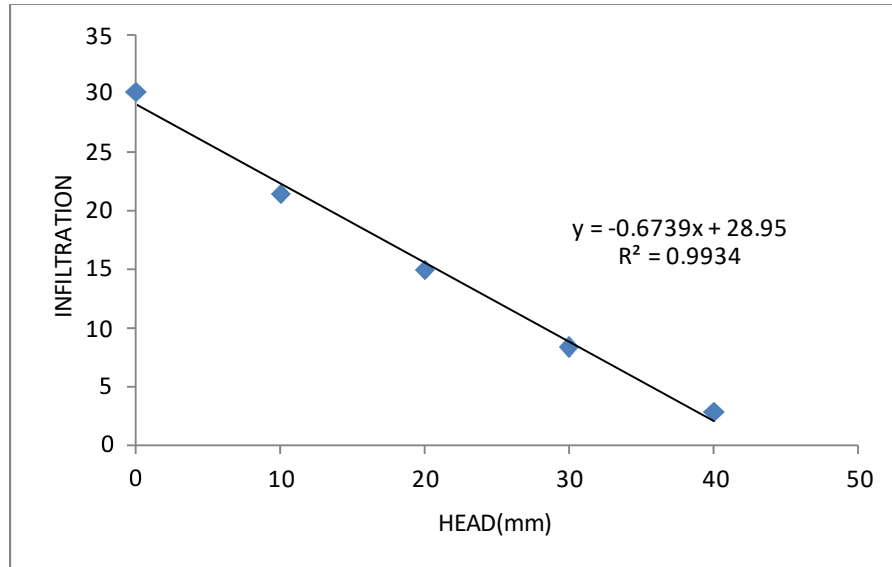


Figure 5.54: Variation of Infiltration rate with Head(mm)

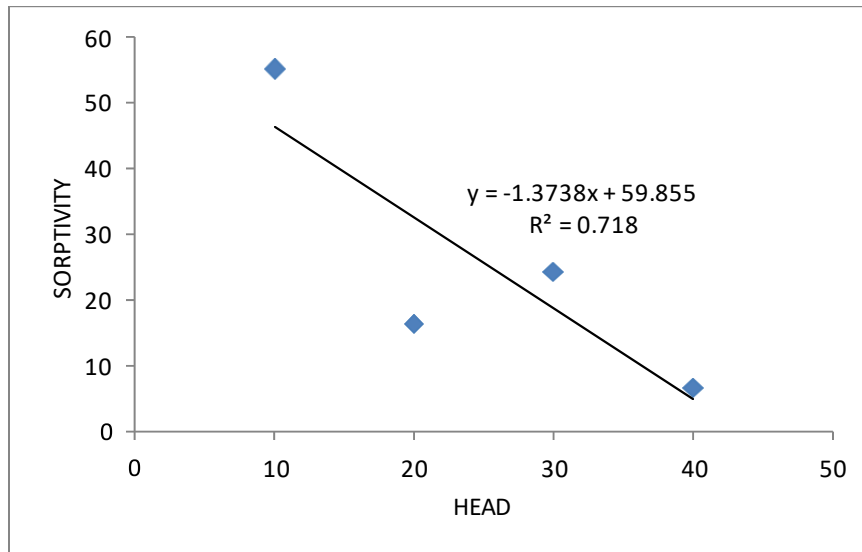


Figure 5.55 Variation of Sorptivity with Head

Figure 5.55 shows the variation of hydraulic conductivity with infiltration rate. It is found that infiltration rate like any other land use/land covers shows a moderately high correlation with hydraulic conductivity (0.768). However, hydraulic conductivity versus sorptivity did not show any significant mutual relationship. As discussed, the reason could be due to the rough surface of the catchment with no or thin layer of soil cover.

