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**Rainfall-Runoff Conditions in
Meghalaya Plateau
(A Case Study of Paham Syiem Watershed)**

Surendra Singh

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**Department of Geography
North Eastern Hill University
Shillong 793 022**

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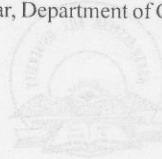
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Surendra Singh
Department of Geography
NEHU, Shillong.

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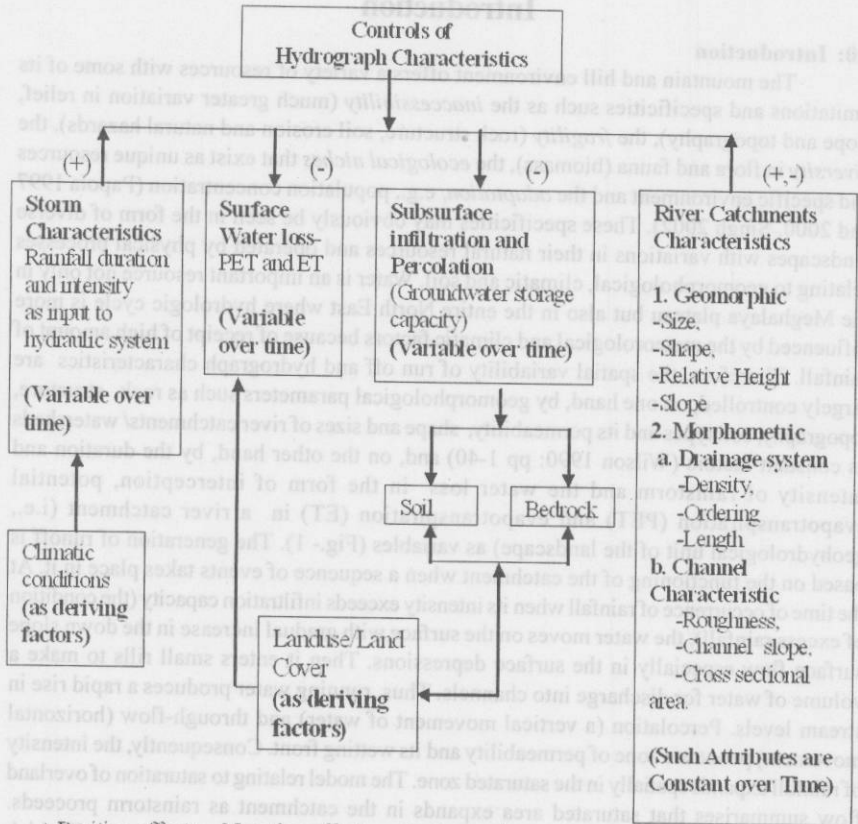
Section – I

Introduction

1.0: Introduction

The mountain and hill environment offers a variety of resources with some of its limitations and specificities such as the *inaccessibility* (much greater variation in relief, slope and topography), the *fragility* (rock structure, soil erosion and natural hazards), the *diversity* in flora and fauna (biomass), the *ecological niches* that exist as unique resources and specific environment and the *adaptation*, e.g., population concentration (Papola 1997 and 2000, Singh 2002). These specificities may obviously be seen in the form of diverse landscapes with variations in their natural resources and operated by physical processes relating to geomorphological, climatic and soil. Water is an important resource not only in the Meghalaya plateau but also in the entire North East where hydrologic cycle is more influenced by the meteorological and climatic factors because of receipt of high amount of rainfall. Therefore, the spatial variability of run off and hydrograph characteristics are largely controlled, on one hand, by geomorphological parameters such as rock structure, topography, soil types and its permeability, shape and sizes of river catchments/ watersheds as constant factors (Wilson 1990: pp 1-40) and, on the other hand, by the duration and intensity of rainstorm and the water loss in the form of interception, potential evapotranspiration (PET) and evapotranspiration (ET) in a river catchment (i.e., geohydrological unit of the landscape) as variables (Fig.- 1). The generation of runoff is based on the functioning of the catchment when a sequence of events takes place in it. At the time of occurrence of rainfall when its intensity exceeds infiltration capacity (the condition of excess rainfall), the water moves on the surface with gradual increase in the down slope surface flow especially in the surface depressions. Then it enters small rills to make a volume of water for discharge into channels. Thus, running water produces a rapid rise in stream levels. Percolation (a vertical movement of water) and through-flow (horizontal movement) penetrate zone of permeability and its wetting front. Consequently, the intensity of rainfall expands spatially in the saturated zone. The model relating to saturation of overland flow summarises that saturated area expands in the catchment as rainstorm proceeds. Furthermore, saturated wedge migrates upslope as to provide more area for runoff which controls the hydrograph pattern of the catchment (Goudie 1993, pp. 436-475). Such components (rainfall and runoff) are variables in space and over time which are to be studied by considering geohydrological parameters of landscape prevalent in the Meghalaya

plateau which is the most humid area over the world. The parametric relationship of rainfall – runoff would be different in such extreme conditions and may produce different results as we usually conceive.



+ Positive effects, - Negative effects on hydrograph

Fig. - 1: Controlling Factors of Runoff

1.1: Climatic Conditions and Monsoon Mechanism

Climatic conditions and distribution of precipitation in the Meghalaya plateau are controlled by the over all larger water circulation system prevalent over the Indian continent and oceanic atmosphere. Classical conjectures of the Indian monsoon and extreme precipitation over Meghalaya provide explanation of the causes of such occurrences. The creation of strong upper westerly which pushes easterlies from South to North in the summer, and consequently, the atmospheric circulation from North to South from Tibetan plateau to the South Indian ocean are considered as major causes (Webster 1987, O'Hare 1997). However, northward moving monsoon in the summer over Bay of Bengal and Bangladesh plains aligning Meghalaya plateau creates convective thunderstorms and tropical cyclones at the time of onset and withdrawal the monsoon over the North-Eastern parts of India. The severity of such occurrences are much more concentrated over the southern slopes of Meghalaya plateau and North-Eastern plains of Bangladesh (forefront of the north moving monsoon) due to orographic effects (O'Hare 1997, Starkel et al. 2002, Starkel and Singh 2004). These phases of precipitation occurrences reflect clearly the distinctions in its spatial as well as temporal variability in the pattern of precipitation and inter- and intra-seasonal shift of the monsoon period and even its length. Floods and landslides occur resultantly in such areas of extreme precipitation.

Nature and types of precipitation, intensity and pattern of rainfall and the atmospheric conditions are more influenced by the temperature structure of air layers between the cloud-base and ground as the ratio of atmospheric lapse rate and freezing line change (Goudie 1993, pp. 426-432). However, a neo-classical interpretation of monsoon shifts and duration of wet seasons is forwarded by defending the causes of changes in the low level wind fields and Outgoing Long wave Radiation (OLR) (Horel et al. 1989, Matsumoto 1992). A sharp regional variation and steep gradients of OLR on the Northern and North-Eastern parts aligning the Himalayan ranges between the Tibetan plateau and the inter-continental great plains including Thar desert were shown under the category of low level wind fields (Matsumoto 1990). These areas show an average spatial variability of OLR about 40 w m^{-2} (from 250 w m^{-2} over the great plains to 210 w m^{-2} over Tibetan plateau) in the month of January, 30 w m^{-2} (250 to 220 w m^{-2}) in March, 40 w m^{-2} (200 to 220 w m^{-2}) in mid of April, 60 w m^{-2} (280 to 220 w m^{-2}) in May, 60 w m^{-2} (285 to 220 w m^{-2}) in June and it continues to prevail throughout the year except July to September in rainy season (Matsumoto 1990, Figs 4 through 14). Zonal wind velocity at 850 mb also plays a great role to create strong easterlies during the time of onset and withdrawal of monsoon in the Northern Indian.

Abundant and scanty rainfall distribution (concentration of rainfall in lower Ganga and Brahmaputra basins), active and break phases of monsoon occurrences at daily and monthly scales (in June and mid - August) in the North East India including Bangladesh are major causes of excessive water availability and flood disaster specially occurred in

1987 and 1988 in Bangladesh (Prasad 1974, Matsumoto 1988, Matsumoto et al. 1996, and Ohsawa et al. 2000, 2001). These evidences show that wind velocity and OLR fields contribute towards the temporal changes in the regional pattern of rainfall and its temporal concentration in some areas with their steep spatial gradients of OLR. In a very recent study on the circulation of atmospheric water conducted by Japan International Cooperation Agency (JICA) starting investigations on diurnal variations of rainfall and upper wind during the monsoon season over Bangladesh, the mid-night – morning (00 – 09 hrs) rainfall peak of diurnal rainfall was identified in the North-Eastern parts of Bangladesh plain aligning Meghalaya plateau (Terao et al. 2006). As a result, maximum of rain depth is found over Cherrapunjee – Mawsynram areas of the southern slopes of Meghalaya plateau (Prasad 1970 and 1974) where the nocturnal jet mechanism may be helpful in hypothesizing the pattern of mid-night – morning peak of diurnal rainfall pattern (Terao et al. 2006).

Rainfall is a major component of hydrologic cycle. The hydrologic system working in the basin/ watershed is activated by the receipt of rain which is variable over time, while features of watershed are considered stable in the sense that the slope, soil and drainage systems are recipient of precipitation and work accordingly.

Effects of severity of precipitation on landscape at its macro areal level were analysed and interpreted by considering its different aspects. Say for example, Starkel (1972) modelled Indian monsoon to show the transformation in relief features especially in the slopes of river valleys and development of new micro-features in the foot hill areas in response to rainfall intensity and its distribution. On the other hand, Matsumoto et al. (1996) emphasized more towards development of model based on the duration and intensity of wet season of Indian sub-continent at temporal scale from annual to day to delineate the areas of heavy rainfall (above 2000 mm) to search the causes of 1987 and 1988 floods which occurred in North Eastern part of India and Bangladesh.

Such studies were conducted at meso regional scale, while geomorphic features of landscape and rainfall intensities were also studied by considering watershed, a geohydrologic unit of micro level in the context of landscape to understand the nature and extent of runoff.

Action of anthropogenic forces and its resultant features in the form of evolving landuses in the watershed constitute another set of parameters which influence the hydrologic as well as geomorphic features in the watershed (Tripathi et al. 1995, Prokop 2005). Development of rainfall-runoff modelling for simulating the availability of water resources, flood conditions, understanding the effects of anthropogenic forces (activities of man in a variety of ways in hydro-geomorphic landscape), improvement in natural landscape, conservation of natural and utilization of human resources, infusion for self sustained development in hill and mountain areas are main hydrologic aspects of watershed (Satapathy and Dutta 2002). Since the pattern of rainfall varies over space at different landscapes

watershed, the established relationships between rainfall and runoff in such watersheds becomes different which evolve different areal pattern. In extreme rainfall conditions as prevalent in the Meghalaya plateau, such relationships may be analysed and interpreted by following two approaches

- (a) Areal differentiations of geo-hydrological phenomena and the study of distributional pattern of available water keeping in view Meghalaya as a whole a geo-ecological unit where precipitation varies over space. In such regional perspectives, one can find the water resource availability and the causes of its areal variations.
- (b) The micro-areal approach to study rainfall-runoff relationship through a representative micro watershed and geological, geomorphological and morphometric parameters, is established by understanding hydrograph characteristics. Generation of parameters relating to geomorphic, soil and landuses in the watershed and establishing their relationships at different stages in the process of evaluating rainfall-runoff equations through hydrographs are the major aspects of watershed management.

1.2: Objectives

Following such approaches for the assessment of water resources and establish parametric rainfall runoff relationship, the regional pattern and sample watershed study are to be pursued in Meghalaya plateau. Therefore, the main objectives of the present research are as

- (i) to understand the distribution of rainfall with special reference to geo-ecological characteristics of Meghalaya plateau,
- (ii) to interpret the spatial pattern of runoff and availability of water in different river catchments, and
- (iii) to analyse the hydrographs of different rainfall conditions for understanding the behaviour of watershed parameters in the process of hydrologic events.

1.3: Methodology and Data Collection

The present study focuses attention towards two major aspects: (a) the assessment of water resource and its regional pattern emerging on Meghalaya plateau and (b) the establishment of rainfall runoff relationship in the representative watershed. Water resource may be/has been assessed in a variety of ways considering hydrological, geo-ecological as well as socio-economic dimensions of water assessment. Geo-hydrological approach of water resource assessment and watershed management is one of the important aspects which may provide a sound base for its availability and management. Measurement of runoff in different river catchments/watersheds, which have been considered as geo-hydrological unit in which rainfall-runoff relationship varies in different hydrological regimes, may help in water assessment. Adoption of water budget approach is perhaps an appropriate way to do so.

A base map analysing the characteristics of drainage systems, contours and general land uses is required for the purpose. Delineation of watershed boundaries at different order tributaries following geo-hydrological criterion and generation of geo-morphological, soil and precipitation data for each delineated watershed are major task. Generation of relevant statistics regarding geomorphic parameters for each and every river catchment at quarter inch (R.F. 1: 253,440) scale of toposheet is considered to be an ideal scale for assessment of runoff in the Meghalaya plateau. The most of the part plateau is covered almost in three toposheets of the same scale: 78/K, 78/O and 83C. River catchments in the entire plateau delineated at lower order are counted 235 in number. The relevant statistics of following attributes were generated for each and every watershed to show the spatial pattern of water resource.

(a) *Geomorphic and Morphometric Attributes*

1. Elevation (in m from a.s.l.)
2. Relative Height (RH in m)
3. Average Slope (S in %)
4. Drainage Density (DD m/km)
5. Bifurcation ratio (Rb)
6. Soil Texture and Water Holding Capacity (St in mm/m)

(b) *Hydrological Attributes*

7. Mean Annual Precipitation (P in mm)
8. Mean Annual Potential Evapotranspiration (PET in mm)
9. Infiltration Rate (INF in mm/hr)
10. Infiltration Depth (mm)

Study of hydrologic cycle is of immense importance for preparing a water budget for river catchments. Since weather statistics are not available for each river catchment as delineated for the entire plateau, the mean annual statistics of precipitation and temperature for an average of 30 years have been used for district headquarters which are the true representatives of diverse climatic regimes of the Meghalaya plateau. The amount and seasonally of water surplus/deficit have been calculated by using water budget equation (as $W = P - PET - INF$) which is operative with the help of conversion tables of the water balance given by Thornthwaite and Mather (1957).

Isohyetal, Iso-PET and Iso-water holding capacity maps were prepared in operation of the above given water budget equation for the stations located in and around the plateau. Finally, after calculating annual values of PET and infiltration depth for each river catchment using interpolation method, the maps showing areal pattern of runoff and quantum of water available in each watershed were analysed in association with the geohydrological attributes of catchments (like catchments size, slope, Bifurcation ration, stream length, precipitation,

PET and infiltration). A step-wise multiple regression analysis was adopted to find out the causes of spatial variability of water resources in Meghalaya plateau.

$$Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 + \dots + b_n X_n \dots \dots \dots (1)$$

where Y = available runoff (in m), X₁, X₂, X₃, ..., X_n are geo-hydrological attributes of the river catchments.

The second and third objectives of the present study are more concerned with the runoff characteristics at the micro areal level of the river catchments. Rainfall-runoff relationship was also studied in detail to understand its close look by selecting an experimental watershed from an ideal river catchments belonging to best representative geo-hydrological conditions of the plateau. Such experimental design is more concerned with the installation of weather station in the watershed and water level recorder at the mouth of it.

Such detail investigation of hydrological cycle provides a sound base of parametric development and rainfall-runoff modelling (Beven 2001:1-23). Watershed management that aims at sustainable development through anthropogenic forces operating on natural resources and conservation the same, is possible through a detail analysis of rainfall-runoff relationship and ecological modelling (Band et al. 1991). However, production systems and people’s involvement who are living in the watershed are to be considered for self sustained livelihood and balance development in the watershed (Thapa et al. 2001, Swain and Routray 2002). A participatory approach may be appropriate for integrated watershed management (Routray and Swain 2004). Landuse is to be considered as major anthropogenic attribute of watershed which not only influence the runoff pattern but also interlink the socio-economic activities of the people living in the watershed. Establishing geo-ecological and landuse relationship through a geographic frame of the selected watershed and isolation of effects of geo-ecological attributes occurring on runoff are also of the dimensions of the present study.

1.4: Literature Review:

Reviewing methodological aspects of the present discussion, it can be said that many and varied rainfall-runoff models were prepared by adopting different approaches. The root of all approaches towards relation of assumption is too deep to predict peak discharge of hydrograph by using ‘rationale method’ which was first developed 150 years back by Mulvaney (1851):

$$Q_p = C * A * R \dots \dots \dots (2)$$

where, Q_p = hydrograph peak, A = Catchment area, R = average rainfall intensity and C = empirical coefficient which varies from storm to storm and from one watershed to another. It shows the behaviour of the watershed towards hydrograph. Runoff coefficients and time

transformation approaches were adopted to describe detailing C coefficient. Routing method by creating a time – area histogram by dividing catchments into the areas of different travel times from the outlet was used to calculate the runoff coefficient for an event.

The hydrologic simulation models based on deterministic approaches are classified into three according to their process-description:

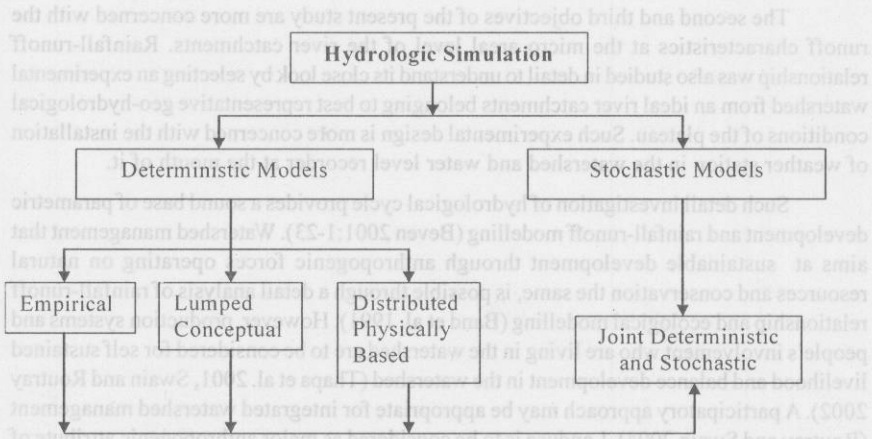


Fig.- 2: Hydrologic Simulation and Modelling

(a) The best known among empirical hydrologic methods is the Unit Hydrograph (UH) to predict entire hydrograph instead of just the peak discharge of different storm events (Sharman 1932, Ponca 1989). Calculation of average peak is basic principle of UH. These principles are based on an assumption of linearity while geomorphic effects of watershed are non-linear. Further Sherman (1932) developed UH to solve the problem of routing and runoff distribution in catchment. Unit hydrograph was one of the most commonly used techniques in establishing rainfall-runoff relationship in the catchment (Bevan 2001:28-29); Unit Hydrograph remains a linear routing technique. Later on, Horton's (1933) empirical work on infiltration capacity of the soil as based on Darcy non-linear flow equation opened a new dimension in rainfall-runoff modelling.

(b) The lumped conceptual models are based on average values over the entire catchment and that the equations are developed to be valid for different scenario within the catchment. The Stanford modelling system is of this type (c.f., Komarawinata 1980). USDA Soil Conservation Services (USDA SCS 1986) developed Curve Number approach using non-linear infiltration capacity with antecedent moisture conditions which has also been

commonly used to predict the runoff. Storm runoff, base flow and effective rainfall calculations are major parameters of this approach. These all are 'lumped based' techniques. The rainfall-runoff relationship is tried for the central Meghalaya plateau using SCS-CN method of rainfall-excess for predicting UH by Prokop (1999) which is a preliminary work initiated by the team of Indo-Polish collaborative Research. There is a need to apply suitable simulation models for prediction of runoff and sediment loss for this area.

Unit source areas, they are now commonly known as hydrological response unit or hydrotops, are identified by overlaying maps of soils and vegetation classification within a raster GIS with pixel of 30 m (Amerman 1965). Topography of the catchment can also be used to define the water flow direction and distance. GIS computer program were used to operate this approach. The Stanford watershed model developed in Stanford University during late 1960s by Crawford and Lindsay, which was based on Hydrocomp Simulation Program which was later widely used in hydrological studies in US and other European countries. The modified Stanford watershed model was used by Komarawinata (1980) to simulate excess surface runoff in the tropical areas for Jainegara Sempor watershed of central Java. It was later realised that routing variability over space is major dimension of watershed for calculation of UH. It is based on lumped method.

(c) In the distributed physically based model, GIS and RS are two major techniques that can support this modelling approach because the flow of water and energy are directly calculated from the St. Venant's equation for overland and channel flow. Richard's equation and Boussinesq's equation are used for unsaturated zone flow and groundwater flow respectively. The model gives more correct description of hydrologic process in the catchment. Several general purpose catchment models like MAKE SHE, IHDM, GNPS, SWRRB and SWAT (Arnold and Williams 1995, Arnold et al. 1996) are comprehensive deterministic distributed and physically based modelling system for the simulation of land-based part of the hydrologic cycle in which Water Movement (WM) is a basic module of the system (Yang 1998, Habib-Ur-Reheman 2001). This model was modified and used by Dutta (1999) and Dutta et al. (2000) for flood simulation occurring in the river catchments. AGNPS model which was developed by US Agricultural Research Services to predict soil loss in the watershed (Young et al. 1987) was used by Babel et al. (2004) and found that it is more suitable tool for runoff and soil loss prediction for tropic of the South-East Asia.

The physical basis of distributed model defined by Freeze and Harlan (1969) was a fully three dimensional model in which, saturated-unsaturated subsurface flow was coupled to a two-dimensional over land flow and one dimensional channel flow description. The overland and channel flows were modelled by grid based catchment. The Systeme Hydrologique European (SHE) is the most widely known model of this type (Beven 2001:124-125). Description of unsaturated and saturated sub-surface flow zones are based on Darcy's law and overland flow and channel flow are described by a diffusion wave approximation through the use of St. Venant equations (Chow et al. 1988). Grid size used for the purpose

has varied in different applications. The topo sequences and their related attributes are also described in the grid-based catchments using GIS and GPS tools of the explanation of geomorphic catchments which contribute to distributed flow in each grid. Hydraulic conductivity, porosity, soil moisture characteristics are considered as parameters for sub-surface flow, where as surface roughness, slope angle and relative height are considered as major parameters for surface flow. Channel flow roughness, over bank flow roughness and local channel bed slope of channel geometry are parameters for channel flow. These all are used in grid-based models especially in SHE. Many more watershed analysis tools like Agriculture Non-Point Source Pollution Model (AGNPS) were developed to predict runoff volume, peak rate and eroded and delivered sediments for single storm events for all points in the watershed by USDA (ARC) in 1987. Its validity was also tested for the tropical conditions (Babel et al. 2004).

Pursuing research on lumped based and physically distributed modelling is largely dependent on monitoring the geo-hydrological phenomena through establishing field observatories and selecting representative watersheds. Experiments related to discharge of water would be conducted for which a long series hourly and daily data of rainfall and discharge rates are required.

