THEME 1

Forest Hydrology

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Forest Hydrology Initiatives and Current Challenges in a Changing Climate in the Philippines

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1.1 INTRODUCTION

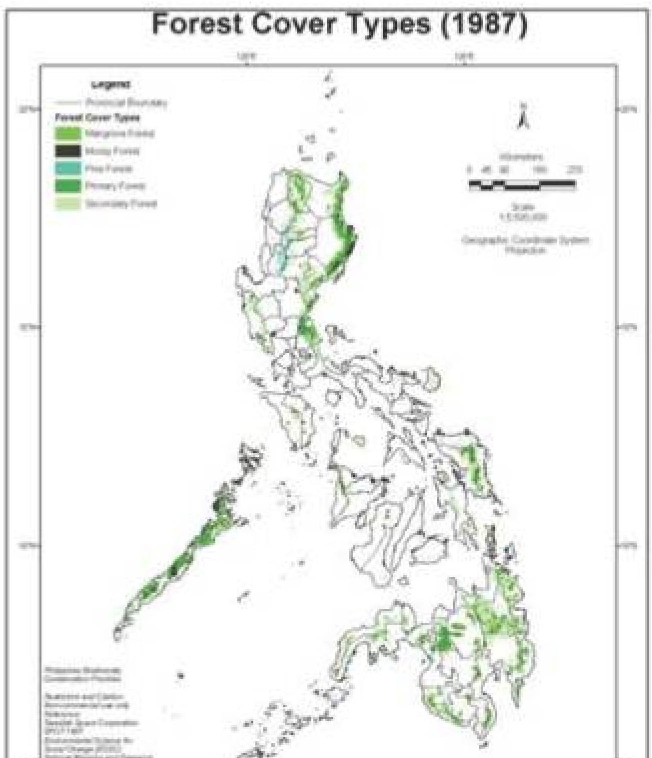
The Philippines' total land area of about 30 million hectares is legally classified as alienable and disposable (A&D) forestland. As of 2012, forestlands covered 52.7 per cent of the country's total land area, and plays critical ecological, economic, social and cultural roles at the local, regional and national scales. Sustaining these roles depends, in part, on knowledge of the dominant hydrological processes and properties of the forest landscapes. Based on 2010 satellite imageries, the total forest cover of the Philippines is estimated at 6.84 million hectares (FMB, 2014). This is only about half of what was existing about half a century ago. To conserve and protect the forest, the old growth dipterocarp forest areas have been placed under the National Integrated Protected Areas Systems (NIPAS) since January 1, 1992. Thus, logging in these areas has been prohibited since then. Ecologically, the forest gives invaluable environmental benefits by serving as an effective protector of the soil and regulator of water flows and carbon cycles; and by providing habitats for a multitude of animal and plant life. Careful protection of the forest is, therefore, of utmost importance. Its destruction is known to have far-reaching effects such as: depletion of potential resource for wood and habitat; threatening of the capacity of the biosphere to regulate atmospheric and hydrospheric cycles; loss of wildlife habitat and species; soil erosion; siltation; flooding and landslide. Deforestation, along with burning of hydrocarbons, is also known to contribute to the CO_2 build-up in the atmosphere.

Hydrological processes at different scales play an important role in maintaining the biodiversity, landscape heterogeneity as well as fresh water supply for domestic and industrial uses. Research in forest hydrology is recognized as the key to understanding the physical, biological, and chemical processes in a watershed and has significance to watershed management. Therefore, forest impact on the water cycle and sediment production has been the major subject in hydrology and water management research since the early 1970s. Facing several environmental problems particularly in the post-logging era (1980s), nationwide reforestation programmes were launched by the government with support from various funding institutions. Effects of forest plantation establishment on hydrologic processes were then carried out by various institutions. This paper presents a brief historical development of forest hydrology research in the Philippines, including some major findings. It also presented the future challenges of long-term forest hydrological and ecological studies that are crucial to clarify the forest influence on hydrological regime under different geographic and forest conditions particularly in relation to the Philippine national greening programme.

1.2 METHODOLOGY

Literature search on the state of the Philippines forests and past initiatives on forest hydrology was conducted through library research and collation of research reports. Research reports included past researches of the then Forest Research Institute to the present Ecosystems Research and Development Bureau. Completed studies from various research institutions were also retrieved. Review of current programmes of the De-

Figure 1.1: Forest types in the Philippines



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partment of Environment and Natural Resources (DENR), the government agency mandated to manage the environment and natural resources (ENR) was also conducted. Of particular focus were those programmes with high relevance to the hydrology of a landscape.

1.3 RESULTS AND DISCUSSION

1.3.1 Forest cover

Philippine forests are classified into different types, namely dipterocarps, pine, submarginal (dominated by grasslands), mossy and mangrove (Figure 1.1). The dipterocarps make up roughly two-thirds of the total forest cover. Dipterocarps are forest stands dominated by trees of the genera Shorea, Dipterocarpus, Hopea, Parashorea, Pentacme and Anisoptera. These species are located in places with high elevations, particularly in regions where precipitation is high. The dipterocarp forest has been the major source for the wood industry of its raw material supply of lumber, pulp and paper, and other wood-based products.

In 1997, the total area occupied by the dipterocarp forests was 3.5 million hectares of which 804,900 hectares are old growth and the remaining are considered residual forests (2.73 million hectares. Pine forest consists of one genus, called Pinus, belonging to the family Pinaceae, and two species. Pine thrives well in high elevations, usually between 500-2700 metres above sea level (masl). In mining areas, pine is used as mine prop (Table 1.1). It is also used as piles, posts and as raw material for pulp and paper manufacturing. In watershed areas, pine trees provide ideal vegetative cover for soil and water conservation. The mossy forest is of little commercial value but important as a protection forest. A great portion of it in northern part of the country has been cleared for vegetable farming. Grassland on the other hand dominates logged forestland. Mangrove forests in the Philippines in 1988 were estimated at 139,725 hectares.

Of the total Philippine forest cover of 6.84 million hectares, open forest accounted for an area of 4.595 million hectares. The rest of the forest types were as follows: closed canopy forest with total area of 1.934 million hectares and mangrove forest with 0.311 million hectares (Philippine Forests: Facts and Figures, 2014; Table 1.2). Current data showed that total forest cover in 2003 decreased by 328,682 hectares (4.59 per cent); that is from 7,168,400 ha in 2003 to 6,839,718 ha in 2010. The closed, open and mangrove forests incurred the following national percentage changes: 24.48 per cent, 5.39 per cent and 25.54 per cent, respectively (Table 1.2).

1.1.2 Forest Hydrology Research

The beginning of scientific research on forest hydrology in the Philippines dates back to the early 1970s with the establishment of hydrological gauging stations in selected watersheds. Under the research division of the then Bureau of Forestry and funding support by United Nations Development Program (UNDP), the hydrology of different vegetation types in Philippines forestland was initiated. Paired catchment approach was established to study the hydrology of dipterocarp forest, pine forest, mossy forest, and grassland watersheds in selected watersheds of the country. Weather stations and weirs/flumes were installed on these watersheds to study the climate, streamflow and erosion rates. Rainfall redistribution under forest canopy was also evaluated to study throughfall, stemflow and infiltration. Plot studies were also

Table 1.2: Forest cover of the Philippines by Region, 2010

Region	Forest *(Area in hectares)*			
	Total	Closed	Open	Mangrove
CAR	773,191	255,552	517,640	
Region 1	124,477	18,390	105,060	1,028
Region 2	1,044,507	485,262	553,344	5,902
Region 3	520,598	225,352	294,291	955
NCR	2,214		2,098	115
Region 4A	269,656	69,544	181,175	18,937
Region 4B	915,664	97,810	744,530	73,324
Region 5	208,015	39,646	143,416	24,953
Region 6	187,319	67,167	110,146	10,006
Region 7	62,065	11,464	35,798	14,804
Region 8	514,464	45,948	426,863	41,654
Region 9	176,918	29,906	120,488	26,523
Region 10	377,858	173,962	197,517	6,379
Region 11	428,716	160,083	265,754	2,879
Region 12	249,050	54,247	193,202	1,601
Region 13	683,112	99,812	557,402	25,898
ARMM	301,894	99,889	146,431	55,574
TOTAL	**6,839,718**	**1,934,032**	**4,595,154**	**310,531**

Table1.1: Pine forests of the Philippines in 1981 and 1997

Region/Forest	1981			1997		
	Closed	Open	Total	Closed	Open	Total
Region 1/CAR	129,203	101,231	230,434	90,300	84,700	175,000
Region 2	3,886	9,806	13,692	33,200	18,100	51,300
Region 3	686	882	1,568	400	500	900
Region 4	-	899	899	-	700	700
TOTAL	**133,775**	**112,818**	**246,593**	**123,900**	**104,000**	**227,900**

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Figure 1.2: Infiltration rate measurement using the double ring infiltrometer

Figure 1.3: Stemflow gage installed on the experimental Benguet pine tree

Figure 1.4: Natural vegetation of secondary dipterocarp forest watershed (left); Imperata dominated grassland watershed (right).

established in many short-term studies by research institutions. These studies provided an early understanding on the hydrology of watersheds under different vegetative types.

1.3.2.1 Rainfall and Interception

Forest canopy provides the first interface through which forest impacts hydrological cycle within the forest ecosystem. Generally speaking, forest canopy interception varied with both the forest ecosystem type, the development stage of the system and the precipitation pattern in a given river basin. Veracion (1982) reported that rainfall interception in heavily thinned Benguet pine plots (70 per cent) produced significantly higher net rainfall (throughfall plus stemflow) than moderately thinned (50 per cent), lightly thinned (30 per cent) or undisturbed plots (no thinning). Control/undisturbed plots produced the highest water loss value followed by moderately and lightly thinned plots. Rainfall interception loss was higher in the control plots because of their denser canopy. Throughfall and stemflow did not vary significantly with different thinning intensities. Positive and linear relationships between throughfall and gross rainfall and between stemflow and gross rainfall were also noted.

Pine forest in Belis, Atok, Benguet has an average yearly rainfall of 2,604.57 mm while temperature and relative humidity is 22°C and 32 per cent, respectively. Pine trees ranged from 10-15 m in total height and from 15-35 cm in DBH. The forest stand was about 20-25 years old. The total rainfall at the two other study sites over the 5-year period ranged from 2,979.60 mm to 4,189.50 mm with a mean of 3,944.80 mm for the mossy forest, while in the Benguet pine, it ranged from 3,206.38 mm to 5,983.19 mm with an average of 3,689.88 mm. In mossy forest, fogdrip ranged

Figure .1.5: Water tight concrete trough constructed at the lower end of the plot for collecting surface runoff

from 264.38 mm in the south exposure areas to 476.46 mm at the west exposure portion of the watershed. Intermediate fogdrip average values were produced by the north and east exposure having 381.55 mm and 348.96 mm, respectively (Mamanteo and Veracion, 1981).

A study by Diaz (1999) stated that water loss through interception was influenced by the amount of rainfall and the density of the crown area. It was also observed in secondary dipterocarp forest the average rainfall interception is 58.9 per cent. An inherent characteristic of dipterocarp forest influenced the hydrologic response of a watershed through its modifying effect in the storage and utilization of rainfall and its role in regulating the flow regime.

1.3.2.2 Streamflow, Erosion and Sedimentation

The Forest also affects streamflow characteristics in various ways particularly the peak flow rate, total discharge and the quality of the runoff. The accumulated effects of forest conditions and various watershed management measures are reflected in the watershed's stream discharge. Forest influence on peak flow rate and total discharge is one of the most concerns to scientists and decision-makers particularly in flood prone regions of the Philippines. Baconguis and Jasmin (1983) reported that mean monthly streamflow differed significantly despite the similarity in rainfall, primarily due to the inherent characteristics of the area (topography, geology, soils) and the vegetation types storing and utilizing rainfall and regulating streamflows. The secondary dipterocarp forest had 55.05 per cent more streamflow than the grassland watershed; the mossy forest watershed has 294.10 per cent more streamflow than the grassland; and the mossy forest had 154.18 per cent more streamflow than the secondary dipterocarp forest. Mean annual streamflow coefficients were 0.1812, 0.2762 and 0.6250 for grassland, secondary dipterocarp forest and mossy forest watershed, respectively. Baconguis (1980) also reported that of the total rainfall in dipterocarp forest, 62 per cent appeared as streamflow, 32 per cent as evapotranspiration and 6 per cent as groundwater recharge. Daño (1994) meanwhile reported that three years after reforestation of grassland watershed with *Gmelinaarborea, the* annual streamflow started to decrease. The decrease in mean annual streamflow was about 186 mm. Reforestation was also found to reduce annual sediment yield by 52 per cent compared to that of an annually burned grassland watershed.

In a study of effects of burning of forestland, Costales (1980) mentioned that the monthly total surface runoff in burned areas ranged from 2.19 mm to 113.28 mm and 1.67 mm to 72.88 mm in the unburned areas. Average monthly surface runoffs for burned and unburned areas were 40.93 mm and 24.89 mm, respectively. The high average monthly surface runoff in burned areas could be due to the amount of rainfall received, the development of re-growths and the available soil moisture.

According to Florido (1981), in his work on thinning of a Benguet pine stand,that there is no significant difference in surface runoff under various thinning intensities. Control plots had the lowest surface runoff during the less rainy months, but had higher surface runoff during the months of continuous and prolonged rainfall. Sediment yield did not vary significantly under the different thinning intensities. Controlled plots gave the highest sediment yield due to high surface runoff.

In another work on thinning in a pine forest stand, Veracion (1982) stated that surface runoff and sediment production varied with stocking levels. Based on all storm events and sizes, the heavily thinned plots significantly produced higher surface runoff and sediment yields than the lightly thinned and unthinned plots. No significant differences in surface runoff and sediment yields were observed between the heavily thinned plots and the intermediately thinned plots and between the lightly thinned plots and the control plots.

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Comparison on various species as protective cover in forestland showed that Moluccan sau was the best protective cover, yielding only 1.044 l/m² total runoff and 1.62 gr/m² sediment yield. It was followed by mixed secondary stand with 3.457 l/m² runoff and 19.68 gr/m² sediment yield, dipterocarp with 5.192 l/m² runoff and 33.75 gr/m² sediment yield and Kaatoan Bangkal with 10.418 l/m² runoff and 118.98 gr/m² sediment yields (Serrano *et al.*, 1974).

At the secondary dipterocarp forest, 85.8 per cent of the variation in surface runoff was due to the combined effects of rainfall amount, rainfall intensity and soil moisture deficiency. Rainfall amount was found to be the most important factor in the variation of surface runoff. For the grassland watershed, similar variables were responsible for 94.7 per cent of the variation in surface runoff. Surface runoff, rainfall amount, rainfall duration and soil moisture deficiency accounted for 90.6 per cent and 76.9 per cent of the variation in sediment production in the secondary dipterocarp forest and grasslands watersheds, respectively (Daño, 1983). Surface runoff; rainfall amount and rainfall duration were highly correlated with sediment production in both watersheds. Surface runoff and sediment production were higher in the grassland watershed than in the secondary dipterocarp forest.

Earlier works in a grassland dominated forestland showed that undisturbed burned plots had the highest increase of surface runoff than moderately grazed plots. Runoff was greatly reduced in the moderately grazed and protected plots. Although the undisturbed burned plot had the greatest increase in surface runoff, it had the least sediment yield. With cultivation on slope, the frequency of runoff increased with decreasing amount of rainfall (Jasmin, 1976). In logged area, analyses showed that there were no significant differences in soil erosion among slopes of varying degrees under the vegetative conditions. There were significant differences only between the unlogged and logged areas (Orallo, 1980).

Soil erosion, sediment transportation and deposition into the reservoir caused great loss of capacity and economic value. A total of 154 priority watersheds support water structures and soil erosion management is a major research and development concern. The importance of these watersheds for sustainable water supply is emphasized in the Forestry Master Plan. The Master Plan provide for the updating of watershed resources. At present, 99 watersheds have an integrated watershed management plans while 114 have a completed watershed characterization report (FMB, 2013). Management of watersheds is critical in promoting the sustainability of all the natural resources in the watersheds.

1.3.3 Challenges of Forest Hydrology and Watershed Management

A major challenge to forest hydrologic research in the country is represented by repeated questions on the role of forests in regulating water. As the national scale reforestation activities continue, the hydrologic roles of the forests will be of great concern among decision-makers and the public. Does forest mitigate water-related disasters, and as to what extent in particular in the face of climate change? How does forest impact the peak flow; does it reduce flooding as forest cover increased? In regions of high water demand, does forest improve water availability? The answer to these questions is very important in the context of National Greening Program (NGP). NGP addresses the priority programme thrusts of the country such as poverty reduction, resource conservation and protection, productivity enhancement and climate change mitigation and adaptation. The programme specifically seeks to plant 1.5 billion seedlings in 1.5 million hectares of public lands nationwide in six years, from 2011 to 2016. It seeks to improve water quality in rivers, reduce the potential for flooding, soak up carbon dioxide out of the atmosphere, and lay the foundation for an expanded wood-products economy. As of 2013, the total area planted was 683,069 hectares resulting to a 46 per cent accomplishment of the programme's total target area.

Long-term monitoring of changes in the hydrological regime particularly in water yield, peak-flow, and low-flow are critical for testing existing principles regarding forest and water relations. Forest management particularly reforestation will have accumulated effects with other land-uses and measures on the watershed processes. To evaluate the hydrological effects of forest management measures at basin scale, the use of physically based hydrological model with the GIS support are crucial especially with the stoppage in monitoring of experimental watersheds starting in the late 1990s. Hydro-meteorologic extremes, steep topography, weak geologic formations, earthquake faults and highly erodible soils are factors contributing to the frequent occurrence of natural disasters particularly landslides. Therefore, watershed management for disaster mitigation and sustainable development is a matter of great importance needing strong public and private support.

Watershed management planning basically needs data or information on the biotic, physiographic, hydrologic and climatic characteristics of the watershed. The information would serve as guide in prescribing appropriate management strategies to attain the desired objectives. Some critical watersheds supporting water infrastructures have been characterized but data on watershed hydrology needs improvement. At present, climate change is the greatest uncertainties, as it is likely to magnify existing impacts and threats. Assessment of impacts of climate change on flooding and water availability provided initial information on changes of hydrologic behaviour of watershed brought about by the changing rainfall pattern, but much need to be done. Basin scale forest hydrological modelling is also a challenging issue in hydrology and watershed management. Extrapolating watershed hydrology results to the regional or basin scale, considering the complex interaction of both biotic and abiotic factors that influenced hydrological dynamics is a great challenge. To date, upscaling of research results is wanting although its importance has long been widely recognized.

1.4 CONCLUSION

The current understanding on influence of forest vegetation on watershed hydrology is mostly based on limited studies in experimental watersheds and plot research studies. A lot of current information is based on studies conducted in foreign countries. The complexity of hydrological processes such as scale dependence, nonlinear behaviour and variability of hydrological environment makes it very difficult, to extrapolate the information from one watershed to another or from one scale to another. We need to re-invest in basic hydrologic research to improve our understanding on the linkages between various land uses and the variables of interest at the watershed scale. Understanding the complex pathways by which subsurface flow moves on hillslopes and its interactions to other hydrologic processes is badly needed. Like other Asian countries, our challenge is to apply the principles to understand how the hydrologic processes will respond to the many forms of change particularly land use and climate change.

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2

Effects of Patterns and Process of Vegetation Restoration on the Precipitation, Water and Sediment in Small Watershed

Jia Luo, Canming Zhang, Yuxin Tian, Xiaoling Zhou, Nan Yang, and Jianhua Chen

2.1 INTRODUCTION

Due to the differences of natural and geographical conditions, research methods, the measure of study area and climatic characteristics all over the world, and the perplexing relationship between forest vegetation and watershed hydrology, at present the influence of forest vegetation on hydrological process has not yet come to a unified conclusion at home and abroad.[1] The role and influence of restoration and reconstruction of the vegetation on small watershed water sediment relationship is the concerns of researchers.[2-4] In this paper, the small Nuer-Zhai watershed is the research object during the process of vegetation restoration and reconstruction for the study of small watershed, and variation characteristics of rainfall-runoff-sediment have been investigated. The study will provide a scientific basis for carrying out large-scale ecological environment construction in Hunan province.

The Nuer-Zhai small watershed is located in Wulei ecological public welfare forest, about 12 km northwest away from the Cili County. It is one of the small second order tributaries of Lishui River and flows roughly from east to west, which positions in the low mountain area of Wuling mountain range. The elevation of the hydrological station of the ditch outlet is 210 m above sea level. The highest peak is 917.4 m and the main ditch is about 1.2 km long. The total monitor area by this hydrological station of the ditch outlet is 2.81 sq.km. The land use condition of small watershed of the main ecological forest is shown in Table 2.1.

2.2 METHODOLOGY

Investigation on the runoff of this Nuer-Zhai small watershed was carried out in the Nuer-Zhai ecological benefit positioning monitoring station which was established in 1998. A 2.5m-wide Parshall flume has been placed in the ditch outlet of this small watershed for investigating the runoff by located observation method since the official starting of observation and recording in 1999. The water level is automatically recorded using a water-level recorder. The water samples are picked three times daily. If flood occurs, two more samples are taken before and after flood peak time, respectively. The sediment transport data is determined by measuring the sediment concentration of each sample. The measurements of atmospheric precipitation, temperature, humidity, evaporation, surface temperature, ground temperature, wind speed, wind direction observation, etc., are performed in a standard microclimate observatory within the watershed terrain open area. The area of this observatory is 25 x 25 sq.m.

2.3 RESULTS AND DISCUSSION

2.3.1 Rainfall characteristics of small watershed

2.3.1.1 Interannual variability of rainfall

Affected by atmospheric circulation, annual rainfall of Nuer-Zhai small watershed changed dramatically (Figure 2.1). Rainfall in the wet year in 2002 reached 1985.8 mm, while in the dry year

Table 2.2: Runoff depth in 2000-2004

Year	2000	2001	2002	2003	2004	Average
Annual runoff depth	570.1	412.2	727.6	630	573.2	582.62
Runoff depth in the flood season	434.9	254.5	583.9	496.6	481.9	450.36
Runoff depth in the dry season	135.2	157.7	143.7	133.4	91.3	132.26

Table 2.1: The land use condition of small watershed of main ecological forest (hm^2)

Year	Woodland	Paddy field	Arid land	Vegetable plot	Channel water area	Road	Housing site	Barren hill	Total
2000	138.11	4.13	25.12	1.52	38.80	24.52	4.60	44.20	281.00
2003	182.61	4.13	11.62	1.52	38.80	24.52	4.60	13.20	281.00
2007	202.32	4.13	5.07	1.54	38.80	24.52	4.62	0	281.00

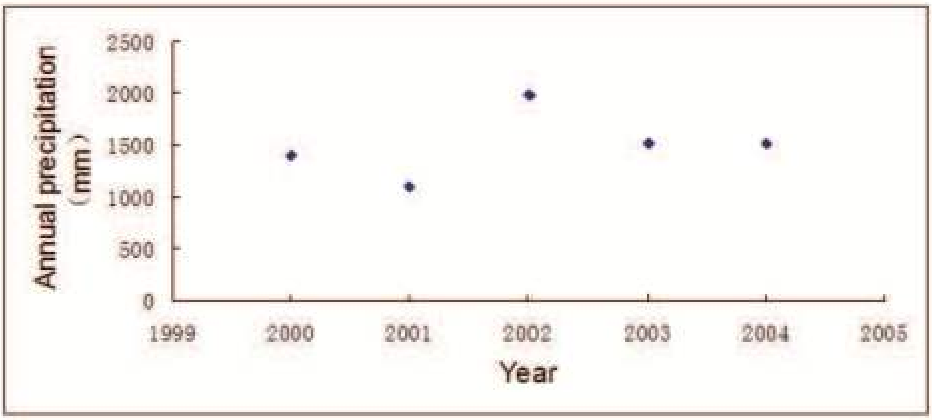

Figure 2.1: Trend of annual precipitation

in 2001, it was only 1095.7 mm. And the difference between the two is 890.1 mm.

2.3.1.2 Annual distribution of rainfall

Monthly rainfall distribution is extremely uneven in the small watershed with large concentration mainly in the flood season (April to August), accounting for 68.5 per cent of its total rainfall volume annually. The maximum rainfall in the small watershed is approximately 74.9 per cent, and the minimum is more than 60 per cent. The monthly distribution trend of rainfall during the year is consistent.

2.3.2 Analysis of the relationship between rainfall and runoff of watershed

2.3.2.1 Characteristic of runoff

According to the measured data of the ditch outlet, the results from 2000 to 2004 are presented in Table 2.2. The average annual runoff depth of the small watershed of Nuer-Zhai is 582.62 mm; runoff depth in the flood season is 450.36 mm, accounting for 77.30 per cent of annual runoff depth; runoff depth in the dry season is 132.26 mm, accounting for 22.70 per cent of annual runoff depth. Based on the coefficient of variation of runoff, annual runoff depth Cv equals to 0.20, Runoff depth in the flood season Cv equals to 0.27; and Runoff depth in the dry season Cv equals to 0.19. This showed that the interannual variation of runoff of small watershed is great, especially during the flood season the fluctuation of runoff, for example, the maximum annual (2002) runoff depth is 2.29 times of that in the minimum years (2001) during the flood season.

2.3.2.2 Effect of rainfall on runoff

Runoff mainly comes from precipitation. Therefore, there is an obvious relationship between runoff and precipitation. The high water period of channel runoff is the precipitation period. Small watershed gully runoff distribution in a year and precipitation tendency is consistent. Small watershed runoff concentration degree is slightly slow to precipitation, the maximum not exceeding 12h, temporal and spatial distribution of precipitation distribution characteristics of runoff decision.

2.3.2.3 Precipitation-runoff model

In order to further study the effect of rainfall on runoff, we take P_i (mm) as the annual rainfall, and Q_i (mm) as the runoff depth to find the relationship between the multiple function expressions. Single factor linear relationship is most closely coupled, $P_i = a + bQ_i$ with a and b as constant. Mathematical model of Nuer-Zhai small watershed and annual rainfall runoff deep were calculated as follows:

$P_i = 115.767\ 8 + 2.7386\ Q_i \quad r = 0.9683 \quad P < 0.01$

Considering small watershed rainfall-runoff models, without considering other factors affecting the runoff condition, the Nuer-Zhai small watershed runoff depth is closely correlated to rainfall. The larger the annual rainfall is, the greater the annual runoff depth is, and vice versa.

2.3.2.4 Decrement of sediment yield

The change law of annual runoff and sediment transport module of Nuer-Zhai small watershed are basically identical. It is mainly because in flood season, storm and floods enforced scour on the surface of the earth. According to observation data, small watershed sediment yield is highly concentrated, and closely associated with precipitation and runoff. Soil erosion of small watershed is mainly caused by the heavy rain of flood season. Sediment transport module of small watershed showed the trend of decline, but the precipitation has a certain impact on it. For example, in 2002 the sediment modulus is larger than that in 2001. This is mainly because the rainfall in 2002 was 1.8 times greater than in 2001. After 1990, with large area, high standards of small watershed ecological ring sediment reduction effect construction, vegetation restoration and reconstruction played a significant effect of sediment reduction. It's supposed that the decrement of sediment yield was zero in 1990.

