Studies on Spring flows in parts of Ghataprabha Sub-Basin, Western Ghats, India

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ABSTRACT

Land and water management issues are the two important aspects which needs immediate attention from both scientific community and administration. In order to address the problems facing in water sector, it is necessary to understand the impacts of proposed land management, vegetative changes, groundwater withdrawals, and reservoir management on water supply and water quality. As acquisition of field data is costly and time consuming, models have been created to test various land use practices and their concomitant effects on the hydrologic budget of watersheds. To simulate such management scenarios realistically, a model should be able to simulate the individual components of the hydrologic budget. In the present study, the hydrological simulation is carried out by using Soil and Water Assessment Tool (SWAT) model, which is integrated with Arc Gis software, to estimate some of the most important parameters of hydrology, such runoff, groundwater recharge and evapotranspiration. The model was applied to Ghataprabha sub-basin, which is a right bank tributary of river Krishna. The analysis was carried out in three phases to understand the hydrological response to catchment characteristics, particularly with reference to catchment area. The calibration and validation of the model was done by using the data of adjoining basin, Malaprabha as there is a lack of rainfall data for the regions in headwaters of Ghataprabha catchment. The model was calibrated and validated by using data for a period 1991 to 1998. Long term mean hydrometeorological data and physical characteristics of the catchment such as land use/land cover, soil type, topography, groundwater level and slope are used as an input to the model. The mean annual groundwater recharge, evapotranspiration and runoff were found to be 18%, 30% and 46% for headwater catchments with a considerable decline with an increase in catchment area. Comparison of measured and predicted values demonstrated that each component of the model is quite acceptable and realistic in nature. However, it is necessary to go data intensive modeling to get an accurate view of the hydrological processes.

Introduction

According to a report of USAID (2009) more than one billion people do not have access to safe drinking water and over 2.5 billion people have inadequate sanitation. In India also the situation is not much different from the other developing countries. Water is life andespecially potable water is essential for life and health. So, access to drinking water,improves overall socio- economic and environmental existence (Gebrehiwot, 2006).In developing countries national and regional governments, local and internationalNGOs and other concerned organizations invest large sums every year for theimplementation of rural water supply projects (Gebrehiwot, 2006). However,construction of water projects does not help if they fail after a short time. In order tomake the investment in water supplies more effective, failure rates of these systemsshould be reduced. According to Gebrehiwot (2006), this can be accomplished bybetter integration of people who receive the water and water project suppliers indecisions concerning planning construction and management of water supply systems.

Enhancing the capacity of the community in planning, implementation, developmentandmaintenance of rural water supply systems are the first step towards thesustainability development of rural water supply schemes. To examine the impact ofthe water supply system socio economically, the full impact should be taken underconsideration (UNICEF, 1999).Involvement of the communities is crucial for the sustainability of rural water supplysystems. Females are responsible for fetching water by carrying a clay pot watercontainer or jar long distances. The rural part of Ethiopian topography has rugged terrain and the water points are far especially during the dry phase of the monsoonfrom the individual households as a result females move up and down by carryingwater (Admassu et.al, 2002). About three hours are being lost per day per householdfetching water by rural households who have no access to safe drinking water sourcesaround their houses (UNICEF, 1999). Sometimes women prefer fetching water fromunprotected spring, river and other sources of it is closely in order to decrease the timespent to fetch water and from these sources they get water free from payment withoutworrying about the quality of water and its consequences (Admassu et.al, 2002). Therefore, it is quite essential to look for an alternative source of water particularly in the head water catchments which can be utilized effectively for agriculture and drinking purposes locally. Head water catchments can play a major role in water conservation and ground water replenishment in the catchment areas and also it can enhance the water availability for the downstream users.

Previous literature on water availability in the mountainous catchments, indicated that, the water stress is said to be primarily due to the fast growing cities combined with the change in land use/land cover changes occurring in most part of the country. It is a fact that land use and land cover change profoundly transformed terrestrial hydrological budgets and processes (Vorosmarty and Sahagian,2000; Stonestrom et al., 2009). Although the effects occur at multiple spatial scales

from local (small basins) to global, the scaleat which local communities and land-use managers are affected is of special concern as decision making on ecosystem services, especially hydrologic services.Despite the hydrologic importance of mountainous catchments in providing freshwater resources, little is known about key hydrological processes in these systems, such as mountain block recharge (MBR) [*Viviroli et al.*, 2007]. The intrinsic complexity of recharge processes and the fact that such processes are extremely difficult to observe contribute to this problem. Without understanding this key hydrological process in mountainous catchments, assessing the impact of climate variability and land cover change in these vulnerable systems will be incomplete and possibly inaccurate. Mountain system recharge (MSR) is the main groundwater recharge component [*Wilson and Guan*, 2004], and it includes infiltration of mountain stream runoff in alluvial fan streambeds (mountain front recharge, MFR) and precipitation infiltration through mountain bedrock (MBR). Although most studies have focused on recharge processes at the mountain front, a possibly large but unknown contribution of recharge comes from MBR in the sky islands of the southwestern United States [*Manning and Solomon*, 2003; *Blasch and Bryson*, 2007].

Therefore, understanding the linkage between mountain water sources and basin aquifers is important [*de Vries andSimmers*, 2002; *Scanlon et al.*, 2006]. MBR influences the mountain groundwater flow system and inter-mountain basin aquifers. Moreover, bedrock groundwater contributes to surface water discharge up to 20%–50% in some systems [*Uhlenbrook et al.*, 2002; *Kosugi et al.*, 2006]. Modeling studies have shown that bedrock permeability and storage capacity have the largest impact on MBR rates [*Forster and Smith*, 1988; *Gleeson and Manning*, 2008]. One of the most interesting part of the hydrologic system in a mountainous catchments is the occurrence of natural springs either in the form of interflow or as artesian springs. These springs plays a significant role in agriculture and water supply to rural communities in the mountainous catchments. However, in the recent years due to population explosion and industrial growth, the sustainability of such Spring water is questionable?

In mountainous catchments, all recharge to groundwater discharges naturally and can be used by a wide variety of organisms, including (but not limited to) mankind, in the special ecosystem that they sustain. Springs are natural outlets through which groundwater emerges at the ground surface as concentrated discharge from an aquifer and are one of the most conspicuous forms of natural return of groundwater to the surface. As spring waters flow down a slope, a portion of the flow may seep into the ground, adding to the recharge of the lower aquifers. In the long history of mankind, these great resources have often been destroyed by diversion or ‘development’ in short-sighted attempts to improve water supplies for human communities. This frequently has had adverse effects on the environs of the original springs and seeps. Springs in the high hills of the Western Ghats (hills), in the western margin of the Indian Peninsula, are no exception. They sustain the life of thousands of human beings, plants, animals, birds and other organisms. In the name of development, these springs are under constant exploitation for local water supply. Their natural settings and sources are often modified, thus diminishing their life and often causing their complete disappearance.

Available literature reveals that little work has been done on the origin of springs in a basaltic terrain. Close examination of such springs in parts of Western Ghats covering Shindudrug district of Maharashtra, Uttara Kannada and Dakshina Kannada districts on the western side and Kodagu

district in eastern part of the state of Karnataka faces severe water crisis during the summer months in-spite of heavy rainfall for a period of about 4 months with an average rainfall of more than 3000 mm. A detailed investigations in Koyna area of Maharshtra by Naik et al (2002) reveals that their origins are dependent on the lithologic character of different basaltic flow units and the existing physiography. Although rainfall, its seasonality and areas of recharge, play vital roles in the recharge of these springs, their yields are also controlled by lithological variations and hydraulic characteristics of their source-aquifers.

While tapping springs for drinking/irrigation purposes, it must be remembered that they also sustain thousandsof other life forms vital to a balanced ecosystem. Changes in the uses of these springs may also affect otherhuman communities downstream. Therefore, before developing spring flow, a trade-off must be made considering local needs and downstream users.

The research challenges of Spring flow analysis are as follows:

(1) How can streamflow recession analysis can be used to improve understanding of Mountain Block Recharge(MBR, as stated by Ajami et al., 2011)processes in a tropical mountainous catchments?

(2) What is the sensitivity of MBR estimates to uncertainty in the derivation of the catchment storage-discharge relations?

(3) What are the contributions of seasonal precipitation (winter versus summer monsoon) to MBR?

(4) What can we infer from storage-discharge relations across nested catchments of increasing size to describe Mountain System Recharge processes in a mountainous catchment?

Study Area

In formerly forested regions in the humid tropics, notably inthe more densely populated regions of south and south–eastAsia such as the Western Ghats of India, major land-coverchanges have occurred at a century time scale. The latter haveincluded permanent deforestation and conversion to a varietyof agro-forestry and agro-ecosystems, regrowth as well as reforestation.Consequently there is a particular need for decisionmakers and policy makers to have information from hydrologicalstudies that address the fundamental processes associated withsuch land cover changes. Over 100 million people depend onsurface water sources in streams and rivers that emanate fromthe Western Ghats. Further this region is a major repository ofcarbon in its forests and soils (Seen et al., 2010) and is a globalbiodiversity hotspot (Das et al., 2006). In an era where variousecosystem services are being recognized and valued, it is essentialfor ecological economists, policy and decision makers to beaware of the synergies and trade-offs between various regulatoryand provisioning services (Elmqvist et al., 2010). Thus an investigationof the hydrological effects of specific land-cover changesis a high priority (DeFries and Eshleman, 2004).

The Western Ghats region of peninsular India is one of the most important regions from the point of view of understanding hydrological service impacts of forest cover change and alsorepresents the complexities of the social use of forests. On the one hand, the heavilyforested Ghats region is the site of historically intense use of forests by local communities formeeting their needs of fuelwood, fodder, grazing, leaf manure, etc., as well as felling by thestate forest department for meeting regional needs of timber. This has resulted in a complexmosaic of relatively undisturbed forest, savannah, grassland and barren lands, interspersedwith monocultural plantations established by the forest department. It is also the site of majorshifts in land-use from "forest" to "non-forest", including agriculture or plantation crops. Stateforestry activities have also significantly affected the composition of these forests. On theother hand, virtually all the major rivers (particularly the important east-flowing rivers) insouthern India originate in the Western Ghats. The changes in land-use and land-cover inthe upstream catchments of these rivers are therefore of critical importance to the millions offarmers on the eastern portion of the Deccan plateau, especially the increasing numbersdepending upon river flows (direct or dammed) for irrigation. They are also likely to be ofimportance to the community local to the Western Ghats themselves, because even in thishigh rainfall region, seasonal scarcity of water is ubiquitous, and fertile soil is at a premium.This study is an attempt to contribute to an improved understanding of the forest-watercommunity linkage through field investigations in the Western Ghats that lie within Karnataka state (see Figure 1). The study is distinctive in its attempt to integrate the biophysical investigation of forest-hydrological changes with the socio-economic investigation of impacts of such changes. We describe below the questions investigated, the framework within which they are answered, the analytical approach, methods used for site selection and for thehydrological and socio-economic studies.