1.5: Design of Watershed

Lumped based rainfall-runoff model was used to establish not only the relationships of topographic factors with landuse parameters, but also to show the effects of topographic, soil and landuse parameters on runoff in the most humid conditions of Meghalaya plateau. An ideal representative watershed of a extent of about 665 ha was selected in the moderate geo-ecological conditions as prevalent in the northern slopes of the Meghalaya plateau, near Nongpoh district Headquarters situated along Gawahati - Shillong National Highway (see more details in Section-III of the Report).

Since watershed geomorphology, geology and distributional pattern of their attributes like bed rock structure, soils, relief features, topographic variations, and morphometric characteristics of the watershed implicitly influence the nature and characteristics of hydrographs, the analysis and interpretation of such watershed attributes were included in the study.

On the other hand, the stage level daily data were manually monitored three times in a day continuously for two years (January 2004 to December 2005). A *pucca* structure of rectangular weir was used at the mouth of the watershed for monitoring stage level statistics with the help of wooden gauge (Table- 1).

Table- 1: Monitoring of Stage Level at the Mouth of Paham Syiem Watershed

Dates	Days	Monitoring No. of Times
01 January- 17 May 2004	138**	2 (M,E)
18 May – 28 May 2004	11	3 (M,N,E)
29 May-31 May 2004	3	No monitoring
01 June – 11 June 2004	11	3 (M,N,E)
12 June- 13 June 2004	2	No monitoring
15 June- 31 December 2004	201	3 (M,N,E)
01 January-31 March2005	90	2 (M,E)
01 April-31 June2005	91	3 (M,N,E)
01 July- 30 September 2005	92	2 (M,E)
01 October-31 December2005	92	Projected*

N.B.: * Daily projections for dry winter 2005 were made to fix semi-log base flow depletion curve considering the corresponding data of winter season 2004.

** inclusive of 29 days of February 2004.

Abbreviations: M= Morning 6:00 a.m, N= Noon 12:00 and E= Evening 6:00 p.m.

Out of a total 731 days (i.e., 2 years), the data for 5 days could not be monitored during monsoon season 2004 which were estimated by using interpolation based on stage level data of the earlier and later parts. Stage level daily data for 92 days of the winter months of the year 2005 were also projected to complete the series of data. Daily averages of the stage level data were used for conversion of stream flow data to discharge rate using standard method for the rectangular weir as

$$Q = 2.28 * \{1.83(h)^{1.5}\}, \dots \dots \dots (3)$$

where Q is discharge rate in m³/s and h is stage head in m (for a 2.28 m width of rectangular weir) that indicates the depth of flowing water with the condition if h= 0, Q= 0. Stage-discharge rating curve was also established to understand their relationship. The hourly statistics of rainfall and other weather parameters were collected by installing automatic weather station near the watershed.

For this particular analysis, a topographic map of the watershed was prepared to conduct a physical survey of the entire watershed at R.F. 1/5,000. Plane Table and GPS were used for the same. With the use of this as base map, many other maps at the same scale were prepared to analyse the areal variations of geo-hydrological attributes of the watershed in detail. Such mapping would help in understanding the nature and characteristics of hydrograph and base flow pattern. Many visits were made to survey the watershed and preparation of geohydrologic map with the help of the villagers.

1.6: Data Limitations:

There were few but important problems faced by the team of investigators during the time if investigation. Firstly, the entire results of the distributional pattern of runoff depth

and runoff volume available in the river catchments are largely dependent on the generation of river catchment-wise statistics of geomorphologic attributes. Due to non availability of toposheets of the latest edition as restricted by the Survey of India (SOI), the toposheets of the old edition (the quarter inch maps of R.F. 1:2,53,440 which were based on the survey conducted in 1951) were used for the purpose. Secondly, the daily rainfall statistics for the corresponding years of the daily records of stage gauge for calculation of daily discharge statistics (2004-2005) could not be monitored satisfactorily because of frequent power failure and the defect of weather station logger installed at Nongpoh for recording the meteorological statistics. Such limitation of the availability of detail rainfall statistics compelled us to opt only the base flow separation approach rather than surface runoff approach for understanding the rainfall runoff relationship in the watershed. Thirdly, the stage level daily data for the winter season 2005 were interpolated statistics because of Project limitations.

1.7: Arrangement of Material:

The entire material of the report is arranged coherently into four sections. The Section – I includes the introductory note on the objectives, literature review and methodology of the present research, while Section-II of the report is devoted to the geohydrological characteristics and runoff pattern to analyse the areal variability of available water quantum in different river catchments and to fix the priorities of the responsible factors. The results of factorial analysis are also presented in this Section. The Section-III deals with the hydrograph analysis and geomorphic features of representative watershed in detail. In the last part of the Report in Section – IV, the concluding remarks and main findings of the research are precisely set in.

Section – II

Geo-hydrological Characteristics and Runoff Pattern

2.0: Introduction

Relief characteristics and climatic factors as actors of hydrological cycle were reviewed by Singh (1996) for the analysis of geo-ecological personality of the Meghalaya plateau. The geological account given by Geological Survey of India is significant to provide background of rock structure in order to understand the work of hydrological parameters. The plateau is geologically an extensive part of Chotanagpur plateau detached from main India shield (the North-Eastern parts of Deccan foreland) by N-S trending Raj Mahal – Garo lineament (Mazumdar 1976). Thus, terrain feature of the Meghalaya plateau are emerging from gneissic complex of Shillong massif which is bounded on all the sides by the faults and lineaments forming a block-uplifted region to its present height of about 2000 m (Murthy 1972 and c.f. Agarwal 1994). The Kopili lineament of the East divides the plateau into two distinct parts – Shillong massif and Mikir Hills. Such geological distinctions provide the unique physiographic features and variations in climatic factors and soils of the landscape. Geological formations are broadly of three types: (i) the gneiss with old inliers called Shella group, (ii) the Shillong group of rocks of the Central part and (iii) the Jaintia and Diasang series of rocks of the eastern parts. Apart from these three dominant series the Barail series and Simsang and Baghmara formations along the Dawki fault upto Baghmara (Garo Hills) are also distinguished by Geological Survey of India.

Relief features and slopes are part of land systems and also attributes to the regional variations of the amount and intensity of rainfall. As a result, they explicitly influence the distributional pattern of water availability.

Contours drawn on quarter inch SOI maps clearly show many distinctive relief features such as

- (i) The uplifted tracts of Khasi Hills of high elevations with flat dissected top ranging from 1,500 to 2,000 m elevations,
- (ii) The escarpment and eroded land features in the central parts which divide the plateau into two broad drainage systems: (a) part of Brahmaputra through Kopili N-E drainage system and (b) directly flow towards Bangladesh.
- (iii) The inter piedmont flats of river valleys with depositional processes and
- (iv) The foot hill flat lands of fertile soils and open river valleys.

The average slope map prepared on the same scale shows that the forelands of Cherrapunjee spur (covering about 200 sq km area of Cherra-Bholaganj Block on the extreme southern border of the plateau) is distinguished as steep slopes from Strong (15-20%) to Highly Strong (30-35%) and even cliffs and Very Steep Slopes in some pockets (35-40%) bordering longitudinally along Dawki fault lineament (Singh 1996: 13-15).

The characteristics of drainage system may provide a suitable base to study interrelated relief and slope properties in connection with water resource assessment, because drainage boundaries follow geohydrological criteria of the regional distinctions of topographies. Three tier drainage system hierarchies were identified to characterise the regional personality of topographic attributes. First order drainage is called river catchments (I,II,III,...,XIV), the second order are sub-catchments (Notated by a,b,c,...) and lower order drainages are named as watersheds/inter catchments (1,2,3,...,int) (See Appendix-I for detail and Fig.- 3). At middle order sub catchments, their areal sizes vary from 247 sq. km. to 901 sq. km. with an average size of 583 sq. km. The average size of the lower order catchments is calculated 136.5 sq. km. (Table-2).

Table- 2: Ordering, Number and Areal Size of Geohydrological Units

Higher Order	Name of the Higher Order Catchments	Area (sq.km.)	Middle Order Catchment		Lower order watershed & Inter catchments	
			Total No	Average Size (sq km)	Total No	Average Size (sq km)
I	Jinjiram	2628.65	4	657.16	19	138.35
II	Balbola	493.16	2	246.58	5	98.63
III	Dhudnai	1629.16	2	814.58	8	203.64
IV	Manki- Singram	1416.26	4	354.06	13	108.94
V	Kulsi	2204.73	4	551.18	19	116.04
VI	Umran	2702.78	3	900.93	13	207.91
VII	Borpani	1695.84	3	565.28	13	130.45
VIII	Kopili	3455.02	5	691.00	26	132.88
IX	Diyung	1161.16	3	387.05	7	165.87
X	Layang	831.30	3	277.10	3	277.10
XI	Lubhar	947.17	2	473.58	7	135.31
XII	Praog	1674.06	3	558.02	8	209.26
XIII	Umsoh - Ryngkew	1568.13	2	784.06	9	174.23
XIV	Kynshi	4560.22	6	760.04	41	111.22
XV	Simsang- Someswari	2910.80	4	727.71	25	116.41
XVI	Daring	1389.29	3	463.09	12	115.77
XVII	Marai	806.54	2	403.27	7	115.22
Total		32,074.30	55	583.17	235	136.49

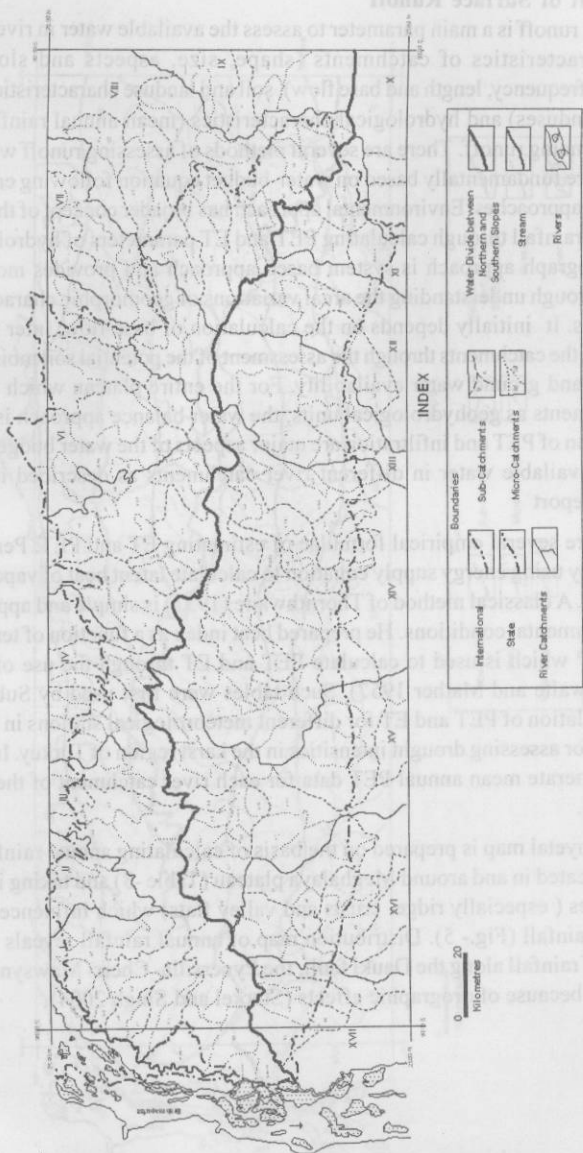


Fig.-3: Meghalaya Plateau - River Catchments

2.1: Assessment of Surface Runoff

Surface runoff is a main parameter to assess the available water in river catchment. The areal characteristics of catchments (shape, size, aspects and slope), stream characteristics (frequency, length and base flow), soil and landuse characteristics (thickness, moisture and landuses) and hydrological characteristics (mean annual rainfall) are main attributes influencing runoff. There are several methods of assessing runoff which differ to each other but are fundamentally based on water-budget equation following environmental and hydrograph approaches. Environmental approach has broader concept of the assessment of net available rainfall through calculating PET and ET parameters of hydrological cycle, while the hydrograph approach is system based approach and provides more details to assess runoff through understanding the areal variations of geomorphic characteristics of a river catchments. It initially depends on the calculation of base flow, inter flow and the overland flow in the catchments through the assessment of the potential soil moisture storage, saturated areas and ground water availability. For the entire plateau which accounts for 235 river catchments as geohydrological units, the water balance approach is appropriate to use. Estimation of PET and infiltration are major aspects of the water budget equation to assess the net available water in different river catchments as described in the earlier section of the Report

There are several empirical formulae of estimating ET and PET. Penman (1948) formulated ET by using energy supply equation to calculate latent heat of vaporisation and evaporation rate. A classical method of Thornthwaite (1931) is simple and applicable in all different environmental conditions. He prepared heat index as a function of temperature as $HI = (T^{\circ}C/5)^{1.514}$ which is used to calculate PET and ET through the use of conversion tables (Thornthwaite and Mather 1957). Such tables were first used by Subrahmanyam (1982) for calculation of PET and ET for different meteorological stations in India and by Baykan (2001) for assessing drought intensities in the karst region of Turkey. Iso-PET lines are drawn to generate mean annual PET data for each river catchment of the Meghalaya plateau (Fig.- 4).

The isohyetal map is prepared on the basis of calculating annual rainfall statistics of 14 stations located in and around Meghalaya plateau (Table -3) and taking in to account the relief features (especially ridge- crusts and valley flats) which influence directly the distribution of rainfall (Fig.- 5). Distribution map of annual rainfall reveals that there is concentration of rainfall along the Dauki fault, the Pynersilla- Cherr- Mawsynram areas of the steep slopes because of orographic effects (Starkel and Singh 2004).

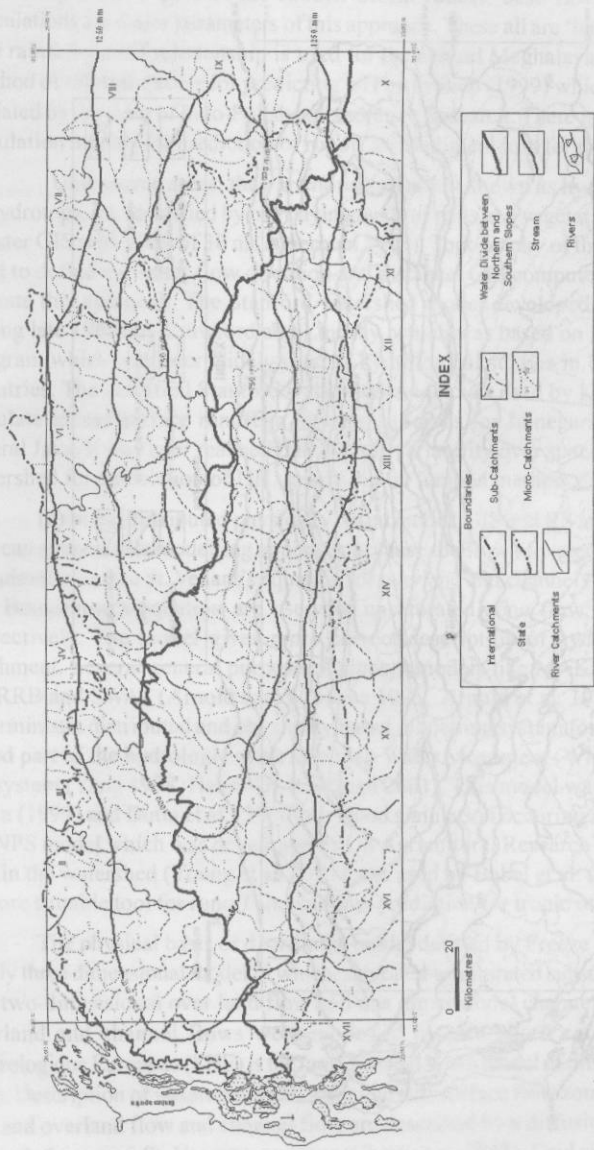


Fig.-4: Meghalaya Plateau - Mean Annual Evapotranspiration

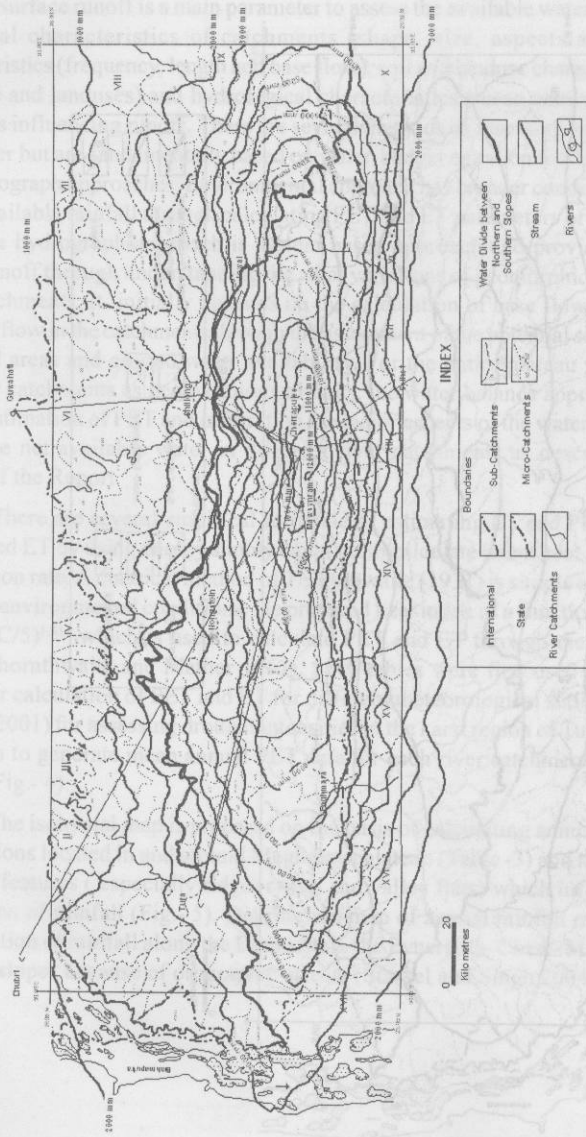


Fig. -5: Meghalaya Plateau - Iso-Hyetal Map (Mean Annual Rainfall)

Table-3: Mean Annual Rainfall of Stations Located in and around Meghalaya Plateau

Sl. No.	Name of Station (Location)	Mean Annual Rainfall (in mm)
1.	Shillong (Central Meghalaya)*	2,271
2.	Dhubri (Lower Assam)*	2,436
3.	Luding (Upper Assam)*	1,161
4.	Gauhati (Central Assam)*	1,538
5.	Silchar (South Assam)*	3,018
6.	Charrapunjee (South Meghalaya)*	11,131
7.	Tura (Far West Meghalaya)*	3,500
8.	Williamnagar (West Meghalaya)**	3,207
9.	Nongstoin (Central West Meghalaya)**	3,698
10.	Baghmara (S-W Meghalaya)**	7,000
11.	Sylhet (N-E Bangladesh)***	2,432
12.	Mymensingh (North Bangladesh)***	1,524
13.	Tangail (Central Bangladesh)***	1,440
14.	Dhaka (Central Bangladesh)***	1,400

N.B. * Rainfall data based on 30 years normal (1960 – 1990)

* Data based on 5 years average (1987-1991)

**Projected through interpolation method for 5 years average

*** Data based on 30 years mean of Monsoon season (June – September) (1951-1980)

Sources: 1) Climatological Tables Part-I, Indian Meteorological department, Pune

2) District Research Laboratories of different District Head Quarters

3) Bangladesh Meteorological Division, Dhaka (BMD).

Secondly, infiltration rate is another parameter calculated empirically as 20 percent of the potential maximum soil retention in the humid conditions for determining runoff in a river catchment (USDA SCS 1972). Following the available data of potential retention capacity of soil moisture of a few stations situated in the plateau, iso-potential retention capacity (Iso-PRC) lines were drawn on the quarter inch map (Fig.-6) and mean depth of annual infiltration (INF in mm) was calculated using following ratios for different area of the Meghalaya plateau:

INF(s) = 0.075 PRC for the catchments located on S-E and Southern slopes

INF(n) = 0.187 PRC for the catchments located on N-E and Northern slopes, and

INF(w) = 0.228 PRC for the catchments located on West and N-W parts.

Thus, infiltration data were generated through the use of above given proportions of potential retention capacity of the soils.

In order to calculate net available rain water in different river catchments, the water budget equation is written as the net effective (i.e. available) rainfall (i.e. called surface runoff, RO) which is the function of PET and INF as

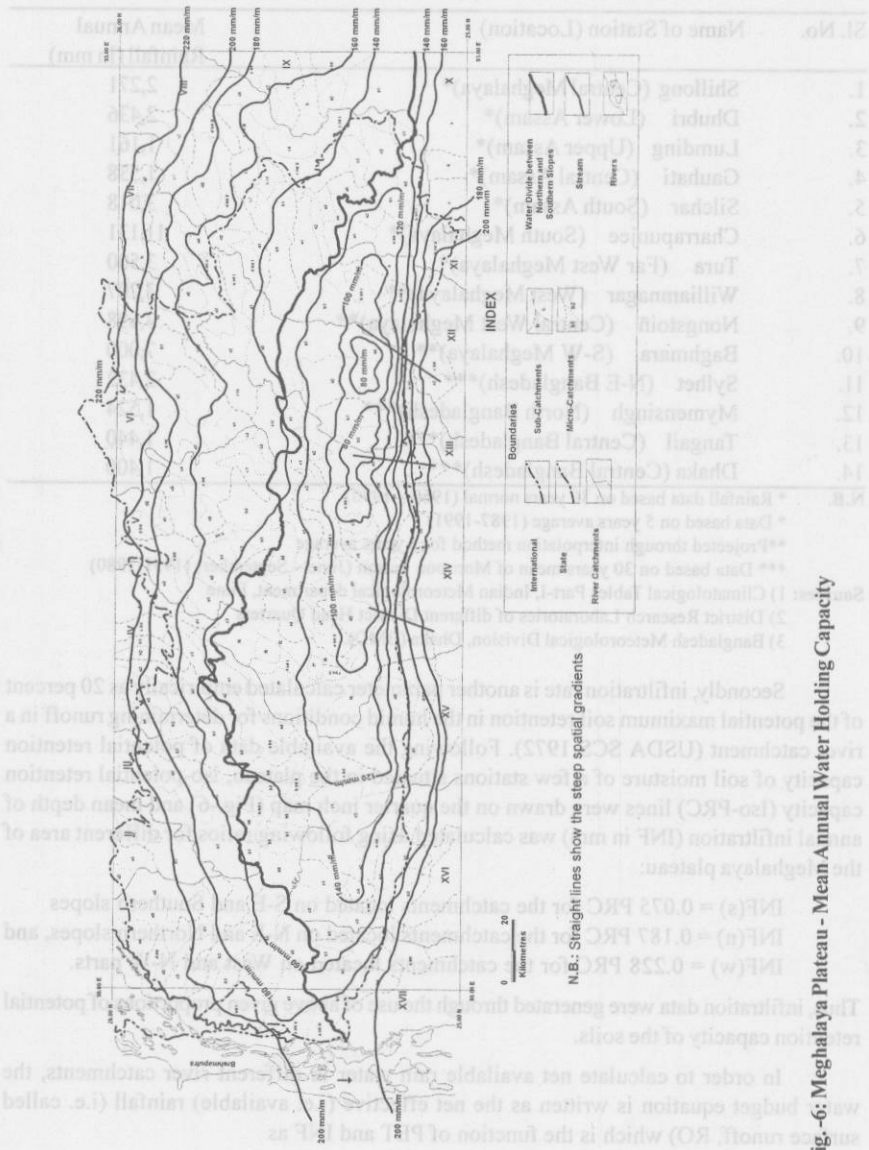


Fig.-6: Meghalaya Plateau - Mean Annual Water Holding Capacity

$$RO = (P - PET - INF) \dots \dots \dots (4)$$

The calculated mean annual values of surface runoff depth are finally converted into its volumetric measurement multiplying it by the total area of the river catchment (Appendix -I)

2.2: Variations of Runoff

2.2.1: The Seasonal Variations: Pattern of mean monthly rainfall and runoff figures for three meteorological stations, namely, Shillong (a representative of the Central part of the plateau), Cherrapunjee (Southern most slopes) and Tura (located in the Eastern parts) show the following interesting features of seasonal variations of runoff in the Meghalaya plateau.