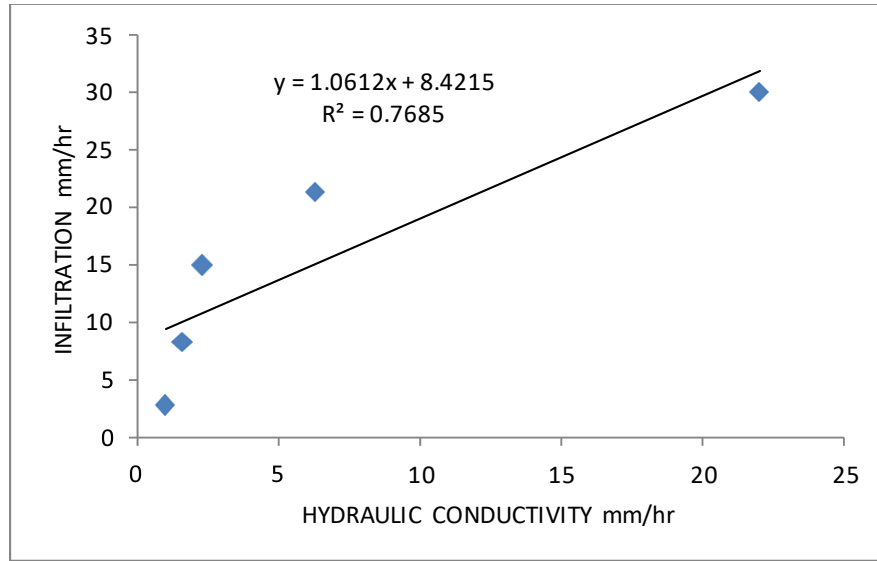


Figure 5.56 Variation of hydraulic conductivity with Infiltration rate

From the figure (5.57) below it is evident that the pore length and sorptivity are closely related in the case of teak plantation. This could be due to the fact that, as the hortonian overland flow is the dominating process in the teak plantation (Purandara et al, 2006), the sorption of the soil depends on the pore characteristics. Therefore, high level correlation is observed between sorptivity and pore length.

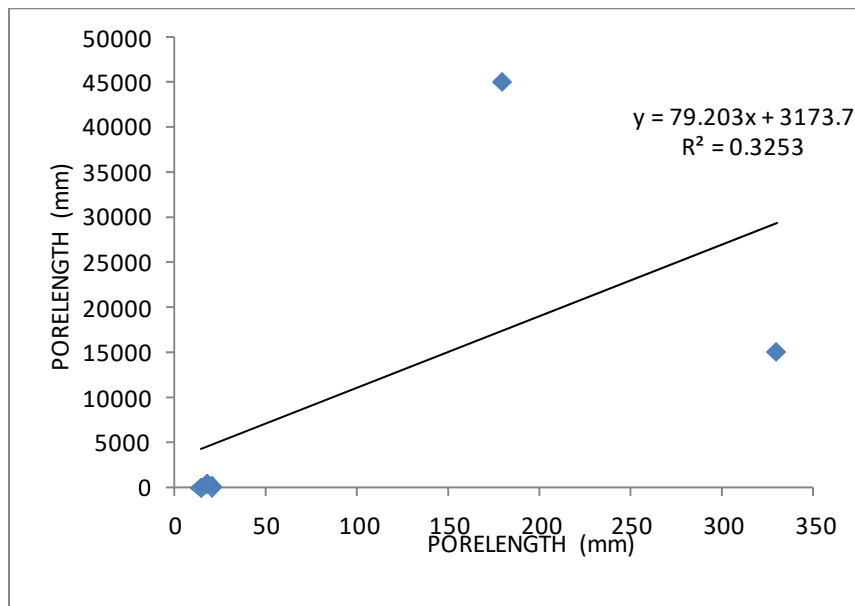


Figure 5.57 Variation of pore length with pore diameter

At the outset, it is evident that the land use/land cover changes have significant impact on the soil hydraulic properties and also on the ground recharge of a particular region.

5.6 ESTIMATION OF RAINFALL RECHARGE TO GROUND WATER

Rapid industrial development, urbanisation and increase in agricultural production have led to freshwater shortages in many parts of the world. In view of increasing demand of water for various purposes like agricultural, domestic and industrial etc., a greater emphasis is being laid for a planned and optimal utilisation of water resources. The water resources of the basins remain almost constant while the demand for water continues to increase. The utilisable water resources of India are estimated to be 1123 BCM out of which 690 BCM is surface water resources and 433 BCM is groundwater resources.

Due to uneven distribution of rainfall both in time and space, the surface water resources are unevenly distributed. Also, increasing intensities of irrigation from surface water alone may result in alarming rise of water table creating problems of water-logging and salinization, affecting crop growth adversely and rendering large areas unproductive. This has resulted in increased emphasis on development of groundwater resources. The simultaneous development of groundwater, specially through dug wells and shallow tube wells, will lower water table, provide vertical drainage and thus can prevent water-logging and salinization. Areas, which are already water-logged can be reclaimed.

5.7 EMPIRICAL METHODS

5.7.1 Krishna Rao Method: Krishna Rao gave the following empirical relationship in 1970 to determine the groundwater recharge in limited climatological homogeneous areas:

$$R_r = K (P - X) \dots(3)$$

The following relation is stated to hold good for different parts of Karnataka:

$$R_r = 0.20 (P - 400) \text{ for areas with annual normal rainfall (P) between 400 and 600 mm}$$

$$R_r = 0.25 (P - 400) \text{ for areas with P between 600 and 1000 mm}$$

$$R_r = 0.35 (P - 600) \text{ for areas with P above 2000 mm}$$

where, R_r and P are expressed in millimetres.