2.3.3 Relationships among typical rainfall characteristics of small watershed and forest 2.3.3.1 coverage and the elements of flood

The flood formation of Nuer-Zhai small watershed is mainly caused by heavy rainfall. In order to analyze accurately and scientifically the relationship between the vegetation restoration and the flood, we chose nine typical rainfall flood processes which

Table 2.3: The characters of typical rainfall and flood process of Nuer-Zhai small watershed

Time (Year-month-day)	Forest coverage rate(%)	Rainfall Characteristic value			Flood peak characteristic value				
		Precipitation		Total precipitation (mm·times⁻¹)	The flood originating lag time of precipitation		Flood peak lag time of precipitation		Flood peak discharge
		1 h before	1 h max		(h)	(min)	(h)	(min)	(m³·s⁻¹)
2000-07-19	49.15	7.8	18.8	51.9	2.2	129	15.2	911	3.2994
2001-06-17	54.43	8.7	17.3	57.3	2.3	140	15.6	935	3.2842
2002-05-28	59.71	6.9	18.5	54.1	2.5	151	16.8	1007	3.0377
2003-05-05	64.99	7.1	19.2	51.6	2.6	157	16.9	1013	2.9938
2004-05-10	66.74	10.1	21.5	78.6	2.8	166	17.1	1028	3.0304
2005-06-05	68.49	8.2	19.4	68.1	3.2	191	17.4	1042	2.9138
2006-10-17	70.25	6.7	25.3	57.7	3.5	209	17.6	1056	2.4390
2007-08-22	72.00	9.3	17.6	57.8	3.8	225	17.9	1071	2.2013
2008-08-03	72.55	10.4	21.5	61.5	4.0	238	18.0	1077	2.1562

have been recently formed for the comparative analysis. Small watershed coverage, typical rainfall and flood characteristics are presented in Table 2.3. It showed that in the same circumstances the rainfall process, with the increase of forest coverage rate of small watershed, the flood originating lag time of precipitation and flood peak lag time of precipitation showed a trend of extending, and flood peak discharge displayed a trend of decrease.

2.3.3.2 Forest coverage rate and flooding mathematical model

In order to study the effects of vegetation restoration on flood process, we set up a flood mathematical model of a variety of functions with the forest coverage rate of F(per cent), its flood lag time Hi start (min), the peak flood peak lag time Hi (min) and $W_{i\,peak}$ of the peak flow (m³/s) flood elements. The forest coverage F(per cent) of flood years is closely coupled with linear relationship among flood lag time difference $H_{i\,peak}$(min), flood peak lag time difference $H_{i\,peak}$(min) and peak discharge $W_{i\,start}$(m³/s), respectively. $F_i = a + b\,H_{i\,start\,(peak)}(W_{i\,peak})$, with a and b as constants. When the forest coverage of Nuer-Zhai small watershed increased one point, the time difference of the floods originating extend 4.2892 minutes and flood peak lagged behind rainfall extend 6.9797 minutes, and the peak flow reduced 0.0455 m³/s.

2.4 CONCLUSIONS

1. Annual precipitation is variable in the watershed due to the effects of air circulation. There are obvious differences in precipitation in a year; the main precipitation distributed in flood season (April to August), and the distribution trend of monthly precipitation almost consistence in a year.

2. The evident difference is in annual runoff in small watershed, and the observable difference is in runoff distribution in a year. The concentrating runoff is the main character ofthe changing runoff in small watershed. There is obvious delay and subduction function for the appearance and volume of flood peak by vegetation recovery and rebuilding of small watershed.

3. The annual sediment transport modulus and the changing law of runoff in small watershed is almost consistent. The sediment is concentrated with precipitation and runoff, and the soil erosion in the small watershed is mainly caused by heavy precipitation.

4. With the large area and high standard ecological environment construction of the small watershed, the sediment transport modulus has been dramatically decreased in small watershed in 1990 to 2008. There is an obvious decrease effect of the decrease sediment transport after vegetation recovery and rebuilding.

5. The forest coverage F(per cent) of flood years have closely coupled with linear relationship among flood lag time difference $H_{i\,peak}$(min), flood peak lag time difference $H_{i\,peak}$(min), peak discharge $W_{i\,start}$(m³/s), respectively, $F_i = a + b\,H_{i\,start(peak)}(W_{i\,peak})$, with a and b as constants. When the forest coverage of Nuer-Zhai small watershed increased one point, the time difference of the floods originating extend 4.2892 minutes and flood peak lagged behind rainfall extend 6.9797 minutes, and the peak flow reduced 0.0455 m³/s.

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3

Water Yield Estimation and Temporal Variability for the Major Reservoirs of India

P.K. Gupta, A.K. Dubey, J.G. Patel and R.P. Singh

3.1 INTRODUCTION

Reservoirs store excess rainfall as surface water for meeting the requirements of water during the monsoon and post monsoon periods. This stored water, known as reservoir, is used for various purposes such as drinking, irrigation, hydropower and industries. Dams play a very important role in the water resources development of the nation. These manmade water holding structures have helped immensely in attaining self-sufficiency in foodgrain production besides flood control and drought mitigation. The Central Water Commission collected and compiled information on storage capacity of major reservoirs, which is vital information for accounting surface water going out of the dam as spillover apart from storage within the system.

Surface water yield is defined as the total water produced as surface runoff within the system such as catchment. Water yield estimation in a catchment is governed by many hydrological parameters, such as rainfall, land use/cover, antecedent soil moisture and soil type. An accurate water yield modelling of catchment will require determination of the spatial and temporal distribution of hydrological parameters. The spatio-temporal variation of these parameters plays a major role in studying the variability of surface water yield production. Remote Sensing, Geographic Information System and advancement of computer technologies have been applied to extract land surface properties at spatial and temporal scales which are very useful input data for hydrological models (Singh and Woolhiser, 2002; Gupta *et al.*, 2008). Using remote sensing data is not only technically viable but also provides a good fit of technologies to maximize the value of available spatial data (Jobin and Pultz, 1997). According to Kite and Pietroniro (1996) benefit/cost ratio ranging from 75:1 to 100:1 can be realized by using remotely sensed data in hydrology and water resources management. Land use/land cover dynamics have the impact on runoff generation process, which influence the amount of surface runoff production. Rainfall is a crucial hydrological parameter, its occurrence and distribution within the catchment is a complex process. Higher intensity rainfall with longer durations can create flooding in the downstream of the catchment. Estimation of surface water yield production is very critical for assessing flood hazards and undertaking reservoir management. Rainfall-runoff models play an important role in understanding the hydrological condition of basin/catchment areas and predicting their behaviour over time. Hydrological model estimated runoff volumes are being used to estimate the total water yield and many water resource applications.

Uniqueness of this study is the delineation of catchments of major water bodies using the power of remote sensing which gives location and extent of all water bodies together due to its synoptic viewing. Spatial locations of water bodies and DEM together have been used to delineate catchments of major water bodies. A conceptual modified curve number model has been used to estimate surface water yield from the catchments of major water bodies as well as river basins. Study has been done with the following objectives;

- Delineation of catchments for the major water bodies and river basins of India.
- Water yield modeling and analysis for the major water bodies.
- Comparative analysis of water yield at different temporal scales for the monsoon period of the year 2012 w.r.t. 2011.

3.2 METHODOLOGY

Hydrological response is governed by a large number of parameters such as terrain, landuse, soil characteristics and the state of the moisture in the soil. The last factor demands a continuous time estimation so as to keep track of the changing moisture conditions and associated effects on other parameters. The curve number model, incorporating some modifications for moisture condition and slope has been used in the present study to carry out the water yield estimation. Windows for analysis such as catchments of major water bodies and rivers have been delineated by processing the DEM and remote sensing derived wetlands. Detailed methodology adopted is presented in Figure 3.2.

3.2.1 Study Area and Data

Major reservoir catchments have been taken as study area. A wetland map at 1:50000 scale, developed under 'National Wetland Atlas: India' project of SAC has been used to identify the water bodies' locations and their extents. A total of 73 major water bodies have been identified based on the water extents having area greater than 5,000 ha (Figure 3.1). These major water bodies along with river catchments have been delineated by processing the DEM. Catchments of major water bodies and river basin scales have been used for the analysis of water yield. Catchment area under the major water bodies is estimated 92.2 M ha. Satellite data derived daily rainfall for the year 2011 and 2012 was downloaded from Climate Prediction Centre (CPC) site

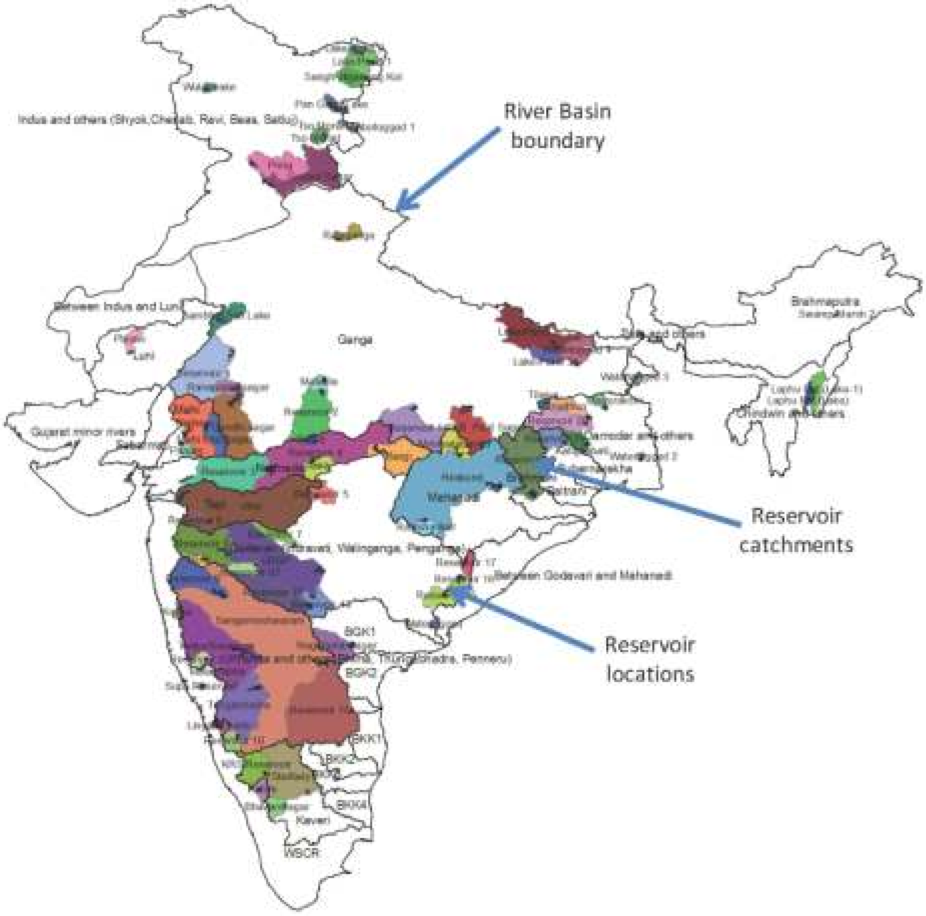

Figure 3.1: Study area showing major river basins along with major water bodies' locations and their catchments

ftp.cpc.ncep.noaa.gov/fews/S.Asia. CPC produces quasi real-time analysis of daily precipitation on a 0.1° latitude/longitude grid over South Asia (70°E-110°E; 5°N-35°N). Daily data from May 1 to September 30 has been used. Average total monsoonal rainfall of 1,360.4 mm and 1,074.4 mm (has been estimated for the year 2011 and 2012, respectively. Monsoonal rainfall deficit is 21 per cent for the year 2012 in comparison to 2011.

In hydrological modeling crop class, vigor is more important than the type of crop cultivated. In general, NDVI is widely accepted and used in many research studies, as it is a good indicator of crop vigor (Zade *et al.*, 2005). Therefore in the present study, existing landuse map (Shefali *et al.*, 2004) has been modified using the NDVI images of SPOT-Vegetation sensor to derive hydrological land cover classes. Soil texture map is taken from Survey of India (SOI, 1978). Fourteen soil textures have been obtained over India. Soil textural map was used to prepare Hydrological Soil Group (HSG) map considering the soil infiltration and drainage characteristics of different soil (A to D; high to low infiltration and low to high runoff). Digital Elevation Model (DEM) from SRTM was used to delineate major water bodies and rivers catchment.

3.2.1.1 Water bodies Catchment delineation

Topography is defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. In this study, 90m resolution SRTM DEM data has been used. Preprocessing of the DEM is one of the important steps needed to be carried out as a first step in automatic extraction of drainage networks and delineation of watersheds/catchments. During DEM generation using the spatial interpolation method, artificial spurious depressions get generated. These depressions or sinks are the cells which do not have neighbours at a lower elevation and consequently, have no downslope flow path to a neighbor cell. Hence for that smoothing, a DEM prior to analysis reduces the size and the number of sinks. In this process, the elevation of sink cells increased until a down slope flow path to an adjacent cell becomes available under the assumption that flow may not return to the sink cell. For delineation of catchment, outlet of the stream was selected and the cells contributing the flow to that stream were marked as a catchment of that outlet. The delineation of a catchment is shown in Figure 3.2.

3.2.1.2 Modified curve number model

The curve number model (SCS, 1972) developed by United States Department of Agriculture (USDA) is an empirical equation predicting runoff from rainfall. This model involves relationship between landuse/cover, hydrologic soil group and antecedent soil moisture to assign curve numbers. The CN, which is also

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known as watershed coefficient is a computed variable and is a function of the runoff producing properties of the watershed. The CN_2 value was determined from the land cover management and hydrological soil groups using NEH-4 table valid for the average antecedent moisture condition (AMC-II). CN_2 value was adjusted for dry (CN_1 for AMC-I) and wet conditions (CN_3 for AMC-III) using relations of Sobhani (1975) and Hawkins *et al.* (1985). This method assumes that CN_2 for average condition is for 5 per cent slopes, which is generally not applicable in the field conditions. Therefore, a slope factor suggested by Sharpley and Williams (1990) has been used to adjust CN_2 for steep slopes using the following formula;

$$CN_{2s} = \frac{1}{3}(CN_3 - CN_2)\,(1 - 2e^{-13.86s}) + CN_2 \qquad (3.1)$$

Where,

CN_2 and CN_3 are the SCS curve number for AMC-II (average) and AMC-III (wet), and s (mm^{-1}) is the soil slope. The CN_{2s} is the slope adjusted CN for average moisture condition and was used instead of CN_2 in the subsequent calculations of the runoff. Slope adjusted curve numbers for moisture conditions I (CN_{1s}) and III (CN_{3s}) have been calculated using the following relationships:

$$CN_{1s} = \frac{4.2\,CN_{2s}}{10 - 0.058\,CN_{2s}} \qquad (3.2)$$

$$CN_{3s} = \frac{23\,CN_{2s}}{10 + 0.13\,CN_{2s}} \qquad (3.3)$$

Where, CN_{1s} and CN_{3s} are slope adjusted curve numbers for AMC-I (dry) and AMC-III (wet) conditions, respectively. Retention parameter, S (mm) was obtained from

$$S = \left(\frac{25400}{CN_s} - 254\right) \qquad (3.4)$$

Where, CN_s is slope adjusted CN for different AMC conditions. Equation to calculate runoff from rainfall is as follows:

for $P > I_a$ else

$$Q = \frac{(P - I_a)^2}{(P + I_a - S)} \text{ for } P > I_a \text{ else} \qquad (3.5)$$

$Q = 0$ for $P < I_a$

Where Q (mm) is surface runoff, P (mm) is rainfall, and I_a is initial abstraction. Furthermore, incorporation of the antecedent moisture in the existing SCS-CN method in terms of three AMC levels allows unreasonable sudden jumps in the CN variation. Therefore, in this study Mishra *et al.* 2005 approach is used to correct for antecedent moisture. The modified runoff method used is as follows;

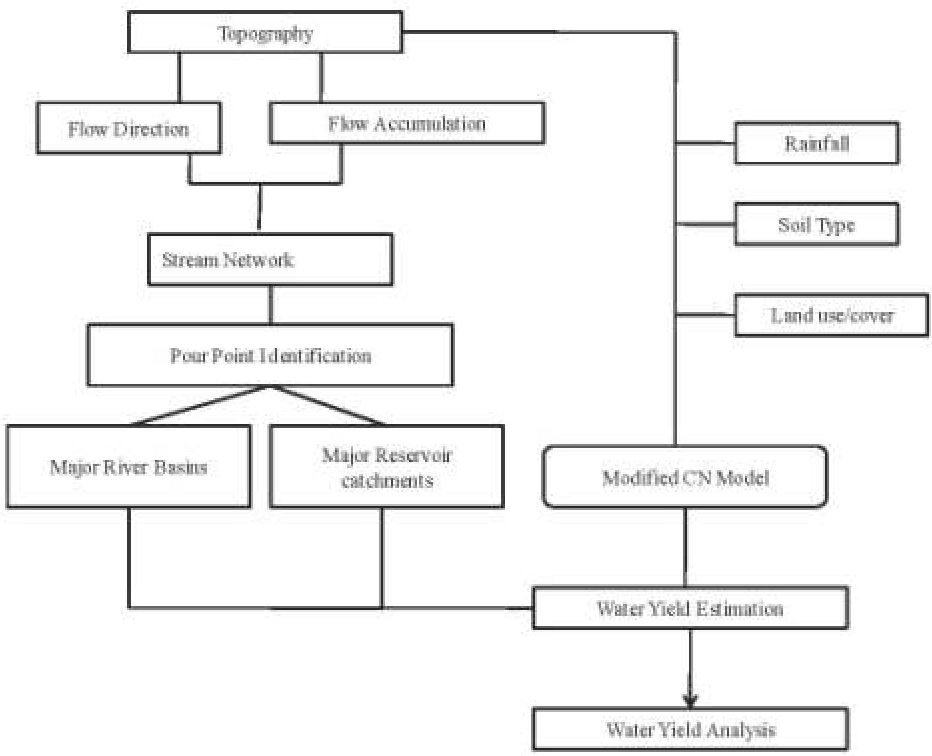

Figure 3.2: Methodology for catchment delineation and water yield estimation

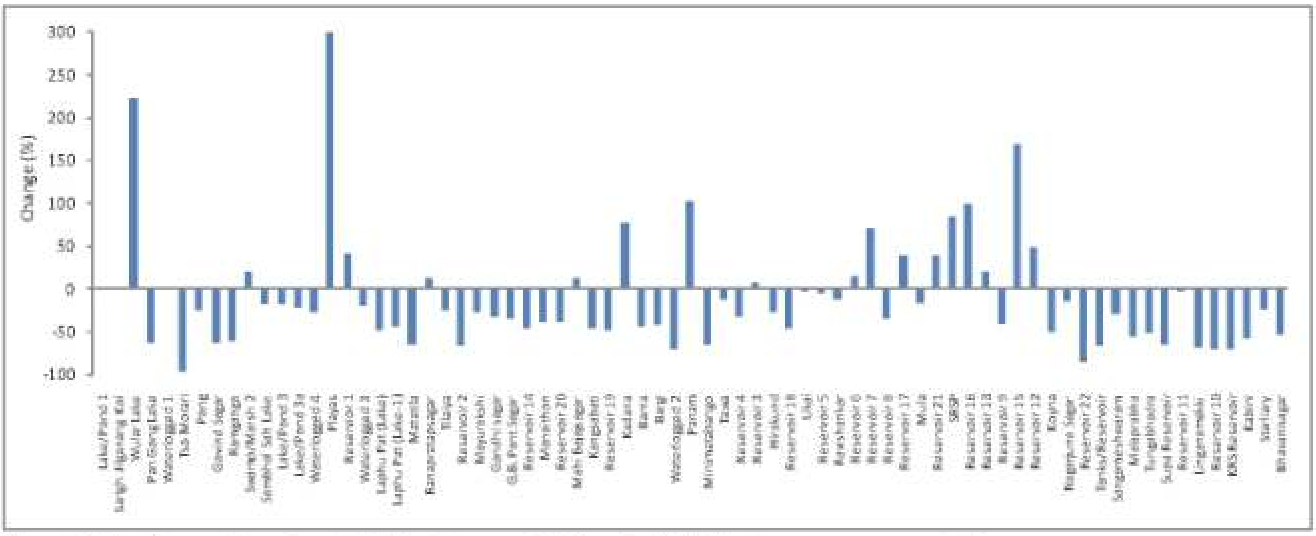

Figure 3.3: Change in water yield for the year 2012 w.r.t. 2011 during monsoon period

$$Q = \frac{(P - I_a)(P - I_a + M)}{(P + I_a + S + M)} \quad (3.6)$$

Where,
M is computed as:

$$M = 0.5\,[-S + \sqrt{S^2 + 4P_5 S}\,] \text{ for } P_5 \geq 0 \text{ and } P \geq I_a \quad (3.7)$$

Here, antecedent moisture is M and P_5 is the antecedent 5-day precipitation amount.

3.3 RESULTS

Modelling of water yield for major reservoirs catchment and river basins was carried out 10*10 km cell by cell basis over mainland of India at daily scale. Results were extracted for various scales such as river basins, major reservoir catchments, etc. Detail results of water yield from the catchments of major water bodies have been presented for the monsoon period of 2011 and 2012. Also, a comparative analysis has been done for the 2012 estimates with the previous year values, i.e. for 2011. Due to non-availability of observed water yield data for the major reservoirs, model results were compared with the observed data available for river basins. Results are presented and discussed in the following sections.

3.3.1 Surface water yield for major reservoirs

Daily water yield maps were aggregated for a month period and extraction was done for the major reservoir catchments as a mask for the year 2011 and 2012. Most of the reservoirs were showing a lower water yield for the year 2012 as compared to 2011 during May to August, although percentage change was higher for the water bodies catchments having the increasing trend in 2012. In the month of June, the water yield was higher for reservoir catchments falling in the North-Eastern part of India for the year 2012 whereas water yield was higher in West Bengal and Central part of India during the same period for the year 2011. Daily water yield maps were aggregated for a month period and extraction was done for the major reservoir catchments as a mask for the year 2011 and 2012. Most of the reservoirs were showing the lower water yield for the year 2012 as compared to 2011 during May to August, although percentage change was higher for the water bodies catchments having the increasing trend in 2012.

During the month of July, water yield reduction was observed in the reservoir catchments falling in the western and west south cost river (WSCR) basin for the year 2012. This water yield deficit in the western and WSCR basin continued from July till the month of August including in the lower part of the Ganga basin. September month has different trends with high water yield production in most of the reservoir catchments for the year 2012 (especially in the western andcentral regions). Total seasonal change in the water yields for 2012 w.r.t. 2011 is presented through Figures 3.3 and 3.4

3.3.2 Water yield comparison with published data

In the absence of water yield for the individual reservoirs, cumulative monsoonal water yield for the major river basins were estimated for the year 2011 and 2012. Basin-wise estimated water yield were compared with the published average water yield data from CWC. Mahi and Godavari basins have shown high water yield for the year 2012 comparing published average values as well as 2011 estimates (Figure 3.5). Rest of the basins presented in Figure 5 showed less water yield for the year 2012.

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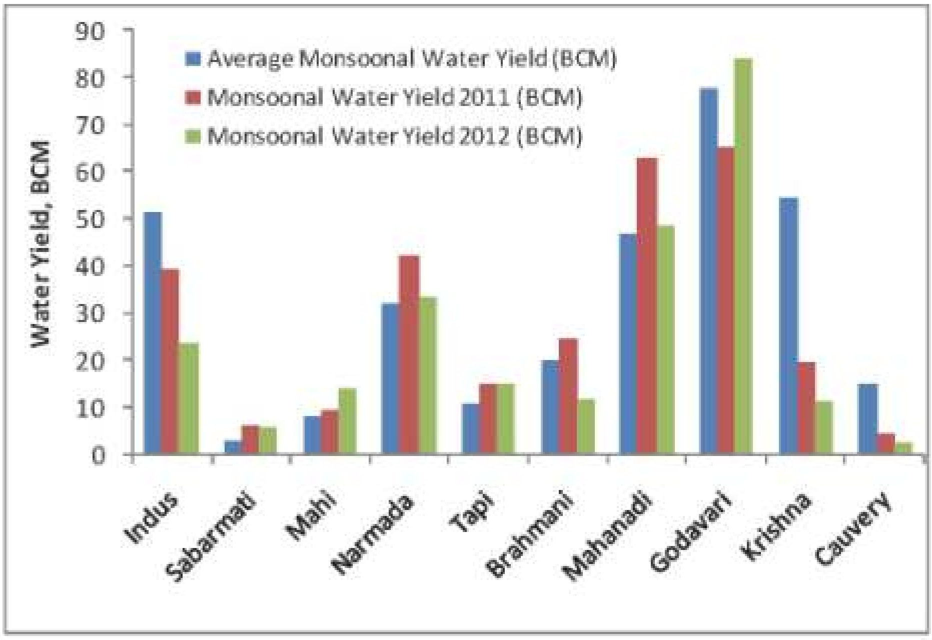

Figure 3.4: Comparison of monsoonal water yield of 2011 and 2012 with the average yield.

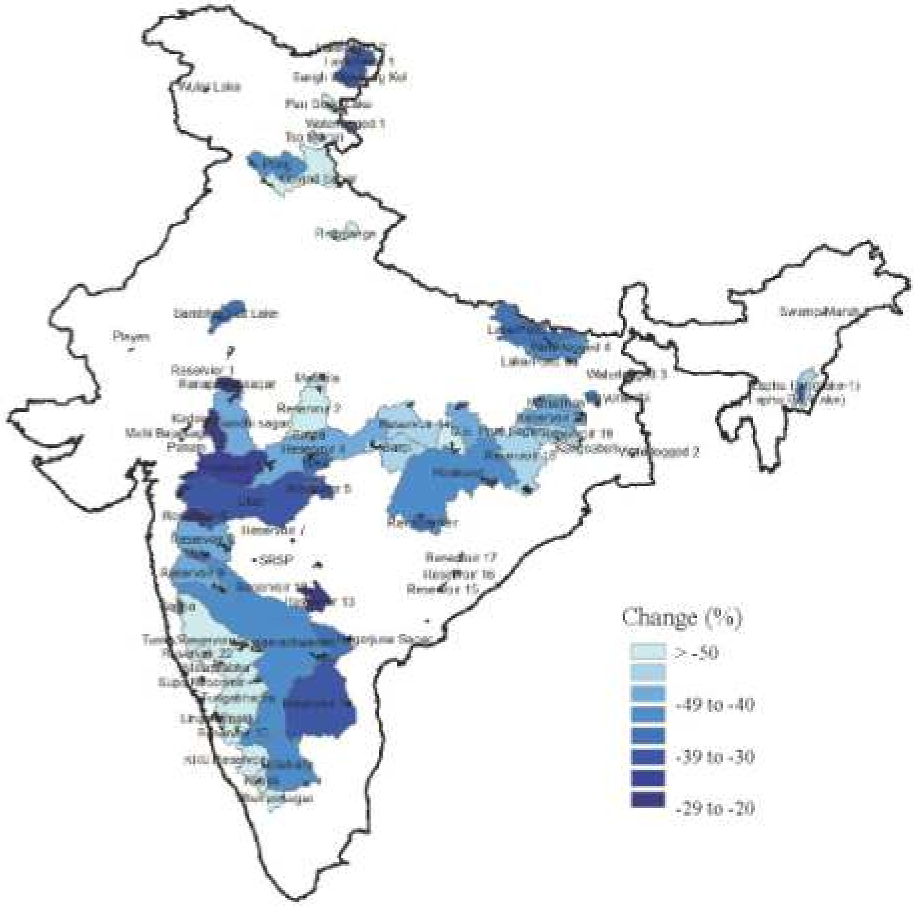

Figure 3.5: Change in water yield in the major water bodies for 2012 with respect to 2011 considering May to September period

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3.4 CONCLUSIONS

Study has been done to quantify the water yield production from the catchments of major water bodies using the conceptual cell based rainfall-runoff model. In the month of June the water yield was higher for the reservoir catchments falling in the North-Eastern part of India for the year 2012 whereas water yield was higher in West Bengal and Central part of India during the same period for the year 2011. July and August months have shown decline in water yield in the reservoir catchments falling in the western and west south cost river (WSCR) basin and lower part of the Ganga basin for the year 2012. The month of September has different trends with high water yield production in most of the reservoir catchments for the year 2012 (especially in the western and central regions). A significant year-to-year spatial as well temporal variability of water yield has been observed. Catchments of major water bodies contributed 242.5 BCM (29.2 per cent of total national water yield) and 182.6 BCM (28.5 per cent of total national water yield) for the year 2012 and 2011, respectively. This shows 24.7 per cent decline in the water yield for the year 2012. The water yield contribution of major reservoir catchments to their respective river basin has reduced in 2012 as compared to 2011 except few reservoirs. Study results is expected to prove useful to all engineers, planners and policy makers of the water resources sector for early assessment of water storage availability and also for planning water management during winter and summer uses.