(a) The curves of runoff depth showing its seasonal variation follows the rainfall curve in all three cases. However, the gaps between the rainfall and runoff depth curves are higher for Shillong, moderate for Tura and very low for Cherrapunjee with a significant variation of their monthly runoff (Fig- 7a, b and c). June and July are the months of high runoff. A mean monthly runoff of about 450 mm was calculated at Shillong and about 835 mm at Tura during the month of June, while it has highest record of more than 2,500 mm at Cherrapunjee in the same month of monsoon season. The higher gap between the curves of mean monthly rainfall and runoff indicates regulation of runoff in the river channels through the factors associating with sub-surface soil and rock structure. Maximum share of rainfall runs off on the southern steep slopes of Cherrapunjee area where thickness of soil is very less and, consequently, the infiltration rate becomes very low. The ground water storage and regulation of runoff in the eastern parts of the plateau is recorded moderate because of coverage of the larger parts of this area under dense forests, deep soils and gravely regolith.

(b) In the Central and Western parts of the plateau (Shillong and Tura), runoff generation starts from mid March and some times from the end of April, while occasional rainfalls are recorded in winters also. Thus, the later part of summer season is the period of sub-surface recharge. It is true for areas covered under monsoon climatic conditions and determines the river regimes.

(c) The maximum gap between curves of the rainfall and runoff depth is recorded during the month of July and August at Shillong areas of the Central plateau. It happens because of high retention capacity of soils. As a result, the highest infiltration rate is recorded during the heavy rainfall period. But, such situation does not prevail in the Southern slopes near Cherrapunjee because of poor retention capacity of soil, thin soil cover, scanty vegetation and degraded landscape.

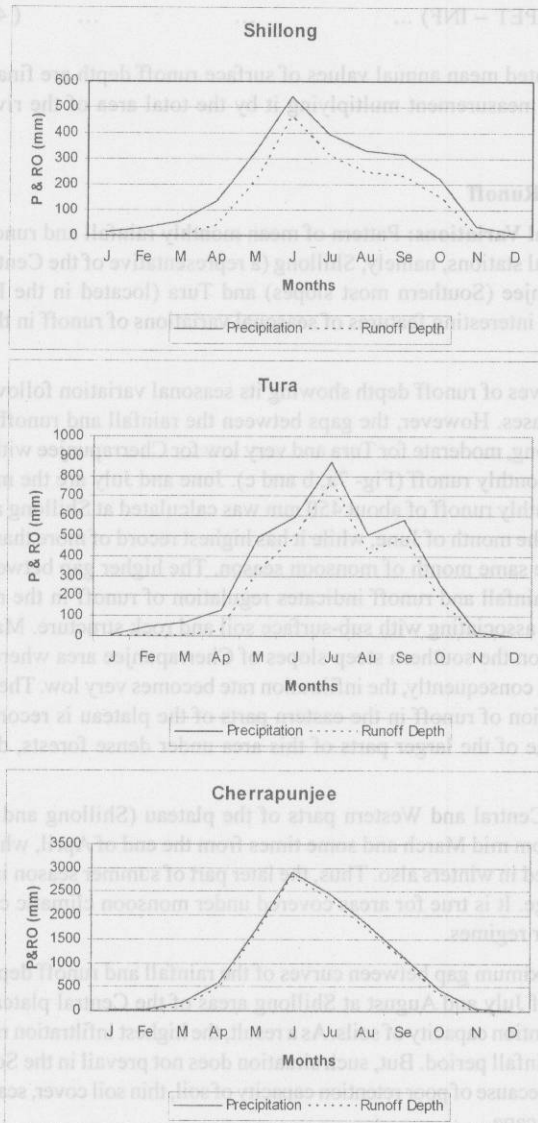


Fig. -7 : Mean monthly Rainfall, Runoff Depth (a) Shillong, (b) Tura and (c) Cherra

(d) Runoff ratio is calculated fairly high throughout the year at Cherrapunjee due to the above cited factors. The direct catchment yield of runoff is observed extremely high especially during the monsoon and extremely low during winters. The runoff ratios were recorded moderate with their fluctuating seasonal trends for the Shillong and Tura stations, the central and western parts of the plateau. In addition, it is also observed that at the time of withdrawal of monsoon (from October to November), the runoff ratios fall almost at the similar rate at all three places (Fig.- 8). It implies that base flow starts contributing and regulating the runoff on the entire plateau from the month of October onwards.

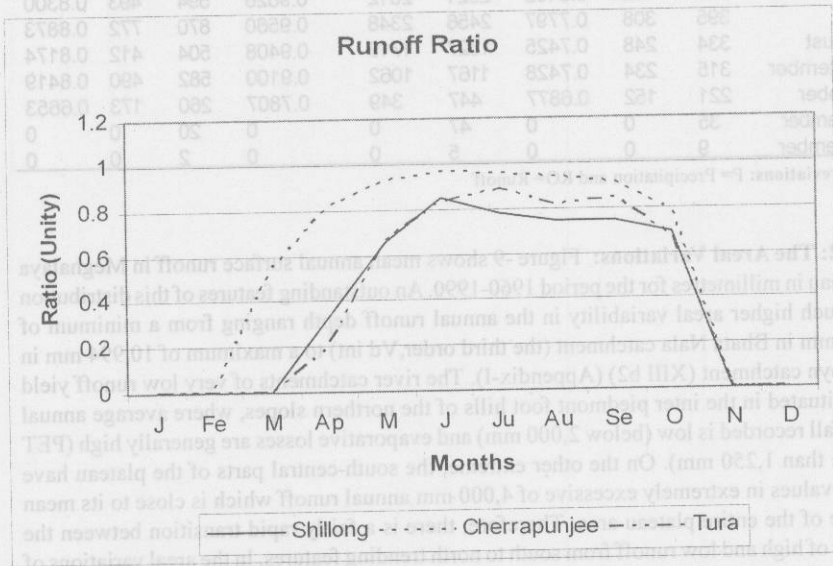


Fig.-8: Mean monthly Runoff Ratio at Three Stations

(e) With the prevalence of monsoon climatic conditions and orographic effects on the rainfall distribution over the entire Meghalaya plateau, the rivers/streams show a marked contrast in the seasonal runoff between runoff in the rainy and dry seasons. On an average 80 percent share of seasonal runoff is contributed during rainy season (April – October) in the plateau. But this figure exceeds upto and even more than 90 percent in the areas located in and around Cherrapunjee spur on the southern slopes (Table-4).

Table-4: Mean Monthly Runoff Ratio at Three Stations

Months	Shillong			Cherrapunjee			Tura		
	P	RO	RO Ratio	P	RO	RO Ratio	P	RO	RO Ratio
January	15	0	0	20	0	0	10	0	0
February	29	0	0	37	0	0	47	0	0
March	59	0	0	179	97	0.5418	68	0	0
April	136	44	0.3235	605	492	0.8132	130	25	0.1923
May	325	213	0.6553	1705	1582	0.9278	491	325	0.6619
June	544	462	0.8492	2921	2812	0.9626	594	493	0.8300
July	395	308	0.7797	2456	2348	0.9560	870	772	0.8873
August	334	248	0.7425	1827	1719	0.9408	504	412	0.8174
September	315	234	0.7428	1167	1062	0.9100	582	490	0.8419
October	221	152	0.6877	447	349	0.7807	260	173	0.6653
November	35	0	0	47	0	0	20	0	0
December	9	0	0	5	0	0	2	0	0

Abbreviations: P= Precipitation and RO= Runoff

2.2.2: The Areal Variations: Figure -9 shows mean annual surface runoff in Meghalaya plateau in millimetres for the period 1960-1990. An outstanding features of this distribution is much higher areal variability in the annual runoff depth ranging from a minimum of 213 mm in Bhata Nala catchment (the third order, Vd int) to a maximum of 10,994 mm in Umpyn catchment (XIII b2) (Appendix-I). The river catchments of very low runoff yield are situated in the inter piedmont foot hills of the northern slopes, where average annual rainfall recorded is low (below 2,000 mm) and evaporative losses are generally high (PET more than 1,250 mm). On the other extreme, the south-central parts of the plateau have high values in extremely excessive of 4,000 mm annual runoff which is close to its mean value of the entire plateau area. Therefore, there is a fairly rapid transition between the areas of high and low runoff from south to north trending features. In the areal variations of runoff on the plateau, the extremely high runoff depth was recorded in the river catchments situated near Cherrapunjee on the central part of southern slopes. Spatial gradient of runoff depth from the Umpyn catchment towards northern slopes of plateau are calculated as an average decrease of 135 mm its depth per km, while its spatial decrease becomes faster at an average rate of 195 mm per km as distance increases on southern slopes towards Sylhet (Bangladesh plains) situated geomorphologically in the close vicinity of the foot hills of the southern margins of the Meghalaya plateau.

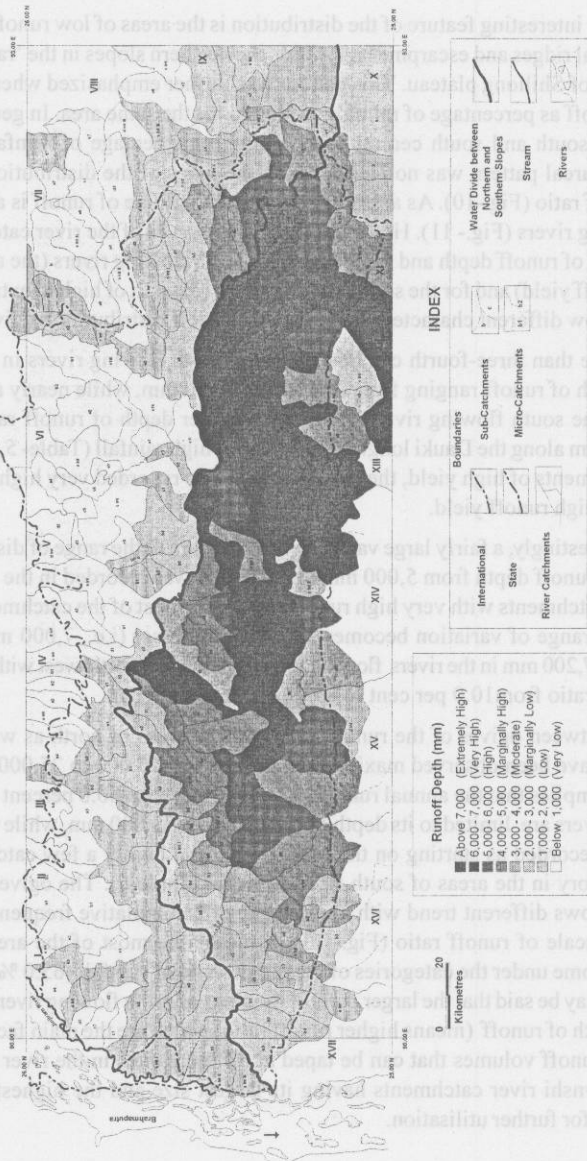


Fig.-9: Meghalaya Plateau - Mean Annual Runoff Depth

Another interesting feature of the distribution is the areas of low runoff extending across the Central ridges and escarpments towards the northern slopes in the 'rain-shadow' of the high hills of Shillong plateau. This pattern was further emphasized when the runoff ratio, that is runoff as percentage of rainfall, is plotted for the same area. In general, in the wetter areas of south and south central parts, a higher percentage of rainfall runs off. Almost similar areal pattern was noticed for both the maps of the distribution of runoff depth and runoff ratio (Fig -10). As a result, a significant volume of runoff is available on the south flowing rivers (Fig- 11). However, frequency curves of the river catchments for the distributions of runoff depth and runoff ratio for north flowing rivers (the areas of low to very low runoff yield) and for the south flowing rivers (the part of high to extremely high runoff yield) show different characteristic features of runoff distribution as given below.

(a) More than three-fourth catchments of the north flowing rivers in the plateau yield lesser depth of runoff ranging from 250 mm to 1,750 mm, while nearly a half of the catchments of the south flowing rivers yield much higher depth of runoff ranging from 5,000 to 8,000 mm along the Dauki longitudinal areas of high rainfall (Table- 5, Fig.-11). In such river catchments of high yield, the runoff ratio is also recorded very high which may be the cause of high runoff yield.

(b) Interestingly, a fairly large variation of 9,300 mm in the range of distribution of average annual runoff depth from 5,000 mm to 6,000 mm was recorded in the areas under south flowing catchments with very high runoff ratio in its most of the catchments. On the other hand, the range of variation becomes significantly lesser (i.e., 7,000 mm) starting from 200 mm to 7,200 mm in the rivers flowing towards north and north-west with fluctuating range of runoff ratio from 10.0 per cent to 85.0 per cent (Fig.-12).

Gaps between ogives of the runoff depth for the areas of north as well as south flowing rivers have been observed maximum in the class of 20,000 to 25,000 mm on the runoff scale. It implies that the annual runoff yield in a more than 80.0 percent areas of the north flowing rivers are limited to its depth of runoff below 25,000 mm, while this level of runoff yield is recorded as starting on the runoff scale and hardly a few catchments fall under this category in the areas of south flowing rivers (Table-6). The ogive patterns of runoff ratio follows different trend with a wider gap of commulative frequencies at 65.0 percent on the scale of runoff ratio (Fig.- 13). It means the most of the areas of south flowing rivers come under the categories of very high share of rainfall (65.0 % and above) that runs off. It may be said that the larger parts of the areas of south flowing river catchments yield higher depth of runoff (means higher runoff ratio) which are the main factors of high availability of runoff volumes that can be tapped at different sites in the river catchments especially in Kynshi river catchments having its largest size and the highest volume of runoff available for further utilisation.

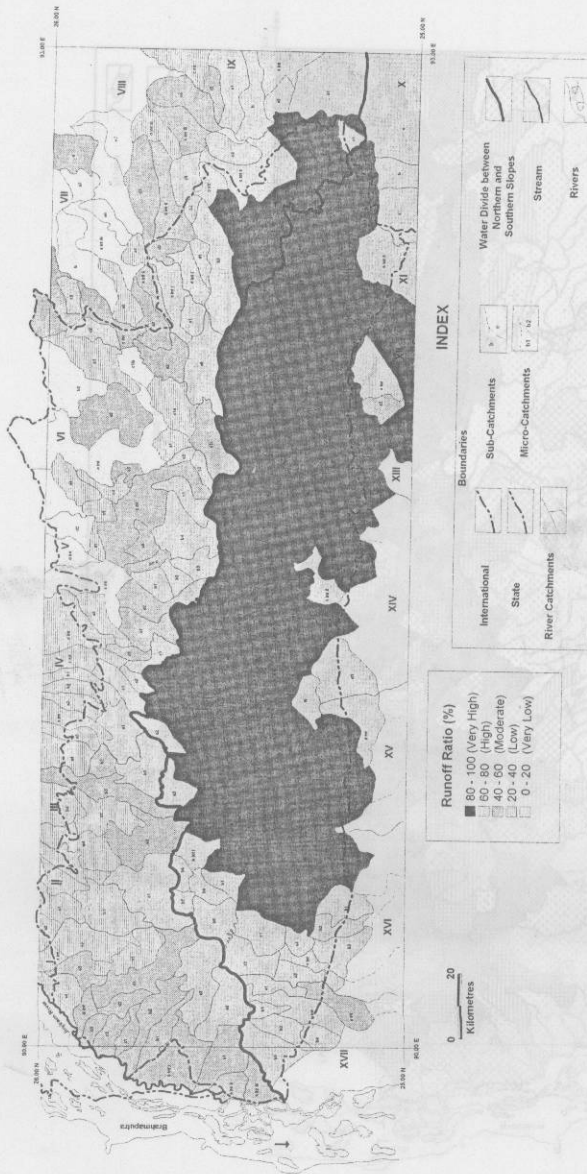


Fig. -10: Meghalaya Plateau - Mean Annual Runoff Ratio

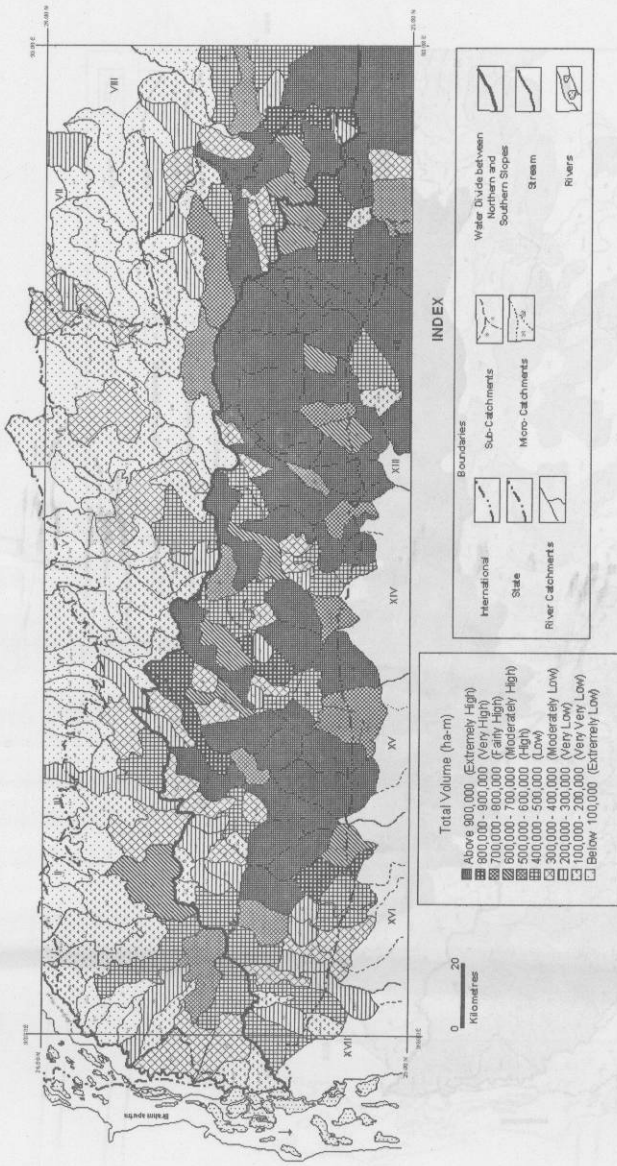


Fig. - 11: Meghalaya Plateau - Volume of Surface Runoff

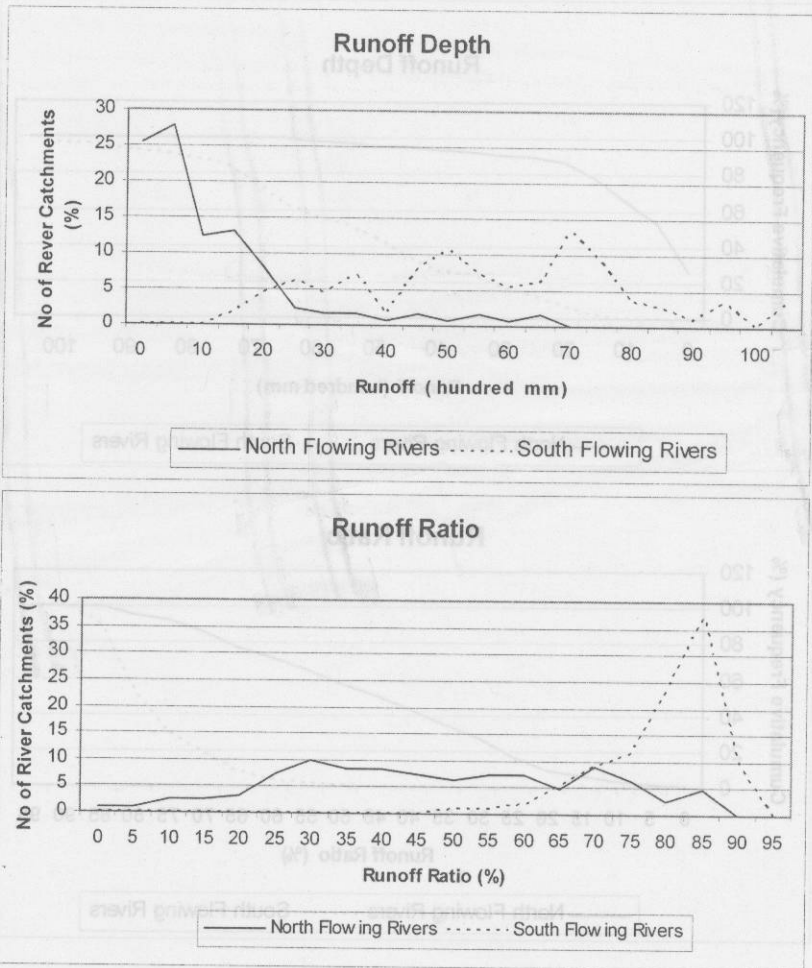


Fig.- 12: Frequency Curves Showing Number of River Catchments by their Runoff Depth and Runoff Ratio

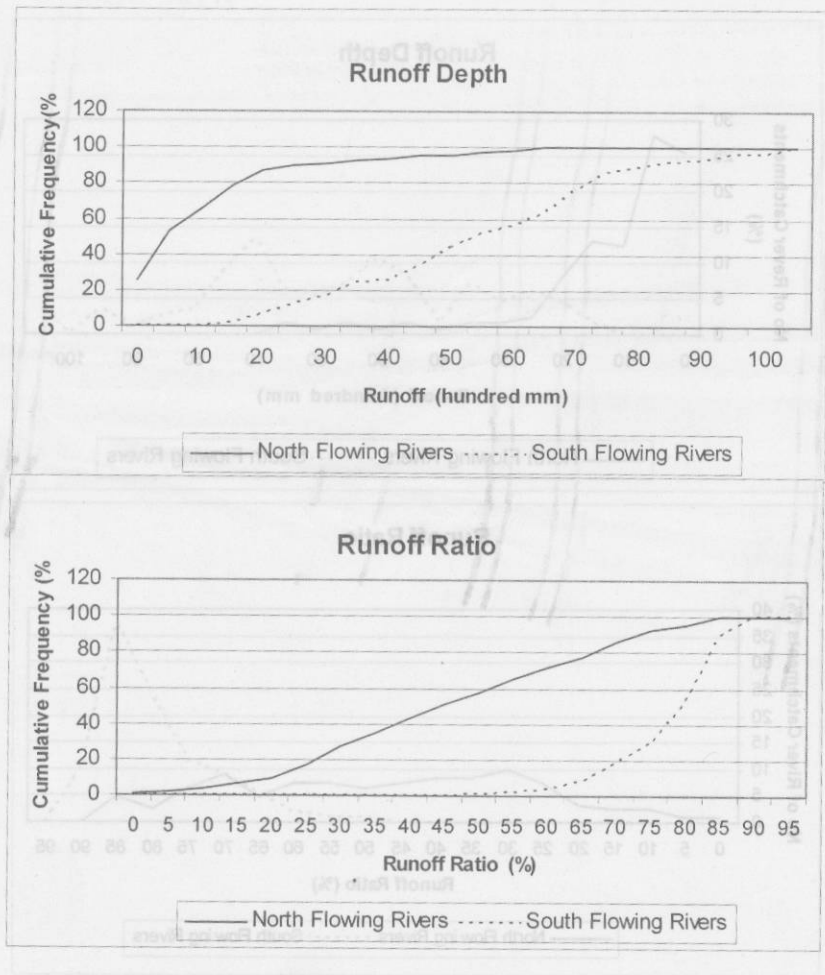


Fig.- 13: Ogives (Cumulative Frequency Curves) Showing Number of River Catchments by their Runoff Depth and Runoff Ratio