Table 5.4 Ground water recharge estimated using Empirical Formula (K. L. Rao method)

SL.No	DATE	RAINFALL in mm	RECHARGE in mm	% Recharge
1	1975-1976	2789.296	766.25	27.6
2	1976-1977	3176.825	901.880	28.3
3	1977-1978	2238.11	573.33	25.6
4	1978-1979	2806.437	772.05	27.4
5	1979-1980	1942.302	469.8	24.1
6	1980-1981	3200.500	910.175	28.4
7	1981-1982	2713.667	739.83	27.26
8	1982-1983	2834.640	782.124	27.6
9	1983-1984	2795.760	768.51	27.4
10	1984-1985	2465.625	652.68	25.4
11	1985-1986	2206.380	562.23	25.4
12	1986-1987	1760.351	406.12	23.07
13	1987-1988	1531.163	325.9	21.2
14	1988-1989	2696.043	733.61	27.2
15	1989-1990	1997.929	489.27	24.4
16	1990-1991	2335.855	607.54	26
17	1991-1992	2225.986	569.09	25.5
18	1992-1993	2526.757	674.36	26.6
19	1993-1994	2690.344	920.62	34.2
20	1994-1995	3526.929	1024.42	29
21	1995-1996	1894.229	452.98	23.9
22	1996-1997	2036.593	502.8	24.6

23	1997-1998	1733.629	396.77	22.8
24	1998-1999	2060.471	511	24.8
25	1999-2000	2530.657	675.72	26.6
26	2000-2001	2021.529	497.53	24.6
27	2001-2002	1974.193	480.96	24.4
28	2002-2003	1766.529	408.28	23.10
29	2003-2004	2449.257	647.23	26.4

Figure 5.58 shows the relationship between rainfall and recharge. The recharge is directly proportional to rainfall, i.e., the increase in rainfall showed an increase in the ground water recharge. The highest rainfall observed is of the order of 3526mm in the year 1994-95 against recharge of 1024mm. The maximum %age of recharge is observed in the year 1993-94 is 34.2% and minimum %age of recharge is 21.2 % in the year 1987-88

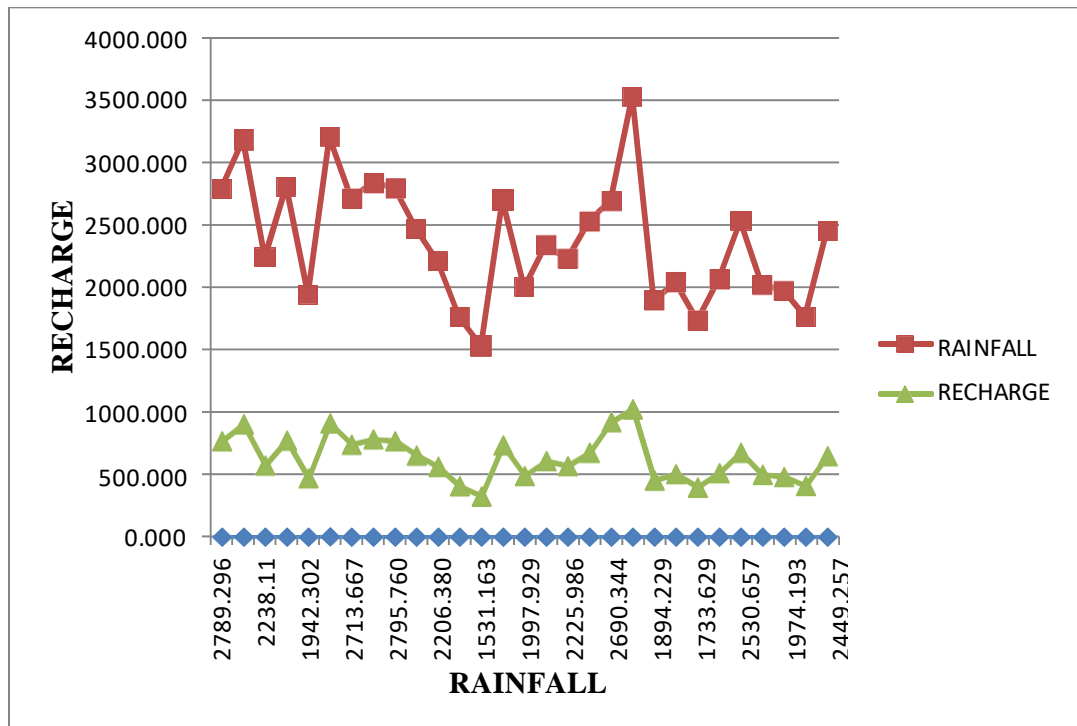


Figure 5.58 Variation of Rainfall with Recharge

The relationships indicated above, which is found to be suitable for the present study area is need to be validated for specific hydrogeological conditions.

5.7.2 Estimation of Ground water Recharge using Ground Level Fluctuation method

Groundwater is believed to contribute to stream flow in two ways; an ephemeral shallow flow system which develops during or soon after rainfall (referred to as inter-flow, quick return flow, or subsurface runoff), and the steady discharge of a permanently saturated zone which maintains stream flow through long periods without rain (base flow). These processes are often considered independently of water movement in the unsaturated zone, but there have been important recent studies of the unified saturated-unsaturated system. Therefore, the ground water level fluctuation study will provide an input to understand the process ground water movement in the study area. Ground water level fluctuation observed for two wells, one located in the Khanapur town area and the other one at Gunji (mostly covered by forest and agriculture land) indicated that, the water level shows almost same throughout the year where as in the case of Khanapur, there is a wide variation in water table and also in recharge characteristic. Ground water level fluctuation observed during the pre-monsoon and post-monsoon seasons of 2013-2014 are presented in (figure 5.59 & 5.60). From the analysis it is observed that the water table is at higher level at Gunji when compared to Khanapur. This is attributed to the forest density maintained along the Khanapur – Gunji belt.