ACKNOWLEDGEMENT

This work has been carried out under the PRogrAmme on Climate change Research In Terrestrial environment (PRACRITI) project on "Impact of climate change on terrestrial hydrology". Wetland map obtained from SAC 'National Wetland Atlas: India' project is duly acknowledged. The authors are thankful to Shri A.S. Kiran Kumar, Director, Space Applications Centre (SAC) for support and encouragement. We are grateful to NOAA, Climate Prediction Centre (CPC) for rainfall data product.

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4

Comparison of Hydrological Regime of a Micro-Watershed having Dense Oak Forest witha Degraded Micro-Watershed

N. Q. Qazi, M. P. Singh, S. P. S. Rawat, S. P. Rai and J. V. Tyagi

4.1 INTRODUCTION

Forests play a major role in regulating stream flow and sedimentation; infiltration, sub-surface flow, soil moisture and ground water storage; interception and evapotranspiration, etc. However, their amount depends on the nature and types of forests and also morphological characteristics of the watershed. The relationship between rainfall and runoff is directly proportional with land use/cover and steepness of the watershed and these are also influenced the sediment and nutrient losses. Furthermore, the infiltration into the soil is directly related to the intensity and duration of rainfall and runoff is the inversely related to the infiltration. The physical characteristics of soil, i.e, soil texture, substrata, geology and slope also affect infiltration, changing the stream flow regimes. Maximum rainfall infiltrates into the soil, creating a base flow and minimising the runoff volume resulting in reduction of sediment load in the streams. The forest influence on water has been a subject of prime importance and of wide interest due to its complicated nature of influence on water resources (Mbano, *et al.,* 2009). At present, many countries are experiencing extensive land use and land cover changes (LULCC). The role of LULCC on hydrological processes has been of interest to many studies because of its crucial role on catchment water balance through evaporation, transpiration and other hydrological parameters. Vegetation, especially in the case of forests, regulates runoff, as it reduces dramatically surface water volume, runoff velocity and peak discharge (Jinchi *et al.,* 2009; Karvonen *et al.,* 1999; Roberto *et al.,* 2005).

Many studies have shown that the variation in runoff is attributed to the vegetation cover and land use management changes (Bryan and Campbell, 1986; Kosmas *et al.,* 1997; Newson, 1985). Removal of forest cover causes important changes in the hydrological balance of a watershed, although the magnitude of the response is highly variable and unpredictable (Anderson *et al.,* 1990). Furthermore,Bosch and Hewlett (1982) have pointed out that increased forest coverage, in place of pasture areas, can trigger a reduction of annual flow up to 40 per cent. In this context, it may be mentioned that there is absence of sufficient forest hydrological studies for different ecosystems under different conditions of forest cover and composition in Indian conditions. Hence evaluating hydrological regulatory functions of forests is difficult in India on account of insufficient data on forest hydrological parameters.

Soil moisture is widely recognised as a key variable in studies related to environment, meteorology, hydrology, agriculture and climate change. From a hydrological viewpoint, soil moisture content controls the partitioning of rainfall into runoff and infiltration and therefore affects runoff, erosion, solute transport, and land-atmosphere interactions, as well as range of geographic and pedogenic processes in catchments (Aubert *et al.,* 2003). The role of soil moisture in hydrological processes has been extensively studied over recent decades at catchment scale and has received increasing attention from the hydrological scientific community. However, soil moisture is one of the most difficult variables to estimate because of its interaction with factors such as vegetation, soil, and topography (Venkatesh *et al.,* 2011). The estimation of soil moisture regimes has to deal with the probability of several conditions of the soil moisture status in an average year, and therefore has to be based on long observation periods. Soil moisture on a catchment scale exhibits a high degree of variability in space and time and is influenced by a number of factors, such as topography (Wilson *et al.,* 2005; Moore *et al.,* 1988; Western *et al.,* 1999), soil properties (Bell *et al.,* 1980), land cover/vegetation (Mahmood and Hubbard 2007; Fu and Chen, 2000), precipitation and other microclimatic conditions (Famiglietti *et al.,* 1998).

The soil and water assessment tool (SWAT) (Arnold *et al.,* 1998), a physically based, spatially distributed model overcomes these limitations and is being increasingly used to assess the hydrological behaviour of large and complex watersheds. Rapid parameterisation of hydrologic models can be derived using remote sensing (RS) and geographic information systems (GIS) as remotely sensed data provides valuable and up-to-date spatial information on natural resources and physical terrain parameters. Numerous studies have described the potential benefits and use of RS and GIS in hydrologic modelling (Hession and Shanholtz, 1988; Maidment, 1993; Srinivasan and Engel, 1991; Bhaskar *et al.,* 1992; Pandey *et al.,* 2005, 2009). Among others, the SWAT model has proven to be an effective tool for assessing water resource and nonpoint-source pollution problems for a wide range of environmental conditions. The model has been widely used in various regions and climatic conditions on daily, monthly and annual basis (Arnold *et al.,* 1998; Mulungu and Munishi, 2007; Muttiah and Wurbs, 2002; Srinivasan *et al.,* 2005; Tolson and Shoemaker, 2007) and for the watershed of various sizes and scales (Kannan *et al.,* 2008, 2007; Rosenthal *et al.,* 1995) tested SWAT predictions of stream flow volume for the Lower Colorado River basin (8927 km^2) in Texas. A GIS-hydrologic model link was used to aid in forming input files. Stream flow was simulated

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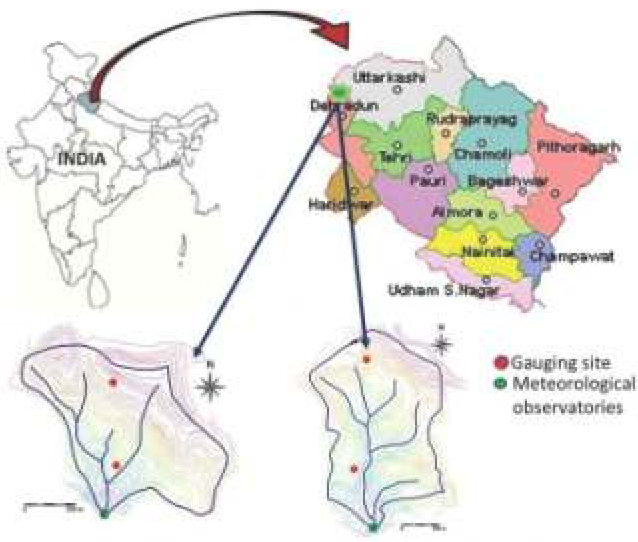
for nine years for four stream gauge locations with 60 sub-watersheds. With no calibration, the model closely simulated monthly stream flow with a regression coefficient (R^2) of 0.75. Bingner (1996) evaluated the SWAT model in the Goodwin Creek Watershed (21.31 sq.km) located in northern Mississippi over a 10-year period. The land use of the watershed was primarily pasture and cultivated field. The Nash-Sutcliffe coefficients (E_{ns}) and R_t values computed with observed monthly flow were all around 0.80. Srinivasan *et al.* (1997) used the SWAT model to simulate hydrology from 1960 to 1989 in the Rio Grande/Rio Bravo river basin (598,538 sq.km) located in parts of the United States and Mexico. The simulated average annual flow rates were compared against USGS stream gauge records. Visual time-series plots and statistical techniques were used to evaluate the model performance.

It is, therefore, essential to study the relationship between different hydrological and vegetative parameters. Paired micro-watersheds under different forest covers have been gauged during the period in order to measure the variation of runoff, soil moisture regime and sediment yield under different rainfall conditions.

Figure 4.1: Location map of Arnigad and Bansigad micro-watershed



4.2 MATERIAL AND METHODS

4.2.1 Study site

Two micro-watersheds, Arnigad (30°26'13.9"N, 78°05'37.4"E) and Bansigad (30°27'9.1"N, 78°02'45.9"E), located 36 km north of Dehradun near Mussoorie (situated on the first mountain ridge beyond Dehradun) in Uttarakhand state of India (Figure 4.1).Arnigad watershed covers 285.7 ha is covered with dense *Quercus* forests and supports moderately dense oak forest with land use of 83 per cent forest, 12 per cent habitation and 5 per cent barren land. Bansigad watershed covers 190.5 ha is covered with degraded forests of *Quercus* and supports moderately degraded oak forest with areal coverage of 65 per cent forest, 5 per cent habitation, 28 per cent barren, and 2 per cent agriculture. Elevations at Arnigad and Bansigad range from 2,220 to 1,640 m above msl and 2,160 to 1,620 m above msl, respectively. The mean orientation of both watersheds is south (Singh *et al.*, 2014). The drainage pattern of both watersheds is of the dendritic type. Annual rainfall in mussoorie is about 2005 mm of which 60-85 per cent is received during monsoon season (June to September). In Mussoorie, mean annual air temperature is 13.7°C. The hottest month is June with an average (1961–1995) air temperature of 19.8°C, and the coldest month is January with an average air temperature of 6° centigrade. The Mussoorie range, constituting the Proterozoic to Lower Cambrian rocks of the Lesser Himalaya is separated from the Cainozoic Siwalik Group and the Dun gravels by the MBT (Thakur and Pandey 2004), that is a north-northeast

Table 4.1: Soil physical properties of study watersheds

Depth(cm)	Soil organic carbon (%)	Organic matter (%)	B. D.(g/cc)	Sand(%)	Silt(%)	Clay (%)	Soil texture
			Arnigad watershed (Dense Oak forest)				
0 - 15	3.31	5.71	1.01	67.75	14.00	18.51	Sandy Loam
15 - 30	2.30	3.97	1.05	66.07	13.33	20.51	Sandy Loam
30 - 60	2.51	4.33	1.08	67.40	14.67	17.83	Sandy Loam
60 - 90	2.41	4.16	1.11	69.17	12.67	18.83	Sandy Loam
90 - 120	1.54	2.65	1.16	67.50	13.00	19.40	Sandy Loam
			Bansigad watershed (Degraded mixed forest)				
0 - 15	2.37	4.09	1.06	74.27	11.33	14.40	Sandy Loam
15 - 30	1.91	3.29	1.09	72.93	11.33	15.83	Sandy Loam
30 - 60	2.07	3.57	1.15	67.80	14.33	15.17	Sandy Loam
60 - 90	1.67	2.87	1.18	73.80	11.00	15.17	Sandy Loam
90 - 120	0.81	1.40	1.20	70.90	12.00	17.05	Sandy Loam

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dipping thrust along which the Lesser Himalayan rocks are thrust over the Siwaliks (Rautela *et al.*, 2010). The main parent material in this area consists of quartzite, schist, slates, phyllite, hard sandstones, limestone and dolomite (Bartarya 1995).

4.2.2 Types of Vegetation

In Mussoorie, vegetation is a climatic climax and belongs to Himalayan moist temperate forest (Raina and Gupta, 2009). In Arnigad and Bansigad micro-watersheds, the dominating tree species is *Quercus leucotrichophora* and it has *Rhododendronarboretum* as its major associate. Main tree species in forest lands in Mussoorie are: *Quercus leucotrichophora, Rhododendronarboreum, Cedrus deodara, Prunus cerasoides, Pinusroxburghii, Mallotus phillippinensis, Lannea coromandelica, Bauhinia purpurea, Flacourtia ramontchi, Melia azedarach, Cassia fistula, Grewia optiva, Dalbergia sissoo, Bauhinia variegate, Terminalia belerica* and *Acacia catechu* etc. (Raina and Gupta, 2009).

4.2.3 Physical properties of the soil

Undisturbed soil samples were collected from the depths of 0 to 15 and 15 to 30 cm using core samplers from five locations in each watershed. The collected soil samples were analysed in a standard soil laboratory for particle size distribution, bulk density, soil organic carbon and hydraulic conductivity (Tyagi *et al.*, 2013) (Table 4.1).

Bulk density of soil is higher with increasing soil depth under dense forest as well as under degraded forest. However, bulk density is less under dense forest (1.01 to 1.16 g/cc) as compared to degraded forest (1.06 to 1.20 g/cc). Overall, there are 3.35 to 6.65 per cent reductions in bulk density under dense forests in comparison to degraded forest, at different depths. Porosity under dense forests is higher (45.03 per cent to 54.23 per cent) as compared to degraded forests (43.10 to 48.57 per cent) and an increase from 2.94 to 11.67 per cent in different depths has been observed in dense forests as compared to degraded forests. Texture seems to be better under dense forest as compared to degraded forest, having higher amount of the fractions (silt and clay) which contains more nutrients. Silt and clay fractions vary from 12.67 to 14.67 per cent and 17.83 to 20.51 per cent, respectively under dense forests while under degraded forests silt and clay vary from 11.00 to 14.33 per cent and 14.40 to 17.05 per cent, respectively. Infiltration characteristics of both the catchments were studied under different forest covers and under different land uses.

The soil textural and physicochemical properties required by SWAT model include soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for each soil type.

4.2.4 Hydrological and meteorological data

The hydrological and meteorological data was recorded from March 2008 to February 2011. For the measurement of rainfall, two tipping bucket rain gauges and two non-recording rain gauges were installed at two different location of each micro-watershed and daily rainfall was recording a teach station. The hydrological data, viz discharge and soil moisture (at different depths) in each micro-watershed was recorded and analyzed. Water discharge-data was recorded on 15 minutes interval through data logger which generated about 53,851 readings. The 8 soil moisture sensors installed in different land use categories of both the micro watersheds generated about 70 readings which were analysed for measurement of soil moisture in the watersheds. To measure suspended load and total dissolved load, 800 waters amples were collected from each micro-watershed for calculation of soil erosion under different forest cover. The infiltration tests were done at four locations of each micro-watershed through doublering infiltrometer. The soil samples were also collected for measurement of physio-chemical properties of soil in different locations of each micro-watershed and were analysed. The meteorological data, viz. temperature, rainfall, humidity, wind velocity and evaporation (about 64,800 readings each) was recorded and analyzed through different instruments in each micro-watershed.

4.2.5 Infiltration Test

Measurement of infiltration rates were carried out using double ring cylindrical infiltrometers (size: 30 cm inner, 45 cm outer diameter and height 45 cm) made of mild steel sheet. Infiltrometers were penetrated into the ground up to 15 cm depth using a wooden hammer striking on mild steel plate appropriately placed on top of the cylinders. Both cylinders were filled with water ensuring equal water levels in inner and outer cylinders. Theinfiltration rates were measured (using constant head method) on the inner graduated cylinder till steady infiltration rate was achieved. Infiltration tests were carried out at four land uses (dense, degraded, open and agriculture forest) in each micro-watershed (Arnigad and Bansigad).

4.2.6 Rainfall-runoff relationship

The relationship between rainfall and runoff is quite essential for monitoring hydrological regulation of forests. For establishment of the relationship, a rectangular cross section with a V-notch sharp-crested weir with apex angle of 120° (Figure 2a) at the medial line of flow was constructed to measure the runoff from each micro-watershed.

a) ***Rainfall:*** Rainfall is predominant form of precipitation and reach at the earth in the form of rain, snow or ice after the process of condensation of total moisture from the atmosphere. The amount of rainfall is expressed in inches or mm and droplet size of rain varies from 0.5 mm to 6 mm. The rainfall in all the major river basins of the country is mostly confined to four monsoon months between June to September during which almost 80 per cent of the total rainfall takes place (CWC, 2005).

b) ***Runoff:*** Runoff is flowing off of the rainfall from the watershed area. Runoff for the rainfall, generated after satisfying the initial losses, evapotranspiration, infiltration and detention storage requirements and quantifying by m^3/sec. Runoff generation in a natural catchment due to storm rainfall is highly complex and spatially and temporally heterogeneous (Robinson and Sivapalan, 1995).

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ESTIMATING THE STREAM DISCHARGE

Stream discharge (Q) is the volume of water that passes through a cross-section in a unit time, generally expressed as cubic metre per second (m^3/s). Following discharge formula for sharp-crested weirs was used (Gregory and Walling, 1973).

$Q = 2.47\ H^{2.5}$

Where Q = Discharge in m^3/s; H = Head of water in metres

Automatic Water Level Recorders (Figure 4.2b) were installed to measure continuous discharge at 15 minutes time interval. For the measurement of rainfall, two tipping bucket rain gauges and two ordinary rain gauges were installed at two extreme elevations of each project area. Present analysis is based on data collected from both the watersheds from April 1, 2008 to March 31, 2011. Other meteorological parameters, i.e., humidity, temperature, evaporation and wind velocity were also monitored using dry and wet bulb thermometer, maximum-minimum thermometer, pan evaporimeter and anemometer.

4.2.7 Sediment Load

The sediment transported by a stream was deposited in the still waters of the reservoir. The water samples for measurement of sediment load was collected bimonthly (fortnightly) but during monsoon, daily sampling was done and in some cases, sampling was on hourly basis and gravimetric method was used for measurement of suspended load. Water sampled was collected in plastic bottle with capacity of 1 litre at the gauging site. The sediment concentration was obtained by filtration method and collected samples were analysed in the laboratory by standard procedure to estimate the suspended sediment concentration (SSC). Suspended sediments were separated by screening with Whatman 42 filter paper. The weight of the sediment was measured by subtracting the weight of the filter paper from the weight of the dried filter paper alongwith the filtered sediment after filtration. Further, before taking the weight of the sediments on the filter paper, it was kept in a desiccator to remove moisture from the sediment. Total Dissolved Solids are measure of the amount of solids in water and it was measured by TDS tester. The tester was fitted with electrode which easily gives readings of TDS just after 5 seconds of insertion of the electrode in water. The range of the meter was 0 to 2000 ppm and the resolution was 10 ppm. The accuracy was ± 1 per cent of full scale.

4.2.8 Soil moisture data

Soil moisture levels can be expressed in terms of soil water content or soil matric potential. In the present study, soil matric potential was measured using electrical resistance probes of 'Water Mark' make that operate on the principle that the electrical resistance of the probe is proportional to its moisture content. Two electrodes are embedded inside the probe with a cable extending to the surface. The probes are buried in the soil at desired depth of measurement. The water moves in and out of the probes in equilibrium with the moisture content in the surrounding soil. The resistance is measured between the two electrodes by attaching a portable meter to the cable. The measurement is related to soil water potential.

Three sites representing topographic highs and lows were established in each watershed for measuring the soil potential. The probes at each site were installed at 0.25 m, 0.50 m and 0.80 m depths, respectively, to monitor the soil moisture at different root zone depths. A hand held read-out unit, when connected to probes, provided the soil matric potential (kPa). The soil matric potential in all the sensors was monitored at fortnightly intervals. While installing the probes, undisturbed soil samples were collected from all three depths at each point in each watershed and soil moisture retention curves were developed for each of the soil samples in laboratory using pressure plate apparatus for the pressures 1, 33, 50, 70, 100, 300, 500, 700, 1000, and 1500 kPa (Tyagi *et al.*, 2013).

Figure 4.2: (a) V-notch sharp-crested weir (1200 angles) with rectangular cross section and (b) Automatic Digital Water Level Recorder

4.2.9 Model Input Data

The basic spatial input datasets used by the model include the digital elevation model (DEM), land use/cover data, soil data and climatic data. The brief methodology for preparation of the data is described as follows (Tyagi *et al.*, 2014):

4.2.9.1 Digital elevation model

DEM is one of the main inputs of the SWAT model to define topography of the study area. Elevation contours at 20 m interval were digitised from Survey of India toposheet (no. 53 J/3) at 1:50,000 scale using ARCGIS software. The digitised contours were used to generate DEM with a grid cell resolution of 30 m. The DEM was used to delineate the boundary of the watershed and analyse the drainage patterns of the land surface terrain. Terrain parameters such as slope gradient and slope length, and stream network characteristics such as channel slope, length and width were derived from the DEM.

4.2.9.2 Land use/cover data

Land use is one of the most important factors that affect runoff, soil erosion and evapotranspiration in a watershed during simulation (Neitsch *et al.*, 2005). As per the Survey of India toposheet, major land use in Arnigad and Bansigad watersheds consists of oak forest with small areas under habitation and barren lands. The extent of various land use classes shown in the Survey of India toposheet (1:50,000 scale) was verified in the field and minor modifications were made in the boundaries of land use classes as per actual extent. For preparation of land use map, the field surveyed land use classes were digitised and converted to raster format with grid cell size of 30 m. The various land use categories and their coverage in both the study watersheds are presented in Table 4.2.

4.2.9.3 Weather data

Meteorological observatories were established within each watershed to monitor daily rainfall, temperature, humidity and wind velocity. Rainfall was measured using tipping bucket rain gauge linked with a data-logger system, and also with ordinary rain gauge for cross check. Maximum and minimum temperature, relative humidity and wind velocity were measured with the help of maximum to minimum thermometers, dry-wet bulb thermometers and anemometer, respectively. The meteorological data was collected from March 2008 to February 2011.

Table 4.2: Major land use classes in Arnigad and Bansigad watersheds

Land use	Arnigad watershed		Bansigad watershed	
	Area (ha)	% total	Area (ha)	% total
Dense Oak forest	244.2	80.22	0	0
Degraded Oak forest	0	0	174.2	83.03
Barren	33.8	11.10	25.7	12.25
Habitation	26.4	8.68	9.9	4.72
Total	304.4	100	209.8	100

4.2.9.4 Hydrological and sediment yield data

The daily discharge and suspended sediment concentration for the period of March 2008 to February 2011 were measured at the outlets of each study watershed. A sharp-crested weir and a digital stage level recorder (Figures 4.2a and 4.5b) was used to measure stream stage. Daily discharge was calculated using appropriate weir formula. The water samples were collected using Punjab bottle samplers and analysed in the laboratory for sediment concentration. Sediment concentration was measured by filtering samples through Whatman filter paper no. 42. The flow and suspended sediment concentration were measured over a range of hydrological conditions and daily values were calculated from the mean of instantaneous values for a given day.

4.3 RESULTS AND DISCUSSION

Over 50 per cent area of the Arnigad is covered with dense Oak forests (0.4< crown density <0.7) and 20 per cent area is covered with very dense oak forests (crown density > 0.7).

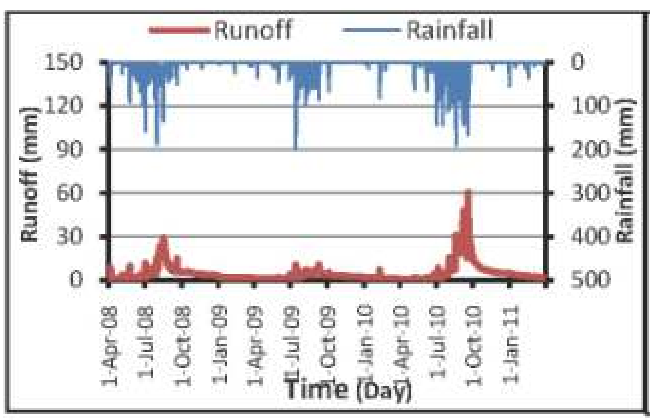

Figure 4.3: Hydrograph of Arnigad project area on daily average basis (Period 1st April 2008-31st March 2011)

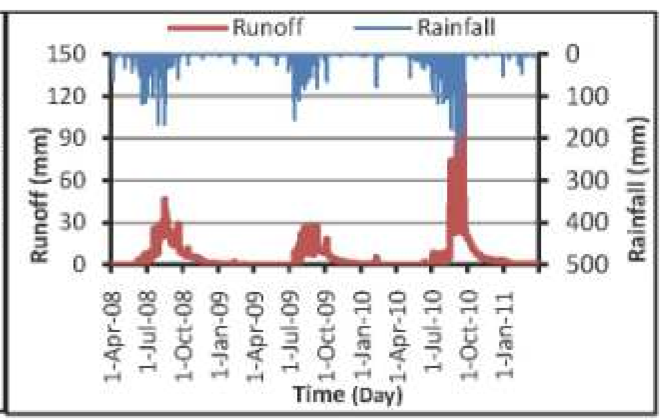

Figure 4.4: Hydrograph of Bansigad project area on daily average basis (Period 1st April 2008-31st March 2011)

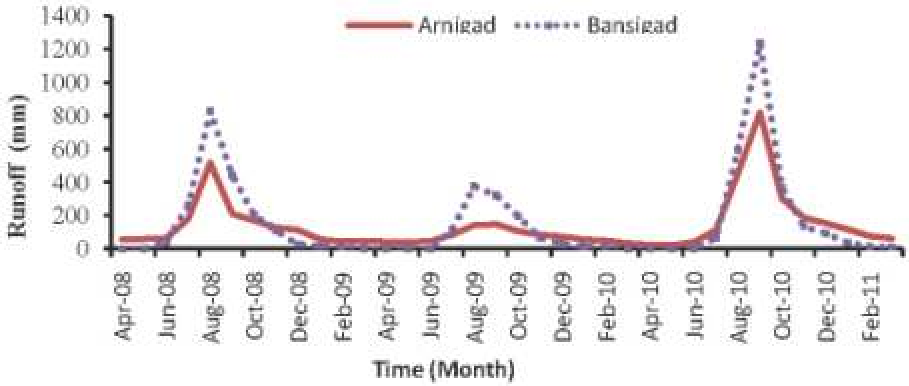

Figure 4.5: Comparative hydrographs of Arnigad and Bansigad on monthly average basis (April 1, 2008-March 31, 2011)

Habitation is mostly on the ridges. About 75 per cent area of the Bansigad is under degraded or open forests. Dense forests also constitute approximately 20 per cent area and habitation covers 5 per cent of the area. Under wooded area in both the catchments, average tree density in dense forests is higher by 30 per cent. Average tree diameter (dbh) in dense forests is 30.6 ± 8.2 cm in comparison to 15.5 ± 6.6 cm in the degraded forests. Average organic carbon content over the depth of 15 cm in the dense forests is 3.31 per cent while it is 2.37 per cent in the degraded forests over the same depth.

Both the sites are located at approximately on the same elevation and on the southern aspect of the same mountain range, having approximately similar meteorological features. Approximately 80-90 per cent rainfall is concentrated in the monsoon period (June-September). Therefore temporal distribution of rainfall is highly uneven over a year. Annual rainfall in both the watersheds is almost equal with variation of 2-4 per cent (Table 4.3).

Discharge of three years shows the pattern of stream discharge from both the catchments (Figures 4.3 and 4.4). Comparison of hydrographs of both the micro-watersheds (Figure 5.5) shows that stream flow of Arnigad is more uniform. Standard deviation of daily average flow for the duration of three years for Arnigad and Bansigad is 5.77 mm and 10.58 mm, respectively. Daily average flow of Bansigad for all the three years is higher by approximately 8 per cent in comparison to Arnigad. Daily average flow for the three years period is 5.1mm and 4.5mm for Bansigad and Arnigad, respectively. The maximum daily flowing Bansigad, in any particular year is approximately two to three times higher than that of Arnigad. Average runoff coefficient of Bansigad for the study period is 0.64 in comparison to the 0.56 ofArnigad, showing higher annual stream discharge from the degraded forest. Total runoff of Bansigad is 5,599 mm against 4,884 mm runoff of Arnigad during the study period in response to the rainfall of 8,780 mm during the same period. This amounts to 238.33 mm/year higher annual discharge for Bansigad in

Table 4.3: Yearly variation of rainfall and runoff (April 2008- March 2011)

Year	Arnigad			Bansigad		
	Rainfall (mm)	Runoff (mm)	Percentage Runoff (%)	Rainfall (mm)	Runoff (mm)	Percentage Runoff (%)
2008-09	2905	1632	56%	2958	1930	65%
2009-10	2019	893	45%	2112	1124	53%
2010-11	3859	2359	62%	3709	2545	69%
Total	**8782**	**4884**	**55.6%**	**8779**	**5599**	**63.8%**

Table 4.4: Runoff statistics for Arnigad and Bansigad(April 2008- March 2011).