Table-5: Frequency Distribution of Runoff Depth

Runoff Depth Class (hundred mm)	North Flowing Rivers			South Flowing Rivers		
	No of Catchments	%	Cumulative Frequency(%)	No of Catchments	%	Cumulative Frequency(%)
0-5	31	25.4098	25.4098	0	0	0
5-10	34	27.8688	53.2786	0	0	0
10-15	15	12.2950	65.5737	0	0	0
15-20	16	13.1147	78.6885	2	1.7857	1.7857
20-25	10	8.1967	86.8852	5	4.4642	6.2500
25-30	3	2.4590	89.3442	7	6.2500	12.5000
30-35	2	1.6393	90.9836	5	4.4642	16.9642
35-40	2	1.6393	92.6229	8	7.1428	24.1071
40-45	1	0.8196	93.4426	2	1.7857	25.8928
45-50	2	1.6393	95.0819	9	8.0357	33.9285
50-55	1	0.8196	95.9016	12	10.7142	44.6428
55-60	2	1.6393	97.5409	8	7.1428	51.7857
60-65	1	0.8196	98.3606	6	5.3571	57.1428
65-70	2	1.6393	100	6	6.2500	63.3928
70-75	0	0	100	15	13.3928	76.7857
75-80	0	0	100	10	8.9285	85.7142
80-85	0	0	100	4	3.5714	89.2857
85-90	0	0	100	3	2.6785	91.9642
90-95	0	0	100	1	0.8928	92.8571
95-100	0	0	100	4	3.5714	96.4285
100-105	0	0	100	0	0	96.4285
105+	0	0	100	4	3.5714	100.0000

Table-6: Frequency Distribution of Runoff Ratio

RO Ratio Class (%)	North Flowing Rivers			South Flowing Rivers		
	No of Catchments	%	Cumulative Frequency (%)	No of Catchments	%	Cumulative Frequency (%)
5-10	1	0.8196	1.63934	0	0	0
10-15	3	2.4590	4.09836	0	0	0
15-20	3	2.4590	6.55737	0	0	0
20-25	4	3.2786	9.83606	0	0	0
25-30	9	7.3770	17.2131	0	0	0
30-35	12	9.8360	27.0491	0	0	0
35-40	10	8.1967	35.2450	0	0	0
40-45	10	8.1967	43.4426	0	0	0
45-50	9	7.3770	50.8196	0	0	0
50-55	8	6.5573	57.3770	1	0.8928	0.892857
55-60	9	7.3770	64.7540	1	0.8928	1.785714
60-65	9	7.3770	72.1311	2	1.7857	3.571429
65-70	6	4.9180	77.0491	6	5.3571	8.928571
70-75	11	9.0163	86.0655	10	8.9285	17.85714
75-80	8	6.5573	92.6229	13	11.6074	29.46429
80-85	3	2.4590	95.0819	26	23.2142	52.67857
85-90	6	4.9180	100	42	37.5000	90.17857
90-95	0	0	100	11	9.8214	100
95+	0	0	100	0	0	100

2.3: Factors Affecting the Distribution of Runoff

There are many and varied factors affecting runoff distribution. However, Ward (1967, pp 326-342) elaborated the main factors of runoff distribution putting them into two groups: the meteorological (rainfall intensity, duration, type of storm and rainfall-evaporation balance) and the catchment factors (geomorphological and drainage network including catchment size and shape). For the present study, the areal pattern of runoff was interpreted by considering seven factors of river catchments to analyse their impact on runoff distribution. They are more related to river catchment size, evaporative demand in the catchment, mean annual precipitation, infiltration, main stream length, slope and the bifurcation ratio of the first order stream network to its second order ones. Some other explicit factors of runoff regulation like relative height, water holding capacity of soils are also included in the present analysis (Table -7).

Table-7: Areal Variations of Geomorphic and Hydrologic Attributes

Sl.No	Attributes	Maximum	Minimum	Mean	SD	CV(%)
1	Area (sq.km.)	563.3	26.98	135.4	91.20	67.27
2	Precipitation (mm)	12000.0	1300.0	4757.8	2846.70	59.83
3	Potential Evapotranspiration (mm)	1320.0	665.0	1080.3	183.28	16.96
4	Water Holding Capacity (mm/m)	228.0	78.0	156.7	33.43	21.33
5	Infiltration Rate (mm/m)	.228	.075	.1531	.06	42.79
6	Infiltration Depth (mm)	51.98	5.85	25.32	13.82	54.66
7	Bifurcation Ratio (I/II)	7	1	2.097	.98	48.77
8	Maximum Elevation (m)	3599	12	887.0	543.50	61.27
9	Minimum Elevation (m)	1960.7	8.84	472.38	419.40	88.80
10	Relative Height (m)	3502.1	.304	414.6	386.00	93.09
11	Stream Length (m)	63086.3	257.5	7891.4	7040.40	89.22
12	Slope (%)	85.6	.007	9.596	22.63	235.83
	Runoff Depth (mm)	10994	10.225	3652.1	2878.10	78.80
	Total Runoff Volume (ha m)	4633805	589.88	481288	577703	119.86

Abbreviation: CV= Coefficient of Variation

A factorial analysis is in fact pursued to understand the distribution of runoff depth and associated factors. It was done in two steps: first, the elaboration of areal variability of each factor and, secondly, the regression effects of these factors on runoff depth and its total volume. Table-7 depicts that the meteorological and hydrological factors like PET, water holding capacity and infiltration rate have much lesser areal variability in their distributions than the geomorphic factors like slope (CV= 235.8%) and relative heights (CV=93.1%). It means the geomorphic features like dissected hill topography, high escarpments, steep ridges, deep valleys have greater influence on the distribution of runoff in the plateau.

Reviewing the literature in this connection, a more complex geomorphic characteristic feature of river catchments of the north flowing rivers of the plateau giving the example of Umiar river catchments (see Higher Order river catchments of the number VI c in Appendix-I) was analysed and interpreted by Agarwal (1994:1-25) by establishing the quantitative relationships among geomorphic including morphometric and geological parameters at different orders of river basin system. She concluded that there is strong correlation among morphometric parameters at higher order river catchments. The degree of association became weak and somewhat insignificant at lower order catchment components. An interesting feature of the analysis about parametric relationship between river catchment area and perimeter of the same order indicates that these parameters do not show a proportionate increase with rise in drainage frequency and drainage density. This feature does not highlight the usual complexity of the geomorphic characteristics (Nir 1957, Singh 1974). Such weak relationships implied that the drainage frequency and drainage density tended to develop topographic features of the catchments instead of catchment's enlargement (Agarwal 1994:165). Another analysis of complex relationship between the sets of geomorphic and hydrologic parameters for the entire Meghalaya plateau generating quantitative statistics of such parameters at the level of river catchments showed a significant relationship among slope gradient, relative height and mean annual rainfall (Singh 1996, Table-12, p.59). It implied the orographic effect on the distribution of rainfall as also stated by Starkel (1972). Such noted relationships of geomorphic and hydrologic parameters indicated a higher degree of areal variability of mean annual rainfall, which is true in the empirical calculation of the present analysis.

The mean annual precipitation varies with a wider range of its distribution of about 11,700 mm from the maximum of 12,000 mm in Umpyn river catchment (XIII b2) situated on the southern slopes to the minimum of 1,300 mm in the lower Umiar river catchment (VIc1iii) located in the north eastern side of the northern slopes. In general, the degree of its areal variability was noticed to be moderate as $CV = 59.8$ per cent. However, the decrease in the spatial gradient of annual rainfall was recorded the highest as 221.5 mm/km between Cherrapunjee and Shillong (on the upper parts of the Southern slopes). It is noticed comparatively lower as 193.3 mm/km on the southern steep slopes between Cherrapunjee and Sylhet in Bangladesh plains (Fig-5, Table-8).

On the whole, the PET (the evaporative demand of atmosphere) and the water holding capacity are more smooth in the nature of their distributional pattern and have lesser degree of areal variability as $CV = 16.9$ per cent and 21.33 per cent respectively.

Since PET is largely dependent on temperature and rainfall (on different atmospheric factors) the ratio between rainfall and PET varies significantly. For example the Thornthwaite and Mather's water balance equation applied for the assessment of water availability in tropical Arunachal Himalaya shows that there is approximately 40 per cent share of rainfall

Table-8: Spatial Gradients of Mean Annual Rainfall

Sl No	Places	Rainfall Differences (mm)	Linear Distance (km)	Spatial Gradient (mm/km)
1	Cherrapunjee- Shillong	8,860	40	221.50
2	Cherrapunjee- Sylhet	8,699	45	193.31
3	Cherrapunjee- Jowai	4,831	55	87.84
4	Cherrapunjee- Mawsynram	260	14	18.57
5	Mawsynram- Dhubari	8,984	180	49.91
6	Mawsynram- Tura	7,920	147	53.88
7	Mawsynram- Baghmara	4,420	91	48.57
8	Shillong- Guwahati	733	60	12.21

as PET. This figure was calculated 32.5 per cent to total rain for the Shillong station, 28.10 per cent for Tura and 9.22 per cent for Cherrapunjee stations of Meghalaya plateau. It varies negatively as rainfall increases in different river catchments (Singh 1996 and 1999). PET changes subject to change in the annual rainfall. Its recorded areal variation is the lowest (CV= 16.96 %) in Meghalaya plateau. PET decreases at the rate of 4.5 mm per 100 mm rain decrease in the depth of rainfall between Cherrapunjee and Shillong (N-S profile) and 1.5 mm per 100 mm decrease in the rainfall between Cherrapunjee and Tura (E-W profile of the plateau) (Fig.-4).

Maximum retention capacity of soils (the water holding capacity of root zone soil of one metre thick) varies spatially in Meghalaya because of differentiation in soil texture and soil depth and was recorded 150 mm for Shillong (a moderate regolith thickness of 3.0 -5.5 m), 92 mm for Cherrapunjee (very less thickness of 0.2 -1.0 m) and 180 mm for Tura (good thickness of 5.0 - 8.5 m). In some of the areas of the southern slopes of Meghalaya plateau where regolith depth is thin and the rock beddings are horizontal and hard in nature (granite and gneissic complex with fault topography), the percentage ratio of initial infiltration have been observed very low only 5 to 10 per cent to potential retention capacity (Starkel and Singh 2003). The areas of northern slopes and eastern parts of the plateau have moderate to high infiltration that is 15 to 25 per cent to the potential retention capacity of soil (PRC in mm) (Fig -6).

2.4: Regression Based Factorial Analysis

Continuing the description of the areal pattern of above cited runoff factors, a step-wise regression analysis was applied to isolate the effects of such influencing factors (as called hereafter independent variables) on the runoff depth and its volume (as called dependent variables).

Regression analysis depicts interestingly that runoff depth is highly and positively affected by the mean annual precipitation received in the river catchments and negatively affected by the evaporative loss in the atmosphere. Precipitation contributes 97.8 per cent to the areal variation of runoff depth, while PET influences only 2.0 per cent of the runoff variation in the plateau (Table -9). Total volume of runoff available in river catchment is also positively related with the catchment size and precipitation. These both factors contribute significantly a share of 31.3 per cent and 43.3 per cent respectively to the areal variability occurring in the distribution of runoff volume available in the river catchments (Table-10). Obviously, larger the size of catchments and higher rainfall increase exponentially the volume of runoff. Present analysis clearly shows the effect of precipitation on runoff depth rather than other geomorphic factors. In fact, geomorphic factors must have influence on the runoff distribution within the catchments as many studies showed that the geomorphic factors of catchments were equally important to study the runoff and discharge rate at the catchments mouth (Das 2002, Raghunath 1985, Ward 1967). It may further be elaborated by taking into account a representative catchment/watershed to establish rainfall-runoff relationships at micro-areal level.

Variable	Regression Coefficient	Standard Error	t-value	Significance Level
X: Slope (%)	0.000E+00	0.000E+00	0.000	0.000
X: Stream Length (m)	2.182E-17	0.000E+00	0.000	0.000
X: Bifurcation Ratio	1.988E-13	0.000E+00	0.000	0.000
X: Infiltration (mm)	1.888E-14	0.000E+00	0.000	0.000
X: Precipitation (mm)	8.44E-17	0.000E+00	0.000	0.000
X: Potential Evapotranspiration (mm)	9.032E-16	0.000E+00	0.000	0.000
X: River Catchment size (sq. km)	1.88E-12	0.000E+00	0.000	0.000
X: Stream Length (m)	2.13E-17	0.000E+00	0.000	0.000
X: Bifurcation Ratio	1.48E-13	0.000E+00	0.000	0.000
X: Infiltration (mm)	1.847E-14	0.000E+00	0.000	0.000
X: Precipitation (mm)	8.38E-17	0.000E+00	0.000	0.000
X: Potential Evapotranspiration (mm)	8.98E-16	0.000E+00	0.000	0.000
X: River Catchment size (sq. km)	1.88E-12	0.000E+00	0.000	0.000
X: Bifurcation Ratio	2.67E-14	0.000E+00	0.000	0.000
X: Infiltration (mm)	7.1E-12	0.000E+00	0.000	0.000
X: Precipitation (mm)	3.2E-17	0.000E+00	0.000	0.000
X: Potential Evapotranspiration (mm)	3.4E-16	0.000E+00	0.000	0.000
X: River Catchment size (sq. km)	6.03E-16	0.000E+00	0.000	0.000
X: Infiltration (mm)	7.12E-12	0.000E+00	0.000	0.000
X: Precipitation (mm)	1.000E+00	0.000E+00	0.000	0.000

Table-9: Step-wise Regression of Runoff Depth (Y_1) with Independent Variables ($X_{1,2,3,\dots,n}$) for a Total Observations (N= 235)

Steps with Variables	Coefficients (bn)	Standard Error (SE)	R ² (increment)
X_1 River Catchment Size (sq. km)	1.5777	2.064	.00250 (.00250)
X_1 River Catchment size (sq. km)	-.9867	2.067	
X_2 Potential Evapotranspiration (mm)	-2.2058	1.0288	.02188 (.01938)
X_1 River Catchment Size (sq. km)	.00655	.0056	
X_2 Potential Evapotranspiration (mm)	-1.0226	.0028	
X_3 Precipitation (mm)	1.0036	.0002	.99999 (.9780)
X_1 River Catchment Size (sq. km)	0.00	6.1E-16	
X_2 Potential Evapotranspiration (mm)	-1.00	3.4E-16	
X_3 Precipitation (mm)	1.00	3.2E-17	
X_4 Infiltration (mm)	-1.00	7.15E-15	1.0000 (.0001)
X_1 River Catchment size (sq. km)	0.00	6.02E-16	
X_2 Potential Evapotranspiration (mm)	-1.00	3.4E-16	
X_3 Precipitation (mm)	1.00	3.2E-17	
X_4 Infiltration (mm)	-1.00	7.1E-15	
X_5 Bifurcation Ratio	0	5.67E-14	1.0000 (0.00)
X_1 River Catchment Size (sq. km)	0.00	1.66E-15	
X_2 Potential Evapotranspiration (mm)	-1.00	8.98E-16	
X_3 Precipitation (mm)	1.00	8.38E-17	
X_4 Infiltration (mm)	-1.00	1.847E-14	
X_5 Bifurcation Ratio	0	1.48E-13	
X_6 Stream Length (m)	0	2.13E-17	1.0000 (0.000)
X_1 River Catchment size (sq. km)	0.00	1.66E-15	
X_2 Potential Evapotranspiration (mm)	-1.00	9.025E-16	
X_3 Precipitation (mm)	1.00	8.44E-17	
X_4 Infiltration (mm)	-1.00	1.866E-14	
X_5 Bifurcation Ratio	0	1.496E-13	
X_6 Stream Length (m)	0	2.185E-17	
X_7 Slope (%)	0	6.60E-15	1.0000 (0.000)

Table -10: Step-wise Regression of Total Volume of Runoff (Y_2) with Independent Variabls ($X_{1,2,3,...,n}$) for a Total Observations (N= 235)

Steps with Variables	Coefficients (bn)	Standard Error (SE)	R ² (increment)
X_1 River Catchment Size (sq.km)	3541.63	343.92	.31277 (.31277)
X_1 River Catchment Size (sq.km)	3619.27	345.66	
X_2 Potential Evapotranspiration (mm)	-289.74	172.04	.32107 (.0083)
X_1 River Catchment Size (sq.km)	3751.96	208.47	
X_2 Potential Evapotranspiration (mm)	-131.67	104.00	
X_3 Precipitation (mm)	134.08	6.642	.75435 (.43328)
X_1 River Catchment Size (sq.km)	3749.53	209.53	
X_2 Potential Evapotranspiration (mm)	-123.28	117.97	
X_3 Precipitation (mm)	132.72	11.14	
X_4 Infiltration (mm)	-372.09	2442.94	.75438 (.00003)
X_1 River Catchment Size (sq.km)	3745.63	211.07	
X_2 Potential Evapotranspiration (mm)	-120.12	119.48	
X_3 Precipitation (mm)	132.67	11.17	
X_4 Infiltration (mm)	-413.73	2458.85	
X_5 Bifurcation Ratio	3554.84	19618.98	.75442 (.00004)
X_1 River Catchment Size (sq.km)	3756.72	221.75	
X_2 Potential Evapotranspiration (mm)	-121.42	119.48	
X_3 Precipitation (mm)	132.69	11.19	
X_4 Infiltration (mm)	-393.17	2467.18	
X_5 Bifurcation Ratio	3909.55	19775.79	
X_6 Stream Length (m)	-475	2.855	.75444 (.00002)
X_1 River Catchment Size (sq.km)	3764.44	221.74	
X_2 Potential Evapotranspiration (mm)	-111.93	120.23	
X_3 Precipitation (mm)	131.39	11.25	
X_4 Infiltration (mm)	-744.47	2486.02	
X_5 Bifurcation Ratio	1061.61	19930.47	
X_6 Stream Length (m)	-1.1122	2.911	
X_7 Slope (%)	-972.43	873.88	.7558 (.000136)

Fig-14: Rainfall-Runoff Relationship through Scatter diagram

Since rainfall is the major factor affecting the runoff, the relationships between them are shown by preparing scatter graphs and the estimates of runoff are made by fitting regression line equations by dividing the plateau in to two: the areas of north flowing rivers which are characterised earlier as the areas of low runoff yield and the areas of south flowing rivers of high runoff yield (see pp 21-28 for details and Fig.- 14). Runoff depth in the areas of north flowing as well as south flowing rivers increases at a rate of unity as rainfall increases; such unitary increase shows an increase in runoff at the almost same proportion as rainfall increases. However, both the areas have different characteristics in their runoff yielding system. As a result, there is record deviation in the levels of runoff depth.

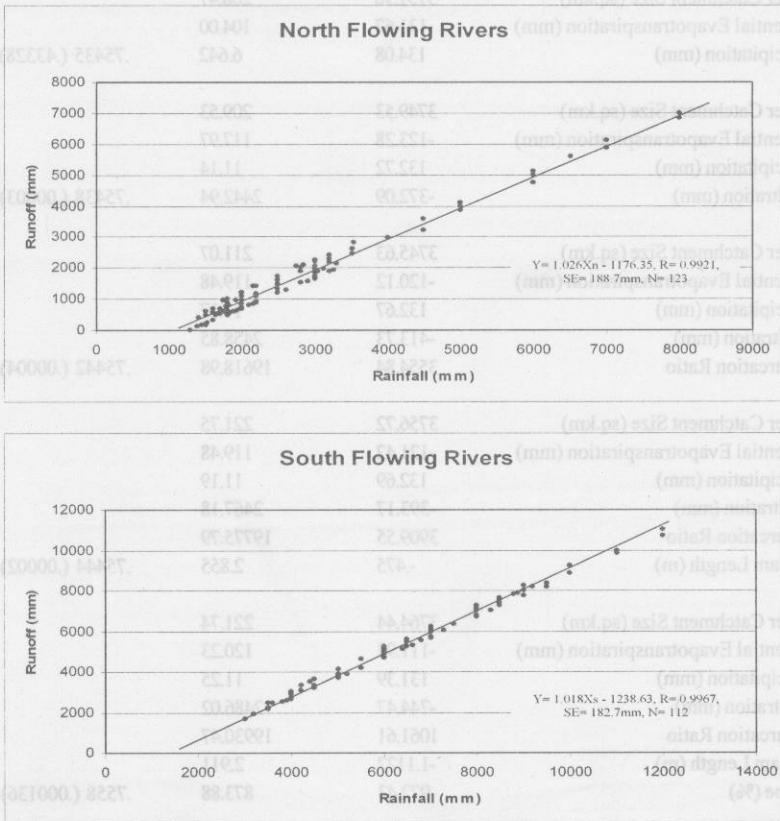


Fig. -14: Rainfall- Runoff Relationship through Scatter diagrams

Calculating mean annual soil moisture (St) and mean annual surface runoff (that has been termed as effective rainfall by many hydrologists), it is found that, due to very less amount of rainfall retention in the form of soil moisture (Sm) as calculated 1,239 mm in some of the areas of Meghalaya plateau, the level of annual soil moisture storage capacity (St) remains very low as 96 mm in the north flowing rivers and 159 mm in the south flowing rivers. It implies that surface runoff tends to start when rainfall occurs at a depth of 1,146 mm in the areas of north-flowing rivers and 1,217 mm in the areas of south-flowing rivers (i.e., if $Y = 0$, $X_{\text{north}} = 1,146$ mm and $X_{\text{south}} = 1,217$ mm as calculated from the concerned regression equations, Fig.-14). It would yield surface runoff of about 66 mm and 137 mm respectively (Table -11). The variation in the potential maximum retention of soil moisture (Sm) and soil thickness (due to the variations in water holding capacity of soils and infiltration rate) may be the most influencing factors for areal differentiations of starting the runoff yield.

Table-11: Annual Water Budget in the Areas of North Flowing and South Flowing River Catchments

Sl.No.	Items	North Flowing Rivers	South Flowing Rivers
1	Potential maximum retention of soil moisture (Sm)*	1,176	1,239
2	Loss by Evaporative Demand (PET)	1,080	1,080
3	Soil Moisture Storage (St= Sm- PET)	96	159
4	Rainfall at Zero Runoff (X)**	1,146	1,217
5	Start of Runoff Yield (X- PET)	66	137

N.B.: * The values of Sm are simply the constants of the concerned rainfall- runoff equations shown by 'a'. It becomes equal to the depth of the maximum retention of soil moisture when it is simplified keeping $X = 0$ in the equation.