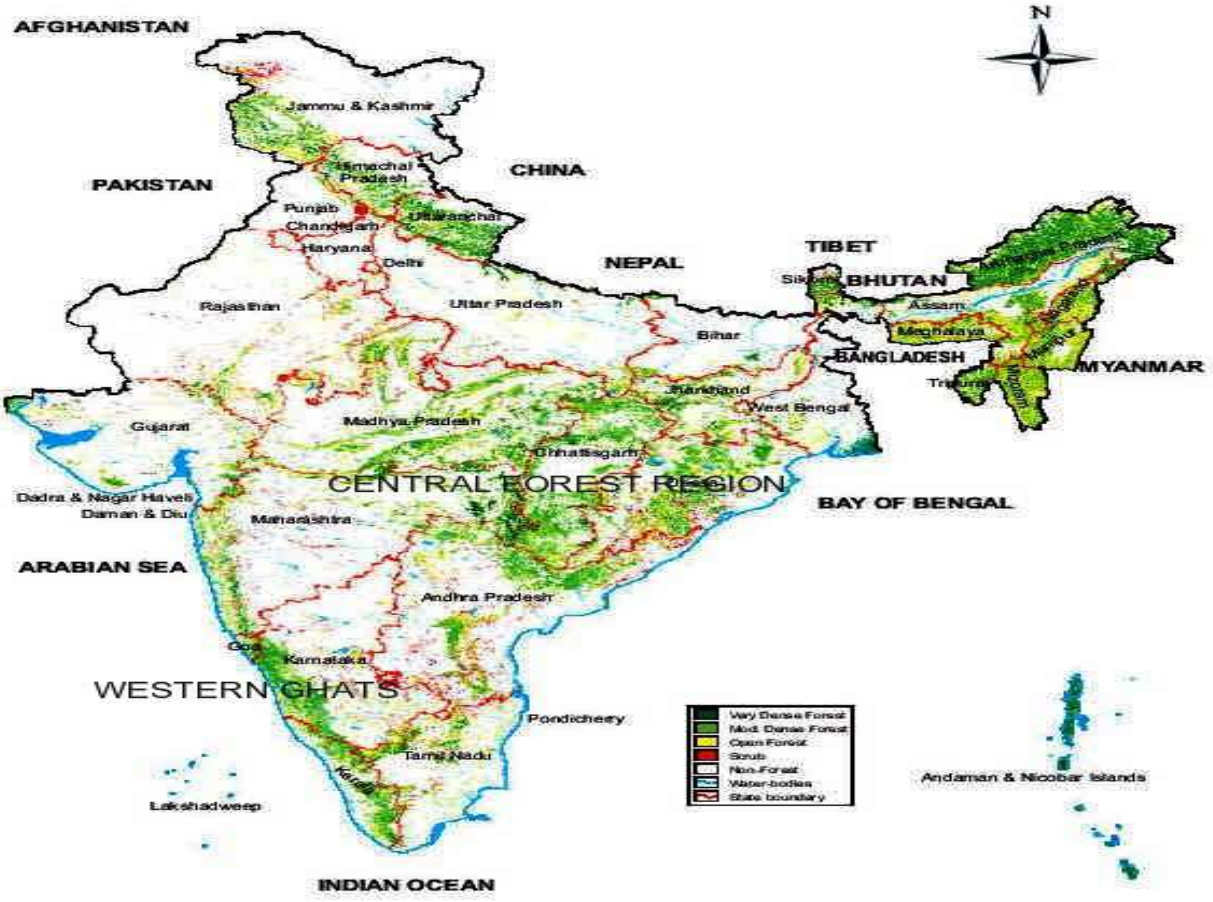


Figure 1. India with Different kinds of Forest

One of the important source of water in parts of Western Ghats are the occurrence of springs. Therefore, spring discharge measurements are of importance for water resources assessment, especially in fractured rocks. Many of the villages in Maharashtra, Karnataka and Kerala are fully dependent on spring water. However, the sustainability of spring water is not studied in detail. Since, the spring water plays a major role in socio-economic development of the forest dwellers as well as the local communities, a detailed study on the occurrence, classification of springs, extent and distribution and sustainability are highly essential. Therefore, the present study is proposed with the following objectives

Objectives of the Study:

1. To evaluate the impact of changes on physiography, climate parameters such as rainfall, evaporation, land use/land cover changes on hydrological regimes in selected watersheds in parts of Western ghat region

2. To understand the role of unsaturated soil zone on hydrological responses of watersheds based on soil hydrological characteristics and monitoring of soil moisture variation during the study period

3. To develop a watershed model, which would help toquantify both streamflow and baseflow.

4. Estimation of interflow in the selected catchments using field and analytical methods

5. Estimation of recharge rates in the selected watersheds using spring flow, rainfall and Temperature data

6. To evaluate the sustainability of the springs in the changing scenario of land use/land covers and its (spring water) role in rural water supply schemes

7. Assessment of water quality of spring water, groundwater and surface water

8. Application of isotope techniques to understand the origin of springs and its source

9. Socio-economic impact caused due to change in spring water flow and land use/land cover changes

Study Area

The catchments in the study area are on the back slopes of theWestern Ghats, deeply dissected, and the geology is dominatedby Greywackes. The soils in both the Coastal and Malnaad basins are deeply weathered. Soils are red and lateritic similar to the description of Putty and Prasad (2000a). In the absence of any deep drilling in the basins, however no detailedsoil descriptions down to bed rock exist. Exposures in hillsand stream banks do suggest that soils extend well beyond 2 min depth.

The main aquifers in the study area are the weathered and fracturedzones of metavolcanics, meta-sedimentary rocks, granites andgneisses, laterites, along with the alluvial patches found alongthe major stream courses. Significantly there is no primary porosity in the hard rocks. It is the secondary structures like joints, fissures and faults present in these formations up to 185 m belowground level (mbgl) which act as a fractured rock aquifer with an effective porosity of 1.0 – 3.0% and contain groundwater. The transmissivity of aquifer material are in the general range from 2.09 to 24.41 m^2/day (CGWB, 2008). Spot surveys undertaken by State and central government in May (pre-monsoon) and November (post-monsoon) 2006 and using a network of 30 of the national hydrograph stations, showed that pre-monsoon water levels vary between 5 and 10 mbgl. These observations were typical over large parts of Uttara Kannada. In the post-monsoon, the prevailing depths within the Coastal and Malnaad areas were respectively 2–5 and 5–10 mbgl (CGWB, 2008).In the absence of any deep drilling in the basins, however no detailed soil descriptions down to bed rock exist. Exposures in hills and stream banks do suggest that soils extend well beyond 2 m in depth. Further no detailed mapping of soil pipe occurrence (Putty and Prasad, 2000a,b) was undertaken, although we have observed soil pipes in the forested catchments in the region and there was evidence of vertical macro-pore flow in soil exposures.

Climate

The climate is classified under Koppen as 'tropical wet and dry'. Rainfall is monsoonal and unimodal (June to September). The annual rainfall varies from 3979 mm in the Coastal zone to 3275 mm in the Malnaad (1950–2000 mm average. Long-term annual reference Potential evapotranspiration (PET) is 1482 mm for the Coastal basins and1527 mm in the Malnaad basins (Hijmans et al., 2005). According to the earlier reported studies, on a monthly basis there is marked reduction in PET following the onset of the monsoon in June untilits termination from October onwards (Hijmans et al., 2005). The dry season lasts from 5 to 6 months and so during this time PET > rainfall. The annual mean temperature ranges from 26.4 _C in the Coastal plains and slopes, to 24.5°C in the Malnaad (Hijmans et al., 2005). Annual average relative humidity is 72.3% in theCoastal basins and 70% on the Malnaad slopes (1960–1990, New et al., 1999).

Maximum rainfall intensities for a duration of 15 min across the study area range from 50 mm/h (1 in 1 year) to 130 mm/h (1 in50 year) (Bonell et al., 2010). Overall these short-term rainfall intensities are comparatively low by global standards for the humid tropics (Bonell et al., 2004). On the other hand, the long duration of rain events (often over several days) ensures very high precipitation totals (Putty and Prasad, 2000a,b) and the latter was also shown in Krishnaswamy et al. (2012).

Vegetation and land-cover/land-use

The natural and modified vegetation of the study area is highly diverse in response to the equally complex geology, geomorphology and climate of the Western Ghats. Based on criteria such as physiognomy, phenology and floristic composition, the vegetation of the study area is classified principally as evergreen and semi-evergreen which are two of the five major floristic types identified within several detailed studies of the region (Pascal, 1982, 1984,1986, 1988; Ramesh and Pascal, 1997; Ramesh and Swaminath,1999). Within the framework of a highly fragmented land coverand land use system (Blanchart and Julka, 1997; Menon and Bawa,1998; Pomeroy et al., 2003; Pontius and Pacheco, 2004; Seen et al.,2010), there are typically three principal stable patterns of land useand management, viz:

- Less disturbed, dense forest (referred to also as Natural Forest, NF, or Forest) which has resulted from a limited extraction regime, and is commonly associated with Reserve Forest patches,

- Dominantly tree savannas (Degraded Forest, DF, or Degraded) that result from intense harvest of fuel wood, leaf and litter manure and grass, as well as intermittent fires (Rai, 2004; Priyaet al., 2007).

- These tree savannas were previously occupied by mostly evergreen and semi-evergreen forest prior to severe disturbance over decadal to century time scales. The specie composition, tree density and basal area of this land cover however can be highly variable between first-order basins.

Methods and Materials

Quantification of Mountain block recharge processes in mountainous catchments. Catchment storage dynamics in response to precipitation seasonality will be investigated by means of recession flow analysis. Further storage-discharge relations may be developed to quantify Mountain block recharge rates for those periods in the catchment that change in discharge is only a function of bedrock storage.

Hydrologic Data collection and Analysis

Streamflow and precipitation data will be obtained for the selected headwater catchments in Western Ghats. Streamflow measurements as well as spring discharges will be monitored during both wet and dry periods.

Spring Flow Discharge measurements

Standard methods such as rectangular notch or V-notches will be used for spring discharge measurements both during pre and post monsoon seasons. This is understand the sustainability of the spring water.

Recession Flow Analysis

The recession flow analysis of *Brutsaert and Nieber*[1977] will be primarily applied to humid catchments. This region is characterized by steep hillslopes with fractured bedrock.It is proposed to apply recession flow analyses of *Brutsaert and Nieber*[1977] for the selected catchments in parts of Western ghats.

Estimation of Soil Hydraulic Properties

Hydrological soil parameters such as infiltration, hydraulic conductivity, porosity and permeability will be determined in the field. Soil moisture characteristics and retention characteristics will be studied in the laboratory.

Pumping & Recovery tests

Pumping and recovery tests will be carried out for open wells in and around the springs in selected area.

Isotope Studies

Spring water, groundwater and surface water will be collected for isotope analyses to understand the origin of spring water. An attempt will be made to find out the recharge factor using isotopic methods.

Water Quality Investigations

Water samples will be collected from surface water bodies, groundwater and springs and will be checked for its suitability for water supply to the rural mass. Attempts will also be made to compare the changes in water quality with respect to change in land use/land cover changes.

Application of Remote Sensing technique & Socio-economic Assessment

Satellite data will be procured for different periods to understand the variation of land use/Land cover changes over the last 2-3 decades. Using the satellite data attempt will be made to identify the spring water locations and its increase/decrease over the years.

Literature Review

Springs are found mainly in mountainous or hilly terrain. A spring may be defined as a place where a natural outflow of groundwater occurs. Spring water is usually fed from a sand or gravel water-bearing soil formation called an aquifer, or a water flow through fissured rock. Where solid or clay layers block the underground flow of water, it is forced upwards to the surface. The water may emerge either in the open as a spring, or invisibly as an outflow into a river, stream, lake or the sea. Where the water emerges in the form of a spring, it can easily be tapped. The oldest community water supplies were, in fact, often based on springs and they remain a favored source, because the water usually has a high natural quality and intake arrangements are relatively straightforward. That suits both the engineers helping to design the water supply system, and the community members who will have to look after it. Because of their popularity, most natural springs have been developed in one way or another as drinking water sources. However, a proper feasibility study, application of some basic design principles and vigilance in protecting the spring and its catchment area will usually lead to improvements in the quantity, quality and sustainability of many such supplies. As in the rest of the book, there is an overriding principle that community members should be fully informed and closely involved in decisions about the tapping, use and protection of spring water sources.

Local people, especially women (as drawers of water), but also farmers, hunters andgrazers, have a good knowledge of the location of springs and their characteristics. These people are the primary sources of information in the identification process. In the dry season, green vegetation in a dry area may also be an indication of a spring source. Some springs form small ponds where animals drink and people may well also scoopwater from there. Others flow as small streams in valleys and can be traced back to the source. The source, though, is not necessarily the first upstream point at which the stream emerges from the ground. In some cases streams may be buried for quite a length and there can be added risks of contamination unless the investigation continues further upstream to locate the true spring.

Various techniques have been used to quantify recharge from mountain systems. These methods rangefrom empirical relationships using annual precipitation, environmental tracers, spatially distributed water balance models, groundwater models, and base flow separation analysis. Empirical equations such as those developed by *Maxey and Eakin*[1949], *Hearne and Dewey* [1988], and *Anderson et al.* [1992] are based on precipitation-recharge relationships, where a certain percentage of precipitation becomes recharge at the mountain front. Recharge in most arid regions is episodic and may be related to large, infrequent, extreme events. As a result, estimating

recharge based on a fraction of annual precipitation can be misleading because it ignores the effect of storm characteristics, soil and bedrock storage, and vegetation dynamics on recharge [*Gee and Hillel*, 1988].