Year	Arnigad				Bansigad			
	Daily Avg. (mm)	Std. Dev. (mm)	Max. Flow (mm)	Min. Flow (March) (mm)	Daily Avg. (mm)	Std. Dev (mm)	Max. Flow (mm)	Min. Flow (March) (mm)
2008-09	4.5	4.6	29	1.4	5.3	8.3	46.1	0
2009-10	2.4	1.5	10.6	1.3	3.1	5.0	27.8	0
2010-11	6.5	8.3	60.5	1.7	7.0	15.3	131.1	0.3
Overall	**4.5**	**5.77**	**60.5**	**1.3**	**5.1**	**10.58**	**131.1**	**0**

comparison to Arnigad (Singh *et al.*, 2014).

Results reveal thatrunoff coefficient for the same catchment varies with the annual rainfall. For Arnigad, runoff coefficient is minimum 0.45 during the year 2009-10 and maximum 0.62 during the year 2010-11. For Bansigad, runoff coefficient varies from minimum 0.53 for the year 2009-10 to maximum 0.69 for the year 2010-11 (Table 4.4). For the amount of rainfall variation of 1,840 mm from the year 2009-10 to 2010-11, change in total runoff from the Arnigad project area is 1,466 mm. Almost 80 per cent of the excess rainfall received during the year 2010-11 in comparison to the year 2009-10, is converted in to runoff. Exactly, similar pattern was observed in the rainfall runoff data of Bansigad catchment (Table 4.3). In Bansigad catchment also, almost 80 per cent of the excess rainfall during the year 2010-11 in comparison to the year 2009-10 converts in to runoff. Runoff coefficient is lower for the watershed with dense forest cover. Once soil moisture deficit is compensated by the rainfall and soil is saturated, most of the excess rainfall is converted in to runoff, irrespective of the forest density (Singh *et al.*, 2014).

Minimum stream discharge in both the catchments has been noticed during the months of April-May. Lean flow discharge in the Arnigad stream is always higher than the stream of Bansigad. Discharge in the stream of the degraded watershed of Bansigad is negligible by the month of March every year. Year 2010-11 witnessed very high rainfall in comparison to the previous two years. Maximum daily flow during the year was measured amounting to 131.1 mm in the stream of Bansigad and 60.5 mmin the stream of Arnigad. Despite very high rainfall during the year,flow in the Bansigad stream was 0.3 mm only in comparison to 1.7 mm in Arnigad stream, measured on March 31, 2011. Overall discharge from Arnigad during the period of three years is lower by 8 per cent than from Bansigad due to higher interception and transpiration losses. However, the Arnigad catchment, which is covered with dense patch of *Qurecus* forest, is able to support higher stream discharge during the non-monsoon period. Higher discharge during non-monsoon period (October to May) indicates that forested catchments produce greater base flows and more natural springs (Shuai Wang *et al.*, 2011). Forest can enhance the soil infiltration which leads to greater percolation to ground water and thus could contribute towards low flow discharge (Bruinzeel, 2004).

Arnigad stream is perennial whereas Bansigad stream is intermittent and it flows for 9 to 10 months only. Flow during the post monsoon season is supported by subsurface base flow in a hilly watershed. Rainfall infiltrates the ground through secondary porosity developed such as fissures, fractures, joints, bedding planes, etc., and re-appears down the slope as spring and seepage. It appears that forest cover influences infiltration process and delays the direct runoff from the catchment.This may be a reason for higher contribution of subsurface flow in Arnigad micro-watershed and subsequently higher stream discharge during the non-monsoon period. The stream emanating from the dense forest cover of Arnigad is generating 2,082 mm runoff in comparison to 1,384 mm runoff from the degraded forest of Bansigad, which amounts to an average of 253 mm higher runoff in a year during the non-monsoon period (October to May) from Arnigad and it was 57 per cent more than the stream discharge of Bansigad during the same period. In degraded watershed of Bansigad, ground water storage is not enough to sustain the stream discharge throughout the year. It may be concluded that ground water recharging is higher in dense forest.

Table 4: Infiltration ratesatdifferentsites of dense and degraded forested micro-watershed

Watershed	Site No. for Infilt. Tests	Initial Infilt. Rate - After 5 minute (cm/hr)	Mean Initial Infilt. Rate (cm/hr)	Steady State Infilt. Rate (cm/hr)	Mean Steady Infilt. Rate (cm/hr)	Total Cumulative Depthto Reach Steady Infil. Rate (cm)	Mean Cumulative Depthto Reach Steady Infil. Rate (cm)	Timeto Reach Steady Infil. Rate (minute)	Mean Timeto Reach Steady Infil. Rate (minute)
Dense (Bansigad)	Site-1	101.04	83.10 + 48.2(SD)	28.89	21.48 + 10.3(SD)	162.50	108.16 + 76.6(SD)	265	197.5 + 59.5(SD)
	Site-2	134.4		30.33		181.93		220	
	Site-3	19.92		8.10		21.88		125	
	Site-4	77.04		18.60		66.34		180	
Degraded (Arnigad)	Site-5	51.96	49.38 + 13.2(SD)	12.69	17.93 + 13.2(SD)	35.10	71.77 + 56.3(SD)	110	170.0 + 51.6(SD)
	Site-6	50.28		24.57		122.77		230	
	Site-7	31.68		2.16		12.38		150	
	Site-8	63.6		32.28		116.83		190	

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However, impact of vegetation on the low flow as observed in this study is in contradiction with many other studies. Douglass and Swank (1972) found that when a hardwood forest was cut, about 60 per cent of the stream flow increase came during the low-flow period, July-November; the pattern is typical in the eastern United States where most precipitation occurs as rain. In India, detailed and long term paired catchment experiments in the Nilgiris, in which the responses from a control catchment under natural grassland were compared with those from a catchment under 59 per cent eucalyptus cover, indicate very significant reductions during the low flows in dry season (Sikka *et al.*, 2003). Whether the higher lean flow discharge or higher ground water storage observed in Arnigad having dense forests in comparison to Bansigad is due to forest cover and favourable humus and subsoil conditions inside the forests or due to favourable geological conditions, is required to be ascertained.

4.3.1 Infiltration rate

Representative mean values of initial and steadystate infiltration rate of these two microwatersheds are summarised in Table 5.5. The present investigations showed that initial infiltration rate varied from 19.92 to 101.04 cm/hr (mean: 83.10$\pm$48.2 cm/hr) and 31.68 to 63.6 cm/hr (mean: 49.38$\pm$13.2 cm/hr) in degraded and dense forested micro-watershed, respectively.

The steady infiltration rates were observed in the order of 8.10 to 30.33 cm/hr (mean: 21.48$\pm$10.3 cm/hr) for the degraded micro-watershed and it ranged between 2.16 to 32.28 cm/hr (mean: 17.93$\pm$13.2 cm/hr) for dense forested micro-watershed.

4.3.2 Sediment Load

Temporal variation of suspended sediment load under dense and degraded oak forested micro-watersheds is presented in

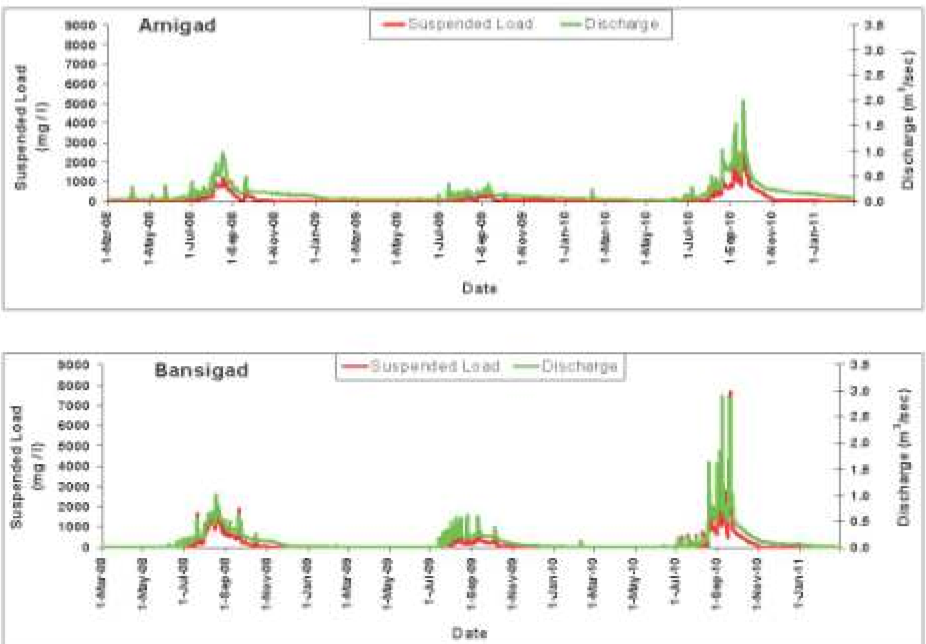

Figure 4.6: Relationship between SSC and discharge on daily basis for Arnigad and Bansigad Sub-watershed.

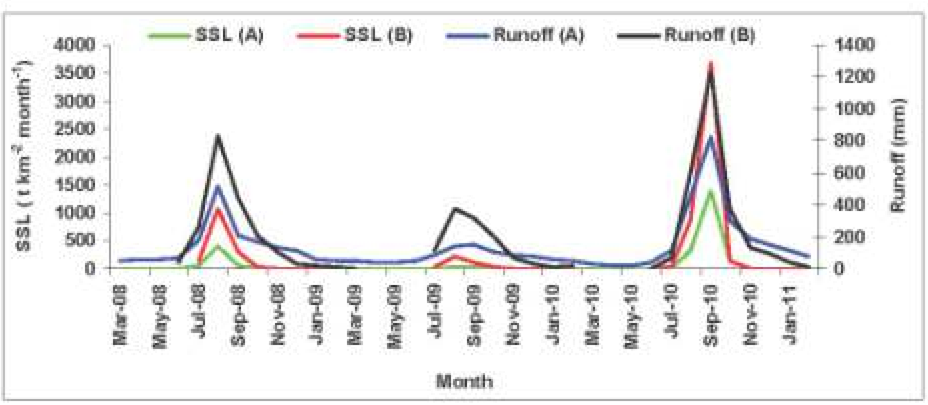

Figure 4.7: Relationship between SSL and runoff for the sub-watersheds

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Figure 4.6(a) and (b). Daily variation of mean suspended sediment concentration (SSC)in Arnigad ranges between 2 to 3,180 mg/l with a mean value of 130mg/l while in Bansigad, it varied between 0 and 7670mg/l, while the mean value of SSC was 217 mg /l. Figure 5.7 shows monthly pattern of SSL and runoff and peaks of these occurred in August (for the first two years) and were in September (for the third year) for the micro-watersheds. The delayed peak in third year was due to delayed monsoon (Qazi *et al.*, 2013).

The sediment data indicate that majority of the sediment load is in the form of suspended sediment which is transported during the monsoon months. On average,780 t/sq.km and 2,124 t/sq.km of SSL occurs during monsoon in Arnigad micro-watershed and Bansigad micro-watershed, respectively. Some amount of suspended loadis also transported during winter(62 t/sq.km in Arnigad and 66 t/sq.km in Bansigad) and negligible amount (3 t/sq.km) occurred during summer season in Arnigad and (0.0009 t/sq.km) in Bansigad due to occasional local rainfall (Table 4.6).

4.3.3 Soil Moisture Variations

As presented in Table 5.7, the observation sites in each watershed exhibited large variation in soil moisture retention capacity both in space and depth. However, it is indicated that Arnigad watershed as a whole has higher moisture retention capacity than Bansigad watershed. For further analysis, monthly soil moisture values were computed from fortnightly field observations at individual sites and depths in both watersheds. The time series data exhibited large variation among the sites as well as along the depth in each watershed. Therefore, mean soil moisture values were computed for analysis of temporal, profile and spatial variation within each watershed and to compare the soil moisture regimes of two watersheds having different forest cover characteristics (Tyagi *et al.*, 2013).

4.3.4 Assessment of calibration results

The observed and simulated daily runoff and sediment concentration during calibration period of June 2008 to May 2010 are graphically presented in Figure 4.8(a, b) for Arnigad and Figures 5.9a and 5.9b for Bansigad watershed. It can be observed that the simulated discharge generally followed the trend to observed discharge in both the watersheds.

A critical comparison of the runoff hydrographs of Arnigad watershed (Figure 8a) shows that the flow peaks are simulated slightly higher than the observed peaks during monsoon seasons both in 2008 and 2009. However, the low flows simulated by the model generally match well with the observed values. In Bansigad watershed, a mixed trend is observed in simulating flows during 2008 and 2009; while, high and low flows are simulated reasonably well during 2008; the high flows appear

Table 4.7: Volumetric soil water content at different sites in the study watersheds

Name of watershed	Site code	Depth (cm)	Volumetric soil water (%) at different pressures		
			1 kPa	33 kPa	1500 kPa
Arnigad (dense oak forest)	AA1	0-25	47.31	33.54	14.69
	AA2	25-50	47.31	33.54	14.69
	AA3	50-80	39.04	28.68	14.45
	AB1	0-25	45.42	33.09	14.79
	AB2	25-50	35.99	24.36	12.61
	AC1	0-25	59.65	40.60	13.37
	AC2	25-50	59.26	41.53	13.23
	AC3	50-80	59.90	41.18	13.49
	Average		49.24	34.56	13.91
Bansigad (degraded mixed forest)	BA1	0-25	52.51	38.17	15.64
	BA2	25-50	30.95	26.20	4.91
	BA3	50-80	20.59	16.86	2.17
	BB1	0-25	41.60	31.50	11.82
	BB2	25-50	31.77	22.63	9.12
	BC1	0-25	55.58	49.69	25.48
	BC2	25-50	54.57	42.32	20.70
	BC3	50-80	51.55	39.31	16.21
	Average		42.39	33.33	13.25

Table 4.6: Seasonal variation of SSL at Arnigad and Bansigad micro-watersheds

Name of watershed	Year	Seasonal Suspended Load (SSL)								
		tonnes			t/sq.km			Percentage(%)		
		Summer	Monsoon	Winter	Summer	Monsoon	Winter	Summer	Monsoon	Winter
Arnigad	2008-09	18.3	1521.8	39.5	6.4	532.6	13.8	1.2	96.3	2.5
	2009-10	1.1	196.6	37.6	0.4	68.8	13.2	0.5	83.5	16.0
	2010-11	2.9	4963.5	456.1	1.0	1737.3	159.7	0.1	91.5	8.4
	Average	**7.5**	**2227.3**	**177.8**	**2.6**	**779.6**	**62.2**	**0.6**	**90.5**	**9.0**
Bansigad	2008-09	0.0	2806.1	44.7	0.0	1473.0	23.5	0.0	98.4	1.6
	2009-10	0.0	673.2	56.7	0.0	353.4	29.8	0.0	92.2	7.8
	2010-11	0.0	8661.1	274.8	0.0	4546.5	144.3	0.0	96.9	3.1
	Average	**0.0**	**4046.8**	**125.4**	**0.0**	**2124.3**	**65.8**	**0.0**	**95.9**	**4.1**

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Table 8: Goodness of fit statistics for Arnigad watershed for calibration period.

Description	E_{ns} (%)	R2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge ($m^3 s^{-1}$)	84.48	0.91	0.111	0.118	0.120	0.143
Sediment concentration (mg l^{-1})	83.11	0.89	82.485	122.820	172.944	158.658

Table 9: Goodness of fit statistics for Bansigad watershed for calibration period.

Description	E_{ns} (%)	R2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge ($m^3 s^{-1}$)	89.74	0.91	0.092	0.108	0.153	0.152
Sediment concentration (mg l^{-1})	82.07	0.86	132.128	178.717	309.983	332.161

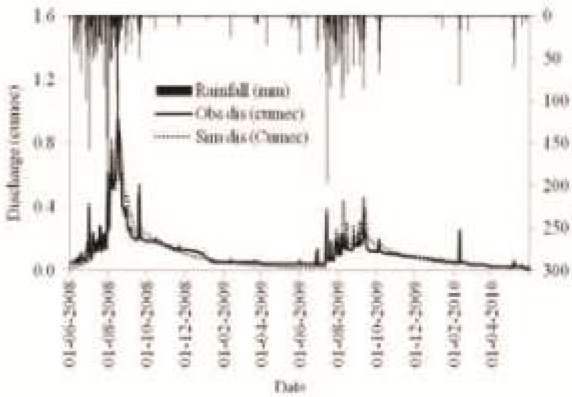

Fig. 4.8a. Observed and simulated daily discharge during calibration in Arnigad watershed.

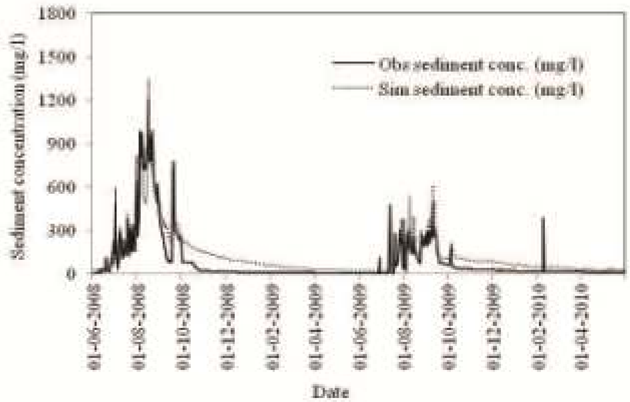

Fig. 4.8b. Observed and simulated daily sediment concentration during calibration in Arnigad watershed.

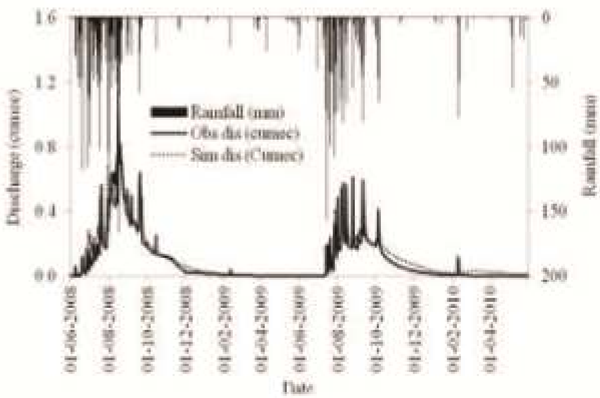

Fig. 4.9a. Observed and simulated daily discharge during calibration in Bansigad watershed.

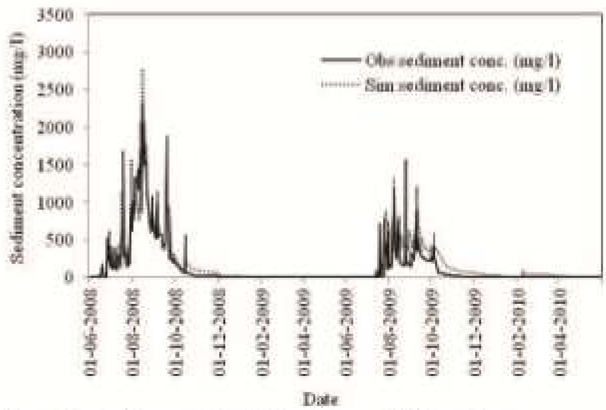

Fig. 4.9b. Observed and simulated daily sediment concentration during calibration in Bansigad watershed.

to be underestimated and low flows overestimated during 2009. A comparison of observed and simulated suspended sediment concentration (Figures 4.8b and 4.9b) shows that simulated sediment concentration also generally followed the observed trend in both the watersheds. Although, model predicted peak values were found both higher and lower than the observed values at different times in both watersheds, the difference was within reasonable limits. The difference in simulated and observed values could occur due to the fact that in practice, high-intensity and even short duration rainfall can generate more sediment than simulated by the model on the basis of daily rainfall (Xu *et al.*, 2009). The simulated sediment concentration during non-monsoon seasons was higher than the observed values in Arnigad watershed. The obvious reason for higher sediment simulation is that the sediment response follows the simulated runoff rate as the sediment generation is largely determined by the runoff quantity. In Bansigad watershed, the simulation of sediment concentration during non-monsoon seasons was reasonably good.

The statistical indices of model performance are presented in Tables 4.8 and 4.9 for Arnigad and Bansigad watersheds, respectively. The analysis for Arnigad watershed showed very good agreement between observed and simulated daily values, with an R^2 value of 0.91, and an E_{ns} of 84.48 per cent in discharge simulation; and an R^2 of 0.88, and an E_{ns} of 83.11 per cent in sediment simulation. In Bansigad watershed too, the model exhibited a very good performance in simulating the discharge (R^2 = 0.91, and E_{ns} = 89.74 per cent) and the sediment concentration (R^2 = 0.86 and E_{ns} = 82.07 per cent) (Tyagi *et al.*, 2014).

4.3.5 Assessment of validation results

For validation, the observed daily discharge and sediment concentration data of the period of June 2010 to February 2011 were utilised and compared with the model simulated values (Tyagi *et al.*, 2014). A visual comparison of the observed and simulated daily discharge and sediment concentration is presented in Figures 4.10a and 4.10b for Arnigad and Figures 4.11a and 4.11b for Bansigad watershed. These results show a good general agreement between observed and simulated trends of discharge and sediment concentration in both the watersheds. Further, it is observed that similar to calibration results, the peak flows are slightly overestimated in Arnigad watershed and underestimated in Bansigad watershed. The flows during non-monsoon season are simulated reasonably accurate in both the watersheds. In estimating suspended sediment concentration (Figures 4.10b and 4.11b), the peak values are observed to be overestimated in both the watersheds. The model also overestimated the sediment concentration during non-monsoon period which is possibly due to the reason that the quantity of sediment generation also depends on the simulated discharge rate as mentioned earlier.

Perfect fit indicates a very good performance of the model in estimating both discharge and sediment concentration for the study watersheds. It can be seen from Tables 4.10 and 4.11 that the R^2 of 0.94 and E_{ns} of 82.78 per cent in discharge estimation, and R^2 of 0.88 and E_{ns} of 83.28 per cent in sediment estimation are computed for Arnigad watershed; and R^2 of 0.92 and E_{ns} of 92.5 per cent in discharge estimation, and R^2 of 0.94 and E_{ns} of 80.67 per cent in sediment estimation are computed for Bansigad watershed. These R^2 and E_{ns} values are of the same order as obtained during calibration which explain that model has performed equally well on the data set used for validation purpose. The model performance with these high values of statistical indices can be rated as more than satisfactory in simulating discharge and sediment concentration from the study watersheds. The aforementioned results can be viewed in the light of the fact that the runoff and soil erosion process in hilly and mountainous forested catchments are highly complex phenomena and affected by interaction among rainfall, runoff, soil texture and structure, land use, land slope and conservation measures. Therefore, magnitude of randomness in daily simulated values may be large in mountainous catchments(Singh *et al.*, 2011). Generally, poor correlation among daily values in SWAT simulation has been reported in literature (Peterson and Hamlett, 1998; Varanou *et al.*, 2002; Spruill *et al.*, 2000). The results of the present study, however, indicate that SWAT can be used for estimation of daily discharge and sediment from forested watersheds in lesser Himalayas.

Table 4.5: Goodness of fit statistics for Arnigad watershed for validation period

Description	E_{ns} (%)	R2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge ($m^3 s^{-1}$)	82.78	0.94	0.273	0.327	0.293	0.369
Sediment concentration ($mg\ l^{-1}$)	83.28	0.88	298.989	397.358	520.740	541.964

Table 4.6: Goodness of fit statistics for Bansigad watershed for validation period.

Description	E_{ns} (%)	R2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge ($m^3 s^{-1}$)	90.50	0.92	0.205	0.250	0.378	0.331
Sediment concentration ($mg\ l^{-1}$)	80.67	0.94	337.922	577.961	853.365	1032.541

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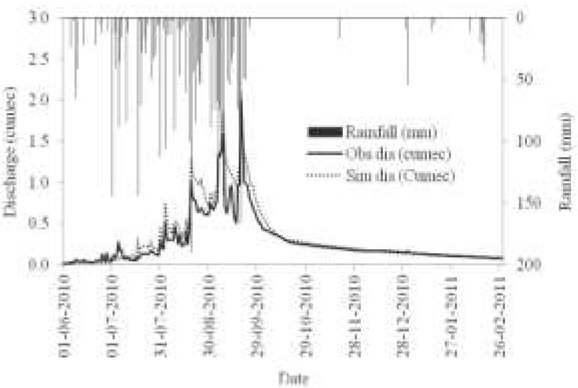

Figure 4.10a. Observed and simulated daily discharge during validation in Arnigad watershed.

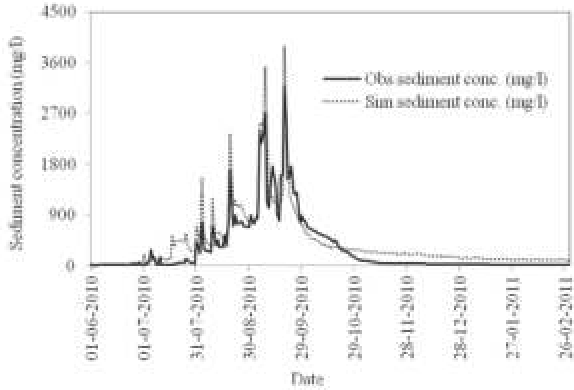

Figure 4.10b. Observed and simulated daily sediment concentration during validation in Arnigadwatershed.

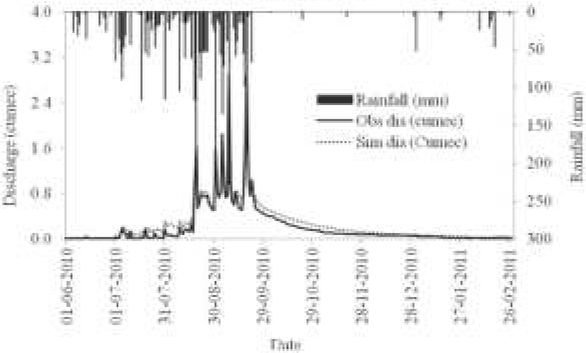

Figure 4.11a. Observed and simulated daily discharge during validation in Bansigad watershed.

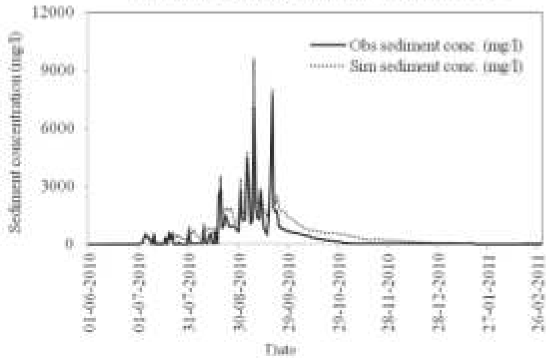

Figure 4.11b. Observed and simulated daily sediment concentration during validation in Bansigad watershed.