** The value of X is calculated by simplifying the rainfall- runoff equations for the given condition as $Y = 0$.



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Section - III

The Hydrograph Analysis

3.0: Introduction

Runoff is an independent factor in modeling the flood simulation (Dutta 1999), assessing the rainfall effects on land use and soil characteristics through integrated watershed management (Rajora 1998) and estimating erosion for improvement the accuracy of the USLE (Kinnell 2005). The distribution of mean annual runoff specified on world map by Lvovitch shows that the areas of lower Ganges and entire Brahmaputra plains including Bangladesh have more than 1,000 mm mean annual rainfall depth which causes occasional floods in the lower parts of the plains (c.f. Ward 1967:348-349). Matsumoto (1988) and his associates (Matsumoto et al 1996) also analysed in detail the causes of Bangladesh floods occurred during 1985 and 1986. Rainfall is some times delayed which create its uneven distributional pattern. For example, at about 20 per cent share of monsoon rain was reduced in the North East India in 2005 because of delayed on set of monsoon (Pattanaik and Hatwar 2006). However, there are various models to understand the characteristics of runoff acted in the river catchments and influenced by the geometry, geomorphology and geology of the catchments. Such models are either based on the analysis of rainfall pattern and its impact on landscape changes (Starkel 1972 and 2004) or changes in hydrologic regimes and landuse in the river catchments of extreme humid areas of North-Eastern parts of India (Goswami 1998, Hofer 1998).

Hortonian classical model of overland flow presents the sequence of events when rainfall intensity exceeds soil infiltration in the catchment. After formation of thin water layer on the surface in such condition of heavy rainfall, down slope surface flow is initiated which causes flowing water accumulation first in surface depressions and then in rills and forms rivulets and further then produce water to stream channels for a rapid rise in stream levels (Goudie 2001:435-437). A more complex model including the effects of underground and sub-surface parameters of catchment, namely, the through flow and overland natural flow, was later on pursued to understand the nature and characteristics of hydrograph and the effects of catchment geomorphology on it. The sequence of events takes place under the model, are implicitly associated with ground water flow, shallow sub-surface stream flow, saturated overland flow composed of direct rainfall and return flow in the lower section of stream close to the mouth of watershed. The stream expansion and the extension

of saturated soil zones are main processes under the effects of a rainstorm. So rainstorm intensity and its duration significantly attribute to the intensification of flows (ground water, shallow sub-surface and saturated overland). However, slope gradients, network characteristics, soil types, landuse patterns, agricultural practices are major causes of variations in the percolation (infiltration) through flow (surface and channel flows) and alterations of catchment hydrograph.

Reviewing literature related to establishment of rainfall-runoff relationship and hydrograph analysis, it is obvious that the Curve Number (CN) method developed by USDA-SCS (1972) is mostly dependent on the overland flow model produced by Horton, while the base-flow separation method for preparation of Unit Hydrograph (UH) is initially based on overland saturation flow model since ground water flow separation is the root of the procedure of this method.

The development of CN establishing rainfall-runoff relationship during rainstorm time is largely dependent on different basin characteristics and soil moisture conditions at the time of occurrence of rainfall like hydrologic soil groups, antecedent soil moisture conditions, landuse and conservation practices followed in the watershed (USDA-SCS 1972). However, hydrograph of a particular storm is the function of two factors: the infiltration rate and the capacity of storage in the soil profile (potential maximum retention soil moisture) to measure the depth of rainfall during rainstorm initially abstracted (Ia) from rainfall intensity (P) for assessing effective (i.e. sometimes called 'net') rainfall which runs off at the starting of rainfall (Q). It acts for development of CN initially assuming that the share of actual moisture retention capacity (Sm) is equal to the share of actual surface runoff (Q) to its potential level (P-Ia). US-SCS (1972) has experienced that about 20 per cent share of maximum retention capacity is contributed by initial abstraction (Ia = 0.2 Sm).

Separation of base-flow discharge in the storm hydrograph is another approach to understand the rainfall-runoff relationship. Base-flow discharge linking with underground water contribution was analysed generally by following semi-log depletion curve

$$Q_t = Q_0 (kr)^t \quad (5)$$

where, kr is recession coefficient, Q₀ is discharge rate at initial time and Q_t is discharge at the end time, t. This equation establishes rainfall runoff relationship on the assumption that the ratio of base-flow discharge for specific duration of time is proportional to the ratio of water retaining in underground storage (S₀ and S_t) during the same time, that is

$$[(Q_0/Q_t) = A(S_0/S_t)] \quad (6)$$

where A is proportionality coefficient and largely dependent on the underground storage characteristics. A slight modification in the semi-log depletion curve was made in its exponential tendency by Wilson (1990) by suggesting a following kind of depletion curve:

$$Q_t = Q_0 e^{-kt} \quad (7)$$

where λ is coefficient of aquifer and e is base of natural logarithm. Separation of base-flow, initial abstraction, effective rainfall depth and storm duration provide the strong basis of the development of UH for understanding rainfall-runoff relationship. Such lumped-modelling approach would be useful for development of parameters relating to watershed characteristics.

3.1: Description of Representative Watershed

A micro-areal geohydrologic unit of a size of about 664.6 ha, named Paham-Syiem watershed that is selected for detail hydrograph analysis, is a part of the larger system of Umran river catchment (designated as VIa2 in the list of the Ordering of river catchments, see Appendix-I, Fig. -15).

It is surrounded by the flat hills and hillocks of about 830 m elevation from a.s.l., flat hill tops in its south-east and eastern parts which separate the watershed from other watersheds in the area. Being its location in the inter-piedmont Nongpoh valley, it receives moderate rain with hyperthermic rainy season. Temperature varies from 20°C to 27°C in July–August and 12°C to 7°C in December with moderate to low daily mean wind velocity of 1-2 km/hr (Syiemlieh 2006). A hill top of 763 m of elevation and a small ridge of moderate elevation of 700-730 m of half a kilometers long act as a water divide on the west and south-western sides of the Paham-Syiem watershed. This ridge is extended upto the Nongpoh town and delineate the western and northern boundary of the watershed. National Highway No. 40 (Guwahati-Shillong Road) passes through its flat narrow foot-ridge side. A motorable unmetalled road about 3 km long running parallel to Paham Syiem stream joints the National Highway where the oval shaped Paham Syiem village is located at a rectangular junction. The watershed extends between 25.892° to 25.917° N latitudes and 91.842° to 91.885° E longitudes and its mouth open towards the National Highway which is the lowest elevated part at 540 m a.s.l.

The contour map of watershed shows its unique relief features. The eroded flat tops, deep stream cutting in the foot hills with regular flow of water, flat longitudinal ridges of moderate slopes in the south, south-western, western and northern parts, the gradual steep gradients of about 40-45 per cent in the eastern slopes with seasonal creeks in the interior part and regular streams in the lower parts, the saturated soil flat lands towards the mouth of the watershed and dissected hillocks of the western slopes are main terrain features. An average slope gradient of about 8.0 per cent was calculated by considering the highest and lowest elevations in the watershed. However, it varies from 45 per cent in the eastern slopes to 13.0 per cent in the interior western part and then to 4-5 per cent in the surroundings of village settlement with the flat land of gentle slope of 1-2 per cent along the National Highway (Fig. -16).

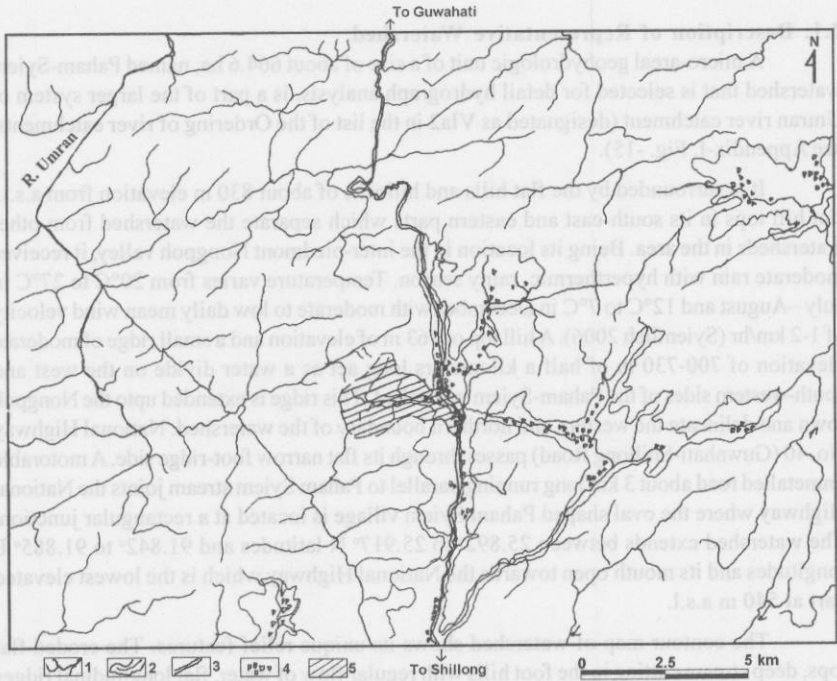


Fig. -15: Paham Syiem Watershed in its Regional Setting

- 1= Streams, 2= Valley lands, 3= National Highway No. 40, 4= Settlements,
- 5= Paham Syiem Watershed (Study Area).

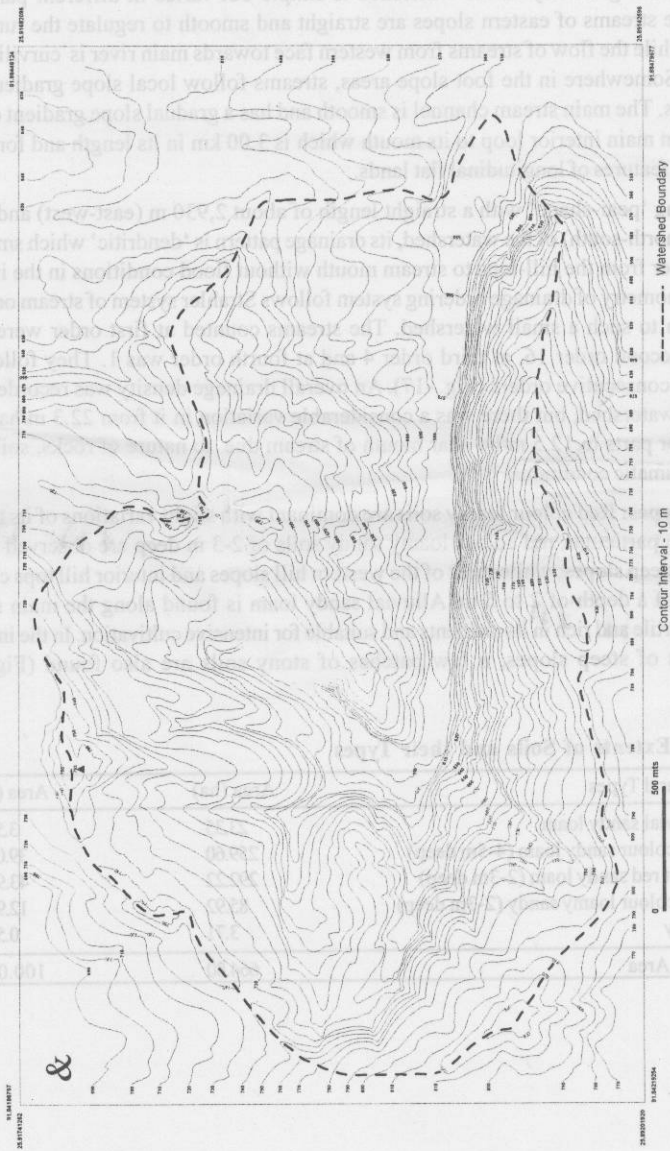


Fig.-16: Paham Syiem Watershed - Contour Map

Channel geometry of the watershed is simple but varies in different parts. For example, the streams of eastern slopes are straight and smooth to regulate the runoff on this slope, while the flow of streams from western face towards main river is curvilinear in its pattern. Somewhere in the foot slope areas, streams follow local slope gradients and form rivulets. The main stream channel is smooth and has a gradual slope gradient of 1.75 per cent from main interior loop to its mouth which is 3.00 km in its length and forms the depositional features of longitudinal flat lands.

Being 'pear-shape' with a straight length of about 2,930 m (east-west) and width of 2,230 m (north-south) of the watershed, its drainage pattern is 'dendritic' which smoothly supplies water from the hill-tops to stream mouth without flood conditions in the interior areas. Morphometry of drainage ordering system follows Strahler system of stream ordering applied even to such a small watershed. The streams counted at first order were 54 in number, at second order 16, at third order 4 and at fourth order was 1. They follow 1:4 between the consecutive orders (Fig. -17). An overall drainage density was recorded 16.8 m/ha in the watershed, but there was a considerable variation in it from 22.3 m/ha in the upper interior parts to 12.5 m/ha near mouth of stream due to nature of rocks, soil types and humid climatic conditions.

3.1.1: Soil Types: Red colour loamy soils are dominant with slight variations of its texture and depth. In particular, red colour loamy sandy soils of 2-3 m deep are observed on the eastern side steep slopes, while most of the western hill slopes and interior hill tops contain sandy loam of a depth of 2 to 5 m. Alluvial sandy loam is found along the main stream valley; it is fertile and rich in its nutrients and suitable for intensive cultivation. In the interior-central parts of steep slopes, a few patches of stony soils are also found (Fig. -18, Table-12).

Table- 12: Extents of Soils and their Types

Sl.No	Textural Types	Area (ha)	Area (%)
1	Alluvial sandy loam	23.35	3.51
2	Red colour sandy loam (4-5m deep)	259.60	39.05
3	Slight red sandy loam (2-3m deep)	292.22	43.96
4	Red colour loamy sandy (2-3m deep)	85.92	12.92
5	Stony	3.71	0.56
	Total Area	664.80	100.00

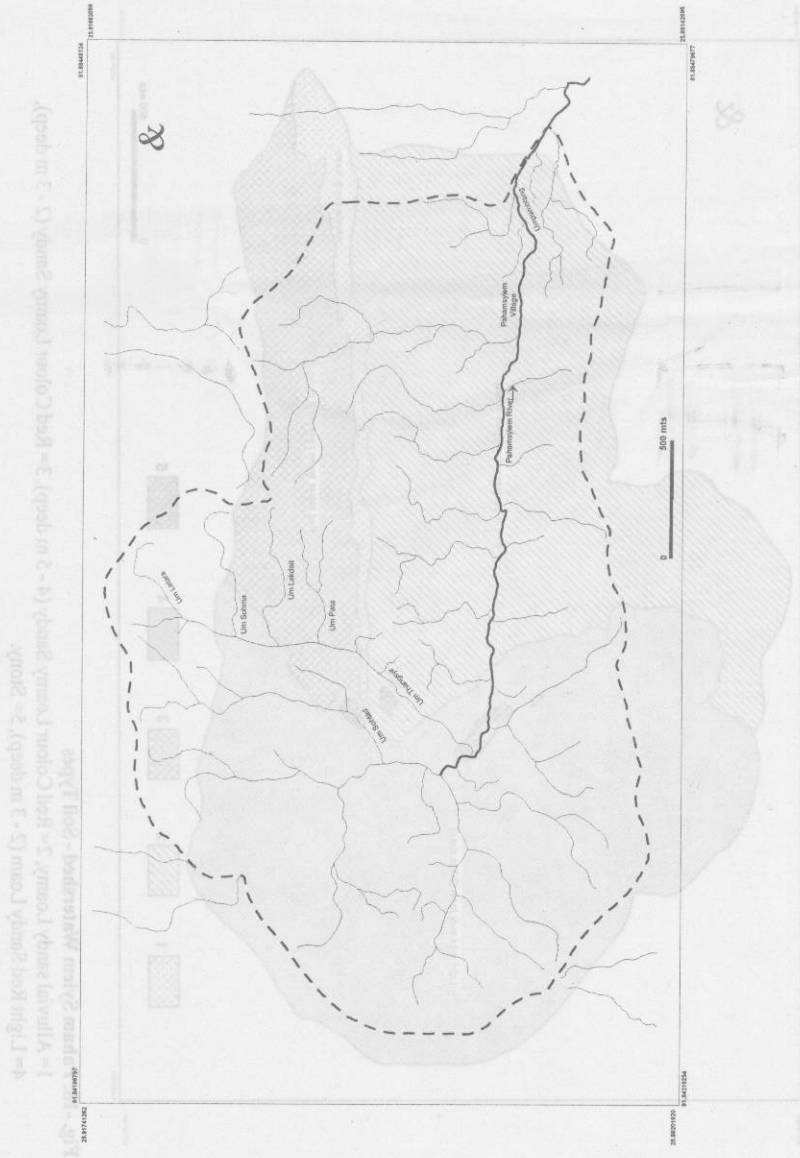


Fig. -17: Paham Syiem Watershed - Drainage System

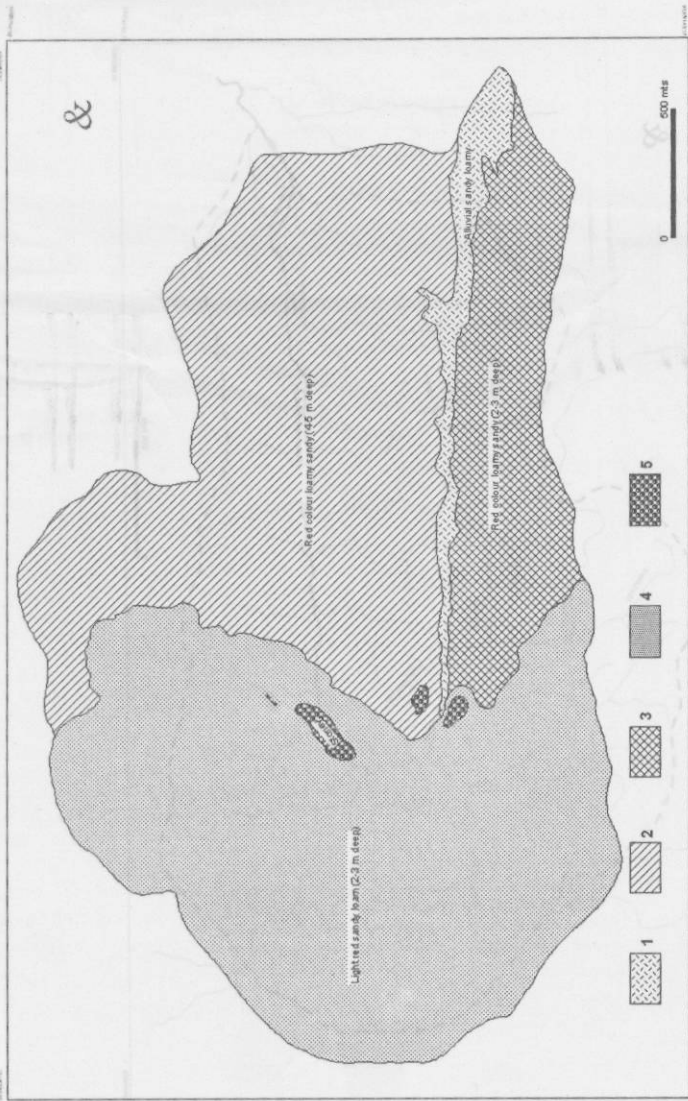


Fig -18: Paham Syiem Watershed - Soil Types
1= Alluvial sandy Loamy, 2= Red Colour Loamy Sandy (4 - 5 m deep), 3= Red Colour Loamy Sandy (2 - 3 m deep), 4= Light Red Sandy Loam (2 - 3 m deep), 5= Stony.

3.1.2: Landuse/Land Cover Pattern: As per the Report of Forest Survey of India which was prepared by considering the base map on the scale of R.F. one million, the total forest cover in the Meghalaya state was reported 70.78 per cent in 1991 and 70.3 per cent in 1993. Further, a detail forest mapping at R.F. 1/250,000 scale was done by Sarma (2003: 147-158) using remotely sensed data for the year 2001-02 under the project entitled 'Forest Mapping of the Meghalaya' sponsored by the State Council of Science, Technology and Environment, Government of Meghalaya, Shillong. Under this project, the forest area including area under jhum re-growth with bamboo for the whole Meghalaya was calculated as 44.71 per cent. It implies that there is a fairly noticeable decrease in forest area at an average annual rate of 2.5 per cent in the Meghalaya plateau during the decade of 1990s (Sarma 2003:156-181).

In the same fashion, there might be decrease in the forest areas in representative watershed due to intensification of agricultural landuse practices, increase in population and market accessibility. However, the land under forest (mixed, dense and thin) and jhum fallow was calculated 410.7 ha (61.7 % to total geographical area) which is higher than the state figures because of jhum fallow and jhum cultivation.

There are some interesting findings drawn from the study of land use planning of the area of Umran basin of about 1,000 sq. km. in which the Pham Syiem watershed is located with the similar topographic and geological features. The findings regarding the land use planning of the basin were drawn by superimposing land use and land form maps prepared at R.F. 1/50,000 scale. The following major landuse features were highlighted as

- (a) The flat valley lands have high level of human interference in the form of intensive crop cultivation in the flat valley or extensive jhum cultivation on the valley slopes.
- (b) The forest lands have low level of human interference though dense forest cover recorded is 20 per cent (below the expected norms of 33.0 per cent).
- (c) Applying USDA based capability classification of land, it is found that the flat valley lands and valley slopes are more suitable for agricultural landuse (Syiemlieh 1997).

It is true for the representative watershed because it has similar geo-ecological conditions and is the part of same universe. There are hardly dense forests in the watershed except a few small patches on the steep slope of sharp valleys. Most of the areas were recorded under mixed thin forest located on western side slopes and secondary forests with jhum fallow on most of the interior and eastern slopes. Land under settlement and roads accounts for nearly 1.71 per cent. The gentle slope and gradual sloppy marginal foot hills with deep soil and sufficient soil moisture are used for intensive cultivation.

An interesting association of slope and drainage system with the landuse is observed in the watershed. Intensive permanent cultivation of commercial crops like chilies, tomato, beans are being practiced on the valley flats. The ginger, broom and rubber plantation are

grown on the valley bottom of gradual undulating slopes. Jhum and jhum fallow on the gentle to steep slopes (10-20 per cent gradients), secondary forests on the steep top of the hills and barren lands on the flat-top of degraded hills are the major components of distribution pattern (Fig.- 19, Table- 13). However, the description of quantitative measurements of such relationships of landuse would be interpreted in detail elsewhere.