Water balance models with various complexities have been used to estimate Mountain Block Recharge (MBR), but the application of these models is often limited because of the large amount of required input data or model structural deficiencies. For example, *Chavez et al.* [1994] developed an analytical relationship between the mean seasonal precipitation and runoff based on a conceptual understanding of hard rock hydrologic processes for the Sabino Creek catchment, Arizona. The input variables to the model were stochastic, but the model was only developed for the summer season because their analytical streamflow modeling did not consider snowmelt contributions to surface runoff [*Chavez et al.*, 1994]. *Guan* [2005] used the HYDRUS-2D model [*Simunek et al.*,1999] at the hillslope scale to identify factors that control distributed MBR. He concluded that bedrock permeability, precipitation, potential evapotranspiration, vegetation, andsoil coverage control the amount of MBR. Although Guan's model is physically based, it is complex, data intensive, and not well tested with actual observations. He suggested that future efforts should focus on better characterization of hydraulic properties of mountain block and precipitation amounts [*Guan*, 2005]. Detailed field studies at Yucca Mountain, Nevada (60 km2), led to the development of a daily water and energy balance model (INFIL) to estimate spatial variability of net infiltration, which is defined as downward flux across the lower boundary of the root zone [*Hevesi et al.*, 2003]. Capillary forces and temporary perched groundwater systems, which may be important components of streamflow and spring discharge in high mountains, are not considered in this model [*Hevesi et al.*, 2003]. This model was refined to a simpler GIS-basedmodel, the basin characterization model (BCM), which runsat the monthly time step for one soil layer without surfacewater routing. The BCM developed by *Flint et al.* [2004] provides a method for estimating regional recharge and inter-basin comparisons using monthly precipitation, air temperature,potential evapotranspiration, soil water storage,and bedrock permeability [*Flint et al.*, 2004].*Manning and Solomon* [2003] developed a methodusing noble gas data to derive recharge temperature, andthey distinguished between the sources of MFR and MBR in the Salt Lake Valley, principal Aquifer in northern Utah.They further combined noble gas recharge temperatures,groundwater ages, and temperature data with heat and fluidflow modeling to characterize bulk fluid circulation in themountain block [*Manning and Solomon*, 2005]. The methodprovided useful information regarding the sources of MBR,but its application in other catchments is expensive, and despitemeasurements at multiple scales, they were unable to determine groundwater circulation depth. Basin groundwatermodels have also been used to quantify MBR, whereMBR is applied as a boundary condition and recharge valuesare obtained during model calibration. Mountain block recharge estimates from these models are often non-unique [*Manning and Solomon*, 2005]. Recently, isotopic data have been used to constrain MBR estimates in groundwater flow models during model calibration [*Zhu et al.*, 2003; *Sanfordet al.*, 2004].

Although many attempts have been made to quantify MBR, less effort has been focused on understanding MBR dynamics in mountainous catchments in relation to precipitation seasonality and catchment storage dynamics. To understand the MBR process, a closer look at catchment storage dynamics and streamflow generation processes is required. *Kirchner* [2009] developed a methodology to quantify catchment dynamic storage based on a streamflow recession analysis

method introduced earlier by *Brutsaert and Nieber*[1977]. Catchment dynamic storage is the transient storage of water that discharges during a recession period [*Vitvar et al.*, 2002]. *Kirchner* [2009] used the central tendency of the recession flow data and fitted a regression model to obtain the catchment sensitivity function. The catchment sensitivity function describes the rate of change in discharge as a result of change in storage for periods when precipitation and ET are small relative to discharge. From the sensitivity function one can obtain the storage-discharge relationship for a catchment [*Kirchner*, 2009]. As highlighted by *Teuling et al.*[2010], the work of *Kirchner* [2009] provides a simple framework to explicitly estimate catchment-scale land surface fluxes such as ET and, as shown in this study, MBR using storage-discharge relationships.

Understanding MBR processes requires a closer look at precipitation patterns, available energy, and catchment storage dynamics. Our conceptual model of MBR is informed by how catchment storage (in soils above the fractured bedrock and in fractured bedrock) varies in response to precipitation seasonality in headwater catchments and by how streamflow recession analysis across a mountainous system reflects these dynamics of catchment storage and MBR in a hydraulically connected system. In a typical semi-arid mountainous catchment, the top of the sky islands, with thicker soils, are the major contributor to MBR [*Wilson and Guan*, 2004]. Lower temperatures and higher precipitation (often in the form of snow) make these areas the principal source of recharge to mountain bedrock aquifers. With the presence of permeable fractured bedrock, precipitation infiltration in sky islands promotes recharge and deep circulation in mountain bedrock aquifers (Figure 2). If the bedrock is relatively impermeable, local flow paths are developed above the bedrock, and thus, most of the recharge originates at the mountain front [*Manning and Solomon*, 2005]. In the Sabino Creek catchment where bedrock is composed of highly fractured granite and gneiss, we expect to have a hydraulically connected fractured storage system that receives infiltration from sky island catchments (Marshall Gulch and the Upper Sabino Creek). In addition, at certain locations of appropriate topography and geological structure along flow paths, this deep groundwater storage discharges water to streams and springs. While these waters can contribute to recharge at the mountain front, we consider their origin driven by MBR.

While Marshall Gulch and Upper Sabino Creek catchments promote infiltration through thicker soil cover over fractured bedrock, steep terrain with thin soils on side slopes at lower elevations of Sabino Creek promotes rapid surface runoff, especially during the monsoon season. If the surface runoff is large enough, it reaches the piedmont zone and infiltrates through the highly permeable sediments in the stream channel and alluvial aquifer and ultimately contributes to MFR at lower elevations.

In addition to bedrock permeability, precipitation seasonality in the catchment controls the seasonal recharge processes and impacts fractured bedrock storage. Our catchment has two distinct precipitation seasons: winter frontal storms from November to March and summer monsoon convective storms from July to September. These wet periods are separated by prolonged dry periods. During the wet seasons some of the water infiltrates through soils at higher elevations into the fractures of the bedrock, contributing to deep-aquifer storage and raising storage in the fractured system. This storage sustains flow in Marshall Gulch, Upper Sabino, and Sabino Creek during dry periods (April–June and mid-September through early November) where water level in the mountain bedrock intercepts land surface in a hydraulically connected system. Replenishing deep aquifer storage is controlled by soil moisture dynamics that can create shallow saturated

zones above bedrock that also allow quick subsurface runoff, especially in the upper part of the mountain system [*Lyon et al.*, 2008]. During dry periods, storage decreases and streamflow drops (lower base flows in early November compared to mid-September and in June compared to April) (Figure 3).

Base flow separation analyses have long been used to estimate groundwater recharge. Although base flow is not entirely recharge, it is often used as a proxy to recharge by assuming that interflow, evapotranspiration (ET), and other losses in the catchment are negligible, and the estimated recharge value is often referred to as base recharge [*Szilagyi et al.*, 2003] or observable recharge [*Holtschlag*, 1997]. *Wittenberg and Sivapalan*[1999] combined base flow separation analysis with inverse nonlinear reservoir routing to estimate groundwater recharge in shallow aquifers of Western Australia while considering ET losses during the summer season only. They assumed a power law relationship between storage and discharge and the slope and intercept of the function derived from series of recession hydrographs that their magnitudes depend on initial recession flow values.

If we are able to estimate storage changes caused by precipitation seasonality in the deep aquifers in fractured bedrock by developing storage-discharge (*S*-*Q*) relationships, we have a means to quantify MBR rates. Dynamic storage changes will be estimated simply by measuring changes in base flow prior to and after the precipitation seasonat a time when all streamflow originates from fractured Bedrock discharge. The latter assumes that there is a unique *S*-*Q* relationship that reveals itself using a base flow recession analysis procedure outlined by *Brutsaert and Nieber*[1977] and *Kirchner* [2009]. Catchment *S*-*Q* relationships derived from recession analysis quantify changes in baseflow as a result of change in storage. To get to *S*-*Q* functions requires inverting the water balance equation [*Kirchner*, 2009], which, as will be shown in this study, can be done analytically under certain conditions. After having identified the *S*-*Q* relationships, streamflow values before and after a precipitation season are used to obtain change in storage, which we interpret as seasonal MBR. This methodof quantifying MBR does not depend on base flow separation as it has been applied previously [*Meyboom*, 1961;*Wittenberg*, 1999]. Developing *S*-*Q* relations during the dry periods at each of the three gauging stations along Sabino Creek catchment, in conjunction with isotope data, will provide insights about MBR dynamics in a hydraulically connected system.

In India, very limited studies have been carried out with respect to land use/land covers changes and its impact on sustainability of springs and groundwater.

Origin of springs in a basaltic terrain has been poorly studied. There is a prevailing misconception that springs issue only from fractures/joints or from basaltic flow contacts. However, the present study reveals that their origins are more dependent on the lithological character of different basaltic flow units and the terrain physiography. In the Western Ghats, springs generally issue at the contacts between (1) laterite and lithomargic clay or poorly lateritized basaltic flow, (2) vesicular basalt and non-vesicular massive basalt, (3) highly weathered massive basalt and moderately or poorly weathered massive basalt or redbole, and (4) talus deposits and hard massive basalt or laterite or lateritized basaltic flow. Springs also emerge from fractures, both horizontal and vertical, and from the intersections of fractures with different orientations. A total of 121 springs were examined during the study, which were distributed at an elevation range of650–1,350 m a.s.l. The maximum concentration, 47%,were between 900–1,000 m elevation. Twenty-two percent of

the springs occur above an elevation of 1,000 m. Springs have an average recharge area of 722 km2 in the Koyna River basin and an occurrence frequency of one spring per square kilometre. Although rainfall and recharge areas play vital roles in the yields of these springs, their yields are largely controlled by lithological variations and hydraulic characteristics of their source aquifers. There is a marked seasonality in the spring flow domain depending on recharge. The mean discharge of the individual springs in winter is about 46 m3/day as against a mean discharge of 28 m3/day in the summer.

Detailed investigations on springs of Western Ghats in parts of Maharashtra (Koyna region) have been carried out by Naik et al (2002). They classified the springs of the Western Ghats as contact springs (89%) and fracture springs (11%). However, because the emergence of groundwater in the form of springs is largely controlled by lithology and the resulting water-bearing properties of the formations, a new classification scheme is proposed that classifies the springs on the basis of their source aquifers and nature of emergence. Thus, contact springs may be further classified into four different categories – 'laterite springs','talus springs', 'vesicular basalt springs' (or 'vb springs'), and 'massive basalt springs' (or 'mb springs').This new classification could also be applied to similar basaltic terrains elsewhere in the world.

The chemical concentrations of the spring waters are heavily dependent on the lithological compositions of the source-aquifers and the residence time of groundwater in these aquifers. The waters are dominated by alkaline earths (Ca2+, Mg2+) and weak acids (HCO3–, CO32–),and are mostly calcium type (84%) and calcium–magnesium type (10%). Chemical qualities of the spring waters are well within the ISI (1983) and WHO (1998) drinkingwater standards, except for that of iron (ISI) in about40% of the samples.

Authors strongly emphasized that the springs of the Western Ghats be tapped effectivelyfor the benefit of humankind. However, it mustbe remembered that they also sustain the life of thousands of plants, animals and other organisms and that the diversion/development of these springs would greatly affect these life forms. Moreover, as these springs flow downhill, they also recharge the lower aquifers, thus enhancing the life of the existing springs at lower levels. Therefore, depending on the situation, a trade-off must be made considering local needs and downstream users. Emphasizing only local human needs might lead to severe intercommunity conflict and negative environmental consequences.

Krishnaswamy et al (2013) carried out investigations on the hydrologic effects of forest use and reforestation of degraded lands in the humid tropics and reported its implications for local and regional hydrologic services. However, such issues have been relatively less studied when compared to the impacts of forest conversion. In particular, the ''infiltration-evapotranspiration trade-off'' hypothesis which predicts a net gain or loss to baseflow and dry-season flow under both, forest degradation or reforestation depending on conditions has not been tested adequately. In this context, few observations were made in parts of Western Ghats region of Karnataka to understand the hydrologic responses and groundwater recharge and hydrologic services linked with three ecosystems, i.e. (i) remnant tropical evergreen forest (NF), (ii) heavily-used former evergreen forest which now has been converted to tree savanna, known as degraded forest (DF), and (3) exotic Acacia plantations (AC, Acacia auriculiformis) on degraded former forest land. Instrumented catchments ranging from 7 to 23 ha representing these three land-covers (3 NF, 4

AC and 4 DF, in total 11 basins), were established and maintained between 2003 and 2005 at three sites in two geomorphological zones, Coastal and Up-Ghat (Malnaad). Four larger (1–2 km2) catchments downstream of the head-water catchments in the Malnaad with varying proportions of different land-cover and providing irrigation water for areca-nut and paddy rice were also measured for post-monsoon baseflow. Daily hydrological and climate data was available at all the sites. In addition, 36 min data was available at the Coastal site for 41 days as part of the opening phase of the summer monsoon, June–July 2005.

Low potential and actual evapotranspiration rates during the monsoon that are similar across all land cover ensures that the main control on the extent of groundwater recharge during the south-west monsoon is the proportion of rainfall that is converted into quick flow rather than differences in evapotranspiration between the different land cover types. The Flow duration curves demonstrated a higher frequency and longer duration of low flows under NF when compared to the other more disturbed land covers in both the Coastal and Malnaad basins. Groundwater recharge estimated using water balance during the wet-season in the Coastal basins under NF, AC and DF was estimated to be 50%, 46% and 35% respectively and in the Malnaad it was 61%, 55% and 36% respectively. Soil Water Infiltration and Movement (SWIM) based recharge estimates also support the pattern (46% in NF; 39% in AC and 14% in DF). Furey–Gupta filter based estimates associated with the Coastal basins also suggest similar groundwater recharge values and trends across the respective land-covers: 69% in NF, 49% in AC, and 42% in DF. Soil water potential profiles using zero flux plane methods suggest that during the dry-season, natural forests depend on deep soil moisture and groundwater. Catchments with higher proportion of forest cover upstream were observed to sustain flow longer into the dry-season. These hydrologic responses provide some support towards the ‘‘infiltration-evapotranspiration trade-off’’ hypothesis in which differences in infiltration between land-cover rather than evapotranspiration determines the differences in groundwater recharge, low flows and dry-season flow. The study concluded that the groundwater recharge is the most temporally stable under natural forest, although substantial recharge occurs under all three ecosystems, which helps to sustain dry-season flow downstream in higher order streams that sustain local communities and agro-ecosystems. In addition to spatial scale effects, greater attention also needs to be given to the role of hydrogeology within the context of the above hypothesis and its implications for hydrologic services.