4.3.6 Assessment of the impact of forest covers types on stream discharge pattern and sediment yield

The assessment of runoff and sediment yield was made based on the total simulation period of three years (Tyagi *et al.*, 2014). The model predicted that mean annual rainfall of 2,925 mm over Arnigad watershed was mainly partitioned among evapotranspiration, ET (27.3 per cent), percolation/ groundwater recharge (62.2 per cent), transmission loss/abstraction (4.5 per cent) and surface runoff (6 per cent). The simulated mean annual water yield amounted to 1,738.5 mm (59.4 per cent) against the observed water yield of 1,622.4 mm (55.5 per cent). In Bansigad watershed, the mean annual rainfall of 2,926.5 mm was partitioned among ET (22.1 per cent), percolation/groundwater recharge (65.8 per cent), transmission loss/abstraction (5.2 per cent), and surface runoff (6.9 per cent) and the mean annual water yield was simulated as 2,030.1 mm (69.3 per cent) against the observed value of 1,863.6 mm (63.7 per cent). These values indicate that the water balance components in both catchments are almost identical. These results can be supported by the fact that the distribution of land use and soil types in both the watersheds is almost similar. Higher ET and lower surface runoff in Arnigad than the Bansigad watershed is obvious due to the difference in forest cover types in Arnigad (dense oak forest) and Bansigad watershed (degraded oak forest). Although, higher water yield is obtained in Bansigad than the Arnigad watershed, the river flow in Bansigad ceases in the month of February or during early March, while Arnigad sustains the river flow throughout the year. Sharda and Ojaswi (2006) reported that root system of an oak tree is very extensive and soil-root complex system of each mature oak tree has a capacity to store several hundred litres of water, which is released as base flow during the lean season.

The mean annual sediment loading from the Arnigad and Bansigad watershed was simulated as 8.45 and 21.97 t/ha, respectively, against the mean observed sediment yield of 10.70 and 24.46 t/ha in respective watersheds. The simulated sediment yield is comparable to observed values in both the watersheds. The high sediment yield in Bansigad watershed can be attributed to degraded forest cover and other anthropogenic activities in the watershed.

4.4 CONCLUSION

In the present study, soil moisture regime was monitored and evaluate the applicability of physically based, distributed parameter SWAT model in estimating discharge and sediment yield from two forested watersheds in lower Himalaya analysed. Overall discharge during the period April 2008 to March 2011 from the Arnigad dense oak forest stream was 4,884 mm in comparison to 5,599 mm from Bansigad degraded oak forest. However, lean flow discharge was found higher from the dense forest. During the three-year period, total lean flow discharge during the non-monsoon period was 2,082 mm in Arnigad stream in comparison to 1,324 mm in Bansigad stream. Soil moisture values in both watersheds show an annual cycle with highs and lows during periods of high rainfall and high evapotranspiration, respectively. The soil moisture storage under dense forest cover was higher than under the degraded forest during all the seasons. The values during monsoon, winter and summer seasons were obtained as 40.33 per cent, 29.29 per cent and 25.95 per cent, respectively, under dense forest; and 39.34 per cent, 25.50 per cent and 22.58 per cent, respectively under degraded forest(Tyagi *et al.*, 2013).The degraded forest exhibited larger spatial variation in soil moisture than the dense forest which had comparative a uniform distribution of trees across the watershed. Similarly, average annual suspended was higher in degraded forest (2,190 t/sq.km/yr) than in dense forest (844 t/sq.km/yr). This indicates that forest controls excess suspended sediment load. Annually, forests reduced 61.44 per cent delivery of sediment load in Arnigad watershed. Maximum load 90.5 per cent in dense micro-watersheds and 95.8 per cent in degraded watershed occurs during monsoon. The SWAT model simulated daily discharge and suspended sediment concentration followed the trend of observed values in both the watersheds (Tyagi *et al.*, 2014). R^2 values of 0.91 and above and E_{ns} values of 82.8 per cent and above both in calibration and validation exhibited high performance of the model in simulating the discharge from the study watersheds. Similarly, the model also performed more than satisfactory on both the study watersheds in simulating the sediment concentration with R^2 values of 0.86 and above and E_{ns} above 80 per cent. The model also simulated the mean annual water yield and sediment yield close to the observed values in both the watersheds. The mean annual surface runoff and water yield over the entire study period were simulated as 6 and 59.4 per cent, respectively, of the mean annual rainfall in Arnigad watershed; and 6.9 and 63.7 per cent, respectively, in Bansigad watershed. The mean annual sediment yield from the respective watersheds was simulated as 8.45 and 21.97 t/ha, respectively. The results indicated that SWAT is capable of estimating the discharge and sediment yield from Himalayan forested watersheds, the estimates of which are often required for operation and management of irrigation and hydropower projects in the region.

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5

Forest Hydrology Experiment and Modelling at Watershed Scale Located in Central India

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5.1. INTRODUCTION

Severe water shortages occur in several parts of the world and this situation is worsening each year. Freshwater withdrawals increase with increasing population and increasing per capita needs. Both ground water aquifers and low-season stream flows are experiencing depletion. While this water use crisis will adversely affect water supplies for irrigated agriculture, drinking supply, etc., for terrestrial and avian fauna, the most serious deficit crunch will be for potable water for humans in our cities, villages and rural areas. Forested catchments supply a high proportion of the water for various purposes in both upstream and downstream areas. There is a need for a better understanding of the interactions between forests and water. Recently, research has shifted to studying large-scale watershed hydrology, climate change impacts, and application of hydrological models. But, forest hydrology in India is in an infant stage. The information to define the entire hydrological system and water budget of a particular forest system is yet to be estimated. Hydrological processes in a forest system are presented in Figure 5.1.

Forests and their management practices have the potential to alter the quantity, quality and timing of water moving through aquifers by altering the interception, evapotranspiration, soil infiltration, base flow, runoff, etc. (Anderson *et al.*, 1976; Ice and Stednick, 2004). Forest hydrology deals with the role of forest over precipitation and water yield production potential of the forest. Therefore, forest influences on various hydrological parameters, viz. rainfall, interception, infiltration, soil moisture, evapotranspiration, groundwater, water yield, soil loss and floods etc. forms an important area of hydrological studies. Previous limited studies (Agarwal *et al.*, 1987; Mehar-Homji 1986; Dutt and Manikiam, 1987; Gupta *et al.*, 2005; Gupta *et al.*, 2012) indicating that forests and rainfall relationship are not linear on a regional scale. Interception studies carried out in India (Dabral and Subbarao, 1969; Mathur *et al.*, 1975)) indicate that the canopy interception varies from 15 per cent to 35 per cent of rainfall in the forest regions. The interception varies not only with canopy density, etc., but also with intensity of rainfall. The analysis of infiltration data from small forests and agriculture watershed in the Doon valley indicated that the rate of infiltration was twice in forest watershed (Shorea Robusta) as compared to agriculture watershed (Dhruvanayayana and Shastri,1983).

It can be depicted that the infiltration rates are relatively more in forested soils as compared to agricultural areas and grasslands.

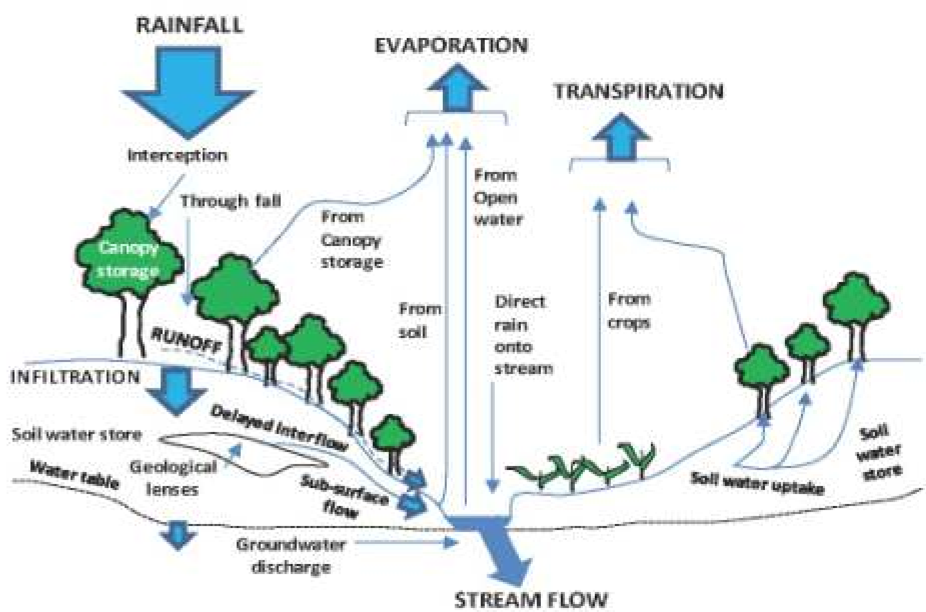

Figure 6.1: Processes for modelling hydrological cycle in the forest system

Much effort has not been made to quantify soil moisture storages under forests. However, forested soils have a better soil moisture retention capacity due to improved soil structure because of more humus and organic content. In general, forests have high evapotranspiration requirement as compared to other land uses. Groundwater relationship with forest is yet to be examined scientifically on large scales. Studies conducted in India and abroad (Hibbert, 1965; Lal and Subba Rao, 1981) have shown increase in stream flow due to cutting and reduction of density of forests. There is need for the management of water resources in forest system involving advance techniques like remote sensing, GIS, distributed physically based hydrological modeling and also in situ observations through hydrological experiments. A study has been done to estimate the water balance components in the forest and neighbouring regions of the Kanha National Park for the conservation and management of water.

5.2 METHODOLOGY

MIKE SHE/MIKE 11 coupled model is a GIS-based distributed model. It is a spatially and temporally explicit, modularized modeling system. This model simulates the complete terrestrial water cycle, including saturated water movement in soils, 2-D water movement of overland flow, 1-D water movement in rivers/streams, unsaturated water movement and evapotranspiration (ET). Saturated water movement in soils is modeled using 3-D Finite Difference or Linear Reservoir. The 2-D water movement of overland flow is simulated using Finite Difference or Subcatchment-based method. The diffusive wave version of Saint Venant equations is used to simulate 1-D water movement in rivers/streams. The unsaturated water movement is simulated using either Richards equation or Gravity Flow or Two-Layer water balance method (Figure 5.2). Detailed descriptions of the model and algorithms can be found in publications (Abbott *et al.*, 1986b; DHI, 2005).

5.3 DATA USED

Three types of datasets such as remote sensing, in-situ measurement and soil physical and channel characteristics were used for the hydrological and hydraulic modelling. Brief summary of datasets used in modelling are as follows;

5.3.1 Remote sensing data

Following remote sensing derived parameters have been used for model setup, delineation of various thematic layers and model testing.

- Digital Elevation Model (ASTER)
- Rainfall (NOAA Climatic Prediction Centre)
- LULC (LISS III)
- LAI (LISS III and MODIS)
- River network (LISS III, Google earth)

5.3.2 In-Situ measurements

Following measurements were used for model initialization, calibration and validation of the model.

- River water level (2 locations)
- Velocity

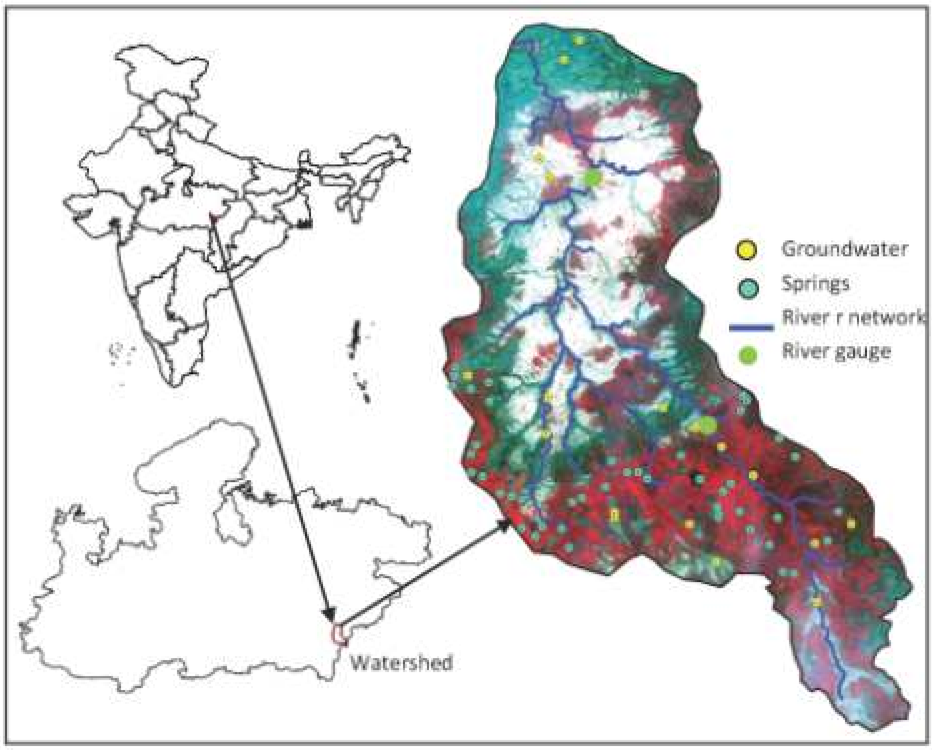

Figure 5.2: Location and details of the study area

- Cross sections
- Groundwater (pre and post monsoon)
- Resistivity survey (groundwater, hydraulic conductivities, soil formations, etc.)
- Rainfall
- Temperature
- Soil moisture
- Leaf area index

5.3.3 Other data

These datasets were used for setting up and as calibration parameters for the hydrological model.

- Soil physical properties
- Channel characteristics

5.4 Study area

The watershed is located within and the buffer regions of the Kanha National Park along the south-east boundary of Madhya Pradesh State (Figure 5.2). Geographic extent is 80°42'E to 81°01'E and 22°02'N to 22°31'N. It covers 972 sq.km. The majority of the area is covered by forest and agriculture. Forest is mainly of deciduous type and found near the southern parts. Main forest types are sal, mixed sal, sal mixed with bamboo and miscellaneous, etc. Agricultural area extends towards middle and northern watershed area. Leaf area index varies from 1.5 to 6 in the study area. Elevation ranges from 523 to 900 metres with an average of 689 metres and the terrain slopes toward the northern side. The soil is mainly loamy. In the study area during the summer, temperature ranges from 11°C to 43°C, whereas in winter it ranges from 2°C to 29°C. The southwest monsoon prevails during late June to September. The maximum rainfall occurs in July and August. The average annual rainfall is 1,225 mm. Groundwater is shallow during monsoon season (surface to 20 feet) whereas pre-monsoon period groundwater table variation ranges from 4 to 49 feet.

These springs are located in the hilly regions. The area mainly consists of basaltic (prophyritic and non-prophyritic), quartz (Mica and k-feldspathic) and granite geological formations. Forest area is dominated by the several perennial and semi perennial springs and basically is geological lenses which store water during the monsoon season and release it to the nearby rivers/channels as the delayed interflow.

6.4.1 Model setup and parameterization

In this study, MIKE SHE was coupled with the river flow routing model MIKE 11 (DHI, 2005; Sahoo *et al.*, 2006), a one-dimensional river/channel water movement model, to simulate the full hydrological cycle of the watershed, including evapotranspiration, infiltration, unsaturated flow, saturated flow, overland flow and stream flow. The main inputs for model included spatial data on topography, soils, vegetation, and drainage network; and temporal data on precipitation and potential evapotranspiration (PET).

5.4.1.1 Unsaturated flow

The Two-Layer Water Balance model (Yan and Smith, 1994; DHI, 2005), which is designed for the areas with a shallow groundwater table, was used to simulate the unsaturated flow for this study. The model divides the unsaturated zone into a root-zone where ET can occur, and a below-root-zone where ET does not occur (Yan and Smith, 1994).

5.4.1.2 Saturated flow

The 3-D Finite Difference method (DHI, 2005) and linear reservoirs methods were used to simulate the saturated flow and delayed interflow for this study. The inputs needed to simulate saturated flow were soil hydraulic properties, including horizontal and vertical hydraulic conductivities, specific yield, and storage coefficient. Horizontal hydraulic conductivity, Overland flow, subsurface flow (lateral flow) and ground water table level are significantly affected by the values of vertical hydraulic conductivity.

5.4.1.3 Overland flow and stream flow

Overland flow was simulated using diffusive wave approximation. The inputs include initial water depth on the surface, surface detention storage, and Manning number. The measured surface water depth was used to initialize the water depth above the ground surface for the model to run. Surface detention storage largely affects routing water toward the stream and water table dynamics. Large values of surface detention storage reduce the overland flow reaching the stream, but increase ponding water that may lead to a subsequent increase in water table level. Manning significantly influences routing overland flow toward the stream and stream flow toward the outlet of the stream with higher values leading to faster water movement.

5.4.1.4 Evapotranspiration (ET)

In this study, daily actual evapotraspiration was estimated using the Kristensen and Jensen model, 1975. Model is based on the effect of the LAI on transpiration and effect of soil and water on evaporation.

MIKE SHE uses variable simulation time steps for different hydrological modeling components and flow characteristics (DHI, 2005; Zhang *et al.*, 2008). Simulation period was taken during 1 June 2010 to 15 August 2012. Model is calibrated based on the modeled and observed measurements on river water level/ discharges and groundwater measurements (Refsgaard, 1997; Gupta *et al.*, 2008).

5.5. RESULTS

5.5.1 Model calibration and validation

Daily River flows for the model calibration (2010) and validation (2011 and 2012) periods show that the model could capture the dominant runoff processes and stream flow dynamics of the watershed (Figures 5.3 and 5.4). However, the model both overestimated and estimated stream flow during the simulation period. Coefficients of determination (R^2) of 0.82 and 0.78 and RMSEs of 10.81 and 32.10 were obtained for the upstream and downstream gauging sites during the study period, respectively.

During the calibration period R^2 values were of 0.81 and 0.78, whereas RMSE values were of 8.8 and 24.0 considering u/s and d/s gauging sites, respectively. A reasonable good match between modeled and observed stream flows for the validation period were also obtained (u/s gauge: R^2 = 0.84 and RSME = 9.73 whereas d/s gauge; R^2 = 0.82 and 27.8). The higher coefficient of determination values between modeled and measured discharge during calibration and validation period for the u/s gauging site were mainly due to the fact that fewer flow events with high peak flows were underestimated compared to d/s gauging site and less modeling errors occurred.

Groundwater table variations over the measurements sites were also compared with the simulated results. Variability of observed and simulated groundwater table over the gauging sites is presented in Figure 5.5. A correlation plot between observed and simulated groundwater depths using point data is presented in Figure 5.6. It has been noticed that simulated groundwater depths' trend line matched very well with the 1:1 line. The Nash–Sutcliffe coefficient and coefficient of determination values were 0.88 and 0.96, respectively, whereas the value of RMSE was 0.61 m. Further, the simulated groundwater table was slightly underestimated with a bias of 0.38 m as compared to observed data. Statistical results show a high coefficient of determination and Nash–Sutcliffe coefficient, lower RMSE, and bias. Hence, model can be considered calibrated and validated for the study watershed.

5.5.2 River flow analysis

Stage-discharge relationships for different streams (number 1 to 11), major nalas (Kashmiri and Pati) and several locations in the main river (upstream, middle stream and downstream) have been developed. Power functions of order 1 and 2 between stage and discharge were fitted. Function coefficients and other statistical parameters have been summarized in Table 5.1. Statistical results show a very good functional relationship between river stage and discharge (R^2 range from 0.62 to 0.99) throughout the river network. River network and stream-discharge relationship for some of the locations is presented in Figure 5.7.

5.5.3 Water balance analysis:

Water balance components were extracted for the whole watershed. Further, results were extracted and analysed for the forested and other land cover classes separately to see the inter linkages between the water balance components of forest regions with the neighbouring areas (Figure 5.8). Rainfall amount for all the three categories viz whole catchment, forest and other classes were of 4230 mm. Out of which surface water which goes to the river, base flow production, evaporation from pond water, canopy water storage and transpiration were 30.6 per cent, 28.4 per cent, 3.6 per cent, 12.7 per cent and 24.9 per cent, respectively, for the whole catchment. Forest area contribution was more for base

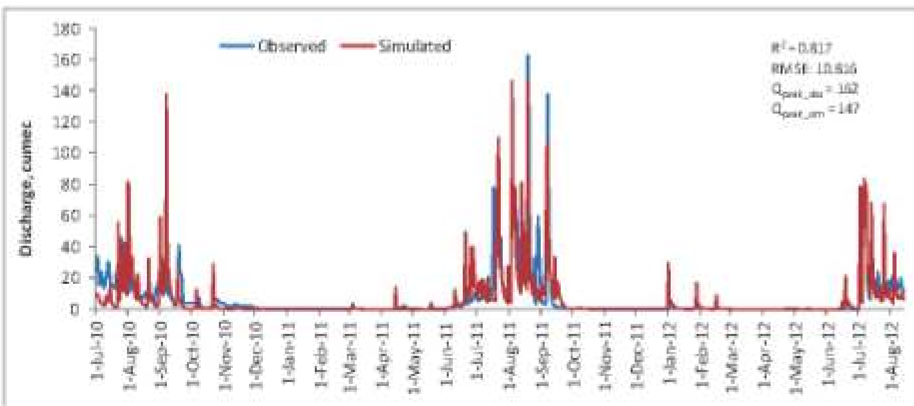

Figure 5.3: MIKE SHE Model simulated at daily time scale for calibration (2010) and validation (2011 and 2012) at u/s gauging site (Kurkuti).

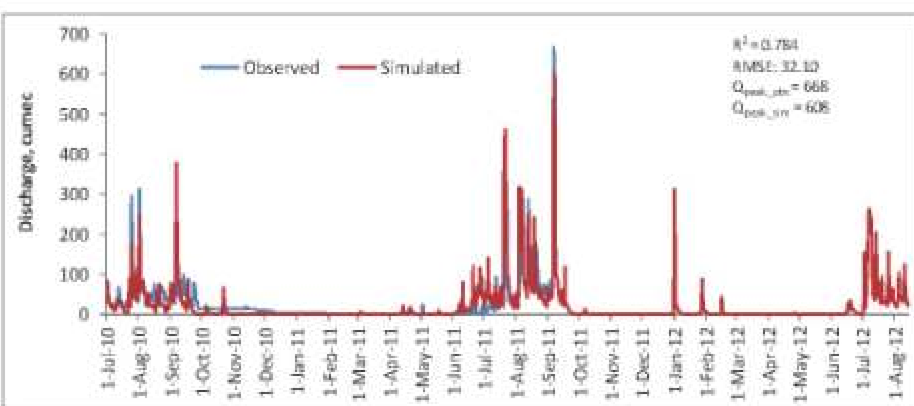

Figure 5.4: MIKE SHE Model simulated at daily time scale for calibration (2010) and validation (2011 and 2012) at d/s gauging site (Sijhora).

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Figure 5.5: Observed and simulated groundwater table variations for the gauging sites in the water shed

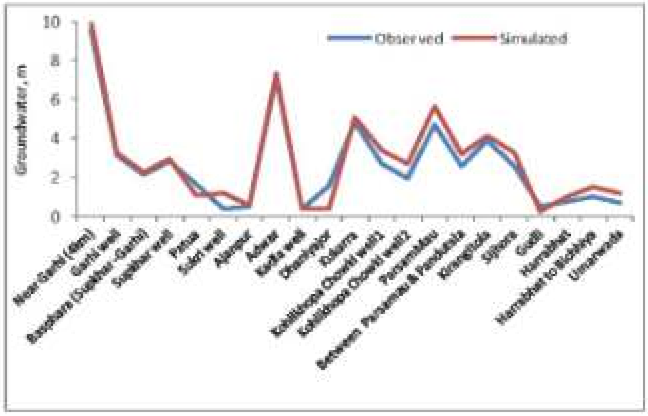

Figure 5.6: Relationship between observed and simulated groundwater table

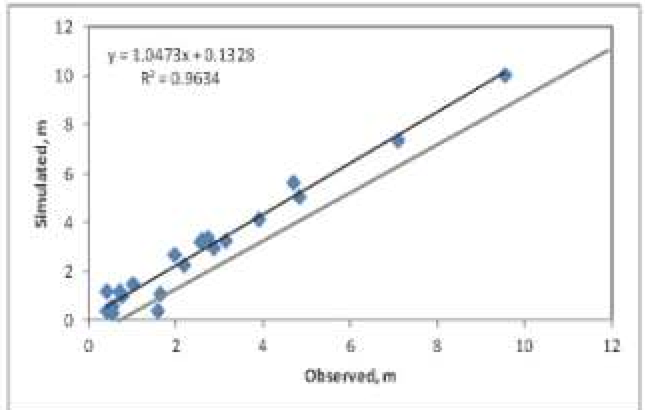

Figure 5.7: River network with stage-discharge relationships for some of the locations

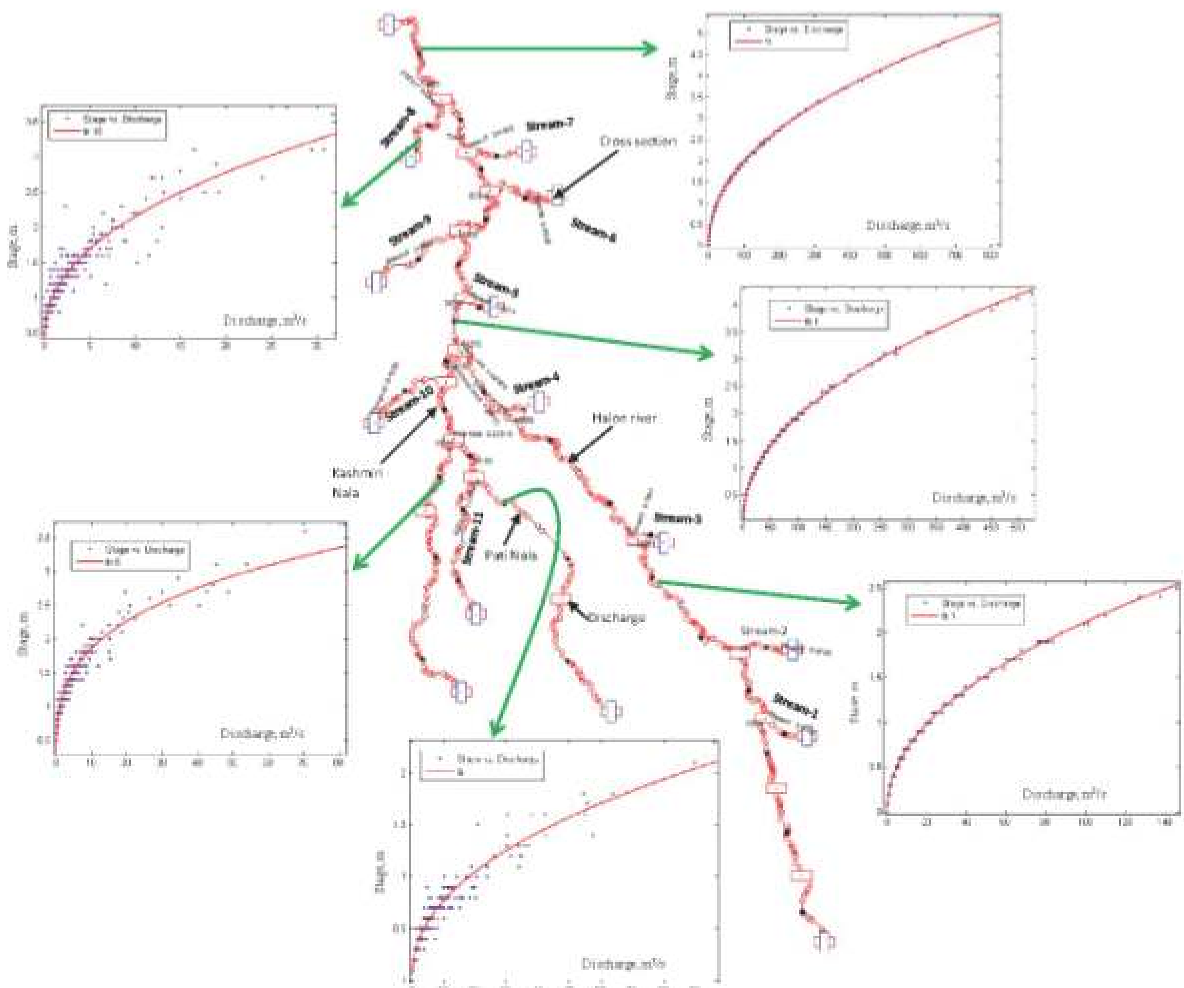

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Table 5.1: Power function coefficients and statistical parameters for the stage-discharge relationships

Sl. No.	Location	a	b	c	R^2	RMSE
1	Halon river up stream	0.2428	0.4715	0.01341	0.9989	0.028
2	Halon river middle stream	0.2207	0.4727	0.01507	0.9987	0.026
3	Halon river down stream	0.2541	0.4537	0.07466	0.9965	0.029
4	Kashmiri Nala at up stream	0.9652	0.2837	-	0.9556	0.112
5	Kashmiri Nala at down stream	0.2584	0.4666	0.4099	0.9969	0.03
6	Pati Nala up stream	0.1431	0.5238	0.03038	0.9723	0.275
7	Pati Nala down stream	0.2834	0.4399	-0.0116	0.9573	0.07337
8	Stream-1	0.6192	0.3675	-0.1083	0.9839	0.0493
9	Stream-2	0.552	0.5044	0.4046	0.9464	0.11
10	Stream-3	0.7402	0.5166	0.3267	0.9563	0.116
11	Stream-4	1.393	0.2281	-0.5263	0.6224	0.3115
12	Stream-5	1.458	0.3481	-0.2564	0.8231	0.3109
13	Stream-6	1.332	0.3016	-0.3346	0.8612	0.3018
14	Stream-7	1.093	0.4247	0.04463	0.8365	0.3122
15	Stream-8	0.9315	0.4996	0.07672	0.9061	0.2705
16	Stream-9	1.578	0.2824	-0.4331	0.8185	0.3229
17	Stream-10	0.6454	0.4373	0.3841	0.9206	0.15
18	Stream-11	0.2684	0.4372	0.01847	0.9824	0.0296

flow (26.9 per cent), transpiration (30.2 per cent) and canopy storage (16.5 per cent) whereas less contribution for evaporation from pond water (0.8 per cent) and surface water (25.6 per cent) was obtained in comparison to other than forest classes. Recharge to the aquifers beneath the spring locations which are basically geological lenses was 34.5 per cent whereas other components contributions were 65.5 per cent, which includes interception, ET, overland water, etc. This water seeps out in flat regions during the post monsoon period and contributes the channel flow. Percentage daily contributions to the main river (Halon) from small streams/Nala were extracted and presented in Figure 5.9. Volume of water contributed by various streams to the main river were also estimated and presented in Figure 5.10. Total volume of water within the river system considering surface water and base flow contributions is estimated of 1994 MCM. Out of that base flow water from the forest region which flows through the river and recharged to the groundwater may be utilized within the forest and neighbouring areas for various applications.