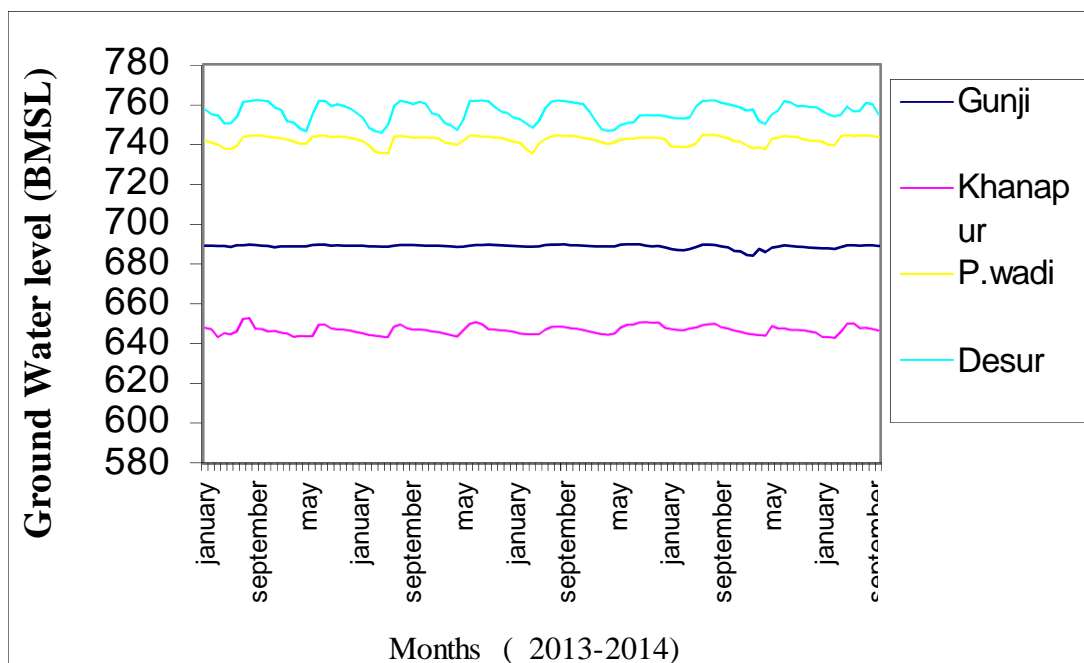


Figure 5.59 Ground water level fluctuation observed under different Land use

Ground water recharge was also estimated by using Ground water estimation Committee norms. Ground water levels data were collected from NIH, Belgaum. Based on the data, the catchment was divided in to three parts upper reach from Kankumbi to Jamboti (a high rainfall area (more than 3500 mm), mid reach from Jamboti to Asoga (moderate rainfall area (more than 2500 mm) and downstream of Asoga, covering the areas of average rainfall (Khanapur, Desur, Santibastwad. Runoff was estimated using SCS curve number method and ET was determined by using soil moisture estimation depletion method.