Table- 13: Distribution of Land Use / Land Cover Patterns. (2006)

Sl.No.	Categories	Area (ha)	Area (per cent)
1	Land under settlement and road	11.400	1.715
2	Mixed thin forest	58.857	8.853
3	Barren land	5.470	0.822
4	Permanent cultivation	25.795	3.881
5	Rubber plantation	9.439	1.421
6	Jhum cultivation (Broom)	70.620	10.622
7	Jhum fallow (Secondary forest)	278.536	41.897
8	Jhum fallow (Bamboo)	73.445	11.041
9	Jhum cultivation (Crop)	129.458	19.473
10	Horticulture crop	0.994	0.149
11	Others	0.785	0.118
	Total	664.800	100.00

N.B.: Area of each category was calculated by putting map on GIS environment

Source: Self Surveyed in March 2006

3.1.3: Zone of Saturated Soil: The geomorphologic as well as land use factors of watershed as described above contribute to the soil saturation and its areal variation. Before the start of effective rainfall (i.e. overland flow), rainstorms water infiltrates and expands the zone of saturated soil and, thereby, influences the hydrograph pattern. Two main hydrological processes accelerate the activities of surface and sub-surface activities as rainfall starts: (i) the expansion of saturated areas and (ii) extension of stream network. As per follow up action of such processes, three zones of saturated soil, namely, the zone of saturated soil at start of storm, saturated soil areas under low-intensity storms and under prolonged and heavy storms, are delineated to find out the effects of watershed factors on hydrograph.

During the dry winter season, the saturated areas shrink to a width of channel of the main stream, Paham Syiem, with low level of water table of about 1.0 m depth in the low flat valley lands. During pre-monsoon time especially in the month of May, the saturated soil areas expand along the main stream and its tributaries with a contribution to channel flow with slight increase in the water table. The areas of saturation are expanded towards valley depressions and valley slopes to the extent of 25.0 per cent. This is achieved with the highest level of underground water and its fast movement in sub-surface and ground water zones during heavy rainstorms in the month of June and July in summer season. The head ward extension of channel network may also be seen in the upper parts of slope depressions in watershed at the time of prolonged heavy rainfall (Fig. - 20).

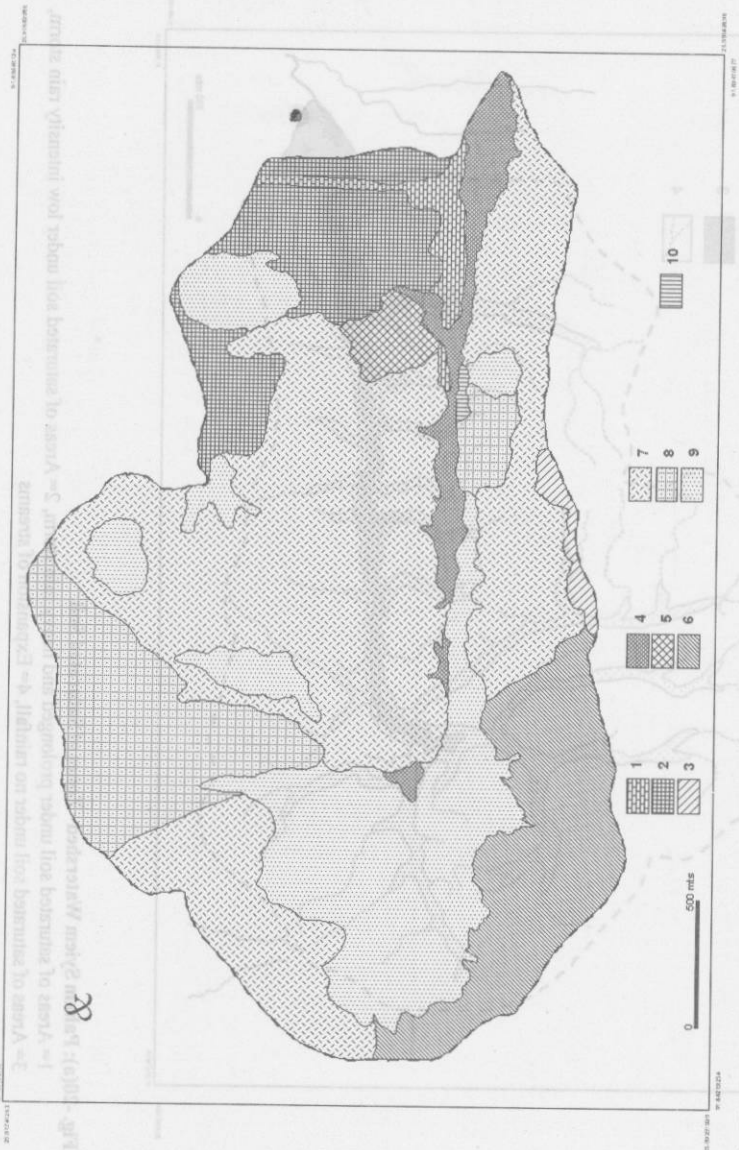


Fig.-19: Paham Syiem Watershed - Land Use / Land Cover

1= Land Settlement, 2= Mixed Thin Forest, 3= Barren Land, 4= Permanent Cultivation, 5= Rubber Plantation, 6= Jhum Cultivation (Broom), 7= Jhum Fallow (secondary Forest), 8= Jhum Fallow (Bamboo), 9= Jhum Cultivation (Crops), 10= Horticulture Crops

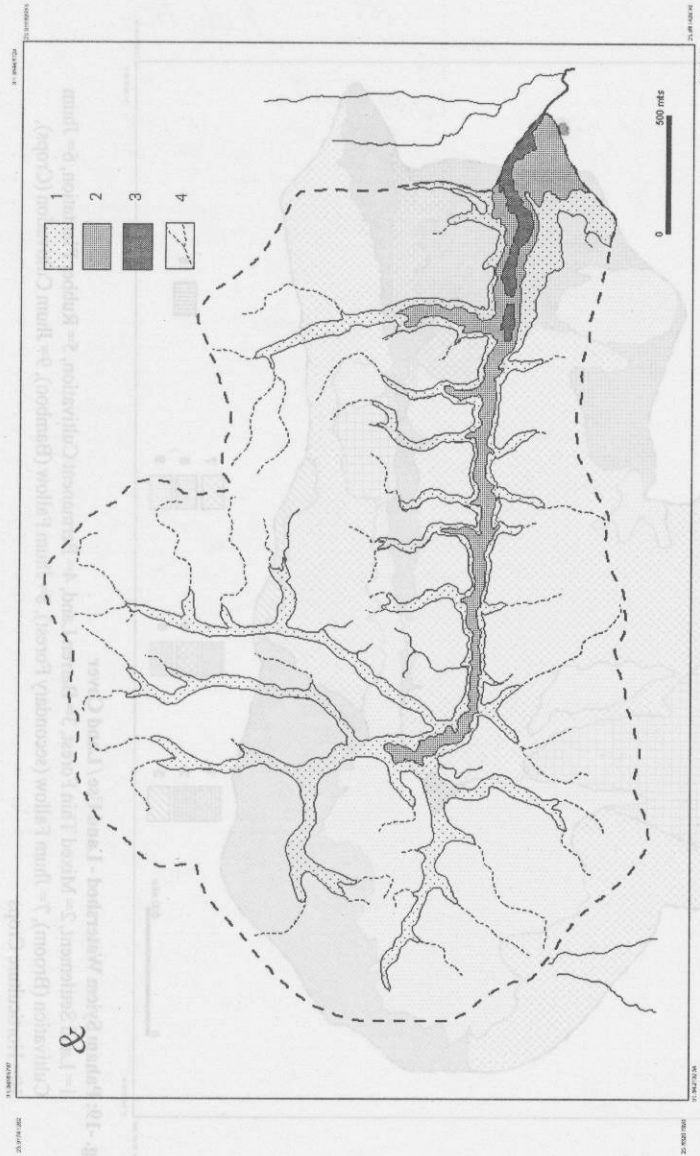


Fig. -20(a): Paham Syiem Watershed - Zones of Saturated Soil
1= Areas of saturated soil under prolonged and heavy rain storm, 2= Areas of saturated soil under no rainfall, 3= Areas of saturated soil under low intensity rain storm, 4= Expansion of streams

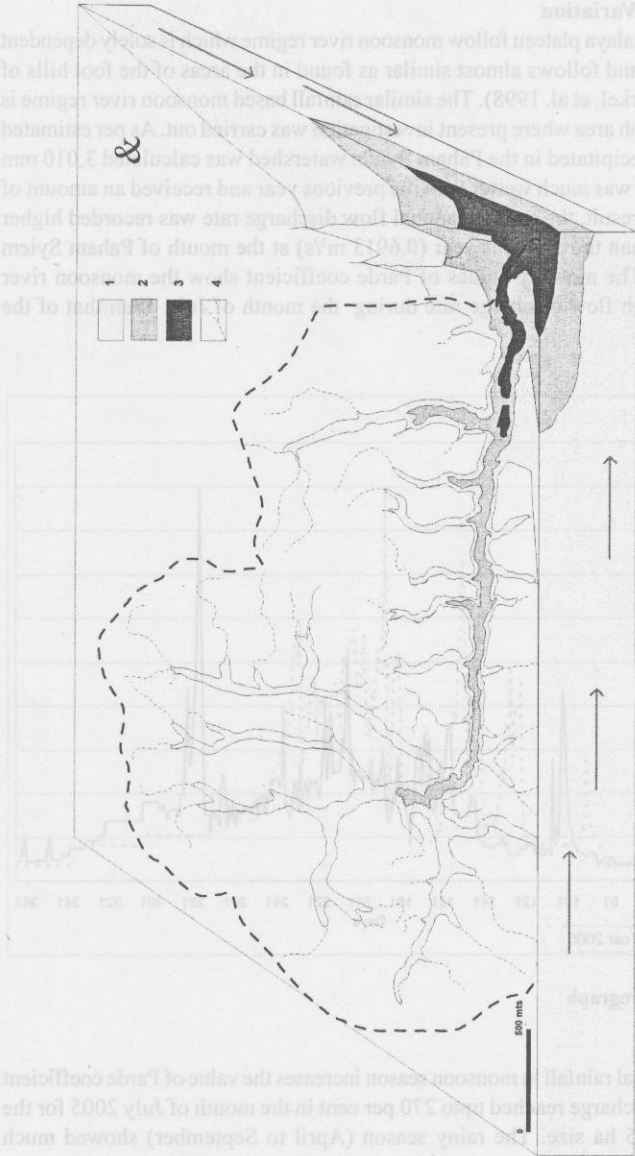


Fig.-20(b): Paham Syiem Watershed - Three Dimensional View of Saturated Soil Zones

- 1= Areas of saturated soil under prolonged and heavy rain storm,
- 2= Areas of saturated soil under low intensity rain storm,
- 3= Areas of saturated soil under no rainfall,
- 4= Expansion of streams

3.2: Flow Discharge Variation

Rivers of Meghalaya plateau follow monsoon river regime which is solely dependent on the rainfall pattern and follows almost similar as found in the areas of the foot hills of Sikkim Himalayas (Starkel, et al. 1998). The similar rainfall based monsoon river regime is prevalent in the Nongpoh area where present investigation was carried out. As per estimated total annual rainfall precipitated in the Paham Syiem watershed was calculated 3,010 mm in 2004. The year 2005 was much wetter than the previous year and received an amount of about 3,275 mm. As a result, the average annual flow discharge rate was recorded higher (0.829 m³/s) in 2005 than the previous year (0.6913 m³/s) at the mouth of Paham Syiem watershed (Fig.- 21). The monthly values of Parde coefficient show the monsoon river regime with a very high flow discharge rate during the month of July than that of the annual average.

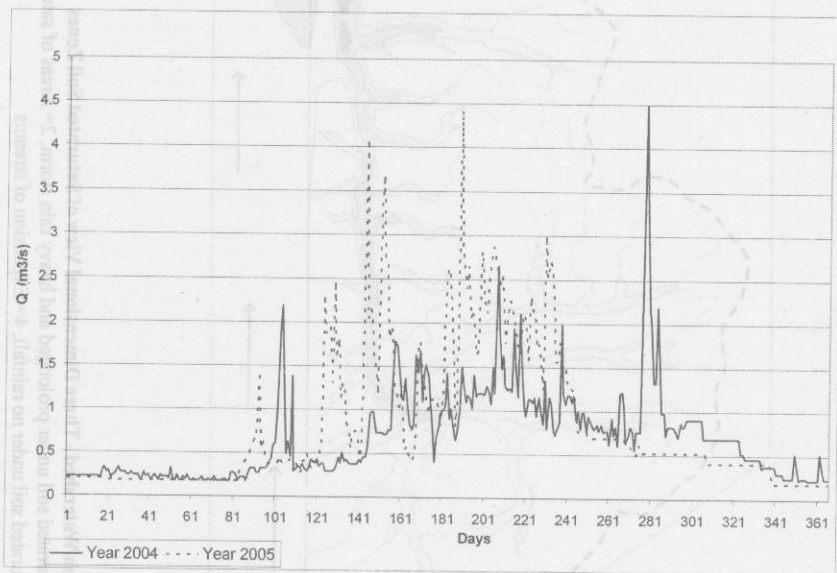


Fig. -21 : Daily Flow Hydrograph

Increasing annual rainfall in monsoon season increases the value of Parde coefficient exponentially. Flow discharge reached upto 270 per cent in the month of July 2005 for the small watershed of 665 ha size. The rainy season (April to September) showed much higher coefficient values which indicate that this is the duration of yielding higher discharge.

Obviously, there was significant fluctuation in the mean monthly discharge rate as Parde Coefficients show (Fig. -22, Table-14) as well as mean daily discharge due to either the erratic rainfall pattern or the small size of watershed which responses to faster flow of surface runoff and channel flow in the watershed. There was hardly any flow in the channel during winter.

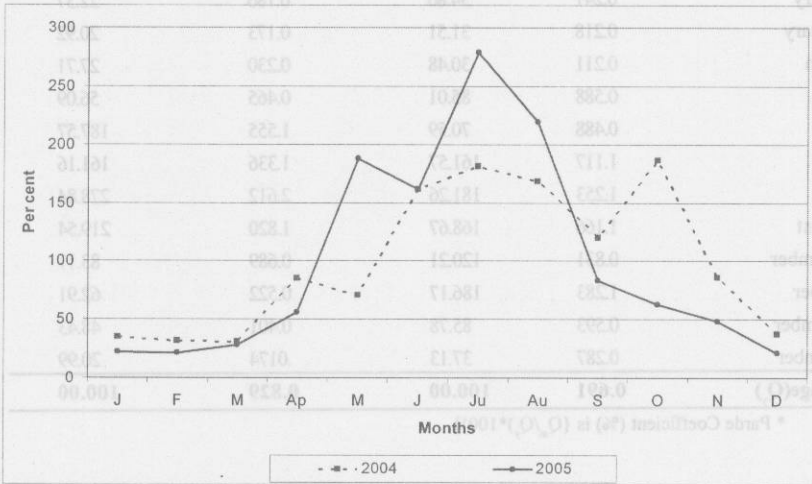


Fig. -22 : Monthly Parde Coefficients

After identifying the days above annual mean of discharge rate, a total number of nine clusters of high discharge duration events were isolated from the daily discharge data. The fluctuating tendencies of these events are interpreted by calculating their durations and temporal variability.

The durations of pre-monsoon higher discharge events (11-14 April 2004 and 3-14 May 2005) are shorter with its fairly higher mean discharge rate of 1.643 m³/s. The discharge events during monsoon period (May – September 2004) were recorded longer in duration and moderate in its average discharge rate. It is not true for the monsoon period of the year 2005 when longer duration events appeared with higher flow discharge. For example, the discharge events of 19 days (22 May – 9 June 2005) and even very long duration of 76 days continuously (17 June – 31 August 2005) produced very high rate of its average discharge of about 2.025 m³/s and 1.958 m³/s respectively. It is worthwhile to note that in the month of October 2004 the hydrographs of the same duration vary in the production of their average daily discharge with different fluctuations due to different rainfall pattern. However, long duration hydrographs have moderate temporal fluctuations varying coefficient of variation from 30.5 per cent to 33.3 per cent (Table-15).

Table- 14: Monthly Flow Discharge (Q) and Parde Coefficient

Months	2004		2005	
	Q _m (m ³ /s)	Parde Coefficient (%)	Q _m (m ³ /s)	Parde Coefficient (%)
January	0.241	34.86	0.186	22.37
February	0.218	31.51	0.173	20.92
March	0.211	30.48	0.230	27.71
April	0.588	85.01	0.465	56.09
May	0.488	70.59	1.555	187.57
June	1.117	161.57	1.336	161.16
July	1.253	181.26	2.612	278.84
August	1.166	168.67	1.820	219.54
September	0.831	120.21	0.689	83.11
October	1.283	186.17	0.522	62.91
November	0.593	85.78	0.401	48.43
December	0.287	37.13	0.174	20.99
Average(Q_y)	0.691	100.00	0.829	100.00

NB: * Parde Coefficient (%) is $\{Q_m/Q_y\} * 100\}$.

Table- 15: Variation in the Hydrographs

Date	Duration (days)	Daily Discharge Rate				
		Max	Min	Mean	SD	CV (%)
11-14 April 2004	4	2.186	1.016	1.643	0.5231	31.878
25 May – 24 June 2004	31	1.792	0.720	1.111	0.3528	31.175
27 June – 20 September 2004	86	2.113	0.720	1.112	0.3401	30.586
22 – 24 September 2004	3	1.218	1.016	1.144	0.1109	09.694
3-13 October 2004	11	4.489	0.977	2.098	1.0962	52.252
21-31 October 2004	11	0.904	0.827	0.884	0.0304	03.438
3-14 May 2005	12	2.470	0.864	1.657	0.4895	29.541
22 May – 9 June 2005	19	4.079	0.977	2.025	0.8712	43.045
17 Jun – 31 August 2005	76	3.013	0.803	1.958	0.6520	33.300

Abbreviations: SD= Standard Deviation and CV= Coefficient of Variation, i. e. (SD/Mean).

Having identified three most relevant hydrological events of different duration from the daily stream flow statistics, the nature and characteristics of these events have been analyzed in detail. Rising and recession coefficients of these hydrographs were calculated by using Barnes equation of Semi-log relationship of the recession components relating to the falling limbs of hydrograph (see Equation - 5). Calculation of Kr coefficients and plotting of depletion curves would help in understanding the separation of stream flow into three types of flow contributions: channel flow, inter flow (sub-surface flow) and base flow (groundwater).

The hydrological event occurred at the time of withdrawal of monsoon when groundwater is perhaps fully recharged has a great significance in changing the general trend of hydrograph. Fast increase at an average rate of 1.52 l/s/day in 5-6 days continuously in the flow discharge pushed its peak upto 4489 l/s and even fast falling it upto 827 l/s in the next 12 days with an average flow of channel recession at 1.15 l/s/day. This figure of recession coefficient is recorded the highest among all three events (Fig.- 23). The events during monsoon period are observed of a long duration of about 3 months and more with a normal rise of 1.06 to 1.11 l/s/day and normal base flow recession of about 1.03 l/s/day in all the cases (Table- 16). The hydrographs of different events may further be analyzed by separating base flow contribution from total stream flow.

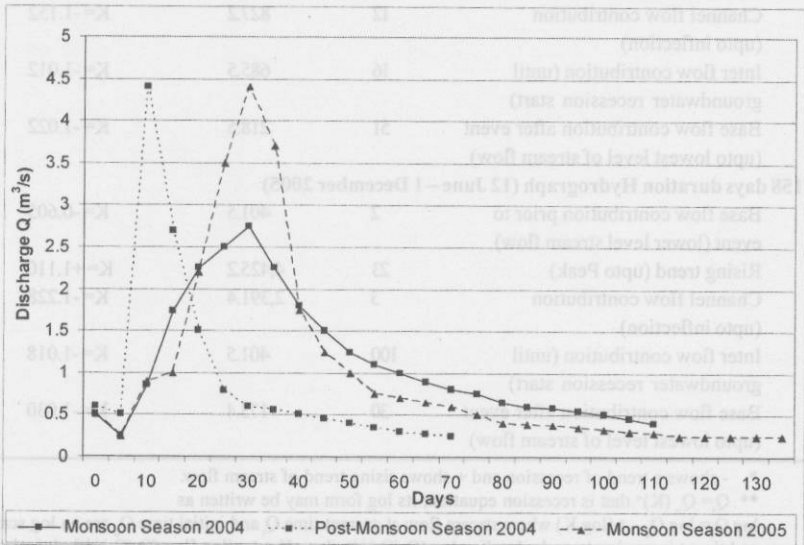


Fig. -23: Stream Flow Hydrographs for Different Seasons

Table- 16: Duration, Rising and Recession Coefficients for Different Contributions to Stream Flow in the Identified Hydrographs

Sl.No	Stream Flow Separation	Duration (days)	Stream Flow (Q) (l/s)	Rising/ Recession rate* (K Coefficient)** (l/s/day)
(A) 97 days duration Hydrograph (23 June – 29 September 2004)				
1	Base flow contribution prior to event (lower level stream flow)	2	401.5	K=-1.371
2	Rising trend (upto Peak)	30	2,656.3	K=+1.065
3	Channel flow contribution (upto inflection)	20	996.7	K=-1.050
4	Inter flow contribution (until groundwater recession start)	30	755.3	K=-1.009
5	Base flow contribution after event (upto lowest level of stream flow)	15	553.1	K=-1.021
(B) 86 days duration Hydrograph (27 September – 21 December 2004)				
1	Base flow contribution prior to event (lower level stream flow)	2	553.1	K=-1.169
2	Rising trend (upto Peak)	5	4,489.2	K=+1.520
3	Channel flow contribution (upto inflection)	12	827.2	K=-1.152
4	Inter flow contribution (until groundwater recession start)	16	685.5	K=-1.012
5	Base flow contribution after event (upto lowest level of stream flow)	51	218.5	K=-1.022
(C) 158 days duration Hydrograph (12 June – 1 December 2005)				
1	Base flow contribution prior to event (lower level stream flow)	2	401.5	K=-0.605
2	Rising trend (upto Peak)	23	4,425.2	K=+1.110
3	Channel flow contribution (upto inflection)	3	2,391.4	K=-1.228
4	Inter flow contribution (until groundwater recession start)	100	401.5	K=-1.018
5	Base flow contribution after event (upto lowest level of stream flow)	30	173.4	K=-1.030

NB: * - shows a trend of recession and + shows rising trend of stream flow.
 ** $Q_t = Q_o (K)^t$ that is recession equation; its log form may be written as $\log Q_t = \log Q_o - t (\log K)$ where stream flow at current time Q_t and initial time Q_o are on log scale and time t is on simple scale, $\log K = \log (Q_o/Q_t)/dt$, then $K = \text{Antilog} [\log (Q_o/Q_t)/dt]$, dt is time duration between Q_o and Q_t .

3.3: Runoff Yield

Among two standard methods of runoff assessment: (a) *The base flow separation* and (b) *The SCS-CN*, the Barnes base-flow depletion coefficient was used to calculate base flow ordinates for the given hydrographs. Direct runoff was calculated to subtract base flow ordinates from the flow discharge and then the Unit Hydrographs for 1.0 cm of effective rainfall (i.e., called sometime net rainfall, an amount after subtracting initial abstraction from total rainfall) for specific duration of effective rain are prepared for analyzing the runoff pattern of Paham Syiem watershed (Tables 17, 18 and 19).