5.6 DISCUSSION

Empirical modeling approach to quantifying the accumulated hydrologic effects of watershed management is limited due to its complex nature of soil and water conservation practices. Therefore, the objective of this study was to evaluate the ability of the distributed and dynamically coupled hydrologic-hydrodynamic model, MIKE SHE to simulate river flow and different water balance components through hydrological experiment and integrating remote sensing inputs. Model calibration and validation suggested that the model could capture the dominant runoff process of the large watershed. We found that the physically based model required calibration at appropriate scales. We conclude that the model was useful for understanding the rainfall and its various partitioning parameters in the forest as well other land cover classes and their interlinking mechanism. However, more measured data with higher temporal resolution are needed to further apply the model for regional applications.

5.7 SUMMARY AND CONCLUSIONS

A coupled Hydrologic-hydrodynamic model was used for modelling water balance components in the forest and neighbouring regions in a watershed to quantify and observe the inter linkages of various water balance components. Model was calibrated and validated for daily river flow and post monsoon groundwater table variations. Following conclusions can be drawn from the analysis;

- Total rainfall during June 1, 2010 to August 15, 2012 was of 4230 mm. Out of which ET is about 48 per cent. Overall transpiration losses (10.6 per cent) and root zone soil moisture (0.041 on volume basis) were more in forest regions compared to other land cover classes.
- Good match between the simulated and observed river

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Figure 5.8: Water balance components for the catchment and land cover classes

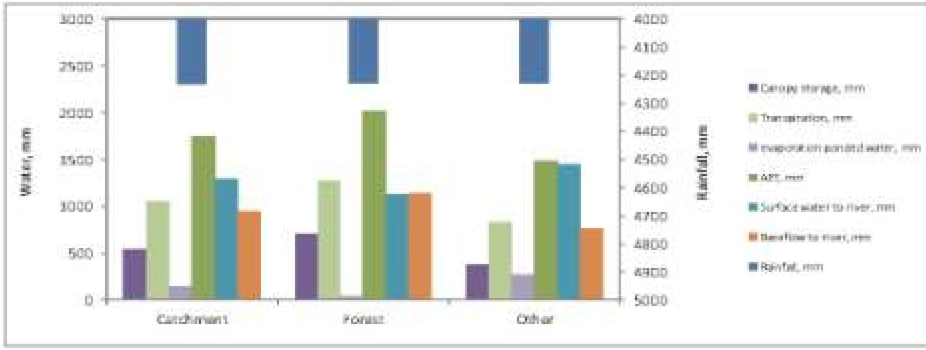


Figure 5.9: Daily percentage of water among different streams and small rivers/nala

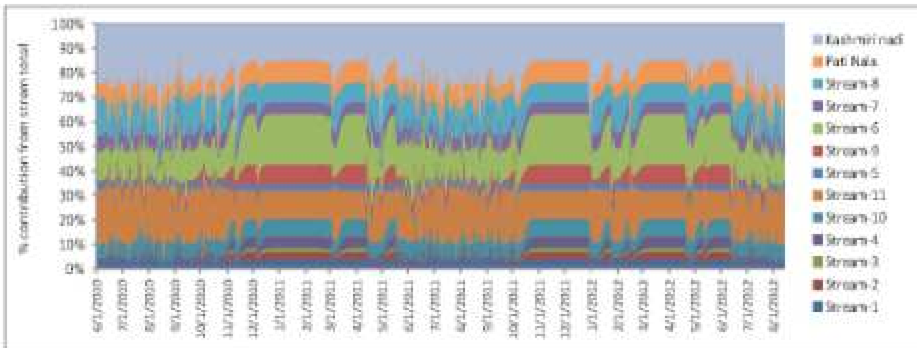
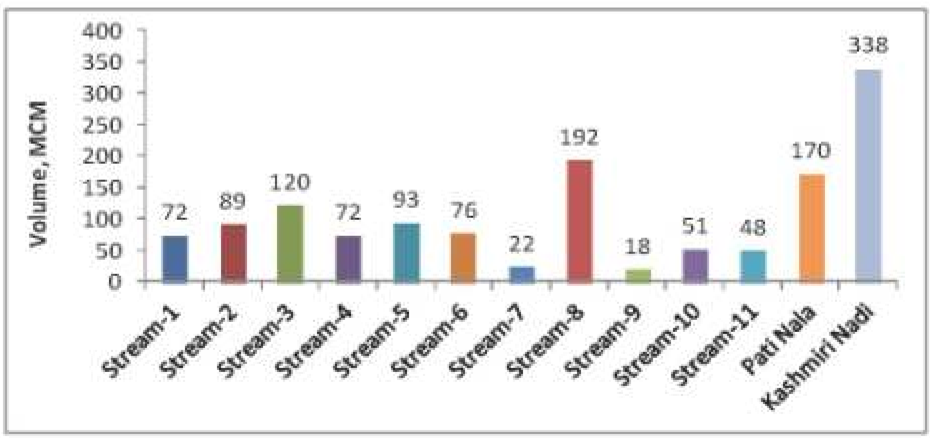


Figure 5.10: Volume of water produced in different streams/rivers/nala



discharges for the upstream (R2=0.81) and downstream (R2=0.81) reaches were obtained. Peak discharges, especially, were well simulated.

- A very good correlation (Nash Sutcliffe coefficient, 0.88) between observed and simulated groundwater for point locations has been obtained. Ground water table was high in the forest regions but overall recharge was more (0.36 m) in the other than forest regions. This is because of base flow contribution from the hilly forest regions to the neighbouring flat areas which attributed for more recharge.
- Simulated water yield ranges from 18 MCM to 338 MCM considering streams and Nalas during the study period.
- Stage-discharge relationships have been developed throughout the river network which includes all the tributary streams, Nalas and several locations in the main Halon river. Developed relationships can be used to estimate how much water yield is produced and going out of the forest system.
- In the forest region, a large amount of water goes in the sub-surface and comes out in the flat areas as baseflow (26.9 per cent of total rainfall) which shows the utility of forest for conserving and managing the water.

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6

Study on Assessment of the Impact of Forestry Plantation on Surface Run-off and Water Quality Related to Maintenance of Forestry Hydrology in Sikkim, India

Pankaj Kumar Roy, Gourab Banerjee, Malabika Biswas Roy and Asis Mazumdar

6.1 INTRODUCTION

Forests affect the hydrology of watersheds in various and complex ways, by increasing evapo-transpiration, increasing infiltration, intercepting cloud moisture, reducing the nutrient load of runoff, and more. Harvesting, shifting agriculture, grazing and invasion by alien plant species may all have profound effects over functioning of watersheds (Friday, 2003). Tabme *et al.* (2011) found that climate change impacts have resulted in a reduction in the temporal spread of rainfall and an increase in the intensity with a marked decline in winter rain. Tabme *et al.* (2011) showed that the subtropical villages (less than 1000 m), especially in the drought-prone zones are more vulnerable due to an increased outbreak of pests, diseases and weeds. Edwards and Withers (2008) reviewed the potential sources of SS, N and P to freshwaters in the UK and the extent to which their hydrological and compositional characteristics influence their likely significance to total annual fluxes and seasonally specific downstream impacts. Edwards and Withers (2008) suggested that small, low-order, headwater tributaries that at first sight might be considered to have only diffuse agricultural P sources are being continuously impacted by other rural sources such as farmyard runoff, septic tank discharge and road and track runoff. Tiwari *et al* (2011) studied the stream discharge analysis under different forest covers of Garwal Himalaya. They found that total annual discharge of the stream under degraded forest cover was higher by 305 mm (19 per cent). Total stream discharge under dense forest during the non-monsoon period from October, 2008 to March, 2009 was higher by 50 per cent as highlighted by Tiwari *et al.* (2011).

The study areas i.e. 346.9 ha – 3.5 sq.km are being considered through reconnaissance survey at different locations namely Nambu and Rimbi in three different areas such as disturbed by anthropogenic activities, undisturbed and pasture area (semi-disturbed) of West Sikkim. The effect of forest on rainfall, the impacts of various forestry activities (thinning, selection fellings, clear-felling) on streamflow, and the soil and water impacts of reforesting degraded or agricultural areas. Similarly, effects of forest management and conversion to other land use on water quality and ways to minimize any adverse impacts are dealt with forest plantation. Water draining from undisturbed forested watersheds is generally of the highest quality, particularly with regard to beneficial uses including drinking water, aquatic habitat for native species and contact recreation. The role of forests for providing water supplies of the highest quality has been one of the driving factors for establishment of forest reserves and for development of forest management practices designed to protect the high quality. The forest management activities such as road construction, logging operation, site preparation for regeneration of forest tree species, and fertilization of existing forests have been shown to alter water quality, primarily by causing changes in sediment loads, stream temperature, dissolved oxygen, and dissolved nutrients, particularly, nitrogen. West Sikkim is a district of the Coloured Stone Carving at Tashiding Monastary Indianstate of Sikkim. Its capital is Geyzing, also known as Gyalshing. The district is a favourite with trekkers due to the high elevations. Other important towns include Pelling and Jorethang. The district has a wide variety of fauna and flora to offer. Since most of the district is hilly it enjoys a temperate climate. Above 3,800 metres, the slopes are full of rhododendron forests. The economy is mainly agrarian, despite most of the land being unfit for cultivation owing to the precipitous and rocky slopes. The region has many power projects and enjoys almost uninterrupted electricity. Roads, however, are in a poor condition owing to the frequent landslides. An attempt has been made to assess the quantum of the stream flow and found the water quality status in the defined study area where on impact of forestry plantation related to maintenance of forest hydrology.

6.2 STUDY AREA

The study area consists of three characters namely as semi-disturbed, undisturbed and disturbed forest as shown in Figure 6.1. These forests area are to be bounded by individual catchment area with different latitudes and longitudes delineated in Table 6.1.

Figure 6.2 indicates the movement of conjectural storm water flow path in different layers of surface and sub-surface profile along with flow direction of West Sikkim. The idealized section showing formation of soil has been found in a good amount of soil moisture in the hill slopes of West Sikkim for plantation depicted as Figure 6.3.

Table 6.1: Description of the study area

Site	Character	Location	Latitude	Longitude	Area (km²)	Elevation (m)
Darap	Semi disturbed forest	Forest Check Post, Darap	27° 18' 15.4" N	88° 11' 15.5" E	0.5	1567
Limbuni Khola	Undisturbed forest	Near Water fall	27° 17' 59.7" N	88° 10' 52.4" E	1.5	1600
Tikjuk	Disturbed forest	Near DFO Office	27° 17' 52.8" N	88° 14' 59.4" E	1.5	1834
Type of tree	Natural regeneration	*Elaecarpus sikkimensis, Engelhardtia spp, Echnocarpus dasycarpus, Castonopsis indica, Betula alnoides, Beilschamiedia spp.*				
	Native	*Alnus nepalensis, Acerob longum, Bambusanutans, Casearia glomerata, Caston opsisindica, Castonopsis tribuloides, Duab anga sonneratiodes, Ficus hookerii, Juglans regia, Litsea polyantha, Machilus spp, Magnolia campbellii, Michelia excelsa, Nyssa sessiliflora, Prunus nepalensis, Quercus spp.*				
	Exotic	*Cryptomeria japonica, Juniperons spp, Cupressus spp.*				
Forest coverage		Moderate to Dense (Canopy cover 60-65%)				
Density of the population		836 per km²				

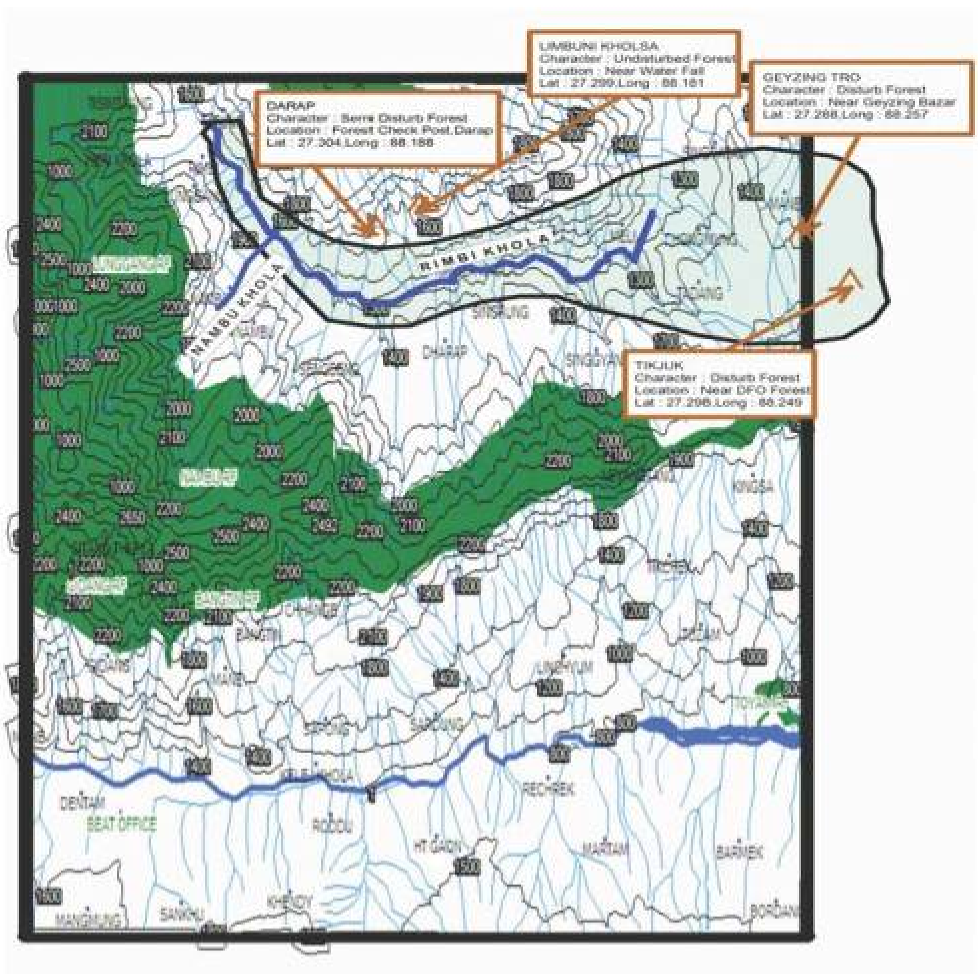
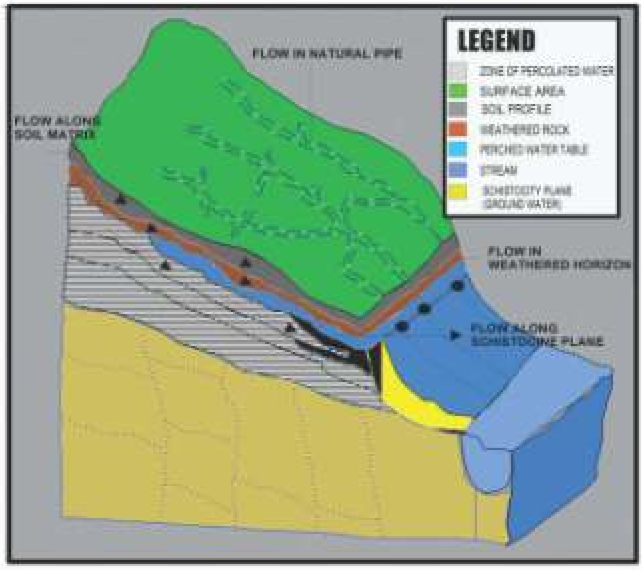


Figure 6.1: Study area delineated in West Sikkim

Figure 6.3: Idealized section showing formation of Soil in the hill slopes of West Sikkim



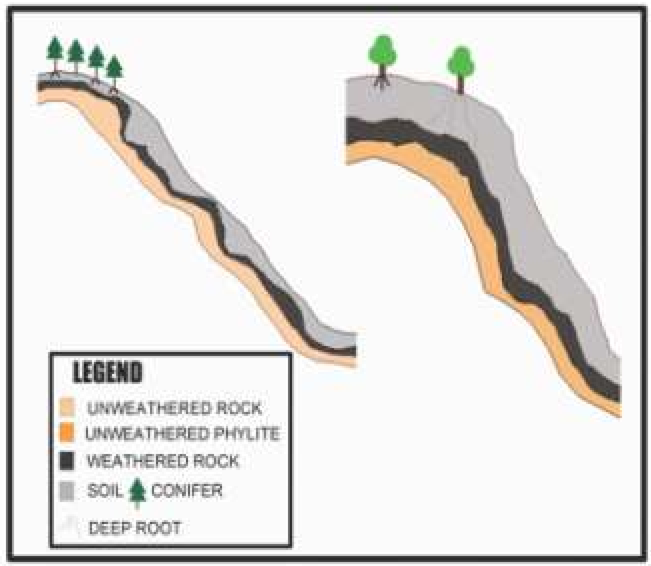
6.3 METHODOLOGY

Hydrological data has been collected from three different catchment areas with the help of non-recording rain gauge, pan evaporimeter, double ring infiltrometer installed at sites and accordingly measured all the parameters related to hydrological components during 2008 to 2010 mentioned in Table 6.1. The runoff has been calculated based on hydrologic budget by considering all the hydrological components. About 57 per cent of total runoff is found to be high as disturbed forest whereas in undisturbed catchment it is to be around 49 per cent as depicted in Table 6.2. The maximum rainfall of undisturbed forest was obtained to be as 92 per cent followed by 73 per cent in disturbed catchment.

Table 6.2: Hydrological Parameters (average) of three different micro-watersheds from 2008 to 2010

Sl. No.	Parameter	Undisturbed	Disturbed	Semi-disturbed
1	Total rainfall (mm)	2950	2878	2801
2	No. of Rainy days	110	130	128
3	Total Runoff (mm)	1470 (49%)	1646 (57%)	1517 (54%)
4	Standard Deviation (m^3/s)	0.005	0.006	0.006
5	Rainfall (June-October)	92%	73%	80%
6	Runoff (June-October)	89%	71%	68%
7	Runoff (Nov-April)	13.2%	10%	11%

Figure 6.2: Conjectural Storm Water Flow Model in parts of West Sikkim



6.3.1 Procedure

- Three micro-watersheds have been selected namely disturbed, semi-disturbed and un-disturbed and separated them at a distance of 12 km. There is no significant variation in climatic parameters and geological conditions.
- Meteorological observations have been installed in three micro-watersheds to measure the rainfall, evaporation, temperature, humidity and wind velocity.
- A meteorological observatory consists of dry and wet bulb thermometer, rain-gauge, pan-evaporimeter and anemometer.
- Water quality parameters have been analyzed during monsoon as well as pre-monsoon period (Figure 6.4).
- Composite weirs (120° V-notch with rectangular weir, Figure 6.5) have been used at three different sites to accommodate to measure stream discharge for the three micro-watersheds during monsoon period as well as during the pre-monsoon period (March-April) V-notches were used to measure the very low discharge.

6.3.2 Data Collection

A non-recording rainguage station and pan evaporimeter were installed in the selected catchment (Figure 6.6). The rainfall and evaporation data has been recorded from May 2008 to December 2010. The historical discharge data of Rangit river was collected from the Central Water Commission (CWC) from July 2003 to December 2009. The rate of infiltration has been calculated by using Double Ring Infiltrometer at five different sites in three different seasons namely pre-monsoon, monsoon and post-monsoon period. At the same time, the soil moisture at 15 cm and 30 cm depth were also measured by using Soil Tensiometer in similar seasons.

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Figure 6.4: Water quality measuring at site by using Rugged Field Kit

Figure 6.5: Discharge measuring by using composite weir installed at site

Figure 6.6: Rain-gauge, Evaporimeter and Double ring Infiltrometer installed at site, West Sikkim

6.3.2.1 Soils and Water Sampling and analyses

A quantitative amount of soils and water were collected in the 0-30 cm soil layer on seasonal basis from different location such as disturbed by anthropogenic activities, undisturbed and pasture area of a forest area situated near a natural canal coming out from the nearby forest. Different parameters of the soil (pH, EC, moisture content, water holding capacity, bulk density, soil texture , C:N ratio, total carbon, soil organic carbon, total nitrogen, total potassium, total phosphorus, total sodium, sodium absorption ratio, total calcium, potassium oxide, phosphoric acid, aluminium content, silica, etc.) and water (pH, turbidity, SS, conductivity, alkalinity, acidity, ammonical nitrogen, COD, BOD, TC, FC, phosphorus, etc.) were analyzed on seasonal basis in the laboratory of School of Water Resources Engineering, Jadavpur University.

6.3.2.2 Statistical Analysis

Analysis of data was carried out with SPSS Software for all soil chemical properties. The aim was to estimate the water-

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conserving effect of forest and also tried to investigate the probability of exceeding and equality of annual runoff and its components in river flowing in forested catchments compared to the areas where forest coverage was poor.

6.4 RESULTS AND DISCUSSION

6.4.1 Stream flow Impact Analysis

- The thickness of humus is varied from 8 to 10 cm.
- It is apparent that infiltration-capacity values of soils are subjected to wide variations depending upon a large number of factors. The values are varied from 1.2 to 1.5 cm/hr for the selected sites at Darap and Limbuni Kholsa whereas the other sites these values have increased by as much as ten times due to a good grass cover or vegetation cover.
- Almost the entire watersheds of the study areas treatment experiments have shown that streamflow increases as forest cover decreases, and vice versa. The reason for this is that forests evaporate significantly more water than grasslands or crops.
- Although transpiration rates (soil water uptake by plants) under conditions of ample soil water do not differ much between forests and non-forests vegetation, rates of evaporation from vegetation wetted by rain (rainfall interception) are much higher from tall, aerodynamically rough surfaces like forests.
- In addition, the deeper roots of trees allow continued water uptake when more shallow-rooted plants have to give up during prolonged rainless periods. Because rainfall interception totals are higher in wetter years, the impact of forest clearance (i.e., after interception falls away) increases with mean annual rainfall.
- Apart from rainfall, the magnitude of the change in annual streamflow is also affected by forest type and slope aspect. Generally, the largest changes are observed in the case of clearing conifers, owing to their dense evergreen habit and high interception, followed by native (but not exotic) forests then deciduous hardwoods leafless in winter or dry season.
- Rainfall and runoff data has been analyzed for the period May 2008 to December 2010.
- Flow in the stream was minimum during months of March-April and maximum during the month of July-August.
- Discharge of stream from the disturbed forest micro-watershed (Tikjuk area) remained negligible for a period of three months from March to May whereas discharge of stream from undisturbed micro-watershed remained low but almost steady (0.0028 m^3/s) during the same period and also discharge of stream from semi-disturbed micro-watershed remained low value 0.0015 m^3/s compared to undisturbed area.
- Maximum daily average discharge in the disturbed and semi-disturbed catchment were recorded on August 24, 2010 (0.053 m^3/s and 0.015 m^3/s, respectively) whereas maximum daily average discharge of 0.01 m^3/s was recorded on July 12, 2010 in the un-disturbed catchment.
- In terms of runoff per unit area, maximum runoffs were 57 mm and 13 mm in disturbed and semi-disturbed catchment on August 24, 2010 and 9 mm in undisturbed catchment on July 12, 2010.
- Runoff coefficients during the monsoon period, (June to September) were 0.55, 0.25 and 0.20 for disturbed, semi-disturbed and un-disturbed micro-watersheds, respectively.
- Standard deviation of daily discharge was 25 per cent higher in disturbed (0.006 m^3/s) than undisturbed (0.005 m^3/s) catchment. These results indicate that runoff was more uniform in case of undisturbed catchment.
- Stream flow form un-disturbed was perennial whereas stream generating from disturbed and semi-disturbed forests were intermittent and it flows for seven to eight months only.
- Stream flow during the post monsoon season is supported by subsurface flow in a hilly watershed, popularly known as base flow of the stream. Rainfall infiltrates the ground through inter-granular pore spaces, openings, fissures, fractures, joints, bedding planes, etc., and reappears down slope as spring and seepage.
- Hydrographs of three different micro-watersheds (Figure 7.8) revealed quick response of rainfall on stream discharge from the micro-watersheds. It is due to the small size and steep slope of both the catchments i.e. un-disturbed and disturbed.
- The recession parts of hydrographs of the two streams differ with each other. The discharge declined slowly undisturbed catchment during post monsoon month while it declined at faster rate in disturbed catchment and stream dries up in summer months.
- Stream flowing through dense forest sustained discharge during non-monsoon months due to input from the sub-surface flow.
- Runoffs in three different catchments were maximum during August and minimum during May.
- Total rainfall received in the undisturbed, disturbed and semi-disturbed micro-watersheds were 2,950 mm, 2,805 mm and 2,801 mm, respectively, generating runoff of 1,470 mm, 1,646 mm and 1,517 mm, respectively, during the year.
- Total runoff in disturbed and semi-disturbed catchments have been found as 57 per cent and 54 per cent, respectively, whereas 49 per cent was received in case of un-disturbed catchment.