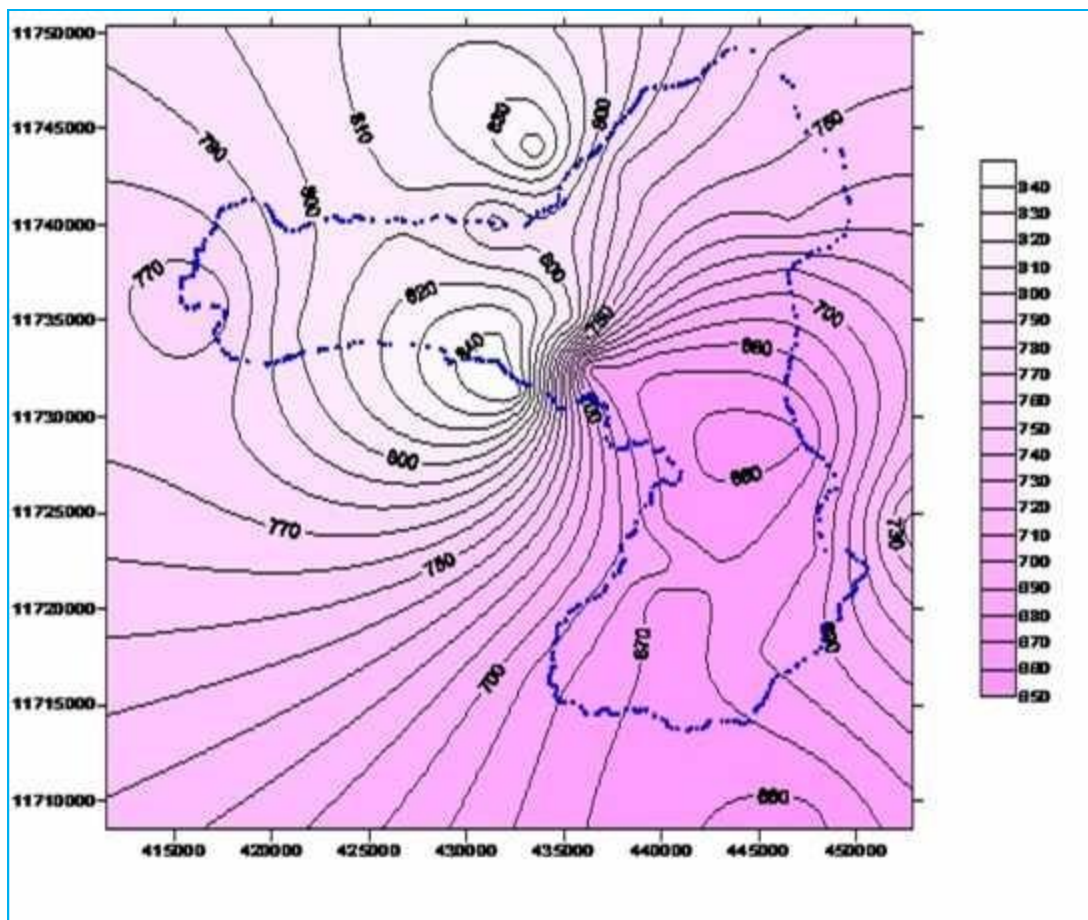


Figure 5.60 a : Ground water Level fluctuation observed during Pre-monsoon 2013-2014

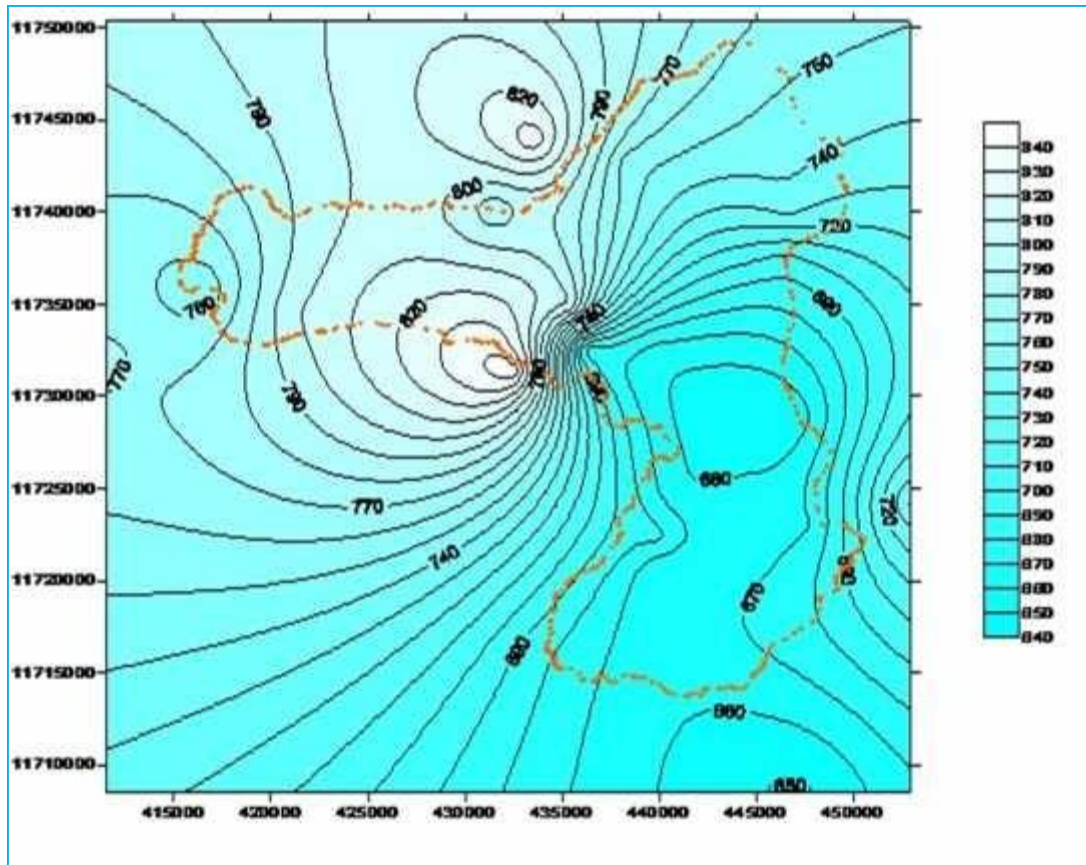


Figure 5.60 b: Ground water Level fluctuation observed during Post-monsoon 2013-2014