Bonell et al (2010) opined that the impact of land use/land cover changes on soil hydraulic properties is one of the most important aspects in hydrology of humid tropical regions. In spite of its greater role, there is comparatively limited information in the humid tropics on the surface and sub-surface permeability of: (i) forests which have been impacted by multi-decades of human occupancy and (ii) forestation of land in various states of degradation. Even less is known about the dominant stormflow pathways for these respective scenarios. Investigations were carried out on field saturated hydraulic conductivity, K* at 23 sites at four depths (0 m, n = 166), (0.10 m, n = 139), 0.45–0.60 m, n = 117, (1.35–1.50 m, n = 117) under less disturbed forest (Forest), disturbed production forest of various local species (Degraded Forest) and tree-plantations (Acacia auriculiformes, 7–10 years old, Tectonagrandis, _25–30 years old, Casuarinaequisetifolia, 12 years old) in the Uttar Kannada district, Karnataka, India, in the Western Ghats. The sampling strategy was also undertaken across three physiographic blocks and under three main soil types. Subsequently the determined K* were then linked with rainfall intensity–duration–frequency (IDF) characteristics to infer the dominant stormflow pathways.

The study reported that there is a decline in K* in an order of magnitude at the surface as result of human impacts at decadal to century time scales in Degraded Forests. The lowest surface permeability is associated with the Degraded Forests over the Laterite (EutricNitosols and Acrisols) and Red soils (EutricNitosols) and infiltration-excess overland flow, IOF probably occurs. Further there is a progressive decline in K* with depth in these soils supporting Degraded Forests. The A. auriculiformes plantations over the Red and Lateritic soils are progressively restoring the near-surface K*, but their K* still remain quite low when compared to the less disturbed forest permeability. Consequently these plantations still retain the 'memory' from the previous degraded state. In contrast the permeability of the Black soils (Vertisols) are relatively insensitive to T. grandis plantations and this soil group has a very low K*, irrespective of land cover, so that IOF likely prevails. Overall, the Laterites are the most variable in K* when compared to the other soil groups. Thus when compared to other studies, IOF is probably more prevalent in this region. More especially so, when taking into account the marked reduction in surface K* during the wet season when compared to dry season measurements. In addition, the study demonstrated the potential for the 'infiltration – trade-off' hypothesis to be realized in this landscape under certain conditions of land degradation and restoration. It is most relevant to the combination of degraded sites and A. auriculiformes plantations on Red or Laterite soils using the less disturbed forests as the baseline. The intensity of forest use and effects of monoculture plantations on soil ecology (relative to native, mixed forests) is likely to be the critical factor in affecting surface K* over time. Predicted changes in the intensity of rain events in the future is likely to enhance overland flow on degraded sites on all soils and especially on Black soils, and restoration efforts by all stake-holders, preferably using native or non-invasive species, are needed to address this concern.

METHODOLOGY

DESCRIPTION OF SWAT MODEL:

SWAT is a physically based, semi distributed river basin or watershed scale model developed by Arnold et al (1998) in order to predict impacts of land management practices on water, sediments, and agricultural chemicals yields in large complex watersheds with varying soil, land use and management conditions over long period of time. SWAT operates on a daily time step and is designed to predict the impact of land use and management on water, sediment, and agricultural chemical yields in ungauged watersheds. The model is process based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, topographical, and soil characteristics. The HRUs are represented as a percentage of the sub-watershed area and may not be contiguous or spatially

identified within a SWAT simulation. Alternatively, a watershed can be subdivided into only sub-watersheds that are characterized by dominant land use, soil type, and management.

Water balance is the driving force behind all the processes in SWAT because it impacts plant growth and the movement of sediments, nutrients, pesticides, and pathogens. Simulation of watershed hydrology is separated into the land phase, which controls the amount of water, sediment, nutrient, and pesticide loadings to the main channel in each sub-basin, and the in-stream or routing phase, which is the movement of water, sediments, etc., through the channel network of the watershed to the outlet. The hydrologic cycle is climate driven and provides moisture and energy inputs, such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity, that control the water balance. SWAT can read these observed data directly from files or generate simulated data at runtime from observed monthly statistics. Snow is computed when temperatures are below freezing, and soil temperature is computed because it impacts water movement and the decay rate of residue in the soil. Hydrologic processes simulated by SWAT include canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, and recharge by seepage from surface water bodies, ponds, and tributary channels. SWAT uses a single plant growth model to simulate all types of land cover and differentiates between annual and perennial plants. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production. SWAT uses the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977) to predict sediment yield from the landscape. In addition, SWAT models the movement and transformation of several forms of nitrogen and phosphorus, pesticides, and sediment in the watershed. SWAT allows the user to define management practices taking place in every HRU.
The hydrology model is based on the water balance equation

$$\mathbf{SW_t = SW + \sum_{t=1}^{t}(Ri - Qi - ETi - Pi - QRi)}$$

Where, SW is the soil water content minus the 15-bar water content, t is time in days, and R, Q, ET, P, and QR are the daily amounts of precipitation, runoff, evapotranspiration, percolation, and return flow; all units are in mm.

Ground water flow contribution to total streamflow is simulated by creating a shallow aquifer storage. The water balance for the shallow aquifer is

$$\mathbf{Vsa_i = Vsa_{i-1} + Rc - revap - rf - perc_{gw} - WU_{SA}}$$

where Vsa is the shallow aquifer storage (mm), Re is recharge (percolate from the bottom of the soil profile) (mm), revap is root uptake from the shallow aquifer (mm), rf is the return flow (mm), $perc_{gw}$ is the percolate to the deep aquifer (mm), WU_{SA} is the water use (withdrawal) from the shallow aquifer (mm), and i is the day.

CONVENTIONAL METHODS

Formulae for estimation of catchment runoff from rainfall are below.

Inglis formula for ghat area

$$R = 0.85P - 30.5$$

Inglis formula for non-ghat areas

$$R = \frac{(P - 17.8)}{254} * P$$

Lacey's formula

$$R = \frac{P}{1 + 304.8f/PS}$$

Khosla's formula

$$R = P - \frac{T - 32}{3.74}$$

Where R=runoff in cm

P=rainfall in cm

F=monsoon duration factor:

S= a value dependent on catchment class characteristic :

0.25---flat, cultivated B.C. soil(A)

0.60---flat, partly cultivated soils(B)

1.00---average(C)

1.70---hills and plains, little cultivation (D)

3.45---very hilly and steep with hardly any cultivation (E)

T= mean temperature in ^{0}F on the entire catchment.

SCS Curve Number method:

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 hillslope 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 .

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).

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

Q is runoff, P is rainfall , 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 $I_a = 0.2S$

For Indian condition applicable equations are below

$$Q = \frac{(P-0.1S)^2}{P+0.9S} \text{ for P>0.1S}$$

$$Q = \frac{(P-0.3S)^2}{P+0.7S} \text{ for P>0.3S}$$

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).

4.4 **Groundwater Recharge estimation methods**

4.4.1 Chaturvedi Formula

Based on the water level fluctuation and rainfall amounts in GangaYamunadoab,Chaturvedi derived an empirical relationship to arrive at the recharge as a functionof annual precipitation (when rainfall exceeds 40cms).

$$R = 2.0\,(P - 15)0.4$$

where,

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

P = annual precipitation, in inches

This formula was later modified by further work at the UP Irrigation Research Institute ,Roorkee, and the modified form of the formula is,

$$R = 1.35\,(P - 14)0.5$$

The Chaturvedi formula has been widely used for preliminary estimation of ground water recharge due to rainfall. It may be noted that there is a lower limit of the rainfall below which the recharge

due to rainfall is zero. The percentage ofrainfall recharged commenced from zero at P = 14 inches, increases upto 18% at P = 28inches, and again decreases. The lower limit of rainfall in the formula may account for thesoil moisture deficit, interception losses and potential evaporation. These factors beingsite specific, one generalised formula may not be applicable to all the alluvial areas.

Krishna Rao's method

Krishna Rao gave the following empirical relationship to determine the ground water recharge in limited climatological homogenous areas.

$$\boldsymbol{R = K\,(P - X)}$$

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

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

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

$R = 0.35\,(P - 600)$ for areas with P above 2000mm

where, R & P are expressed in millimetres.

RESULTS AND DISCUSSION

Application of SWAT Model

The SWAT model was set up for the Ghataprabha sub basin, following the step by step procedure outlined in the SWAT user guide (Luzio et al., 2002). The basin was divided into 3 major sub-basins and each sub-basin sub divided into smaller sub-basin based on the DEM and stream network of the study area. The minimum and maximum sizes of the sub-basins were 13.09km^{2}and 1229.28km^2, respectively. The sub-basin delineation was followed by automatic parameterization of streams and subdivision of the sub-basins into Hydrologic Response Units (HRUs) based on soil and landuse data and a predefined threshold of 05% soil and 05 % landuse. The maximum HRU size was446.27 km^2 and the minimum was 0.17 km^2. The model was simulated for the period: 1990-2005.

The sensitivity of SWAT-simulated discharge to model input parameters was analyzed using the automatic sensitivity analysis technique. The purpose of the sensitivity analysis was to determine the most sensitive model parameters that needed to be given high priority during model calibration. Two cases of sensitivity analysis were done. The abstraction coefficient, soil evaporative compensation factor (ESCO), and the threshold water depth in the shallow aquifer for revap (GWQMN) were the three most sensitive model parameters for the Ghataprabha sub-basin.

In SWAT, the first level of sub-division is the sub-basin. The number of sub-basins obtained in a watershed is determined by the minimum threshold input value for defining a drainage area. The number of sub-basins modeled in SWAT influences the number of climate stations (more importantly, the number of rainfall stations) that are utilized in the modeling of the output. Since rainfall is the major input to the hydrological system, the modeled output can be affected. Generally, the higher the number of sub-basins modeled in a watershed, the higher the number of rainfall stations utilized by the model. Consequently, the model output is more accurate. The HRU is the lowest sub-division in SWAT, and the number of them modeled is determined by the land use and soil threshold defined by the user. Increasing the number of HRUs in a watershed with diverse plant cover increases the accuracy in the prediction of loadings from sub-basins, which in turn results in a more accurate output (Neitsche et al., 2005). Prior to the calibration of the Ghataprabha sub-basin SWAT, the effects of the number of rainfall stations and land use on the model output were assessed through different scenarios which were developed from 3 sub-basin thresholds and 3 land use/soil thresholds within each of the sub-basin thresholds. The results show that increasing the number of major sub-basins (from 1 to 3) basically, to define the runoff coefficient with regard to the larger catchment. As there was a larger variation with regard to the estimated runoff and observed flow in Daddi, the present exercise provided more and more accuracy in runoff prediction due to the number of HRU's characterized by different land use and soil characteristics.