6.4.2 Water Quality and Soil Analysis

Dissolved oxygen (DO) is a critical water quality parameter for characterizing the health of an aquatic system. It is a measurement of oxygen dissolved in water which is available to fish and other aquatic life (Table 6.3). The DO content of water results from the photosynthetic and respiratory activities of the flora and fauna in the system, and the mixing of atmospheric oxygen with waters through wind and stream current action. The optimum level of dissolve oxygen i.e. 7 to 8 mg/L is said to good for agricultural prospect. The DO content more than 6.0 mg/L

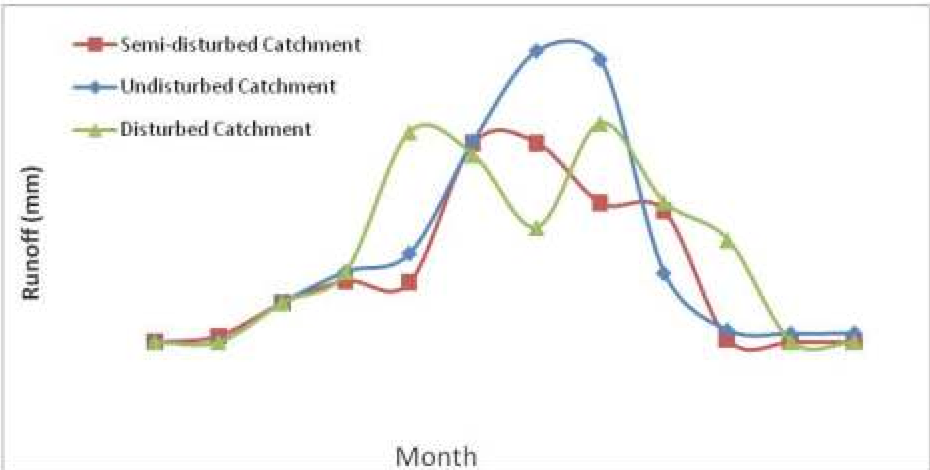

Figure 6.8: Monthly variation of stream discharge (2008-2010) in three different micro-watersheds

is favourable for plants for their maturation as highlighted in Table 3.pH values between 7 and 8 are optimal for supporting a diverse aquatic ecosystem. A pH range between 6.5 and 8.5 is generally useable. The range of pH of the water taken from the field is suitable for the plant since it lies between 7 to 8 and is safe for human requirements. Biochemical oxygen demand (BOD) is a measure of the amount of oxygen consumed by the respiration of microorganisms while feeding on decomposing organic material such as algae and other dead plants. Excessive nutrients (phosphates and nitrates) can cause algal blooms, and their eventual decomposition can cause massive fish kills if BOD drastically lowers dissolved oxygen levels. The biochemical oxygen demand should not be so great as to lower the dissolved oxygen to an unacceptable level (6.0 mg/L or less). The range of BOD of the water taken from the field is suitable for the plant since it just in the range of 0.5 to 1.9. These very low values of BOD indicate that people of this area use sanitary system and do not dispose their excreta into the field. Fecal coliform bacteria indicate the likely presence of water-borne pathogenic (disease-causing) bacteria or viruses, including E.coli. They are present in the intestinal tracts of all warm-blooded animals, including humans. Fecal coliform levels are measured in fecal colonies (FC) per 100 ml. Fecal coliform levels in freshwater should not exceed an average count of 100 colonies. Fecal coliform of less than 50 ml MPN/100 is optimal. For marine waters, fecal coliform levels should not exceed 14 MPN/100 ml. The health standard for drinking water is zero whereas for swimming 200 MPN/100 ml and for partial body contact (boating) 1000 MPN/100 ml. A maximum fecal coliform of 100 MPN/100 ml as found out for semi-disturbed catchment is safe for plant use but in case of disturbed catchment it has found 800 MPN/100 ml indicated anthropogenic activities.

Soil at undisturbed catchment has favorable amount of nitrogen for the plant growth whereas disturbed catchment has slightly more as obtained from the field data during survey depicted in Table 6.4. Therefore, the mixing of soil un-disturbed, disturbed and semi-disturbed catchments are needed in order to get a homogeneous nitrogen concentration in the soil. Soil at disturbed catchment has little more nitrogen than required for plant and semi-disturbed catchments have favorable amount

Table 6.3: Average water quality in three different seasons

Sl No.	Parameter	Un-disturbed catchment	Disturbed catchment	Semi-disturbed Catchment
1	pH	7.12	7.10	7.12
2	BOD, mg/L	<1.00	1.9	1.20
3	COD, mg/L	3.00	7.00	4.00
4	Turbidity, NTU	4.50	5.40	4.50
5	Total Hardness(as $CaCO_3$),mg/L	18.00	16.00	16.00
6	Alkalinity($CaCO_3$),mg/L	12.00	18.00	12.00
7	Ammoniacal Nitrogen (as N), mg/L	0.012	0.14	0.033
8	Phenolphthalein Acidity ($CaCO_3$), mg/L	1.00	1.00	1.00
9	Total Suspended Solids, mg/L	3.20	8.50	5.40
10	Conductivity (μmhos/cm)	38.50	45.80	42.80
11	Dissolved Oxygen (as O_2), mg/L	6.00	4.70	6.10
12	Total Coliform Organisms, MPN/100 mL	2.20	3×10^3	1.20×10^3
13	Fecal Coliform, MPN/100 mL	<1.10	0.80×10^3	0.10×10^3

of nitrogen for the plant growth. Therefore, these two soils is also need to be mixing properly. Net impacts on water quality depend on prior land use and crop management, current forest management practices, soil type, local hydrology, and climate. In general, conversions to forestland have the potential to reduce erosion and subsequent sedimentation, as well as reduce levels of dissolved nutrients and pesticides in surface runoff and groundwater. These improvements in water quality are a function of lower amounts of runoff and leaching as well as lower concentration of potential pollutants that are expected to result from the conversion of forestland. Water draining from undisturbed forested watersheds is generally of the highest quality, particularly with regard to beneficial uses including with drinking water, aquatic habit for native species, and contact recreation. Our results show consistent patterns of relatively high water quality draining forested catchments i.e. un-disturbed in comparison to other land uses such as agriculture or urbanization (disturbed or semi-disturbed catchment). Recognition of the relative role of forests for providing water supplies of the highest quality has been one of the driving factors for establishment of forest reserves and for development of forest management practices design to protect this high quality.

Table 6.4: Result of the soil test

Sl No	Parameter	Unit	Result		
			Disturbed catchment	Un-disturbed catchment	Semi-disturbed Catchment
1	pH	-	5.24	4.93	5.03
2	Electrical Conductivity	µs/cm	60	46	37
3	Moisture Content	%	7.7	2.5	6.1
4	Water Soluble Aggregates	%	0.026	0.022	0.017
5	Water holding capacity	kg/kg	0.392	0.346	0.378
6	Bulk Density	gm/cm³	1.39	1.41	1.37
7	Soil Texture	-	Sandy Loam	Sandy Loam	Sandy Loam
a)	Sand	%	54.5	53.8	50.6
b)	Silt	%	29.3	28.1	29.2
c)	Clay	%	16.2	18.1	20.2
8	Carbon Nitrogen Ratio (C:N)	wt. basis	11.2	12.3	11.7
9	Total Carbon (C)	g/kg	45.6	50.4	99.5
10	Soil Organic carbon	gm/kg	10.7	2.8	17.1
11	Total Nitrogen (N)	mg/kg	957	228	1457
12	Mineral Nitrogen	mg/kg	216	48	248
13	Total Potassium (K)	mg/kg	6237	6222	6640
14	Total Phosphorus (P)	mg/kg	428.1	227.9	404.8
15	Total Sodium (Na)	mg/kg	1398	1319	1524
16	Sodium absorption Ratio	-	11.1	13.2	14.2
17	Total Calcium (Ca)	mg/kg	3164	2807	2971
18	Na_2O	mg/kg	1884	1778	2054
19	K_2O	mg/kg	11127	7495	7999
20	P_2O_5	mg/kg	1013	539	958
21	Al_2O_3	mg/kg	38164	47590	42443
22	SiO_2	mg/kg	77.7	75.1	64.4

Table 6.5: Pearson correlation coefficients for Water Quality

		Disturbed catchment	Un-disturbed catchment	Semi-disturbed Catchment
Disturbed catchment	Pearson Correlation coefficient	1	-0.179	0.982**
Un-disturbed catchment	Pearson Correlation coefficient	-0.179	1	-0.134
Semi-disturbed Catchment	Pearson Correlation coefficient	0.982**	-0.134	1

**. Correlation is significant at the 0.01 level (2-tailed).

In some cases forest management activities such as road construction, harvesting, site preparation for regeneration of forest tree species, and fertilization of existing forest have been shown to alter water quality, primarily by causing changes in sediment loads, stream temperature, dissolved oxygen, and dissolved nutrients, particularly nitrogen.

6.4.3 Multivariate statistical techniques

One way ANOVA has been used to statistically analyze 13 parameters as in pH, BOD, COD, turbidity, TH, alkalinity, ammoniacal nitrogen, phenolphthalein acidity, TSS, conductivity, DO, TC, FC at three different catchments namely disturbed, semi-disturbed and disturbed, using IBM SPSS Statistics 20.The parameters are checked for interdependency. Similarly Briz-Kishore and Murali (1992) described that the analyzed data could been used to evaluate not only eigen values and eigen vectors but also to develop a correlation factor using statistical software to reveal hydro-chemical characteristics of a watershed.

Table 6.5 showed that the strong and positive correlation is to be developed in between disturbed catchment and semi-disturbed catchment where the pearson correlation coefficient value is found to be as $R^2 = 0.982$, thus it indicates the output of water quality will be more deteriorated while water transports through disturbed catchment and semi-disturbed catchment as well and whereas the water quality particularly dissolved oxygen, turbidity and coliform bacteria will be improved to a greater extent compared to input water and the rest of the parameter will

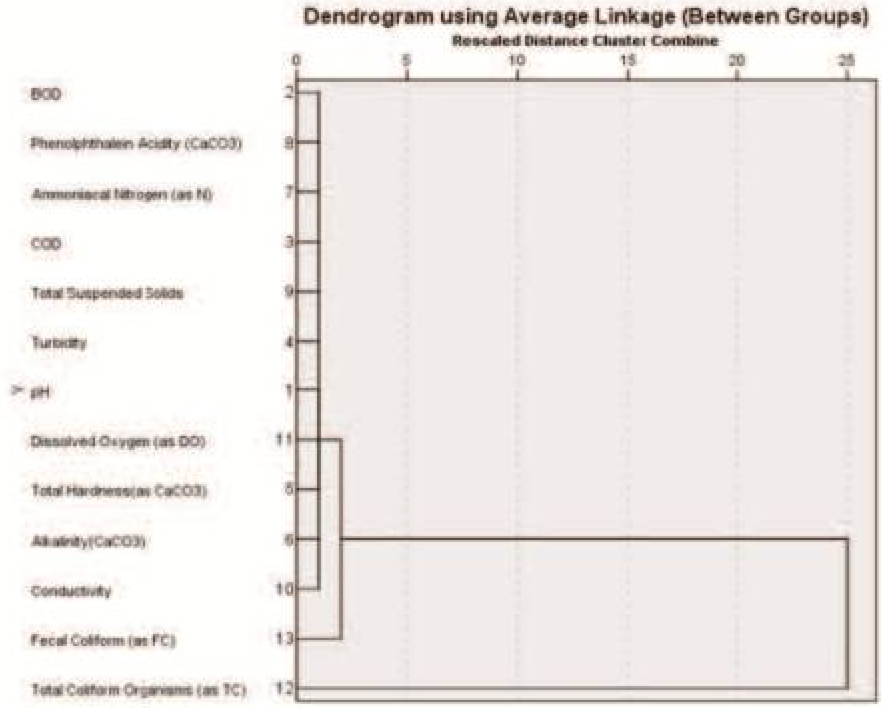

Figure 6.9: Dendrogram analysis for water quality

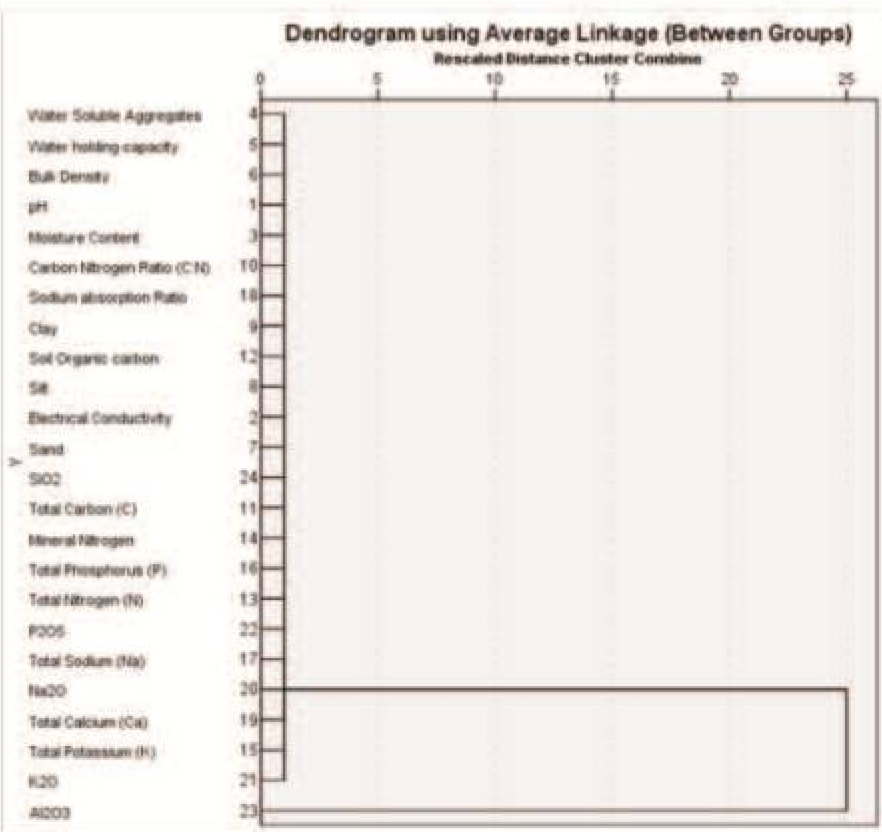

Figure 6.10: Dendrogram analysis for soil quality

Table 6.6: Pearson correlation coefficients for soil sample

		Disturbed catchment	Un-disturbed catchment	Semi-disturbed Catchment
Disturbed catchment	Pearson Correlation coefficient	1	0.987**	0.992**
Un-disturbed catchment	Pearson Correlation coefficient	0.987**	1	0.999**
Semi-disturbed Catchment	Pearson Correlation coefficient	0.992**	0.999**	1

**. Correlation is significant at the 0.01 level (2-tailed).

remain unchanged as it shows the pearson correlation coefficient value (R^2 = -0.179) depicted in Table 6.5.

Figure 6.9 shows that the model has been clustered into three groups, namely smaller cluster (BOD, phenolphthalein acidity, ammoniacal nitrogen, COD, total suspended solids, turbidity, pH, Total hardness, alkalinity, conductivity), larger cluster (dissolved oxygen, Fecal coliform) and very larger cluster (dissolved oxygen, Fecal coliform, Total coliform). It means the length of smaller cluster has low distance, high similarity and also closer to each other than for other two clusters.

A total of 22 soil samples have been used to analyze the pearson correlation coefficients using IBM SPSS Statistics 20 in between disturbed, un-disturbed and semi-disturbed catchment. From Table 6.6, it shows that the strong and positive correlation has been obtained in between disturbed catchment and semi-disturbed catchment (R^2=0.992), which indicates the disturbed catchment increases the nutrients value (N, P, K, Na, etc.) at a higher level followed by semi-disturbed catchment.

Figure 6.10 shows that the model has been clustered into two groups and these are smaller cluster (water soluble aggregates, water holding capacity, bulk density, pH, moisture content, carbon nitrogen ratio, sodium absorption ratio, clay soil organic carbon, silt, electrical conductivity, sand, SiO_2, total carbon, mineral nitrogen, total phosphorus, total nitrogen, P_2O_5, total sodium, total calcium, total potassium, K_2O) and larger cluster (Na_2O, Al_2O_3). Thus the results highlight the length of smaller cluster has low distance, high similarity and also closer to each other.

6.5 CONCLUSION

1. Firstly, comparatively less runoff from forest watershed (un-disturbed catchment) during the rainy months shows that forest controls excess runoff in the downstream against the overall impact of forests on the hydrological regime of watershed
2. Annual runoff from dense forest was lower than that of disturbed catchment.
3. Secondly, forests induce infiltration which leads to more uniform flow round the year from the un-disturbed forest watershed.
4. Net impacts on water and soil quality will depend on prior land use and crop management, current forest management practices, soil type, local hydrology, and climate.
5. Conversions to forestland may have the potential to reduce erosion and subsequent sedimentation, as well as reduce levels of dissolved nutrients and pesticides in surface runoff and groundwater.
6. Improvements in water quality will be a function of lower amounts of runoff and leaching as well as lower concentration of potential pollutants that will be expected to result from the conversion of forestland validated experimentally in case of un-disturbed catchment.

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7

An Insight into Subsurface Aquifer Characteristics Sourced Within the Forested Catchment through Isotopic Investigations of Spring Flow in Pauri Urban Area, Uttarakhand, India

S. Tarafdar, K. Kumar, Bhishm Kumar, S. P. Rai

7.1 INTRODUCTION

The population in town of Pauri in Pauri district of Uttarakhand State, India is growing exponentially (annual average growth rate of 2 per cent) and is expected to cross over 50,000 population (fixed as well as floating) by 2025. The rising population is not only going to create an additional demand for water in the already scares town but will also induce changes in landuse/ landcover causing an increase in impervious cover through catchment urbanisation in the headwaters (Sharp, 2010). The major water supply to this expanding town comes from the river pumping scheme on Alkananda River at Srinagar approximately 30 km from Pauri town. The urban water demand is partly met by the naturally existing springs and handpumps constructed by the Jalsanthan Department, Pauri. The depth of drilling of constructed water wells during the 1980s used to be up to 50m only, but in recent times the drilling depth has gone as deep as 80 to 100 m, indicative of lowering of water table in Pauri urban area. The understanding of subsurface hydraulic characteristics of these hardrock aquifers or aquifer system is lacking as geohydrological investigations are never been carried out by the drilling agencies entrusted for groundwater development through groundwater wells construction. Spring-flow monitoring and measurement of its stable isotope and electrical conductivity variability can provides an excellent insight into subsurface hydrogeological characteristics (Kresic, 1997, James *et al.*, 2000, Meriano *et al.*, 2011 and Tarafdar *et al.*, 2012)

The stable isotope of hydrogen and oxygen are widely applied in water resources investigation due to its conservative nature (Clark and Fritz, 1997). In this paper, we examine the variability of oxygen and hydrogen isotope in precipitation and ground water (spring and handpump) during the monsoon period of 2010 and for the entire period of 2011. The objectives of the study was to develop the meteoric water line for the study area, essential for gaining an insight into the interconnections between springs and groundwater wells, and preliminary understanding of the aquifer characteristics through application of electrical conductivity and stable isotope data.

7.2 STUDY AREA

Pauri Urban area spread at an elevation range from 1700 to 1800m, between latitudes 30°05'N and 30°10'N and between longitudes 78°40'E and 78°45'E (Figure 8.1). It is the district head quarter with population of around 27,000 (Census of India, 2001). The steep urbanised hillslope comes under micro catchment of Khandha River, a tributary of river Alaknanda.The spring within the study area is gravity-drainage flow falls under the fracture springs category of Bryan's classification (Bryan, 1919). Land-use-land-cover of the study area falls under three broad categories, i.e., forest cover (reserve and village forest), urban area and agriculture land. Geologically, the study area is mainly dominated by Pauri Phyllites. The regular foliation/ bedding and fractures in the Phyllites act as a conduit for the recharge of the springs in the area. The study area has humid temperate climatic and average annual rainfall for the district is 1,582.6 mm (Indian Meteorological Department).The study area received above normal rainfall during the monsoon period of 2010 and near normal rainfall in 2011 monsoon. But the year 2009 was drought year with deficient rains all over India.

8.3 METHODOLOGY

Spring discharge of one representative spring within the urban area was measured with a volume calibrated bucket and stopwatch at daily time step. Three to five readings were taken daily and average value was recorded. Along with discharge data, electrical conductivity of the spring water samples of was also measured daily from May 2010 to April 2011 using a portable conductivity meterwith temperature compensation at 25°C (µS/cm). A digital rainfall event logger was installed to record the precipitation data. Event loggers are most commonly used with tipping-bucket rain gauges, where each tip of the bucket represents 1/100" of rain.

Weekly spring water samples were collected along with the event based rainfall samples during the monsoon period (JJAS) of year 2010 using ordinary rain gauge. The rainfall samples were collected at Checha village at approximately 1500m elevation and following the guidelines of IAEA. Water samples from almost all the hand pumps (12 number) spread within the urban area

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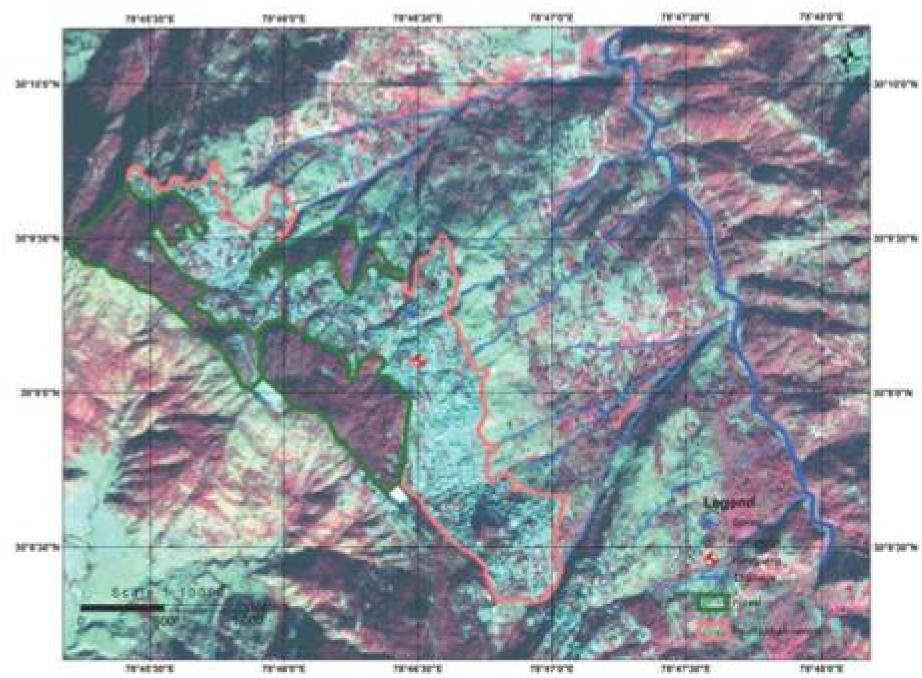
Figure 7.1: Study area map with locations of spring, handpump and rain gauge prepared using liss-IV satellite data.



were collected on August 27, 2010 to decipher the influx of new recharged water due to monsoonal rain. In the subsequent year (2011), weekly to bimonthly water samples of spring water, rainfall and one of the groundwater handpump were sampled for a period of March to December 2011. The hand pump identified for year round sampling was selected at the upslope of the spring. All the water samples were collected in 15ml HDPE narrow mouth bottles and sealed. The isotope analysis of water samples was carried out at National Institute of Hydrology (NIH), Roorkee, using Dual Inlet Isotope Mass Spectrometer (DIIRMS), for $\delta^{2}H$ and continuous flow isotope ratio mass spectrometer (CFIRMS) for $\delta^{18}O$ following the standard procedure (Epstein and Mayeda, 1953; Brenninkmeijer and Morrison, 1987) and the measured values of ($\delta 2H$ & $\delta^{18}O$) are based on VSMOW-II (Vienna Standard Mean Oceanic Water-II).

7.4 RESULTS AND DISCUSSION

A plot of spring hydrograph (Figure 7.2) for year 2010 and 2011 reveals that a minimum discharge of around 10 lpm is maintained during the winter(January and February) and summer period (March to May) of 2010 and during the monsoon period peak flow of 92 lpm is observed. The peak in spring flow coincides with the peak in the rainfall. Similar pattern is also observed in 2011. The difference noted during the 2011 is that the spring maintained a higher baseflow (approx. 20 lpm), sharp peak and relatively gradual decline during recession period. It is worthwhile to mention here that the year 2009 was a year of moderate drought during which the study area received deficient rainfall whereas 2010 was a year of surplus rainfall. A significant rise in the baseflow observed during 2011 is caused by the above normal rainfall in the study area during 2010. The total rainfall recorded during the year 2010 and 2011 was 167.74 cm and 168.45 cm, respectively. The observed monsoon rainfall (JJAS) in both the year is more than 75 per cent of the total yearly rainfall. The electrical conductivity of spring flow in the beginning was recorded around 600 μS/cm (with temperature compensation at 25°C), which increased to 838 μS/cm with peak flow (peak of EC curve on 8/8/2010). This was followed by a sharp decline in the conductivity and subsequent recovery of conductivity value. The sharp decline shows an influx of new water after high conductivity old groundwater is being pushed through the aquifer matrix deciphering the piston-flow mechanism.

7.4.1 Isotopic characteristics of precipitation

Rainfall isotopic characterisation of the study area from the precipitation sample collected between June to September 2010 shows an enriched value in June and as the monsoon progresses the average isotope composition becomes more and more depleted (Figure 7.2). The $\delta^{2}H$ and $\delta^{18}O$ values of the rainfall samples ranged from -149.15‰ to 47.46‰ and -19.71‰ to 6.00‰. The average and median $\delta^{18}O$ value(dash line in box plot) for monsoon season(JJAS) of 2010 is close to -10.00‰ and -12.52‰, respectively.