Table 5.5: Estimated Runoff, ET and Ground recharge under different land covers

Sl no	Land use type	Estimated Runoff (%)SCS	Estimated ET (%) Soil moisture depletion method	Percentage Recharge based on GEC norms (%)
1	Forest	22.68	31.63	43.0
2	Agriculture	27.55	23.24	31.25
3	Barren land	46.50	18.78	32.25
4	Scrub	44.25	22.10	18.15
5	Acacia plantation	28.00	24.55	35.25
6	Eucalyptus	28.78	23.19	29.30
7	Teak	22.09	28.75	27.1

The ground water recharge estimated by using GEC norms shows that the highest recharge is expected in forest land irrespective of the higher ET. This is attributed to higher infiltration characteristics of the forest soils. Minimum recharge was noticed in scrubs. This clearly demonstrates the fact that the selective reforestation will influence the ground water recharge.

5.8 MODELING OF MALAPRABHA REPRESENTATIVE BASIN USING PROCESSING MODFLOW

The purpose of the model conceptualization is to develop theoretical of the system to be simulated by simplifying a system to an extent that a logical model approach with appropriate model algorithm can be defined (Rientjes, 2007). Conceptual model describes how water enters the aquifer system and flows and leaves the system. Conceptual models are quite useful to understand the hydrological system with respect to aquifer properties, flow characteristics and boundary conditions.

5.8.1 Malaprabha Catchment:

The catchment boundary was demarcated by using ILWIS software. The model domain has 39 columns and 39 rows with 1000 m grid size. The cells in the boundary of the basin are the inactive cells and rest of the cells are taken as the active cells.

In the present study the following assumptions were made in the conceptualization process.

- (1) The model consists of a single layer.
- (2) The model is two dimensional.
- (3) The aquifer is unconfined.
- (4) The aquifer has a constant thickness.

Vertical movement of water is considered on the recharge areas. Kankumbi and Gunji areas were regarded as sources of recharge. It was assumed that the high amount of recharge enters aquifer by horizontal movement of enhanced infiltration from topographically high and forested areas surrounding the basin while small contribution is from the black soils and degraded forests.

5.8.2 Boundary conditions

Boundary conditions as defined by Anderson and Woessnez (1992) are mathematical statements specifying the dependent variable (flux) at the boundaries of the problem domain. In steady state simulation, the boundaries largely determine the flow pattern. Therefore, correct selection of boundary conditions as critical step in the model design.

During conceptualization, the model boundary conditions need to be specified. In the higher elevation and forested parts of the catchment i.e. at Kankumbi, Chigule, Gunji etc. higher recharge of about 30 % of the average annual rainfall was considered. In the downstream side, near Khanapur and adjoining urban areas lower rate of recharge was assumed as 15%. In the eastern and western part of the catchment no flow boundary was considered.

5.8.3 Lithological units

Lithology represents the hydrogeological characteristics of the particular region. The information pertaining to the study area was obtained from Karnataka State Ground Water Department. In the model top soil layers were assumed to be of higher recharge. The bottom layers, just above the hard rocks were taken as low recharge zone. It was also assumed that in areas of Hortonian overland flow and saturation overland flow, the major portion of the water move as interflow. Surface Water Body: In the Malaprabha sub- basin, there are number of surface water bodies including lakes and minor irrigation tanks. The river discharges all the water to the Naviluteerth dam located about 40-50 km downstream.

5.8.4 Source and Sinks

Rainfall is the major source of recharge. Apart from rainfall, irrigation return flow, recharge from tanks etc also plays a significant role in recharging the ground water. Evapotranspiration and well abstractions are considered as the important sinks which can be included in the model.

5.8.5 Model Inputs

Information from the geological map like structure, lithology and stratigraphic units were combined together with DEM data to create background map. Structures indicate areas of no flow, while DEM indicates areas of topographic divides, surface water bodies and elevation of the surface. Lithology is important for indicating the extent of the aquifer thickness. All hydrogeological data were collected during the field investigations.

5.8.6 Model Execution and Calibration

The execution of the model was accompanied by the entry of prepared data input into the selected computer code and interpretation of the model results. Numbers of run were performed until acceptable results were obtained. This step was followed by the model calibration. The calibration involves fitting of the parameters like boundary conditions and stresses in order to find a good match between the simulated and observed state variables.

5.9 MODEL RESULTS

5.9.1 Recharge and Transmissivity: In the study area, high recharge was observed from topographic elevations and forested watersheds and lower recharge in the downstream and urbanized areas. In the present study, 2 scenarios have been simulated considering the extremities of the climate, particularly, rainfall pattern. The first scenario represents the hydraulic head of 1.5 m above the river bed. This is followed by 1m, 0.5m and 0.1m were taken as second, third and fourth scenarios respectively. In all the cases with and without abstraction were considered for the analysis.