Model Calibration

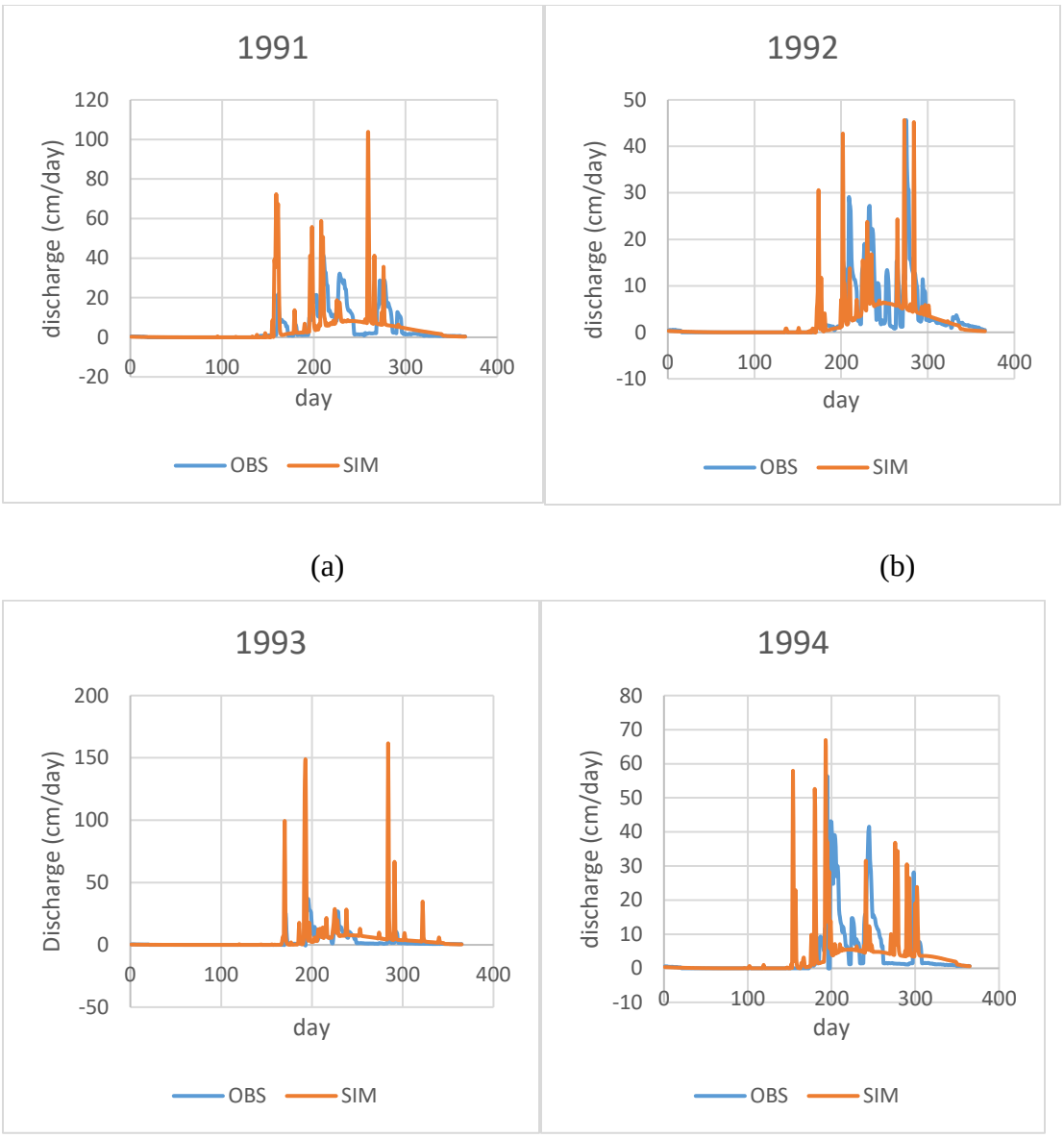
The SWAT model was calibrated with the data obtained for adjoining basin, viz. Malaprabha sub-basin at Khanapur (520 km^2). The calibration was done manually, using measured daily stream discharge data of Khanapur and following the procedure outlined in the SWAT user manual

(Neitsch et al., 2002). Calibrations were done for discharge. The first step in the calibration process was the calibration for water balance and discharge for mean annual conditions in the calibration period. This was followed by monthly and daily calibrations. The calibration process focused on adjusting model-sensitive input parameters determined from the sensitivity analysis to obtain best fit between simulated and observed data.

Model Calibration

In any modeling study, calibration of the model is an important task. In the present study, SWAT model was calibrated with reference to Bellary nala catchment. The model was set up in a GIS environment, simulations were carried out for a period of 8 years (1991 to 1998). Land use, soil and elevation maps were downloaded from the website swat.tamu.edu. It was further verified with the base maps collected from local state and central government agencies. Weather parameters such as daily precipitation and temperature values were also collected from the Karnataka State Groundwater Department. Rainfall and temperature are the primary data which was an input to the model and parameters such as relative humidity, wind speed and solar radiation were simulated using IMD weather generator database. The model was then calibrated using SWAT-CUP for a period of four years from 1991 to 1994 using observed daily runoff data at the Hudli gauging station. The model was validated for the remaining four years i.e. 1995 to 1998.

The observed and calibrated curves of daily discharge for the years 1991-1994 are shown below (figures 5.1).



(a) (b)

(c) (d)

Figure 2 Graphs showing observed and simulated daily discharge for (a) 1991; (b) 1992; (c) 1993; (d) 1994

Calibration is the process of matching the simulated values with the observed values by iteratively changing the parameters until a good correlation is obtained. For this model, the calibrated values of the parameters are shown in the table 5.1:

Table 1 Calibrated values of SWAT parameters

S. No.	Parameter_Name	Fitted_Value	Min_value	Max_value
1	R__CN2.mgt	-0.020000	-0.200000	0.200000
2	V__ALPHA_BF.gw	0.450000	0.000000	1.000000
3	V__GW_DELAY.gw	51.000000	30.000000	450.000000
4	V__GWQMN.gw	0.900000	0.000000	2.000000

Here, the parameters refer to the following:

CN2 = Initial SCS runoff curve number for moisture condition II

ALPHA_BF = Base flow alpha factor

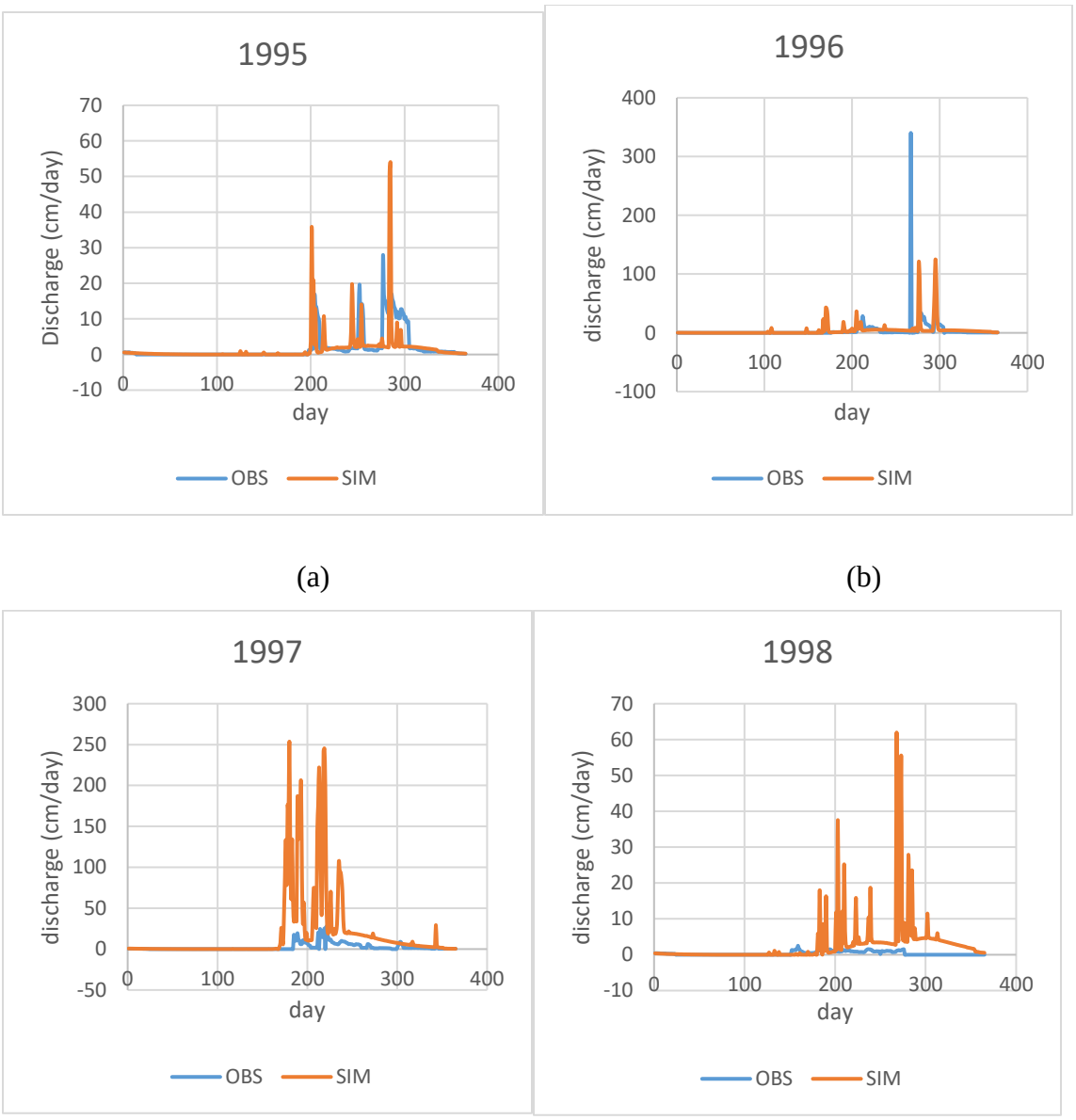
GW_DELAY = Groundwater delay (days)

GWQMN = Threshold depth of water in the shallow aquifer for return flow to occur (mm H_2O)

Additional information about the various parameters in SWAT model can be obtained in the official SWAT documentation. It can be downloaded from www.swat.tamu.edu.

Model Validation

The SWAT model for Malaprabha catchment was validated for a period of four years (from 1995 to 1998) for daily discharge data at Khanapur gauging station. The results of the validation process are shown in figure 5.2. It is noticed that there is a considerable match between observed and simulated results.



(a) (b)

(c) (d)

Figure 3 Graphs showing observed and simulated daily discharge for (a) 1995; (b) 1996; (c) 1997; (d) 1998

Model Output:

Ghataprabha Sub basin

The SWAT model was run for 16 years data (1990-2005) drawn from SWAT India data base. Initially, the model was run on monthly basis. The average monthly rainfall varied between 0.01 mm during January month to a maximum of 411.2 mm in the month of July. Further, it is noticed

that there is a considerable quantity of baseflow in the stream from November to February. ET shows variation between 7 mm to 66.7 mm. In the small basin Average rainfall ranges from 0.01 mm to 411.20 mm. Runoff ranges from 0.09 mm to 241.51 mm. In the medium sub-basin, it showed slightly reduced runoff as compared to the smaller sub-basin. This is quite expected as the rainfall is quite higher than the medium and larger basin. However, monthly average of runoff, baseflow, ET etc were quite comparable. Table 5.1 shows the output (annual average) of SWAT model.

Table 2 Comparison of SWAT output of Ghataprabha sub-basin with varying catchment areas

BASIN VALUES	Large basin (CA = >8000 sq km)	Medium basin (CA = > 2500 sq km)	Small basin (CA = > 1000 sq km)
Precipitation (mm)	930.5	964.7	1343.5
Surface runoff (mm)	296.95 (31.93%)	306.88 (31.81%)	641.84 (47.7%)
Lateral soil flow (mm)	0.97 (0.001%)	2.14 (0.022%)	3.68 (0.027%)
GW(shallow AQ) (mm)	111.70 (12.11%)	115.59 (11.99%)	220.88 (16.44%)
Revap(shallow AQ soil/plants)(mm)	7.14 (0.07%)	8.07 (0.083%)	10.86 (0.08%)
Deep AQ recharge (mm)	6.26 (0.06%)	6.51 (0.067%)	12.20 (0.09%)
Total AQ recharge (mm)	125.11 13.56	130.17 13.05	244.00 18.16
Total water yield (mm)	402.81 (43.28%)	416.59 (43.1%)	858.94 (63.95%)
ET (mm)	519.2 (55.79%)	533.6 (55.35%)	461.3 (34.33%)
PET (mm)	1829.9	1919.8	1920.2

Area of basin (Sq.km)	8615.23	2626.78	1005.18

Figure 5.3 shows the variation of runoff in 3 sub-basins varying in size. It is observed that the highest runoff (47.7%) is in the smaller basin which is having highest rainfall. However, in the medium and larger catchments, runoff is found to be almost identical.