Table- 17: Direct Runoff and Unit Hydrograph for 1.0 cm of Effective Rainfall over Watershed for 97 Days Rainstorm (23rd June-29th September 2004)

Time (days)	Total Runoff Ordinates (l/s)	Base Flow Ordinates (l/s)	Direct Runoff (col 2- col 3) (l/s)	Unit Hydrograph (l/s per cm of Pnet)
(1)	(2)	(3)	(4)	(5)
0	500	500	0	0
5	250	250	0	0
10	855	240	615	5.19
15	1730	180	1550	13.07
20	2250	110	2140	18.05
25	2500	100	2400	20.25
30	2750	100	2650	22.36
35	2250	110	2140	18.05
40	2100	120	1980	16.71
45	1500	185	1315	11.09
50	1250	250	1000	8.44
55	1100	265	835	7.04
60	1000	285	715	6.03
65	900	350	550	4.64
70	800	500	300	2.53
75	750	700	50	.42
80	650	650	0	0
85	600	600	0	0
90	580	580	0	0
95	540	540	0	0
100	500	500	0	0

Runoff Duration	= 65 Days
Total Volume of Runoff Produced	= 7,879,680 m ³
Average Runoff Volume Produced per day	= 121,225.8 m ³ /day
Total Storage in Channel	= 17,342.64 m ³
Share of Channel Storage to Total Runoff Volume per cm of Pnet	= 26.53 %
Pnet= (P-Losses) = (Qdt/A)	= 118.53 cm

Table- 18: Direct Runoff and Unit Hydrograph for 1.0 cm of Effective Rainfall over Watershed for 86 Days Rainstorm (27th September-21st December 2004)

Time (days)	Total Runoff Ordinates (l/s)	Base Flow Ordinates (l/s)	Direct Runoff (col 2- col 3) (l/s)	Unit Hydrograph (l/s per cm of Pnet) (5)
(1)	(2)	(3)	(4)	(5)
0	600	600	0	0
5	500	500	0	0
10	4400	400	4000	77.29
15	2700	410	2290	44.25
20	1500	420	1080	20.87
25	790	435	355	6.86
30	600	450	150	2.90
35	560	475	85	1.64
40	500	500	0	0
45	450	450	0	0
50	400	400	0	0
55	350	350	0	0
60	300	300	0	0
65	275	275	0	0
70	250	250	0	0

Runoff Duration	= 25 Days
Total Volume of Runoff Produced	= 3,438,720 m ³
Average Runoff Volume Produced per day	= 137,548.8 m ³ /day
Total Storage in Channel	= 10,126.08 m ³
Share of Channel Storage to Total Runoff Volume per cm of Pnet	= 18.20 %
Pnet= (P-Losses) = (Qdt/A)	= 51.75 cm

A long duration rainstorm of 97 days occurred during monsoon season of the year 2004 and produced a total volume of runoff of about $788 \times 10^4 \text{ m}^3$ in the effective rainfall duration of 65 days (i.e. 2/3 duration of the total hydrograph period). A similar trend of runoff yield may also be noticed for the long duration monsoon storm of the year 2005 (Table -19). However, the nature of Unit Hydrograph for the post monsoon season when the occasional rainstorm occur in such saturated antecedent moisture conditions appears to be different. A 86 days discharge hydrograph (27 September – 21 December 2004) produced $344 \times 10^4 \text{ m}^3$ in the runoff period of 25 days. Interestingly, the average runoff yield per day was calculated higher ($13.75 \times 10^4 \text{ m}^3/\text{day}$) in this short duration discharge hydrograph. There are two main reasons behind higher average yield of runoff in post monsoon discharge hydrological events:

Table- 19: Direct Runoff and Unit Hydrograph for 1.0 cm of Effective Rainfall over Watershed for 158 Days Rainstorm (12th June-1st December 2005)

Time (days)	Total Runoff Ordinates (l/s)	Base Flow Ordinates (l/s)	Direct Runoff (col 2- col.3) (l/s)	Unit Hydrograph (l/s per cm of Pnet)
(1)	(2)	(3)	(4)	(5)
0	500	500	0	0
5	250	250	0	0
10	900	250	650	5.63
15	1000	210	790	6.36
20	2200	200	2000	16.11
25	3500	190	3310	26.66
30	4400	100	4300	34.64
35	3700	120	3580	28.83
40	1750	180	1570	12.65
45	1250	230	1020	8.21
50	1000	250	750	6.04
55	750	265	485	3.90
60	700	350	350	2.82
65	650	450	200	1.61
70	600	500	100	0.8
75	500	500	0	0
80	400	400	0	0
85	350	350	0	0
90	300	300	0	0
Runoff Duration			= 60 Days	
Total Volume of Runoff Produced			= 8,253,360 m ³	
Average Runoff Volume Produced per day			= 137,556 m ³ /day	
Total Storage in Channel			= 13,940.2 m ³	
Share of Channel Storage to Total Runoff Volume per cm of Pnet			= 20.98 %	
Pnet= (P-Losses) = (Qdt/A)			= 124.15 cm	

(a) The higher runoff ratio because of full saturation of groundwater storage capacity, lesser infiltration and percolation rates during post monsoon time, and

(b) The small size catchment area which reduces catchment lag time (i.e., traveling time) to run water fast to the mouth of watershed. It is true in the present case.

Catchment lag (t_p in hours the time duration between the centroid of the unit rain of specific duration and runoff peak flow) is directly related to the interaction of total length of longest water course (L in km) with the length of water course from its outlet to the point inside to the centre of catchment (L_{ca} in km) and inversely related to overall slope of the water course (S in its unitary gradient value). After Snyder (1938), Linsley, et al. (1958) established such geomorphological parametric relationships in its log form

$$t_p = ct \{ L * Lca \}^n / S^{0.5} \quad \dots \quad (8)$$

where *ct* and *n* are coefficients, *ct* is proportionality coefficient for catchment parameters and calculated by Linsley, et al. (1958) as 1.715 for the mountain region, 1.03 for foot hills and 0.05 for valleys and the value *n* is 0.38 constant for catchments of humid USA. For Indian conditions, Mutreja (1986) reported the coefficient values as *ct* = 1.13 and *n* = 0.2769 for mountain and hill areas. Thus, log-log equation for catchment lag time of the present case of Paham Syiem watershed may be written as

$$t_p = \{ 1.13 (L * Lca)^{0.2769} / S^{0.5} \}, \quad \dots \quad (9)$$

The lag time calculated by inserting the parametric values as *L* = 4.28 km, *Lca* = 1.78 km and *S* = .07136 for the present watershed in the given equation, is observed 7.5 hours. It implies that surface runoff takes 7 to 8 hours to reach at mouth of the catchment after full saturation of soil conditions. As a result, the monsoon duration has many peaks of long duration hydrographic events.

Further, the Unit Hydrographs (UHs) reveal that in post monsoon discharge hydrograph produces the highest runoff rate of about 77.3 l/s per unit of 1.0 cm of effective rainfall just after 5 days of starting the runoff and gradually diminishes to 16 l/s after 20 days from the peak. In monsoon season, the process of runoff yield is noticed slower with its gradual increase upto peak of 22 to 30 l/s after 25 days of the starting of runoff (Fig.-24a). Channel flow contribution to the runoff starts after 35 days in summer time. In the monsoon season, short duration UHs show that the contribution of channel flow to runoff starts just after 10 days from the start of UH. In post monsoon season, the peak of UH is observed at very high runoff rate of about 77.3 l/s/cm of rain. After that the rate declines very fast (Fig.- 24 b).

It may be said that the small duration rainstorm of high intensity occurred generally in the post monsoon season yield more runoff with high peak of UHs. The long duration monsoon storms produce more quantum of runoff with moderate peak of UHs.

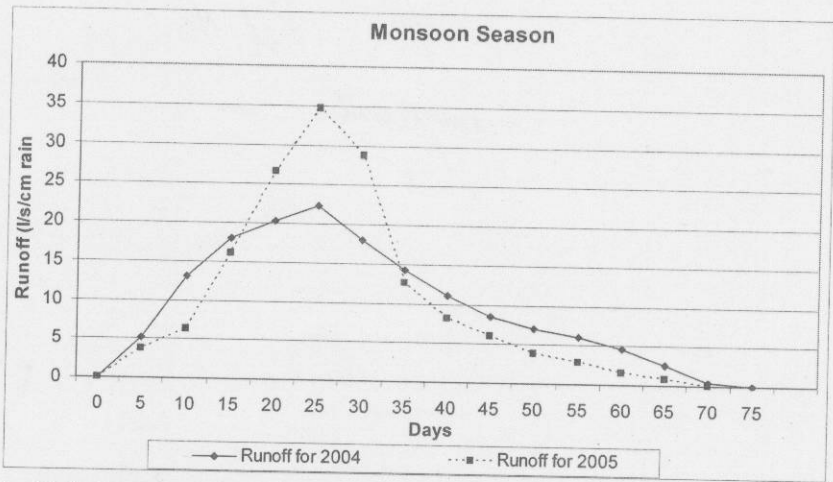


Fig. -24(a): Unit Hydrographs for Monsoon Seasons

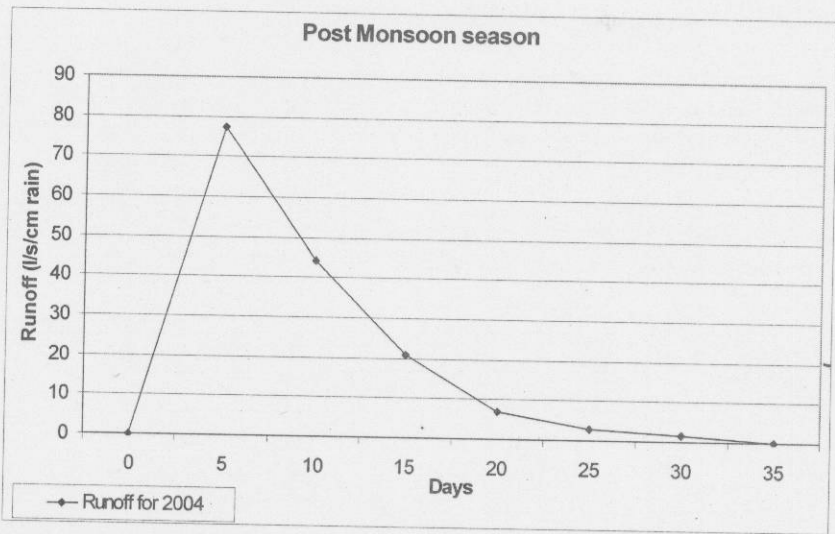



Fig. -24 (b): Unit Hydrographs for Post Monsoon Seasons



Section - IV

Conclusions and Initial Findings

4.0: Conclusion

The purpose of this Section of the Research Monograph is to summarize the findings that have been arisen in the preceding discussion. They can be summarized in two ways as follows:

- (a) The rainfall and runoff pattern in Meghalaya plateau are more diversified because of its complex geomorphic background.
- (b) Stream discharge follows monsoon river regime with subsequent rainstorm events which develop a continuous chain of discharge hydrographs of long durations.

There are many more interesting findings in the present research which can be elaborated here in the form of generalization. Of course, monsoon mechanism which is the source of seasonal as well as areal variations of the rainfall, the runoff is controlled consequently by the complex geomorphic features of the plateau. As a result, the rainfall pattern seems to be more erratic and create extremes in its seasonal and areal variations. The areal variability in the spatial gradients of runoff depth in Meghalaya plateau varies areally from an average decrease of 135 mm/km on the northern slopes to about 200 mm/km on the southern slopes. It is caused due to the topography and direction of the movement of SW monsoon. Dry adiabatic laps rate of 2.10°C per 300 m upto the elevation of 1,000 m a.s.l. at windward side of the southern slopes of the plateau (where Thangkharang park is located) and wet adiabatic laps at rate of 2.5°C per 300 m from the elevation of 1,000 to 1,960 m (from Thangkharang to Shillong) are main causes of rainfall variations on windward side. On the other hand, on the lee ward side in the rain shadow areas of warming the northern slopes between Shillong and Gauhati, there is an increase in temperature at dry adiabatic rate of 1.93°C per 300 m (Fig. - 25). So 'fohn' moisture laden winds vary significantly the rainfall pattern of the plateau.

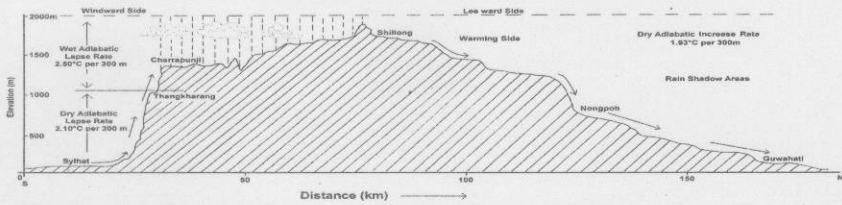


Fig. – 25: Mechanism of Moisture Laden winds in Meghalaya Plateau.

4.1: Initial Findings

The salient features on initial findings inferred from the Section II and III of the monograph are summarized below:

- (1) In the distribution of runoff depth and runoff ratio, there are two concentration hubs of frequencies of river catchments, which show that most of the rain shadow areas of northern slopes yield low runoff depth (5,000 – 25,000 mm) rather than the wind ward areas of southern slopes (50,000 - 75,000 mm). Thus, the distributional pattern follow higher degree of its areal variability. It appears similarly in the areal pattern of runoff ratio.
- (2) Runoff depth and runoff volume available in the river catchments are directly related with rainfall depth. Rainfall is the most influential factor for yielding runoff. Therefore, the areal pattern of rainfall is in consonance with the areal pattern of runoff depth. In spite of similar conditions of potential retention of soil moisture and water loss by evaporative demand all over the plateau, the threshold of runoff yield is different in the areas of northern slopes from the areas of southern slopes because of area differentiations in the soil moisture storage. Soil moisture storage is the direct function of thickness of soils and type of bed rock structure. Thus, soil thickness and geological structure are indirect factors influencing the runoff depth in the plateau.
- (3) The geo-hydrological investigation of micro areal watershed of about 665 ha reveals that soil, slope and land use are major factors which alter the shape, size and expansion of saturated soil areas at the time of occurrences of rainstorm which directly have the impact of discharge hydrographs of different rainstorms. The lag time of the watershed was recorded 7-8 hours with the highest runoff yield rate of 77.0 l/s per unit of 1.0 cm of effective rain during shorter rainstorms of post monsoon seasons. In normal monsoon seasons, the runoff yield rate was calculated upto 22 to 30 l/s with its fast rise and gradual decrease after 25 days.

- (4) The characteristic features of hydrograph analysis show that a total volume of $55 \times 10^3 \text{ m}^3$ to $65 \times 10^3 \text{ m}^3$ per centimetre of effective rain is produced in the normal conditions of rainstorms in monsoon season of 100 days. One-fifth share of the entire volume of runoff is contributed by channel storage with occasional floods in the low land areas near the mouth of the watershed. This is a noticeable runoff volume available in the watershed of 6.65 sq. km. on the northern slopes of the plateau. The direct runoff rate is recorded $137.5 \times 10^3 \text{ m}^3/\text{day}$ which is also giving a satisfactory runoff yield (Table-20).

Table -20: Characteristics of Different Unit Hydrographs

Sl No	Items	Monsoon 2004 (June-Sept)	Post-monsoon 2004 (Sep- Dec)	Monsoon 2005 (June- Dec)
1	Duration of Discharge Hydrograph (days)	97	86	158
2	Number of days for Runoff Yield	65	25	60
3	Total Volume of Direct Runoff Produced (m^3)	7879×10^3	3438×10^3	8253×10^3
4	Average Direct Runoff Volume (m^3/day)	121.2×10^3	137.5×10^3	137.5×10^3
5	Net rainfall (P-losses) (cm)	118.5	51.75	124.148
6	Peak runoff rate in unit Hydrograph (l/s/cm)	22.36	77.29	34.63
7	Runoff rate at Inflow (l/s/cm)	11.09	20.86	8.2
8	Total volume of runoff per cm of P_{net} (m^3/cm)	65.3×10^3	66.45×10^3	55.6×10^3
9	Total storage of runoff in channel per cm of P_{net} (m^3/cm)	173.3×10^3	13.94×10^3	10.1×10^3
10	Share of channel storage to total runoff (%)	26.53	20.98	18.20

In the end, it can be said that the lumped approach of hydrograph analysis which has been applied for establishing rainfall-runoff relationship in the watershed, have some limitations. It does not analyse the effects of distributed geomorphologic attributes in its spatial perspective of catchment. More details of hydrograph analysis may be possible to use physically based distributed modelling with hourly hydrological events data to assess the hydrograph trends more details and accurate. The stochastic model for validation and prediction of hydrologic events may also be used for further rainstorm and hydrograph analysis.

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Appendix- I: Name and Ordering of River Catchments in the Meghalaya Plateau

Sl. No.	Catchment order	Catchment name	Area (sq. km)	Runoff Depth (mm)	Total Runoff (m ha)	Runoff Ratio (RO/P)	Precipitation (mm)	Infiltration Depth (mm)	Bifercation Ratio(I/II)	Stream Length (L in m)	Slope (%)
1	la1	Darnu	182.3	1708.96	311543	0.5696	3000	41.04	4.5	4506.163	1.837
2	la2	Rongkhon	205.1	2128.52	436559	0.6469	3290	36.48	3.4	9024.6528	2.185
3	la3	Ganol	262.7	1958.52	514503	0.6277	3120	36.48	2.75	3218.688	12.327
4	la int i	Kalo	277.6	1304.4	362101	0.5016	2600	45.6	2.25	13518.4896	5.027
5	la int ii	Chhota	81.34	1696.68	138007	0.5655	3000	43.32	3	6437.376	0.426
6	la int iii	Rongkha	97.31	1946.68	189431	0.5989	3250	43.32	3	12231.0144	0.224
7	lb1	Singwi	106.1	1206.68	126028	0.4826	2500	43.32	1.14	8368.5888	0.586
8	lb2	Gatwang	189.2	1216.68	230195	0.4866	2500	43.32	1.85	10299.8016	2.462
9	lc1	Kacha	59.18	914.4	54114	0.4156	2200	45.6	1.2	4506.1632	2.543
10	lc2	Gime	82.58	924.4	76336	0.4201	2200	45.6	1.6	3218.688	2.102
11	ld1	Ringgi	271.5	1529.4	415232	0.5462	2800	45.6	2.9	30577.536	1.840
12	ld2	Rom	68.73	904.4	62159	0.4110	2200	45.6	1.6	15449.7024	1.665
13	kd3	Chota Rom	49.93	890.96	44486	0.4049	2300	49.02	2.5	1287.4752	1.848
14	ld int	Burha Rom	59.05	1586.664	93708	0.5471	2900	48.336	1	7081.1136	0.533
15	le1	Diti	157.4	716.68	112805	0.3583	2000	43.32	2	4506.1632	2.462
16	le2	Atagar/Didak	198.5	849.4	168605	0.3950	2150	45.6	3	10299.8016	2.864
17	le3	Bhagua	103.7	1890.96	196094	0.5909	3300	49.02	3.2	14162.2272	0.429
18	le4	Jhingiram	127.6	785.296	100203	0.3739	2100	49.704	4	8368.5888	0.485
19	le int	Lower Didak	48.82	683.7	33378	0.3418	2000	51.3	3	12874.752	0.485
20	lla1	Rongi	102.3	638.7	65339	0.3275	1950	51.3	5	7081.1136	6.960
21	lla2	Upper Rongi	48.26	638.7	30823	0.3275	1950	51.3	0	4699.28448	5.188
22	llb1	Didiram	228.5	548.016	125221	0.2962	1950	51.984	2.3	6437.376	5.639
23	llb2	Lower Didiram	114.1	489.4	55840	0.2718	1900	45.6	2.87	12231.0144	2.285
24	llb3	Jihar	80.84	589.384	47645	0.3102	1900	50.616	4	7402.9824	7.007
25	llla1	Damring	335.2	1636.24	615507	0.6120	3000	38.76	3.6	4506.1632	7.399
26	llla2	Rengri	254.5	1461.24	371885	0.5844	2500	38.76	1.14	10299.8016	1.870
27	llla3	Chidrang	170.8	708.96	121090	0.3544	2000	41.04	2.28	10299.8016	3.793
28	llla4	Damring	187.9	904.4	94776	0.2802	1800	45.6	1.72	6437.376	6.013
29	lllb1	Chichara	183.6	2465.8	452720	0.7045	3500	34.2	1.23	34761.8304	0.725
30	lllb2	Chil	61.52	1336.24	82205	0.5344	2500	38.76	1.27	7724.8512	1.795
31	lllb3	Dhudnai	132.8	524.4	268895	0.4844	2500	38.76	1.09	7081.1136	6.800
32	lllb4	Lower Dhudnai	167.3	1873.08	313366	0.6181	3000	31.92	1.66	9012.3264	6.578
33	lla1	Upper Iideek	85.63	600.54	51424	0.3160	1900	44.46	2	14162.2272	3.768
34	lla2	Lower Iideek	75.06	600.54	45076	0.3160	1900	44.46	1.33	7081.1136	5.742
35	lla3	Thokhol N	146.6	604.4	89605	0.3181	1900	45.6	3	6115.5072	3.738
36	lla4	Chota Thokhol	107.4	552.12	59297	0.2984	1850	47.88	1.66	9656.064	4.236
37	lva int	Manji	96.76	554.4	53643	0.2996	1850	45.6	1.5	5149.9008	5.379
38	lvb1	West Singra	67.61	584.4	39511	0.3108	1880	45.6	0	8368.5888	1.682
39	lvb2	Gijang N	107.1	1983.976	210341	0.6546	3000	36.024	1.5	6437.376	9.578
40	lvb3	Umijau	44.32	2168.08	96089	0.6775	3200	31.92	2	5793.6384	5.387
41	lvb4	Umtyseng	81.27	2048.08	166447	0.6826	3000	31.92	1.5	10299.8016	6.832
42	lvb5	Singram	135.1	599.22	80954	0.3187	1880	30.78	0	7724.8512	3.799
43	lvb6	East Singra	44.04	839.66	36978	0.4198	2000	35.34	2	2574.9504	2.722
44	lvb7	Boko N	258.1	504.4	130185	0.2802	1800	45.6	1.6	11587.2768	4.7664
45	lvb8	Umsir	143	972.25	139031	0.4861	2000	27.75	1.75	7724.8512	5.689
46	lvb9	Umngi	167.8	972.25	163143	0.4861	2000	27.75	1.66	14162.2272	7.655
47	lvb10	Doiang N	107.7	491.7	52956	0.2980	1650	33.3	1.28	2574.9504	13.601
48	lvb11	Kulsi	255.2	316.7	80821	0.1979	1600	33.3	3	17380.9152	2.593
49	lvb12	Umkannem	80.68	1597.25	128866	0.6389	2500	27.75	1.16	9656.064	10.015
50	lvb13	East Syana	53.83	1899.1	102228	0.6782	2800	25.9	2	9656.064	7.127
51	lvb14	Umsohlans	91.4	2794.47	255414	0.7938	3520	25.53	1.75	10299.8016	5.782
52	lvb15	Umtysung	235.1	2073.175	487403	0.7274	2850	26.825	1.62	5793.6384	7.386
53	lvb16	Syanu	47.08	1097.25	51658	0.5486	2000	27.75	2	5149.9008	5.918
54	lvb17	Umrina	99.92	1732.25	173086	0.6929	2500	27.75	4	5149.9008	2.083
55	lvb18	Umdan	42.41	2351.695	95918	0.7538	3000	28.305	7	6437.376	1.183
56	lvb19	Umnongkrem	27.21	1421.325	38674	0.6610	2150	28.675	0	1931.228	11.837
57	lvb20	Umrut	63.66	668.55	42559	0.3932	1700	31.45	1.4	9334.1952	5.143
58	lvb21	Umshail	56.66	492.625	27912	0.2985	1650	32.375	1.5	643.7376	47.348
59	lvb22	Umng	69.02	980.4	67667	0.5106	1920	29.6	1.5	2896.8192	20.286
60	lvb23	Khri	30.3	786.7	315702	0.4322	1820	33.3	1.9	31543.1424	4.376
61	lvb24	Khuna Khemdi N	46.56	541.7	19804	0.3186	1700	33.3	1.5	3218.688	6.401
62	lvb25	Umshroor	110.4	314.85	34759	0.1967	1600	35.15	1.75	6795.2448	7.386
63	lvb26	Bhata N	115.8	213	24665	0.1420	1500	37	0	7724.8512	4.245
64	lvb27	Umyleng	72.84	718.55	52339	0.3592	2000	31.45	2.66	643.7376	11.837

Contd...