(a) Contours for 1 m head above riverbed:

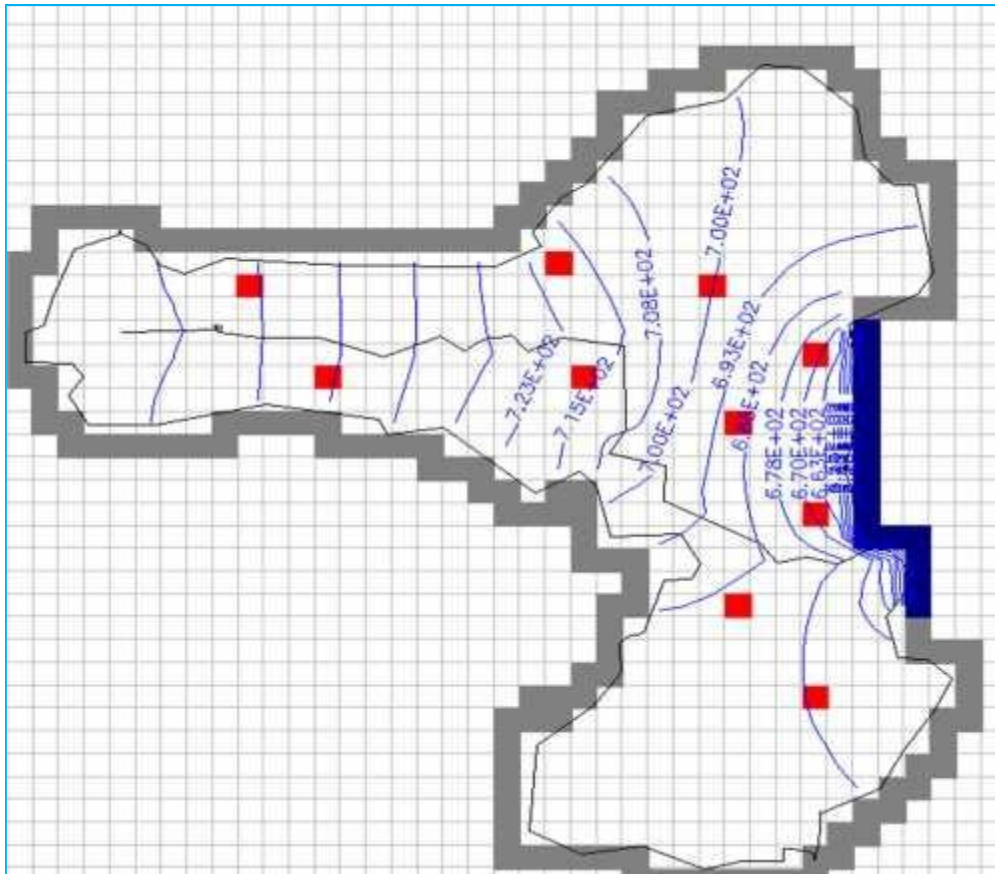


Fig. 5.61 (a) With Pumping

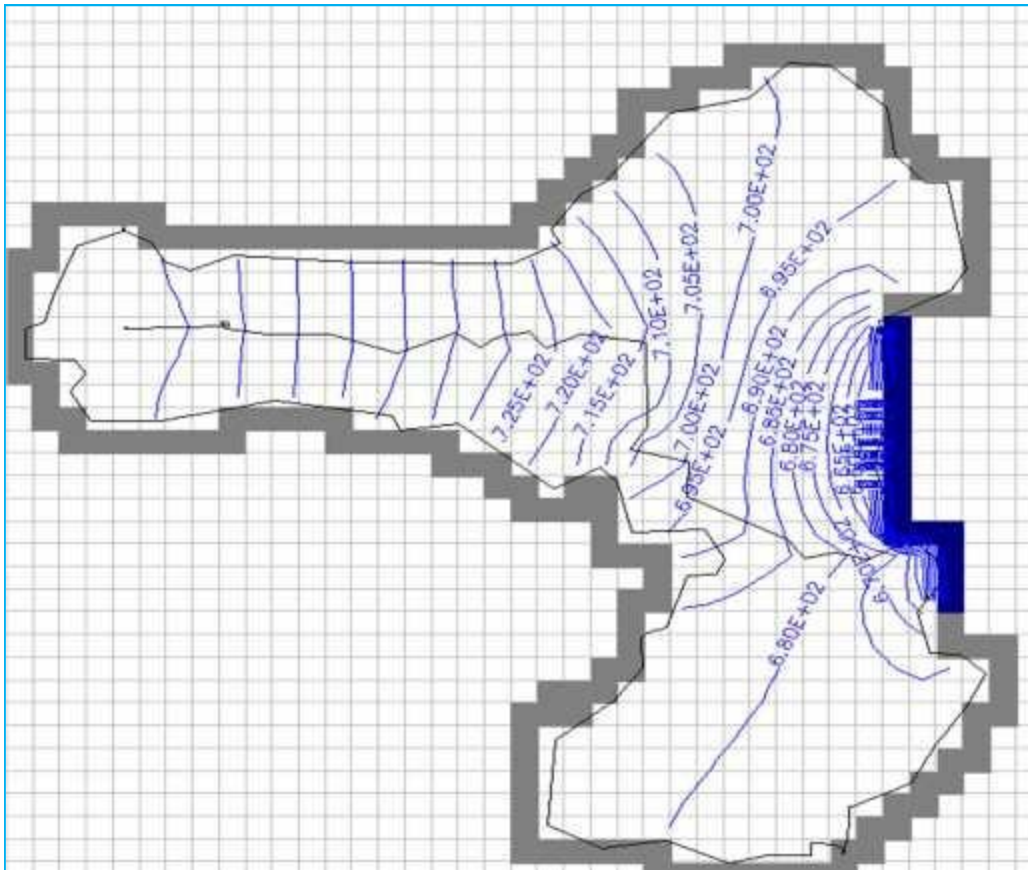


Fig. 5.61 (b) Without Pumping

It is found that in the Malaprabha representative basin, there is no significant influence of river recharge to the aquifers. In the entire above generated scenario, water level remained almost similar. However, a small shift in the flow pattern was observed. In order to verify the model results a social interactive session was held with the villagers and farmers. According to the observations made by the local public in the catchment area, there is no significant relation with the variation of ground water level with river heads except in few localities. These areas are quite close to the river flow regime. This indicates that there are instances of influence of surface water on ground water recharge. River aquifer interaction is considerably lower due to the geomorphology, soil type and geological conditions. This needs further studies to conclude the results with regard to the surface- ground water interactions. A comparison of the observed data with the simulated results showed a close proximity indicating the applicability of the model.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Therefore, PMWIN model may be used to determine runoff of a forested watershed with reasonable accuracy. Deep percolation in black cotton soils (as prevalent in the study area) is less due to very low infiltration rates as observed by the authors during field investigations for the present study (varied between 2 mm/hr and 6 mm/hr). Due to the presence of high litter and organic matter in the top layer, initial infiltration is relatively high and the moisture remains in the top soil layer due to typical nature of black cotton soil (Purandara et al, 2000).

1. The soil moisture recharge estimated over the catchment is 250 mm. This value of soil moisture recharge can be considered as the water stored for the crop in the root zone over the basin after the monsoon of each year, supplemented by the limited rainfall for the rest of the year. The ratio of surface runoff to groundwater recharge is established as 9.1: 1. Having this rough idea of ground water recharge and the amount of water stored in the root zone, the cropping pattern in the catchment area can be defined suitably to use the water available as both surface and ground water resources in the catchment optimally. A precise geo-physical study is required to estimate accurately the ground water recharge over the catchment. Several models, which are more or less based on physical processes, have been developed to estimate stream-flow from rainfall and catchment data. PMWIN and ILWIS are the two-dimensional models which take care of various components such as precipitation, runoff, infiltration, water uptake, transpiration, evaporation and drainage components. From the present study it is estimated that the percentage recharge of rainfall taking place under different forest covers.