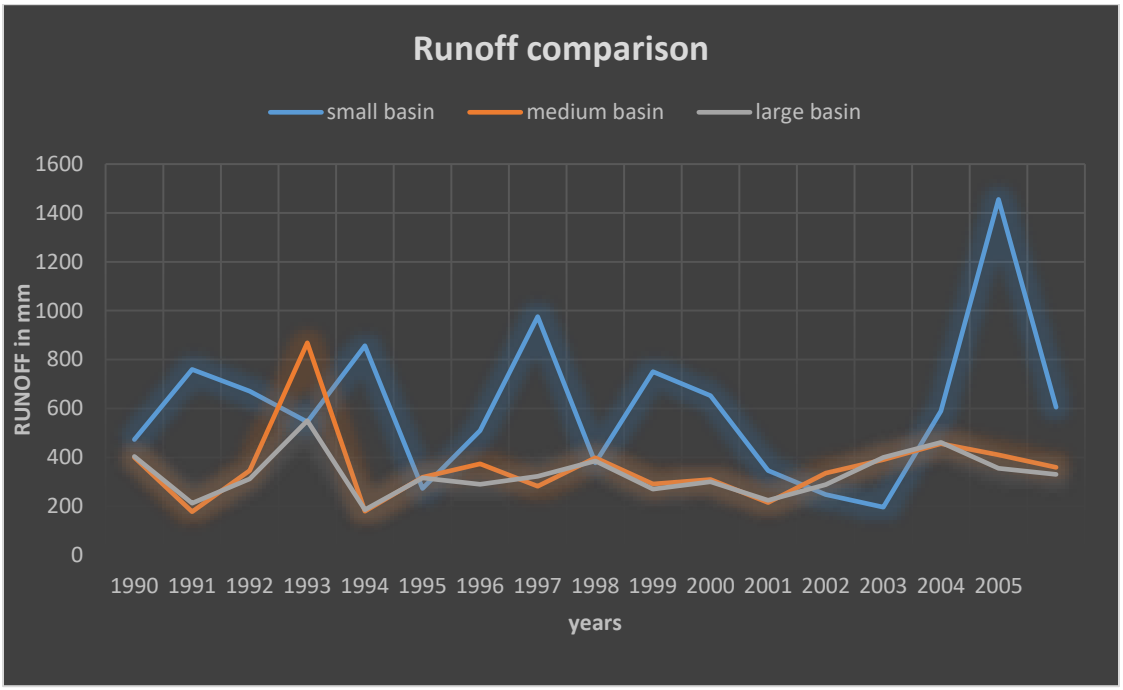


Figure: 4 Comparison of estimated runoff in three sub-basins

Table 2 shows the annual variation of runoff in three catchments. It is noticed that both rainfall and runoff significantly high during 1997 and 2005. Maximum rainfall of 2348 mm and the estimated runoff was 1456 mm during 2005. However, in the medium and larger basin there was no significant increase in the rainfall or runoff. This clearly indicates the role of catchment area and characteristics on runoff.

Table 3 Annual Variation of Runoff in three Catchments.

Year	Rainfall (mm)	Small basin Runoff	Rainfall (mm)	Medium basin Runoff	Rainfall (mm)	Large basin runoff (mm)

		(mm)		(mm)		
1990	1129.15	473.38	1138.52	399.73	1116.54	402.93
1991	1499.19	759.49	648.28	177.17	722.05	211.88
1992	1303.54	671.02	1129.45	345.72	1052.02	312.02
1993	1174.73	544.22	1563.25	868.65	1224.74	549.76
1994	1585.45	856.4	713.28	179.79	712	185.34
1995	697.38	272.93	942.29	317.9	925.96	315.98
1996	1123.74	509.64	972.26	373.67	851.69	288.84
1997	1725.81	976.31	946.51	281.89	998.49	322.16
1998	1007.12	377.72	1089.68	397.84	1029.92	384.49
1999	1381.47	750.75	922.14	290.07	874.58	269.41
2000	1327.22	651.95	1031.81	308.92	984.03	299.77
2001	937.76	346.11	876.12	215.34	887.11	224.5
2002	729	247.9	1020.85	335.66	908.78	288.63
2003	628.37	195.87	1092.54	389.66	1088.24	399.8
2004	1331.3	589.27	1204.52	455.37	1214.19	461.48
2005	2347.91	1455.56	1129.42	409.98	1024.82	354.81
Average	1245.57	604.90	1026.30	359.21	975.94	329.48
Percentage		48.56		35		33.76

Runoff Estimation using SCS CN method:

The runoff was estimated using curve number method. Data pertaining to soil type, texture, organic matter, infiltration rates and hydraulic conductivity were collected from NIH, Belagavi. Curve

numbers were fixed accordingly. Rainfall data was collected from the SWAT India data base. 102 events have been selected from 16 years data (1990-2005). The estimated runoff for each event is shown in Table 5.4.

Table 4 Estimated Runoff using SCS method (small basin)

Events	**Rainfall in mm**	**SCS Runoff in mm**	**Events**	**Rainfall in mm**	**SCS Runoff in mm**	**Events**	**Rainfall in mm**	**SCS Runoff in mm**
1	35.57	0.298	36	35.1	0.2668	71	303.95	102.84
2	65.67	0.574	37	320.45	114.65	72	190.05	123.211
3	210.09	155.622	38	134.02	9.27	73	95.96	22.26
4	375.55	316.97	39	98.53	39.33	74	31.06	0.076
5	303.57	233.478	40	146.28	13.41	75	34.56	0.3
6	71.74	9.66	41	343.01	131.28	76	228.68	53.66
7	21.65	0.091	42	369.2	151.19	77	296.96	98.01
8	65.27	0.539	43	179.83	27.507	78	208.04	106.14
9	57.35	0.068	44	205.65	40.63	79	113.56	3.86
10	31.94	0.087	45	158.5	106.71	80	68.91	28.14
11	77.47	2.06	46	127.62	7.37	81	231.6	55.401
12	397.9	326.48	47	44.2	1.09	82	92.6	20.31
13	599.08	362.416	48	385.93	164.216	83	330.43	121.95
14	298.6	241.46	49	507.32	447.33	84	114.23	4
15	107.27	2.61	50	631.8	570.46	85	49.04	3.96
16	315.82	111.3	51	22.82	0.052	86	227.29	52.85
17	425.67	195.95	52	106.8	2.53	87	175.06	78.87
18	346.78	288.706	53	43.07	0.97	88	105.83	58.82
19	61.7	5.61	54	37.44	0.43	89	41.68	0.81
20	150.34	14.91	55	70.43	1.07	90	91.99	0.556
21	26.84	0.003	56	238.46	58.32	91	67.76	0.77
22	35.73	0.309	57	341.66	283.67	92	364.66	274.25
23	264.55	76.013	58	172.34	76.69	93	290.42	178.72
24	437.78	205.83	59	152.93	15.899	94	419.06	359.95
25	278.24	221.58	60	129.41	79.88	95	152.85	15.86
26	58.24	0.099	61	26.82	3.38	96	58.76	0.12
27	259.44	72.77	62	86.6	0.222	97	43.88	1.06
28	44.28	1.114	63	390.03	167.24	98	418.62	190.249
29	87.41	0.22	64	658.41	529.6	99	940.13	878.12
30	471.19	233.5	65	153.75	102.29	100	450.51	391.05
31	615.24	554.49	66	89.55	0.369	101	475.55	352.45
32	253.64	184.63	67	270.29	79.78	102	173.39	77.53
33	143.24	92.56	68	86.41	0.1724			

34	201.42	58.05	69	244.37	63.16			
35	82.22	0.02	70	494.64	253.26			

From the above analysis, it is evident that the runoff is significantly high during the monsoonal rainfall as compared to the rainfalls occurred during pre-monsoon and post-monsoon periods. The relationship between rainfall events and the runoff is shown in figure 5.5

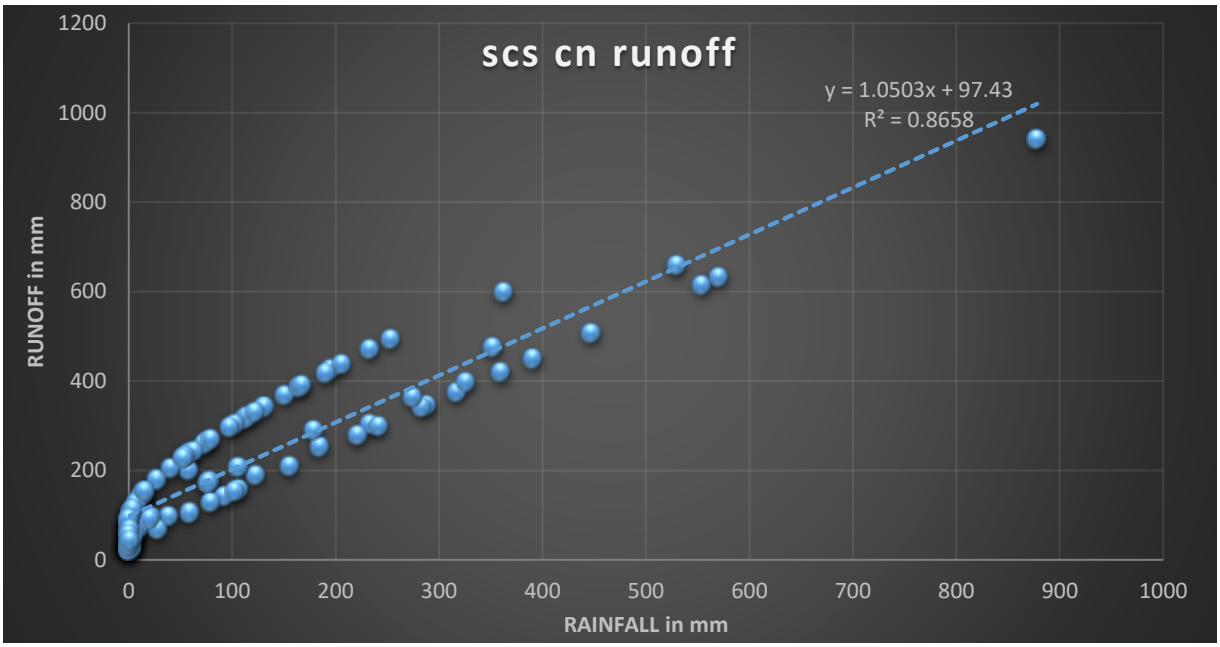


Figure 5 Graph showing Rainfall-Runoff relation of event based.

Runoff Estimation using Conventional Methods

Table 4 shows the runoff estimated by empirical methods such as Inglis, Lacey and Khosla methods for the Ghataprabha sub-basin up to Daddi (small basin). The results obtained by these methods are compared with the SWAT output. The runoff value estimated by SWAT model varies between 31% and 62% with an average of 45.91%. According to Inglis formula, the surface runoff vary from 36% to 67% with an average runoff of 57.57% . Lacey's methods showed variation between 26% and 57% and average is 39.92%. However, the runoff estimated by Khosla's method deviated far off from the predicted runoff using SWAT. Both Inglis and Lacey's method predicted relatively closer values as compared to Khosla's method.

Table 4 Estimated Runoff by SWAT model and Conventional methods

year	Rainfall in mm	Swat Runoff in mm	% Runoff	Inglis Runoff in mm	% Runoff	Lacey's Runoff in mm	% Runoff	Khosla's Runoff in mm	% Runoff
1990	1129.15	473.38	41.92	654.77	57.98	436.32	38.64	1013.90	89.79
1991	1499.19	759.49	50.66	969.31	64.65	682.70	45.53	1383.94	92.31
1992	1303.54	671.02	51.47	803.00	61.60	548.75	42.09	1188.29	91.15
1993	1174.73	544.22	46.32	693.52	59.03	465.00	39.58	1059.48	90.19
1994	1585.45	856.4	54.01	1042.63	65.76	744.03	46.92	1470.20	92.73
1995	697.38	272.93	39.13	287.77	41.26	195.29	28.00	582.13	83.47
1996	1123.74	509.64	45.35	650.17	57.85	432.95	38.52	1008.49	89.74
1997	1725.81	976.31	56.57	1161.93	67.32	846.44	49.04	1610.56	93.32
1998	1007.12	377.72	37.50	551.05	54.71	362.23	35.96	891.87	88.55
1999	1381.47	750.75	54.34	869.24	62.92	601.20	43.51	1266.22	91.65
2000	1327.22	651.95	49.12	823.13	62.01	564.55	42.53	1211.97	91.31
2001	937.76	346.11	36.90	492.09	52.47	322.03	34.34	822.51	87.71
2002	729	247.9	34.00	314.65	43.16	210.72	28.90	613.75	84.19
2003	628.37	195.87	31.17	229.11	36.46	163.07	25.95	513.12	81.66
2004	1331.3	589.27	44.26	826.60	62.09	567.29	42.61	1216.05	91.34
2005	2347.91	1455.56	61.99	1690.72	72.00	1331.29	56.70	2232.66	95.09
Avg	1245.57	604.90	45.91	753.73	57.57	529.61	39.92	1130.32	89.63

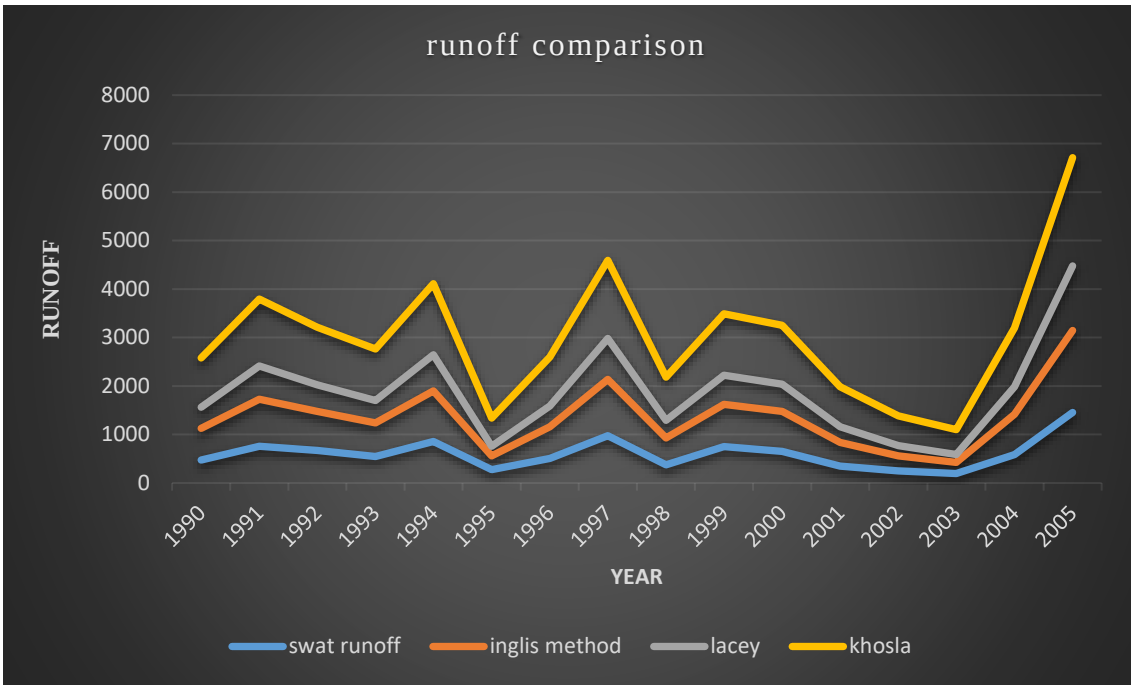


Figure 6 Comparison of Runoff estimated by different methods

Figures 7, 8, 9 and 10 show the relationship between rainfall and runoff estimated by SWAT model, Inglis method, Lacey formula and Khosla's method respectively.