66	Vla2	Unran	316.9	967.625	306640	0.5529	1750	32.375	3.25	1931.2128	19.728
67	Vla3	Upper Umrew	43.95	750.4	32980	0.4215	1780	29.6	4.5	1287.4752	17.755
68	Vla4	East Umrew	111.7	588	65679	0.3920	1500	37	3	1931.2128	35.511
69	Vla int	Lower Umrew	563.3	314.85	177355	0.1967	1600	35.15	3	3218.688	28.409
70	Vlb1	Umnsiang	216.7	467.07	101214	0.3113	1500	32.93	3.14	3218.688	9.469
71	Vlb2	East Umnsiang	230.6	161.15	37161	0.1111	1450	38.85	2.62	643.7376	23.674
72	Vlc1i	Upper Umiam	184.1	895.4	278021	0.4974	1800	29.6	2.33	3218.688	26.041
73	Vlc1ii	Middle Umiam	175.5	388.55	69190	0.2736	1420	31.45	2.66	1287.4752	71.022
74	Vlc1iii	Lower Umiam	80.86	10.225	826	0.0078	1300	39.775	1.66	643.7376	47.348
75	Vlc2	East Umswai	310.5	2059.1	175703	0.7487	2750	25.9	3.5	3218.688	16.571
76	Vlc3	Umswai	85.33	1221.88	224948	0.6109	2000	28.12	2	1287.4752	17.755
77	Vlc int	Umiam Interfluve	310.5	1066.7	331210	0.4848	2200	33.3	0	643.7376	82.859
78	Vla1	Upper Umkhan	70.07	1424.1	99786	0.6473	2200	25.9	2.66	5793.6384	6.581
79	Vla2	Umiew	139.2	1023.175	142425	0.5684	1800	26.825	3.5	1287.4752	13.328
80	Vla3	Mynten	130.3	696.325	90731	0.4352	1600	28.675	3	10943.5392	4.414
81	Vla4	Mynshrehn	56.49	570.4	32221	0.3565	1600	29.6	4	7081.1136	1.988
82	Vla5	Ummat	115.5	570.4	65881	0.3565	1600	29.6	3	5793.6384	3.609
83	Vla6	Umud	81.71	116.7	9535	0.0833	1400	33.3	3	7402.9624	4.117
84	Vla7	Sonaidong	79.27	161.15	12774	0.1074	1500	38.85	3.66	4184.2944	2.432
85	Vla8	Sonai	237.8	2264.85	538581	0.7549	3000	35.15	3	22530.816	3.561
86	Vla int i	Upper Umkhen	139	1222.25	169892	0.6111	2000	27.75	2.25	4506.1652	10.004
87	Vla int ii	Middle Umkhen	80.8	770.4	62248	0.4280	1800	29.6	2	31865.012	2.054
88	Vla int iii	Lower Umkhen	184.6	213	39319	0.1420	1500	37	2	26393.2416	1.039
89	Vlb	Myntriang	248.2	211.15	52407	0.1407	1500	38.85	3.6	63086.2848	1.434
90	Vlc	East Sonai	132.9	1659.3	220520	0.5531	3000	40.7	3.33	6115.5072	4.116
91	Vlla1	Umuiore	190.5	5100.95	971730	0.8501	6000	24.05	2.5	19955.8656	2.836
92	Vlla2	Umtarang	67	5600.58	375238	0.9616	6500	24.42	1.5	17702.784	5.343
93	Vlla3	Khanker	58.04	6099.285	354002	0.8713	7000	25.715	2.66	2253.0816	2.870
94	Vlla4	Rashu N	71.6	6977.43	499583	0.8721	8000	22.57	2	10299.8016	11.624
95	Vlla5	Umpawat	93.48	6851.875	640513	0.8564	8000	23.125	1.66	7724.8512	4.782
96	Vllb1	Mynsan	104.2	4099.1	427126	0.8198	5000	25.9	1.5	955.6064	1.585
97	Vllb2	South Myntang	28.39	1898.175	53889	0.6779	2800	26.825	1.6	7081.1136	6.705
98	Vllb3	Myntang	299.4	2425.58	726218	0.7579	3200	24.42	1.66	1287.4752	7.883
99	Vllc int	Myntang	73.34	2298.175	168548	0.7181	3200	26.825	3	9334.1952	5.404
100	Vllc1	Dikisim	47.34	4724.47	223656	0.7874	6000	25.53	2.125	3504.5568	7.508
101	Vllc2	Wahkynriam	157.9	5850.225	923718	0.8357	7000	24.975	2	6115.5072	3.239
102	Vllc3	Umphung	91.72	6850.95	628369	0.8563	8000	24.05	1.9	3218.688	6.893
103	Vllc4	Umrang	108.9	3597.25	391740	0.7993	4500	27.75	1.6	5793.6384	1.557
104	Vllc5	Dinar Umphar	117.6	2595.4	305219	0.7415	3500	29.6	1.16	5149.9008	4.178
105	Vllc6	Langkni	192.6	967.7	186186	0.4833	2000	33.3	1.33	9012.3264	1.775
106	Vllc int i	Upper Kopili	175.6	4974.1	873451	0.6290	6000	27.75	2.08	3892.2556	9.627
107	Vllc int ii	Middle Kopili	304.1	3972.25	1207961	0.7944	2500	29.6	1.6	13196.6208	3.515
108	Vllc int iii	Lower Kopili	141.4	1470.4	207914	0.5981	3000	25.9	2.5	8368.5892	4.308
109	Vllid1	Myntang N	55.54	2224.1	123526	0.7413	2000	28.305	1.14	2896.8192	5.723
110	Vllid2	South Mynniang	62.87	1096.695	69949	0.4222	2000	30.625	3	6437.376	8.953
111	Vllid3	Mingia	221.7	844.475	187220	0.7228	2800	25.9	1.25	4828.032	4.734
112	Vllid int i	Upper Mynniang	100.5	2024.1	203422	0.5320	2200	29.6	1.66	8046.72	5.178
113	Vllid int ii	Middle Mynniang	199	1170.4	232939	0.5483	1800	33.3	2	4506.1632	10.815
114	Vllid int iii	Lower Mynniang	113.6	641.7	7287	0.3565	1800	33.3	2	4506.1632	10.815
115	Vllle1	Kalanga N	233.3	233.925	54574	0.1538	1520	36.075	3	30899.4048	2.624
116	Vllle2	Dera juri	145.4	231.15	33509	0.1520	1520	38.85	1.6	7081.1136	5.767
117	IXa1	Dalaimar	390.4	3224.1	1258698	0.7164	4500	25.9	2	17059.0464	4.180
118	IXa2	Dihamlai N	74.97	3947.25	288428	0.7694	5000	27.75	1.75	9656.054	1.098
119	IXa int	Diyung	143.6	2970.4	426549	0.7426	4000	29.6	2.5	9334.1952	4.506
120	IXb	Langlair	168.8	2971.88	501653	0.7429	4000	28.12	4	4184.2944	7.626
121	IXc1	Didarbi N	191	470.4	471846	0.7058	3500	29.6	1.5	12552.8832	2.636
122	IXc2	Longku N	61.69	870.4	59683	0.4852	2000	29.6	1.5	7724.8512	2.604
123	IXc int	Lower Diyung	130.7	598	76951	0.3360	1750	37	1.5	8368.5892	3.372
124	Xa	Kayang	535.9	2188	1172549	0.6251	3500	12	1.25	10943.5392	11.257
125	Xb	Larang	109.1	3187.625	347769	0.7083	4500	12.375	2.5	11587.2768	7.891
126	Xc	Gurma	186.3	3186.5	593544	0.7081	4500	13.5	1.33	4506.1632	22.585
127	Xla1	Saipung	88.85	7491.75	665641	0.8813	8500	8.25	2.2	7081.1136	3.228
128	Xla2	East Saipung	92.87	7366.75	684150	0.8666	8500	8.25	1.5	9012.3264	5.773
129	Xla int	Umilumar	128.5	6741.375	866296	0.8426	8000	8.625	1.5	10299.8016	7.649
130	Xlb1	Umphung	123.1	6741	829817	0.8426	8000	9	1.66	6759.2448	20.526
131	Xlb2	Dikisim	190	5540.25	1052647	0.8147	6800	9.75	2	6437.376	16.666
132	Xlb int i	Luhra	38.05	5238.75	199334	0.8059	6500	11.25	0	257.49504	28.562
133	Xlb int ii	Lubhra	285.8	5085.75	1453507	0.7946	6400	14.25	1.5	4184.2944	24.322
134	Xla	Praog	221.3	7238.75	1601935	0.8516	8500	11.25	3.5	5149.9008	13.038
135	Xllb1	Myntidu	256	7891.375	2020192	0.8866	8900	8.625	6.5	13518.4896	1.519
136	Xllb2	Umrpong	122.5	8191.75	1003489	0.8904	9200	8.25	4	13518.4896	2.480
137	Xllb int i	Upper Hari	130.4	8367.5	1091122	0.8807	9500	7.5	2	7081.1136	7.937
138	Xllb int ii	Lower Hari	528	7038.525	3716341	0.8480	8300	11.475	0	1287.4752	3.929

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139	Xllc1	Umtlyngai	168.9	6039.875	1020134	0.8273	7300	10.125	3	8046.72	4.424
140	Xllc2	Nayapara	70.36	1893.5	133226	0.5917	3200	16.5	2.5	3962.4256	0.007
141	Xllc int	Lower Goyain	176.6	2735.6	483106	0.6839	4000	14.4	2	4506.1632	0.067
142	Xllla1	Umgot	396.8	7239.5	2872633	0.9049	8000	10.5	2.25	17380.9152	3.507
143	Xllla2	Umдон	280.2	8241.75	2309338	0.9157	9000	8.25	2.75	14162.2272	11.676
144	Xllla3	Umngi	89.61	8863.75	794280	0.8863	10000	11.25	1.5	10621.6704	12.307
145	Xllla4	Umkreem	68.4	8869	615508	0.8869	10000	6	2	5149.9008	5.782
146	Xllla5	Dhamalia	108.1	5736.5	625852	0.8195	7000	13.5	1.6	3540.5568	6.189
147	Xllla int	Piyaingang	272.5	5736.5	1553196	0.8195	7000	13.5	2.3	5471.7696	7.809
148	Xlllb1	Umrew	173.5	9953.25	1733828	0.9084	11000	6.75	1.66	7724.8512	17.586
149	Xlllb2	Umypn	84.77	10394	931961	0.9161	12000	6	1.5	5793.6394	10.832
150	Xlllb int	Dhalai	92.25	9684.5	910000	0.8967	11000	10.5	2.5	6437.376	11.467
151	XlVa1	Upper Umiew	46.59	7240.25	339495	0.9050	8000	9.75	0.5	3218.688	0.075
152	XlVa2	Mosingi	38.3	9241.6	353963	0.9241	10000	8.4	1.25	4570.53696	6.668
153	XlVa3	East Bagra	51.81	10932.5	569521	0.9160	12000	7.5	2	643.7376	47.348
154	XlVa4	Sonai	161.6	7738.75	1250582	0.8598	9000	11.25	1.66	4506.1632	23.383
155	XlVa int	Umiam	421.6	10791	4633805	0.9159	12000	9	2.55	14805.9648	8.076
156	XlVb1	Umtukang	96.55	7798	747103	0.8597	9000	12	1.71	9012.3264	4.146
157	XlVb2	Umparsumal	130.4	7798	1009035	0.8597	9000	12	1.8	3218.688	6.903
158	XlVc1	Umngi	69.65	6240.25	434633	0.8914	7000	9.75	4	7081.1136	1.243
159	XlVc2	Umnongsung	69.19	6239.5	431711	0.8913	7000	10.5	1.5	11587.2768	1.914
160	XlVc3	East Mukai	46.25	7994	369722	0.8882	9000	6	1.75	2574.9504	15.411
161	XlVc4	Umsrow	38.88	9933.25	398537	0.9084	11000	6.75	3	4184.2944	29.166
162	XlVc5	North Mukai	31.3	8868.1	277571	0.8868	10000	6.9	3	3862.4256	15.782
163	XlVc6	Lower Dhamalia	84.21	10696	900625	0.8912	12000	15	1.75	3540.5568	6.430
164	XlVc int i	Umngi	145	9994.15	1449151	0.9085	11000	5.85	2	16415.3088	7.510
165	XlVc int ii	Mukai	104.7	4739.5	496225	0.7899	6000	10.5	1.125	4828.032	11.313
166	XlVc int iii	Dhamalia	49.58	8196	-406308	0.8626	9600	15	0	1287.4752	17.755
167	XlVd1	Umriang	175.6	7743.25	1359714	0.8603	9000	6.75	1.4	10299.8016	12.778
168	XlVd2	Kynchiang	181.9	7742.875	1408428	0.8603	9000	7.125	3.25	8368.5888	8.730
169	XlVd3	Baul	257.4	4685	1205919	0.7808	6000	15	2.5	8046.72	3.988
170	XlVd int i	Upper Dukatja	118	5238	618084	0.8730	6000	12	5	19312.128	2.388
171	XlVd int ii	Lower Dukatja	114.5	6739.5	771672	0.8424	8000	10.5	2	4506.1632	9.151
172	XlVe1	Khyntsi	239.4	7241	1733495	0.9051	8000	9	2.6	27036.9792	1.140
173	XlVe2	North Kynshi	108.3	5240.25	567519	0.8733	6000	9.75	2.25	3540.5568	3.305
174	XlVe3	Umkyrtha	93.35	5115.25	477508	0.8525	6000	9.75	2	9656.054	2.244
175	XlVe4	Umrlang	133.6	5115.85	683477	0.8526	6000	9.15	2.33	1931.2128	74.968
176	XlVe5	Nongpathar	57.71	7116	410664	0.8895	8000	9	1.5	3862.4256	3.890
177	XlVe6	Umsingsong	46.67	7115.625	332086	0.8894	8000	9.375	2	4506.1632	7.623
178	XlVe7	Umphyrphra	40.27	7116.15	286567	0.8895	8000	8.85	1.5	6437.376	1.178
179	XlVe int i	Kynshi	65.85	6116	402738	0.8737	7000	9	2	3540.5568	3.830
180	XlVe int ii	Lower Kynshi	112	7492.5	839160	0.8814	8500	7.5	2	16415.3088	5.536
181	XlVf1	West Umwasan	77.86	5115.25	398273	0.8525	6000	9.75	1.5	3540.5568	2.337
182	XlVf2	East Umwasan	234.3	4615.1	1081317	0.8391	5500	9.9	2.4	32830.6176	3.012
183	XlVf3	Wankaw	219.1	5991	1312628	0.8558	7000	9	2.4	10621.6704	3.360
184	XlVf4	Wahlyet	211.7	7366.75	1559540	0.8666	8500	8.25	1.16	13196.6208	2.258
185	XlVf5	Wahblei	55.1	7115.625	392070	0.8894	8000	9.375	1.33	6759.2448	1.037
186	XlVf6	Upper Wahblei	124.1	7115.1	882983	0.8893	8000	9.9	1.6	9334.1952	2.429
187	XlVf7	East Wahblei	26.98	7616.6	250495	0.8960	8500	8.4	1.6	5149.9008	5.918
188	XlVf8	Riangmaw	39.8	7792.275	310132	0.8854	8000	7.725	1.5	5793.6394	7.291
189	XlVf9	North Riengmaw	92.52	4742.5	438776	0.7904	6000	10.5	2	6115.5072	1.285
190	XlVf int i	Upper Wahblei	87.27	7616	664648	0.8960	8500	9	2	3862.4256	2.178
191	XlVf int ii	Lower Wahblei	61.03	7491.75	457221	0.8813	8500	8.25	2	643.7376	12.121
192	XlVg1	Rengshi	92.83	3614.875	335568	0.8033	4500	10.125	2	9656.054	2.635
193	XlVg2	Ronga	75.7	3514.65	266059	0.7987	4400	10.36	2.33	7724.8512	2.217
194	XlVg3	Rongit	92.95	3314.5	300882	0.7891	4200	10.5	1.66	4506.1632	2.117
195	XlVg4	Riangdthr	157.9	5615.4	886671	0.8639	6500	9.6	2	7724.8512	3.712
196	XlVa int i	Rongdi	180.5	5115.625	923370	0.8526	6000	9.375	1	14805.9648	3.339
197	XlVb1	Rongni	67.11	3863.9	259306	0.7727	5000	11.1	2	7081.1136	4.304
198	XlVb2	Rompli	50.46	4114.5	207617	0.8229	5000	10.5	1.28	6437.376	1.354
199	XlVb3	North Rompli	30.79	5989.5	184416	0.8566	7000	10.5	2	3218.688	6.660
200	XlVb4	Rongtham	82.11	4614.275	378878	0.8389	5500	10.725	2.5	1931.2128	6.660
201	XlVb5	Wahby	60.54	4989.35	302055	0.8315	6000	10.66	1.66	6759.2448	2.949
202	XlVb6	Simsang	44.75	2488.9	111378	0.7111	3500	11.1	1.5	3218.688	3.295
203	XlVb7	Riangmaw	44.42	2463.75	109439	0.6843	3600	11.25	1.33	4506.1632	15.340
204	XlVb8	Simsang	147.6	2863.375	422634	0.7158	4000	11.625	2	5149.9008	5.918
205	XlVb9	Someswari	66.38	3063.225	203336	0.7293	4200	11.775	2	7402.9824	11.860
206	XlVb10	Nongriang	57.09	6366	363434	0.8488	7500	9	1.33	11265.408	3.882
207	XlVb int i	Middle Simsang	89.51	2988.9	267536	0.7472	4000	11.1	2.5	2886.8192	7.007
208	XlVb int ii	Lower Simsang	90.42	5490.475	496448	0.8446	6500	9.525	2	8046.72	3.887
209	XlVc1	Chebe	175.3	6365.4	115854	0.8487	7500	9.6	2.5	5793.6394	5.029
210	XlVc2	Rongpha	160.2	5740.1	919564	0.8200	7000	9.9	2	643.7376	11.837
211	XlVc3	Ranghi	74.14	6991	518312	0.8738	8000	9	2		

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212	XVc int i	Lower Someswari	210.9	6741	1421676	0.8426	8000	9	1.75	3862.4256	5.831
213	XVd1	Rongva	352.5	5687.4	2004808	0.8124	7000	12.6	1.42	11587.2768	8.193
214	XVd2	Mahadeo	198	6715.975	1329763	0.8394	8000	11.025	1.5	12874.752	3.920
215	XVd3	Karnoi	119	6706.825	798112	0.8393	8000	11.075	1.5	12231.0144	4.515
216	XVd int	Kharnoi	189.7	3885.6	737098	0.7472	5200	14.4	1	6115.5072	5.332
217	XVla1	Daring	166.3	4843.08	902265	0.8071	6000	31.92	1.42	14162.2272	8.097
218	XVla2	Bolmagi	51.21	5216.94	267159	0.8026	6500	33.06	1.66	1931.2128	6.202
219	XVla3	Ramshali	125.1	5213.52	652211	0.8020	6500	36.48	1.6	3218.688	6.685
220	XVla int	Nitai	151.4	5314.66	804639	0.8052	6600	35.34	2	7081.1136	2.806
221	XVlb1	Romkhalii	129	3711.24	478749	0.7422	5900	38.76	1.75	6437.376	2.594
222	XVlb2	East Romkhalii	92.95	4692.38	435156	0.7820	6000	37.62	2	5149.9008	1.479
223	XVlb3	Upper Romkhalii	139.9	2664.4	372749	0.6991	4000	45.6	2.66	5149.9008	1.491
224	XVlc1	Bugi	150.9	3840.8	579576	0.7681	5000	34.2	1.62	6437.376	7.831
225	XVlc2	Norang	145	3340.344	484349	0.7422	4500	34.656	1.75	7724.8512	15.033
226	XVlc3	Chapera	97.4	3713.52	287092	0.7427	5000	36.48	2	643.7376	14.171
227	XVlc4	Ragu	56.2	4718.08	265156	0.7863	6000	31.92	2.2	12874.752	0.771
228	XVlc int	Bhugai	84.02	4208.96	353636	0.7652	5500	41.04	1.66	4506.1632	4.884
229	XVlla1	Thalang	80.99	3710.1	300490	0.7420	5000	39.9	2	1609.344	2.627
230	XVlla int	Lower Thalang	148.7	1634.4	243035	0.5448	3000	45.6	2	3862.4256	1.972
231	XVllb1	Bangdra	40.22	2514.204	101121	0.6616	3600	35.796	1.33	6437.376	2.594
232	XVllb2	Sanda	97.4	2693.52	262348	0.6733	4000	36.48	2.33	1287.4752	2.864
233	XVllb3	Daring	192.6	2178.96	419667	0.6225	3500	41.04	2.2	6115.5072	1.255
234	XVllb4	Maijhi	71.53	2144.4	153388	0.6126	3500	45.6	1.5	1931	3.945
235	XVllb int	Marisi	175.1	2564.4	449026	0.6575	3000	45.6	1.66	2574.9504	6.463

Mean Values		136.48	3652.13	481667.120	0.6540	4758	25.32	2.10	7891.4536	8.597
Standard Deviation		91.79351	2878.175	577367.590	0.2275	2847	13.83	0.98	7940.4816	22.633
Coeff of Variation (%)		67.2547	78.80813	119.86859	34.794628	59.832	54.659	46.7752	89.2165	235.838

About the Author

Surendra Singh did his Ph. D. in Agricultural Geography in 1979 and is currently working as Professor in the Department of Geography at North-Eastern Hill University, Shillong - 793022 (India). He contributed many research articles on agricultural sustainability which published in different Journals of National as well as International repute. He visited many research Institutions under collaborative work including Institute of Geography and Spatial Organization, Polish Academy of Sciences, Warsawa, Institute of Soil and Cultivation, Pulawy (Poland) to deliver a series of lectures and also has been Visiting Professor to teach a course on Agricultural Development (January - April 2004) at the Asian Institute of Technology, Bangkok. His major interests are in sustainable agricultural development especially the development of tools for prediction of crop yield. He is at present the coordinator of Special Assistance Programme (SAP) at Department of Geography in the University, sponsored by University Grants Commission, New Delhi.

E-mail - surendra_singh1@hotmail.com