2. The study revealed that the forests in spite of higher ET values, the percentage of recharge are also more when compared to other land covers. The percentage recharge estimated for scrubs is minimum (18%).
3. Rate of recharge in an acacia plantation is high when compared to other types of plantation (eucalyptus and teak).

4. A preliminary conclusion is also drawn from the field and modelling studies that there is no drop of water table in a plot having eucalyptus plantation. However, a detailed investigation under different soils and geology is also required to establish the results.
5. Rate of infiltration, soil moisture status and hydraulic conductivity also favours the above observations.
6. The soil moisture recharge estimated over the catchment is 250 mm. This value of soil moisture recharge can be considered as the water stored for the crop in the root zone over the basin after the monsoon of each year, supplemented by the limited rainfall for the rest of the year.
7. The ratio of surface runoff to groundwater recharge is established as 9:1. Having this rough idea of ground water recharge and the amount of water stored in the root zone, the cropping pattern in the catchment area can be defined suitably to use the water available as both surface and ground water resources in the catchment optimally. A precise geo-physical study is required to estimate accurately the ground water recharge over the catchment.
8. Ground water flow contribution to stream flow depends on stream morphology and land use pattern.
9. The saturated hydraulic conductivity of the soil exerts a far greater influence on the runoff generating system than do the properties of the rainfall event or the slope of the soil surface.
10. Saturation of the transient wetlands results from local infiltration rather than from lateral subsurface water movement.
11. Soil moisture studies at various sites conducted reveals the change in moisture content with depth and this also depends on land use and land cover.

6.2 RECOMMENDATIONS

1. It is necessary to strengthen the monitoring net work in the study area particularly rainfall, evaporation, ground water levels and temperature
2. Soil moisture monitoring should be done with respect to rainfall events and also based on land use/land covers.
3. Long term infiltration measurements should be done to understand the redistribution of soil moisture and ground water recharge characteristics
4. Detailed information on soil type, plant growth and Evapotranspiration should be gathered through experimental means.
5. Watershed based study in different scales should be encourage

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