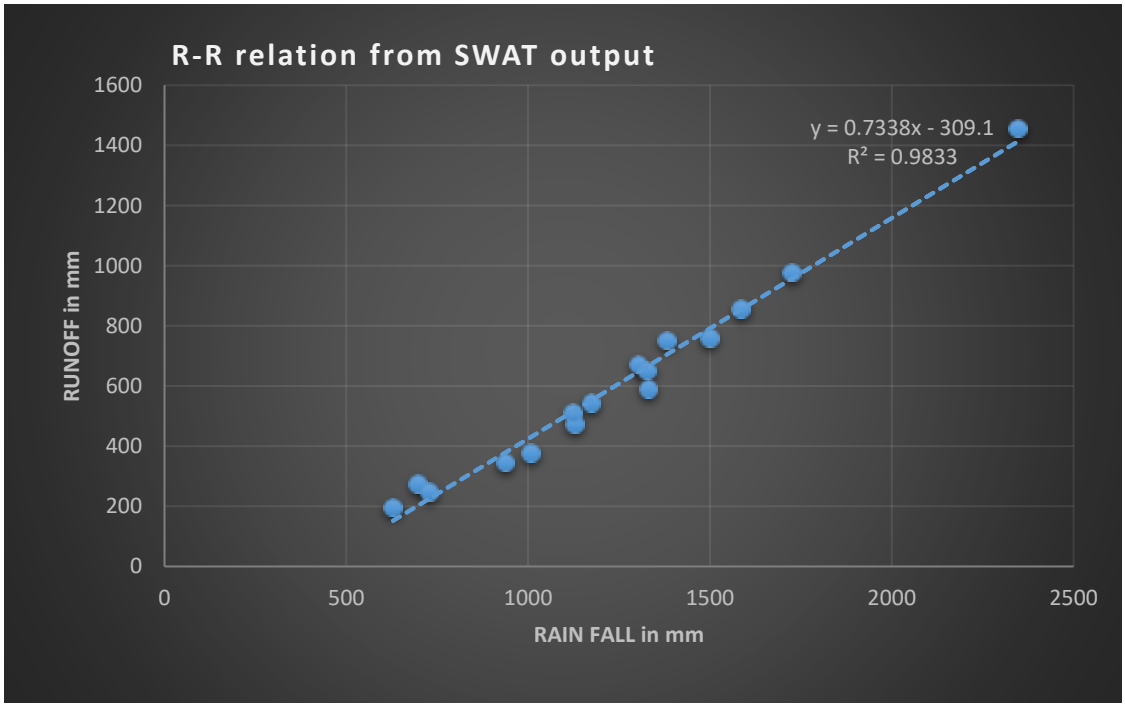


Figure 7 Rainfall – Runoff Relation from SWAT output

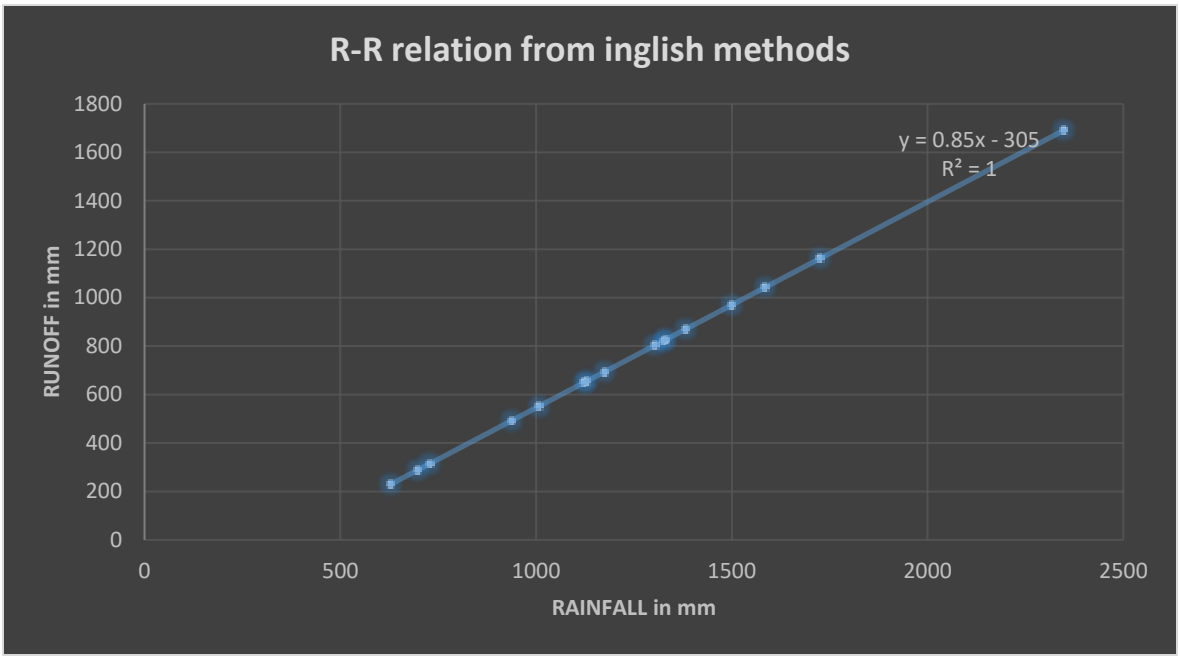


Figure 8 Rainfall Runoff Relation (Inglis method)

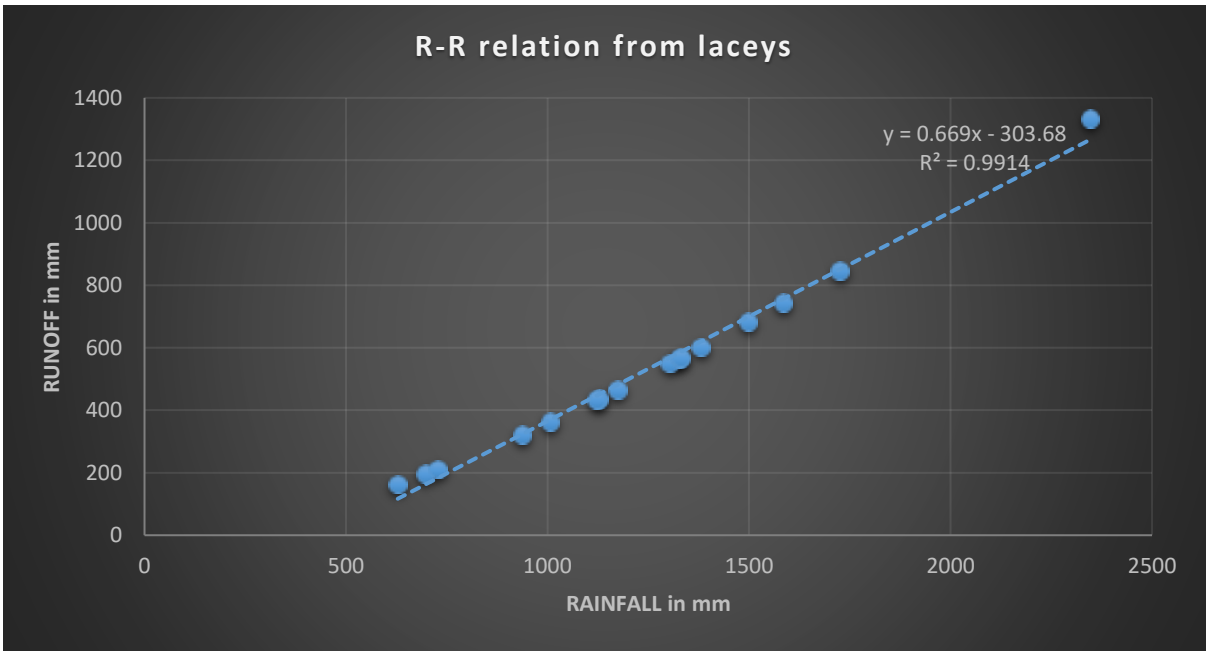


Figure 9 Rainfall Runoff Relation (Lacey's method)

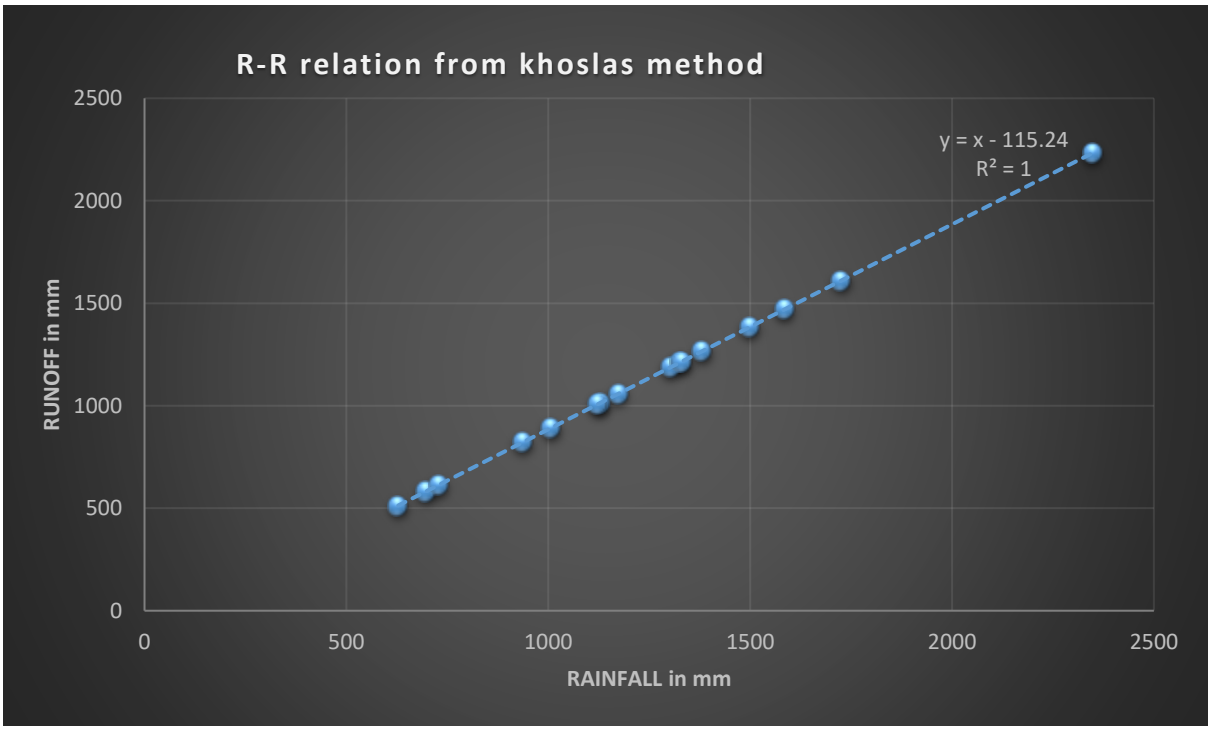


Figure 10 Rainfall Runoff Relation (Khosla's method)

Groundwater Recharge Estimation using ArcSWAT and Conventional methods

Table 6 illustrates the mean of annual rainfall, runoff, evapotranspiration and recharge during 1990 to 2005. Groundwater recharge and surface runoff increases and decreases with precipitation and they show the same trends throughout the years. However, evapotranspiration shows a constant trend throughout the years. This is not unexpected since ET is a function of solar radiation, wind speed and daily dew point (Linsley et al. 1982).