Monthly isotopic variability (Figure 7.3 and Table 7.1) observed for the year 2011 (February to August) showed an enriched value in February and premonsoon period and gets depleted in the month of July and August 2011 as observed in 2010 also. The $\delta^{2}H$ and $\delta^{18}O$ values of the rainfall samples ranged from -141.92‰ to 27.15‰ and -18.70‰ to 3.85‰. The average

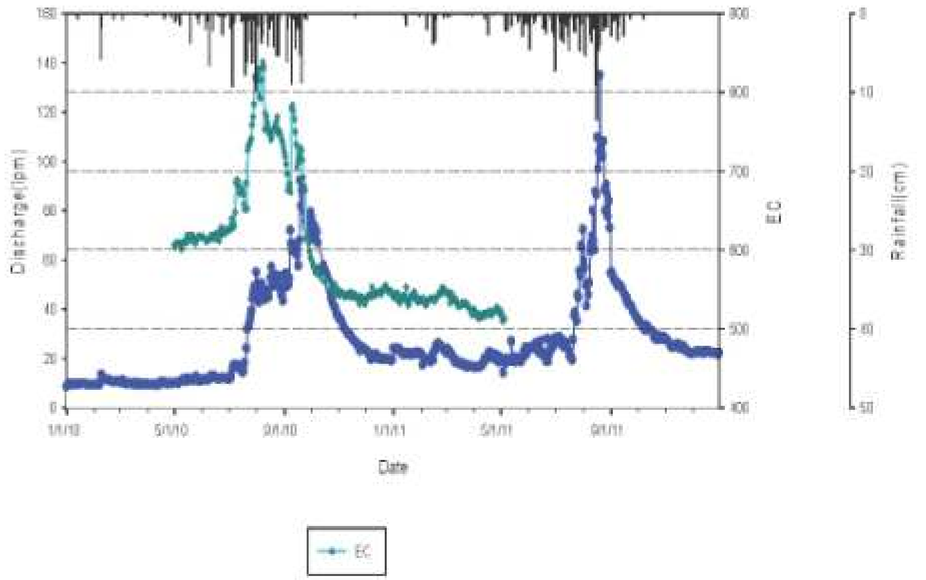


Figure 7.2: Time series of spring discharge (in lpm, liters per minute) and electrical conductivityfor 2010 and 2011 as well as rainfall data in cm

Figure 7.3: Box plot of monthly δ18O isotope content of precipitation samples for the year 2010 (monsoon) and 2011 (year round) for Pauri urban area

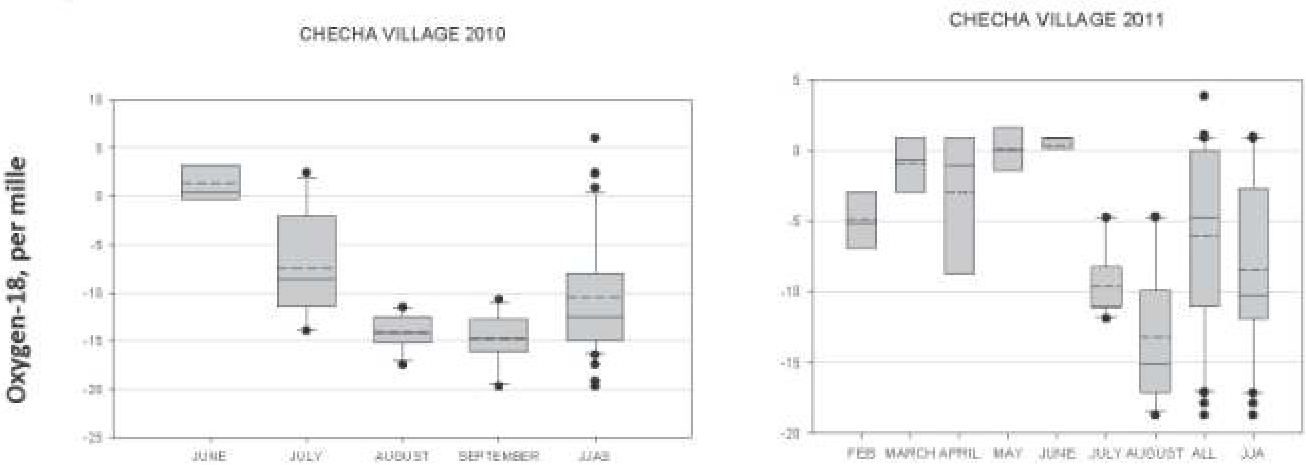


Table 7.1: Monthly average of rainfall samples collected from location name Checha village at an elevation of 1500m.

Month	Total Rainfall(cm)	n	Oxygen-18			Deuterium		
			Average	SD	n	Average	SD	N
Feb	10.26	6	-4.88	2.47	6	-23.49	18.56	6
Mar	0.78	3	-0.89	2.01	4	3.60	15.18	4
Apr	2.66	3	-2.94	5.11	3	-11.46	43.35	3
May	4.83	6	0.12	2.32	6	7.56	12.56	6
Jun	13.18	13	0.31	1.26	8	13.25	9.12	8
Jul	11.25	11	-9.57	2.55	11	-68.00	21.15	11
Aug	28.87	12	-13.19	5.06	12	-97.29	41.78	12

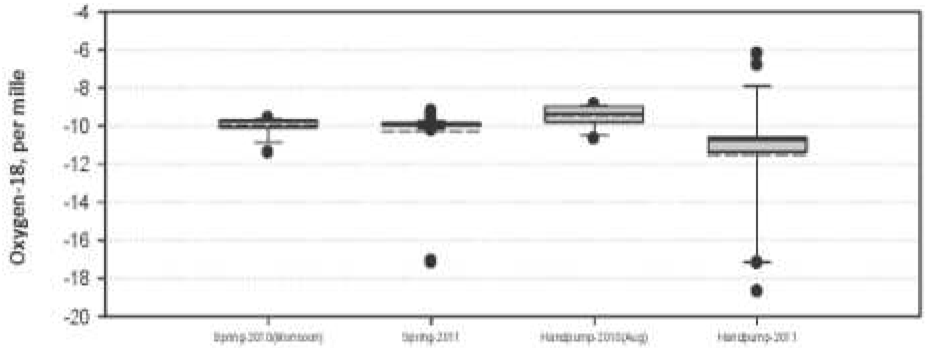


Figure 7.4: Box plot of δ¹⁸O isotope content of spring and hand pump water for the year 2010 (monsoon) and 2011 (year round)

Table 7.2: Monthly average of groundwater samples collected from Handpump near DAV school at an elevation of 1580m.

Month	Oxygen-18			Deuterium		
2011	Average	SD	n	Average	SD	n
Mar	-10.66	0.08	2	-72.96	0.08	2
Apr	-10.71	0.04	2	-72.89	0.04	2
May	-10.70	0.07	3	-73.09	0.11	3
Jun	-10.68	0.13	3	-72.75	0.56	3
Jul	-10.89	0.74	6	-75.19	7.36	6
Aug	-16.03	3.43	5	-118.25	28.96	5

Rejected Values

		Oxygen-18	Deuterium
1-Aug-11	Handpump	-39.29	-6.22
29-Aug-11	Handpump	-44.43	-6.81

Table 7.3: Monthly average of groundwater samples collected from spring location named diptidhara

Month	Oxygen-18			Deuterium		
2011	Average	SD	n	Average	SD	n
Mar	-10.00	0.02	2	-68.07	0.02	2
Apr	-9.99	0.01	2	-68.13	0.15	2
May	-9.94	0.06	7	-67.69	0.31	7
Jun	-9.82	0.02	2	-66.03	0.14	2
Jul	-9.86	0.15	6	-66.16	1.13	6
Aug	-11.96	3.55	7	-83.93	29.47	7
Sep	-10.04	0.07	4	-68.68	0.46	3
Oct	-10.04	0.28	4	-67.77	0.80	4
Nov	-9.93	0.16	3	-68.15	0.61	3

and median δ¹⁸O value for monsoon season (JJA) of 2011 is close to -8.51‰ and -10.00‰, respectively. The observed value is found to be more enriched compared to the monsoon period of 2010 because the September rainfall which is having the most depleted isotopic signatures could not be collected in 2011. The average and median δ¹⁸O value for all the observed months in 2011 is close to -6.00‰ and -5.00‰, respectively.

7.4.2 Isotopic characteristics of groundwater:

Weekly samples of spring discharge during monsoon period of 2010 and weekly to bimonthly sampling in 2011 (Table 7.2) reveals average value of δ¹⁸O around -10‰ (Figure 7.4), which is indicative of the seasonal biases towards the monsoon recharge. The data collected from the 12 hand pumps on August 27, 2010 also showed a close to -10‰ value indicative of the fact that springs and hand pumps are tapping the same groundwater aquifer. The year round sampling of a single hand pump (bimonthly as well as weekly) showed a little more depleted value. As compared to the high seasonal rainfall isotopic data variability, the observed temporal variability of groundwater δ¹⁸O time series data for 2011 (Table 7.3) is found stable. This might be due to the influence of thick soil cover (≥ 2m) and relatively deeper groundwater in the catchment area of the spring and handpump.

7.4.3 Relationship of δ²H and δ¹⁸O

The plot of δ²H and δ¹⁸O from 44 rainfall event samples from June to September 2010 collected at three different locations within the study area is presented in Figure 7.5.

The regression line drawn between δ18O - δ D defines the local meteoric water line (LMWL) and is represented by following equation, $R^2 = 0.995$. The LMWL matches quite well with the regional meteoric water line developed for western Himalaya () by Kumar *et al.* (2010). It is interesting to note that the samples from both the groundwater sources, i.e., the springs and hand pump tapping different depths, all plot on the regression line, indicating that rainfall as a common source of recharge and the recharge process is faster as effect of evaporation is not observed on the isotopic signatures of groundwater from springs and handpumps.

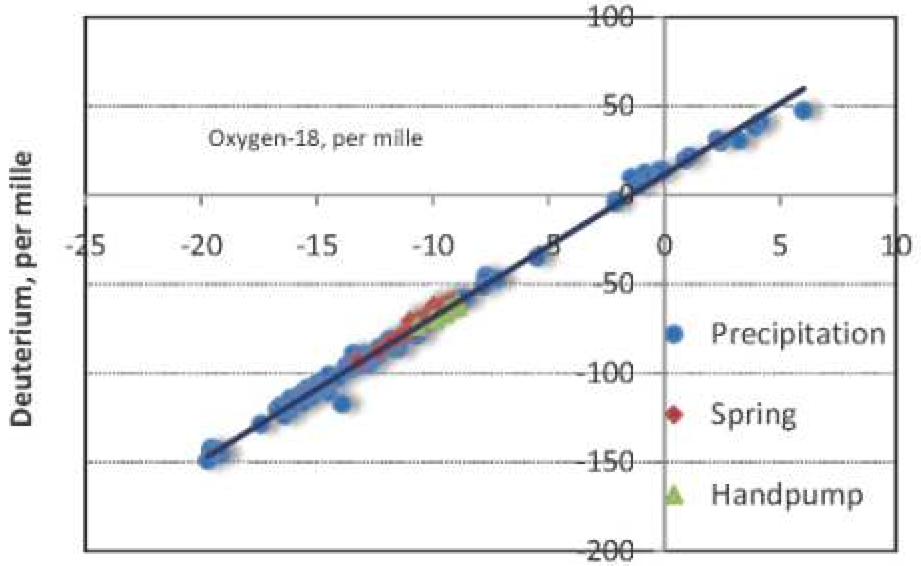


Figure 7.5: The δ18O - δD best fit line defining the local meteoric water line with groundwater samples from springs and Hand pumps

7.5 CONCLUSION

Future demand for water is going to increase in this expanding town of Pauri. Understanding of the linkages between the naturally available spring water resources and groundwater extraction in the source area of spring through water well construction is vital for the water resource sustainability of this urban centre. Spring hydrograph baseline data highlights the availability of water in surplus monsoon season and summer low-flow period for two successive years (2010 and 2011).The electrical conductivity data measured over a period of one year gives an insight into the subsurface mechanism of interaction of monsoon rainfall with the already stored groundwater in the aquifer matrix. The isotope (δ^2H and $\delta^{18}O$) time series data of rainfall samples for 2010 and 2011, ranged from -149.15‰ to 47.46‰ and -19.71‰ to 6.00‰. The average and median $\delta^{18}O$ value for monsoon season (JJAS) of 2010 is close to -10.00‰ and -12.52‰, respectively. The observed groundwater isotope temporal variability data indicate a very small seasonal variability and significant damping of the precipitation in the unsaturated zone. An obvious seasonal bias towards the monsoon recharge is found as the average isotope content for groundwater (spring and hand pump) was found close to -10.00‰. The local meteoric water line (LMWL) developed from isotopic composition of precipitation corresponds well with the humid regions and with the regional meteoric water line developed for western Himalaya. Groundwater samples plot on the LMWL indicating rainfall as a common source of origin.

ACKNOWLEDGEMENT

The authors wish to thank the ex-Director (Dr. L.M.S. Palni) of the Institute (G.B. Pant Institute of Himalayan Environment and Development) for the guidance and support.

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8

Water Volume Estimation in Forested Landscape using RS and GIS based Variables in Far Western Region of Nepal

Basanta Raj Guatam and Timo Tokola

8.1 INTRODUCTION

Natural resource management in mountainous regions requires an understanding of the variability of these resources in time and space and the role of local people (Naiman 1997). Land use change is a crucial issue in mountainous areas due to slope steepness (Tokola *et al.*, 2001), deforestation, forest degradation, agricultural expansion and population pressure. Land use change followed by soil losses and the impact on the water quality are a serious problem caused by a complex bio-physical, socio-economic and technological factors in the mountain region of Nepal (Sitaula *et al.*, 2001). Forest, soil and water are the most important natural resources of Nepal (Khanal and Bastola, 2005). It is possible to monitor water quality using remote sensing. Finding a spatial distribution of water quality information from satellite-based observations is an important aspect in making a Water Use Master Plan (here after WUMP). The regular updating of spatial distribution of water quality information using remote observations is very important for a long-term water management plan (Chen *et al.*, 2007).

A non-parametric method, kNN, has been used extensively for forest inventory in several countries (Tokola *et al.*, 1996; Katila and Tomppo, 2001). Several different satellite materials in connection with a forest inventory with the reference sample plot method were compared (Tokola *et al.* 1996; Tokola and Shrestha, 1999). kNN was first introduced by Kilkki and Paivinen in 1986 for forest inventory in Finland. With this method, the field information is propagated to the entire population of pixels in a satellite image based on spectral value. The satellite materials and the spectral distance measures are compared by calculating the accuracy of field plot wise estimation for volumes of growing stock by tree species. Zhou (2008) applied kNN to estimate soil erosion in a mountainous watershed in China.

8.2 STUDY AREA

The study area is located (Figure 8.1) in Dadeldhura district of Far-Western Region, Nepal. The two Village Development

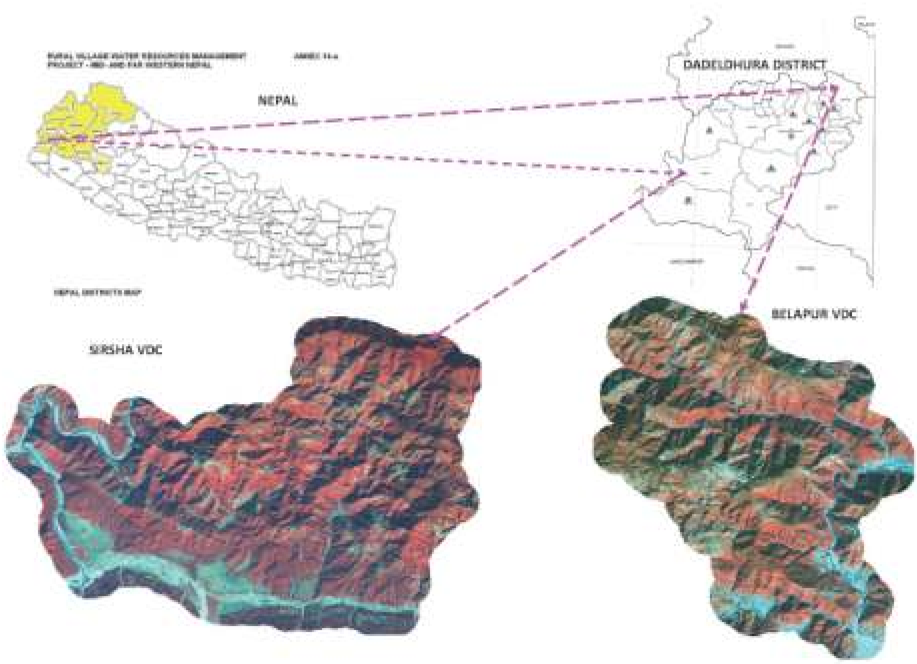

Figure 8.1: Study area and its location

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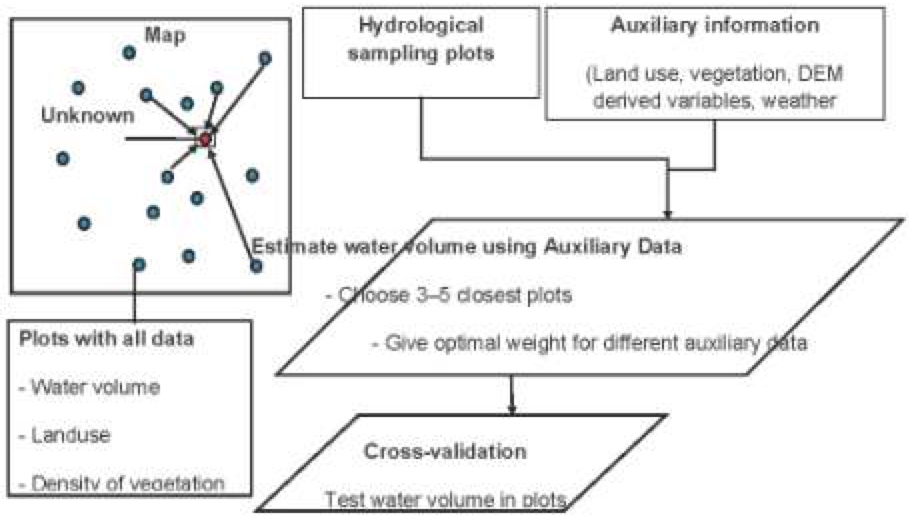

Figure 8.2: Concept in water volume estimation

Committees (here after VDC) were selected in the present research are Shirsha and Belapur. Both VDCs have high priority to prepare WUMP under the Rural Village Water Resource Management Project. The geographic location of the study area lies between the geo-coordinates of 29°06'52.53"N to 29°25'44.31"N and 80°14'00.13"E to 80°48'00.01"E.

8.3 MATERIALS AND METHODOLOGY

Aster image acquired on December 2007 was used in the present analysis. The imagery was purchased from the USGS Earth Resources Observation and Science (EROS) and geometrically rectified with the UTM/WGS 84 projection. The contour map was obtained from RVWRMP which was created in 40 m contour intervals from 1:50000 scale topographic maps. A Digital Elevation Model (DEM) was generated in ArcGIS software. A land use map was prepared in ERDAS using ASTER imagery of the study area. A total of 514 field sample plots data on water volume were collected for Srisha and Belapur VDC. The descriptive statistics showed the mean and standard deviation for observed water volume was 8.23 and 37.67 lps (litre per second), respectively. The maximum measured water volume was 523 lps and minimum measured water volume was 0.001 lps.

Refe (field sample plot method) software was used through MS DOS in combining field and satellite data so that each field sample plot on water volume got the corresponding pixel value of the satellite imagery (Tokola *et al.*, 1996). A conceptual approach for water volume estimation is presented in the Figure 8.2.

The concept is that similar water volume locations exist within a large reference area covered by the satellite data. The responses of the pixels within satellite imagery are dependent on the state of water resources. Hydrological sample plots along with other auxiliary information (land use, topography, weather etc.) can be used to estimate water volume (Figure 8.2). In the kNN method, the information of unknown pixels is searched with reference to the few closest pixels whose information is already known. The image information, band weight, spectral distance, number of nearest neighbors and land use information were the main parameters used in present analysis. The three nearest sample plots were used from water volume sample plots to estimate the water volume of unknown pixels. Three Aster bands namely band 1 (green), band 2 (red) and band 3 (NIR) were used with the pixel size 15×15 m to predict water volume.

The kNN based algorithm requires three important decisions that are necessary before applying the algorithm. The first decision is the distance function to be applied, the second decision is the nearest sample plots to be used and the third decision is the method in allocating weights to the nearest sample plots. The similarity between the water volumes locations were estimated using the GIS variable-based Euclidean distance function. A weighted Euclidean distance function was used in the present analysis using following formula (Tokola *et al.*, 1996).

$$d_{ij} = \sqrt{\sum_{h=1}^{nch} (p_h c_{ijh})^2} \qquad 8.1$$

Where,
dij = Euclidean distance between pixel i in the study area and the pixel of a water volume plot j
nch = number of GIS layer
cijh = difference in values of pixels i and j on GIS layer h and
ph = weighting parameter for GIS layer h

The similarity between water volume estimates can be used to weigh single measurement plots. The inversely-distance-based method was used in allocating area weights to the nearest water volume plots. Weights were given inversely proportional of the weight exponent to the distance function using following formula (Tokola *et al.*, 1996).

$$w_{ij} = \frac{(\frac{1}{d_{ij}})^t}{\sum_{j=1}^{k} (\frac{1}{d_{ij}})^t} \qquad 8.2$$

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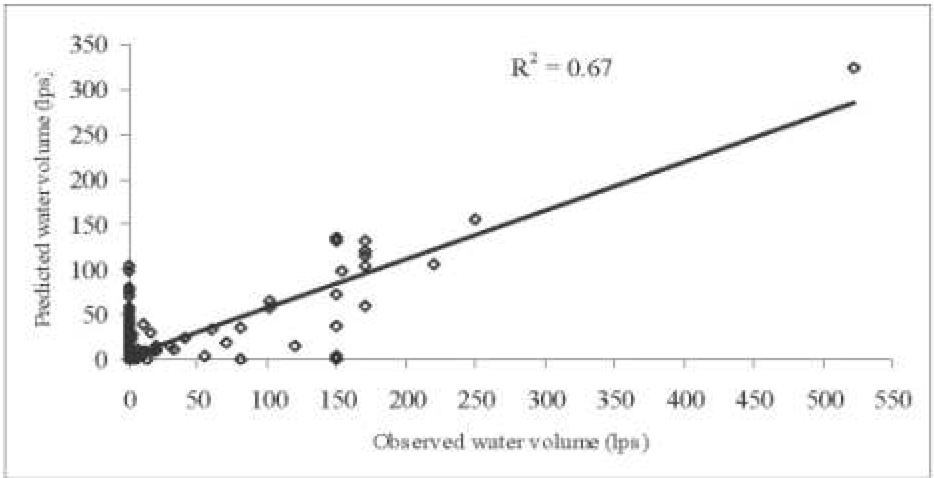


Figure 8.3: Observed and predicted water volume using satellite imagery

Where,
wij = the weights of pixel i for the water volume plot j
k = number of nearest water volume plot used
t = weighting parameter of GIS-variable based distance
Water volume y was estimated for pixel i using following formula

$$y_i = \sum_{j=1}^{k} w_{ij} y_j$$

Where,
yi = water volume for pixel i
yj = field measured water volume y, per unit area, on nearest water volume plot j, measured in field

Topographical and other hydrological parameters were also used to predict water volume. Slope, aspect and flow accumulation data were combined with satellite imagery. Flow accumulation is a raster of accumulated flow to each cell that flow into each down slope cell. High flow accumulations are areas of concentrated flow and can be used to identify stream channels. The flow accumulation map was derived from DEM in ArcGIS.

8.4 RESULTS

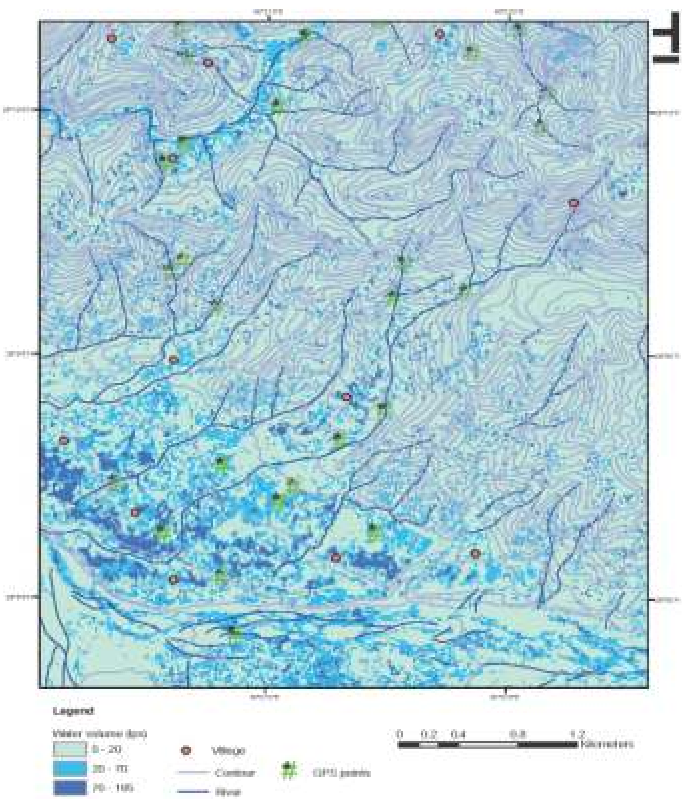
The results showed that the kNN method predicts higher water volume areas more accurately when compared to the lower water volume areas (Figure 8.3). The R^2 of the analysis was 0.67. The coefficient (R^2) of the method explains 0.67 of the water volume estimation using kNN.

The result was classified in three classes (Table 8.1) to simply the statistics. Table 8.1 shows that high water volume areas can be estimated using kNN. Though the RMSE of the class III (high water volume) is high, the class value is also higher in comparison to class I (low water volume) and class II (medium water volume). The average observed value of the class III was 133.926 lps. The final output map demonstrates that the predicted high water volume areas are located in flat surfaces and river channels are linked with those water areas (Figure 8.4).

Table 8.1: Predicted water volume classes and their statistics (lps=Litre Per Second)

Data	Class I: Low water volume (0–20 lps)	Class II: Medium water volume (20–70 lps)	Class III: High water volume (70–165 lps)
Average of residuals	1.261	-13.289	16.767
Count of residuals	468	29	17
Sub of residuals	590.223	-385.393	285.03
Average of observed	2.549	25.443	133.926
Average of predicted	1.288	38.733	117.159
Real value of the class	2.549	25.443	133.926
Bias of the class	1.261	-13.289	16.766
RMSE of the class	27.283	71.565	69.131
Total average of residual	0.953		
Total count of residual	514		
Total sum of residual	489.868		
Total average of observed	8.186		
Total average of predicted	7.233		

Figure 8.4: An output map of water volume estimation using kNN algorithm



DISCUSSION

The approach illustrated in the present analysis is a demonstration of the kNN method for intensive future research. Due to the limited field sample data and other limitation (human error during data collection, shadow effect in the hilly terrain etc), the result showed high RMSE. A large number of field sample plots along with other variables are needed for accurate estimation (Tokola *et al.*, 1996; McRorberts *et al.*, 2002). The result seems quite good for higher water volume areas (e.g. >50 lps). The satellite imagery used in water volume estimation, was acquired in December. December is a moist month in the study area. The reflectance from the moist soil and vegetation might have some dominant effect on the satellite imagery which leads to predict higher number of low water volume areas. In this study, the kNN method was used with only Aster imagery. It would be good to test the methodology with different satellite materials so that a comparison can be made for better prediction.

The field data on water volume was collected using different methods (bucket method, area velocity method, etc.) depending upon the velocity of the water in the study area. It would be better to apply a uniform method during field data collection for reliability and accuracy in the variables. Katila and Tomppo (2001) found a decrease in RMSE until the k value reached 20 to 30. Tokola *et al.* (1996) and Nilsson and Ranneby (1997) noted that the 10 to 15 nearest plots are needed in estimating forest variables. But in the present analysis when the nearest plots were increased from 3 to 5, the RMSE also increased. It is exactly the opposite of the record of Katila and Tomppo (2001), Nilsson and Ranneby (1997) and Tokola *et al.* (1996). The present findings lend support to Koukal *et al.* (2007), Franco-Lopez *et al.* (2001) and Moeur and Stage (1995). They suggest a much smaller value of k is necessary to retain the variation of the original data.

The present result showed a high RMSE and a bias in the datasets. The level of association between the spectral variables and water volumes is likely low. Nevertheless there are always possibilities to improve the level of association between the variables. For example, spectral information of the original band was used in the present analysis. Derived measures such as band ratios and vegetation indices can be used in addition to the original bands (Tokola *et al.*, 1996; Tomppo and Halme, 2004; Gjertsen, 2007) to improve the result. Other possibilities include using auxiliary information such as site index maps, land capability maps, or soil maps. Topographic normalizations could be used to overcome the problem of terrain effects in a hilly country like Nepal

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