Table 6 Estimated Ground water recharge using SWAT model and Conventional methods

Year	Rainfall in mm	GW R in mm	% Recharge	Chaturvedi (mm)	% Recharge	Krishna Rao (mm)	% Recharge
1990	1129.1	218.7	19.37	205.2	18.17	204.14	18.07
1991	1499.1	274.1	18.28	236.4	15.76	292.92	19.53
1992	1303.5	227.9	17.48	224.7	17.24	257.422	19.74
1993	1174.7	217.9	18.55	225.8	19.22	258.57	22.01

1994	1585.4	305.7	19.28	252.7	15.94	346.71	21.86
1995	697.38	94.56	13.55	162	23.22	110.915	15.90
1996	1123.7	225.0	20.02	223.2	19.86	252.46	22.46
1997	1725.8	283.7	16.43	256.0	14.83	358.15	20.75
1998	1007.1	195.3	19.39	197.1	19.57	184.132	18.28
1999	1381.4	271.5	19.65	242.8	17.57	312.94	22.65
2000	1327.2	230.1	17.34	224.4	16.90	255.795	19.27
2001	937.76	178.9	19.07	182.8	19.50	151.66	16.17
2002	729	130.2	17.86	162.0	22.22	110.83	15.20
2003	628.37	84.79	13.49	143	22.75	79.87	12.71
2004	1331.3	289.5	21.75	221.4	16.63	247.56	18.59
2005	2347.9	451.5	19.23	299.2	12.74	672.455	28.64
Avg	1245.57	230	18.17	216.19	18.26	256.03	19.49

From the analysis, it is observed that the groundwater recharge varies from 13% to 22% with an average of 18%. Interestingly, both Chathurvedi formula and Krishna Rao methods also shows similar recharge values. This clearly demonstrates the applicability of ArcSWAT model in predicting groundwater recharge.

The second goal in this study was to assess the correlation between the groundwater recharge and precipitation. Figures 11,12, 13 show the relationship between rainfall and groundwater recharge.

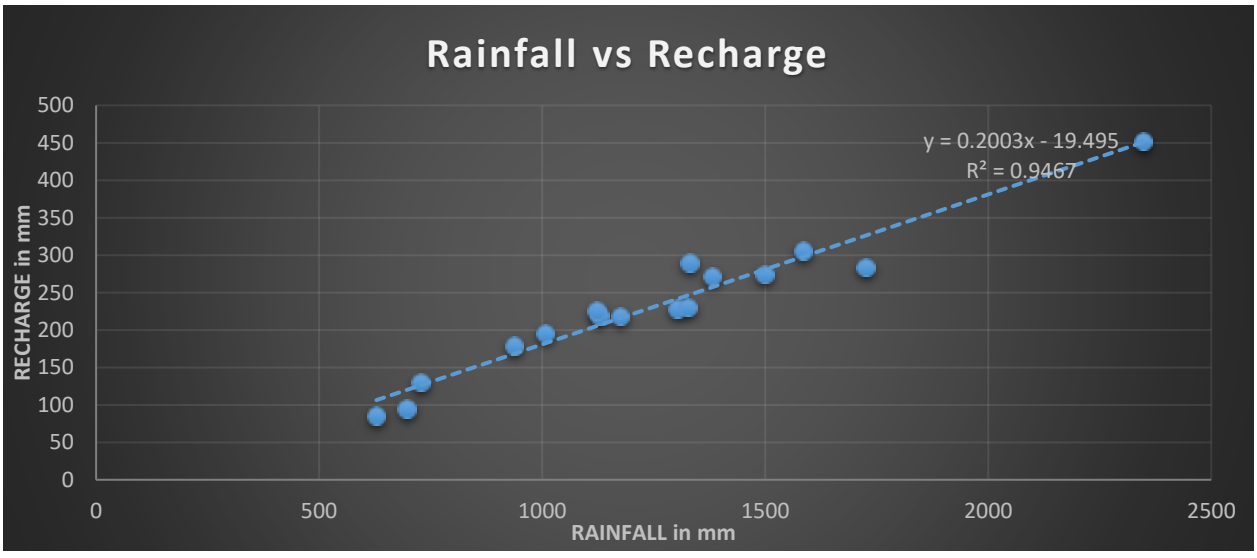


Figure 11 Rainfall-Recharge Relation (SWAT output)

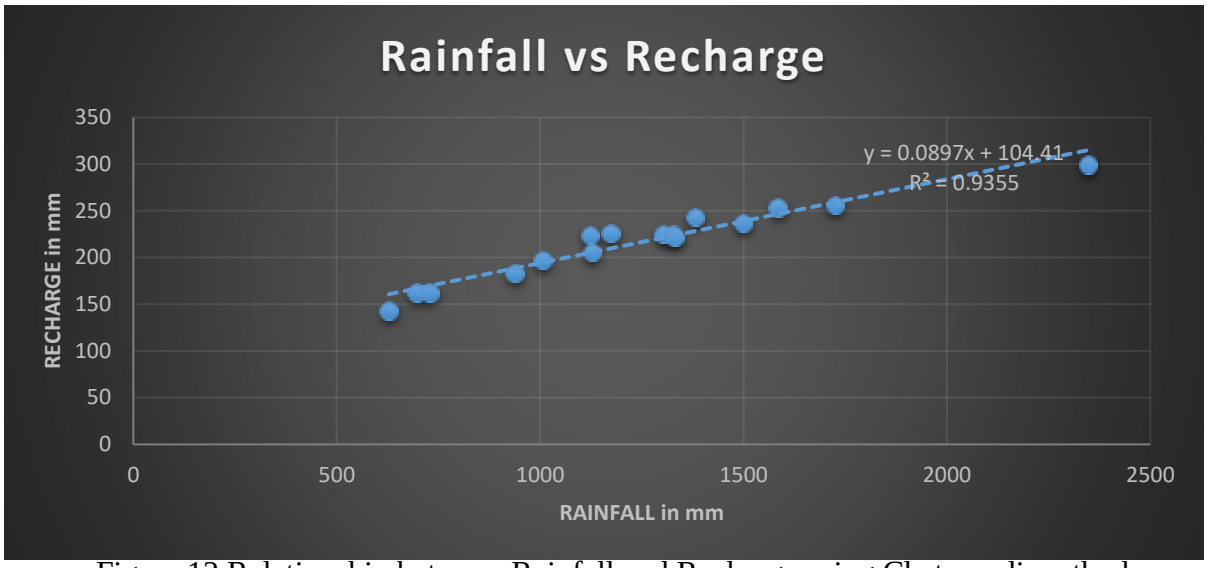


Figure 12 Relationship between Rainfall and Recharge using Chaturvedi method

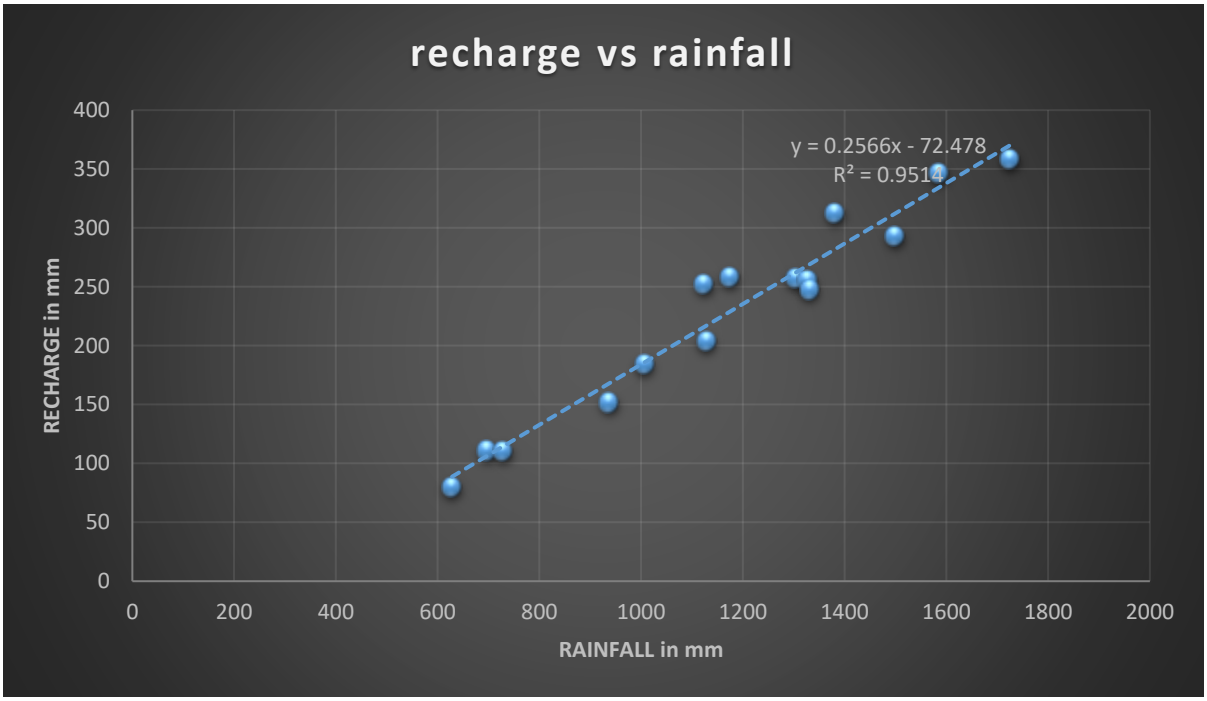


Figure 13 Rainfall Recharge Relation. (Krishna Rao's method)

In all the above methods, the regression coefficient R^2 values vary between 0.93 and 0.95. This substantiates that the well developed regression equations are also quite efficient in estimating the groundwater recharge.

The following are the important sites were springs are distributed and used for water supply. S

1. Kormalwdi 2. Devalkadilwadi 3. Masure 4. Nerur K Nerur 5. Devasu 6. Sawarwad 7. Kalmbist 8. Shirshinge.

Investigations were carried out in the above areas to identify, demarcate and to understand the socio-economic importance of the springs. It was noticed that the above villages are fully fed by springs for both drinking and agriculture purposes. In each village the population is about 500-800.

Table 7. Values of the Concentrations (mg/l) obtained by analysis

Samples	Chlorides	Alkalinity	Acidity	Hardness
Bore well 1	11.91	180(HCO^{3-})	0	76
Bore well 2	37.72	308(HCO^{3-})	16	32
Bore well 3	13.92	200(HCO^{3-})	24	124
Bore well 4	13.9	332(HCO^{3-})	12	96
Spring water 1	9.92	40(CO^{3-})	2	40
Spring water 2	9.92	20(HCO^{3-})	2	0
Spring water 3	0	30(OH^{-})	2	90
Spring water 4	0	20(HCO^{3-})	12	0
Spring water 5	9.92	30(HCO^{3-})	2	40
Spring water 6	9.92	30(HCO^{3-})	12	30

Table 8: Different Parameters for samples collected.

Samples	pH	Conductivity (µS/cm)	TDS (mg/l)
Bore well 1	7.69	800	560
Bore well 2	7.33	800	480
Bore well 3	7.47	120	78
Bore well 4	7.35	190	133
Spring water 1	9.31	78	49
Spring water 2	8.94	40	22
Spring water 3	9.23	39	24
Spring water 4	8.74	48	32

Spring water 5	8.30	41	28
Spring water 6	8.33	38	26

Conclusions

Detailed investigations on springs of Western Ghats in parts of Maharashtra (Koyna region) have been carried out by Naik et al (2002). They classified the springs of the Western Ghats as contact springs (89%) and fracture springs (11%). However, because the emergence of groundwater in the form of springs is largely controlled by lithology and the resulting water-bearing properties of the formations, a new classification scheme is proposed that classifies the springs on the basis of their source aquifers and nature of emergence. Thus, contact springs may be further classified into four different categories – 'laterite springs','talus springs', 'vesicular basalt springs' (or 'vb springs'), and 'massive basalt springs' (or 'mb springs').This new classification could also be applied to similar basaltic terrains elsewhere in the world.

The chemical concentrations of the spring waters are heavily dependent on the lithological compositions of the source-aquifers and the residence time of groundwater in these aquifers. The waters are dominated by alkaline earths (Ca2+, Mg2+) and weak acids (HCO3–, CO32–),and are mostly calcium type (84%) and calcium–magnesium type (10%). Chemical qualities of the spring waters are well within the ISI (1983) and WHO (1998) drinking water standards, except for that of iron (ISI) in about40% of the samples.

Authors strongly emphasized that the springs of the Western Ghats be tapped effectively for the benefit of humankind. However, it mustbe remembered that they also sustain the life of thousands of plants, animals and other organisms and that the diversion/development of these springs would greatly affect these life forms. Moreover, as these springs flow downhill, they also recharge the lower aquifers, thus enhancing the life of the existing springs at lower levels. Therefore, depending on the situation, a trade-off must be made considering local needs and downstream users. Emphasizing only local human needs might lead to severe intercommunity conflict and negative environmental consequences.

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