

**Runoff and Sediment Yield Modelling for Agroforestry
Watersheds under Climate Change**

*Thesis submitted in partial fulfilment of the
requirements for the award of the degree of*

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in

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by

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Under the supervision of

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Dedicated to

My Beloved wife Sonam, and Parents

For Unconditional Love, Support and Care



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CERTIFICATE

This is to certify that the thesis entitled “Runoff and Sediment Yield Modelling for Agroforestry Watersheds under Climate Change” submitted by Arpit Chouksey, Roll No. 10610409 to the Indian Institute of Technology Guwahati, for the award of the degree of Doctor of Philosophy in Civil Engineering is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

May, 2018

(Prof. Subashisa Dutta)



Abstract

In sub-tropical agroforestry watersheds, where the hillslopes are characterized by high degree of soil macroporosity and the area receives extreme rainfall events frequently during the monsoon seasons, rapid overland and subsurface storm flow from the adjacent hilly areas often triggers devastating flash floods in the rivers. Soil erosion is a hazard traditionally associated with agriculture in sub-tropical and rainfed areas and is a threat to long-term soil productivity and sustainable agriculture. The soil loss associated with overland runoff and saturation excess overland flow affect several lives those depend on agriculture. Past efforts to reduce flooding and soil erosion in two agroforestry watersheds viz., Baronda and Kesinga, have been less successful mainly because many of the studies carried out, implemented hydrological and soil erosion models which are not well suited or developed for sub-tropical regions. The objective of this study was, therefore, to understand runoff and erosion processes by investigating plot as well as watershed scale observations and to use these relationships to model runoff and sediment yield. The investigations were carried out to represent the important components that relate hydrologic inputs to outputs. Runoff generation processes were investigated at six hillslope plots representing different land use / land cover. The observations of rainfall and runoff at hillslope plots located in part of Brahmaputra basin revealed that rainfall depth has major influence on runoff generation process. The rainfall depth above a threshold value which vary with land use / land cover, generates the surface runoff. It was also observed that threshold value of rainfall depth varies within a season and its variability can be characterized with the degree of vegetation and soil saturation. This new recognition of a clear threshold behaviour and its dependability on vegetation and soil moisture may be a way forward in collapsing the vast array of process complexities into an integrated hillslope behavioural description. However, in humid, upland regions dominated by agriculture and forests, detailed process-based studies that explore the interface between vegetation, soil moisture, runoff and sediment generation processes, have not been widely attempted. To examine the rainfall-runoff-sediment dynamics at watershed scale, two agroforestry watersheds in part of Mahanadi river basin were considered. The analysis of runoff response to rainfall at watershed scale revealed linearity between rainfall-runoff relationships during monsoon season. In addition, curve number at watershed scale was estimated by using SCS-CN method. The high curve number at both the watersheds indicated the flashiness behaviour. The threshold values of rainfall depth and soil saturation were also estimated by binary classification technique. The sediment concentration follows a power relationship with runoff and the relationship coefficient varies

seasonally. Besides this, the soil saturation and vegetation condition primarily control the runoff and sediment generation process at watershed scale. Therefore, the relationship between Normalized Difference Vegetation Index (NDVI) and sediment-runoff power relationship coefficients were established during pre-monsoon, monsoon and post-monsoon seasons. The results showed that sediment concentration and NDVI are inversely linear related during pre-monsoon and post-monsoon season. However, the opposite trend was depicted for the monsoon season. Therefore, it was argued that relationship between NDVI and Universal Soil Loss Equation (USLE) 'C' factor is only applicable for non-monsoon season.

A semi-distributed runoff and sediment yield model incorporating threshold behaviour of rainfall for runoff generation and effect of vegetation on sediment generation process, was developed based on process relationships from various investigations at hillslope plot and watershed scales. It was assumed that sediment concentration is transport limiting during pre-monsoon period and became source limited during rainy season. The model predicted daily runoff and sediment concentrations well in two agroforestry watersheds. The performance of developed model Rice Irrigation and System Evaluation (RISE) was evaluated and compared with Soil and Water Assessment Tool (SWAT) by measures of goodness-of-fit. The parameter sensitivity of the model was analyzed for threshold rainfall depth and degree of vegetation. The RISE hydrological and sediment model was simulated for the period from 1951 to 2060 for two agroforestry watersheds by using the historical as well as future projected meteorological dataset under RCP 4.5 and 8.5 obtained from National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). To derive future NDVI time series, the historical NDVI and rainfall relationships were established. It was found that rainfall and NDVI are statistically significant correlated at monthly time scale. Wet and dry years were identified based on the temporal annual and monthly rainfall anomalies from 1951-2060. It was realized that the extreme wet and dry year follows a cycle of about 12-15 years. However, no significant trend in monthly or annual rainfall time series was observed. The simulated runoff and sediment yield were analyzed monthly during 1951-2060 for both the watersheds under both RCP's. It was predicted that the period around year 2043/2044 is likely to have extreme runoff and sediment concentration. In addition, seasonal upper envelope equations were applied to forecast the extreme runoff and sediment response to future rainfall events. The modelling approach presented here may be a way forward for the community having limited observed dataset for hydrological and sediment modelling under climate change scenarios.

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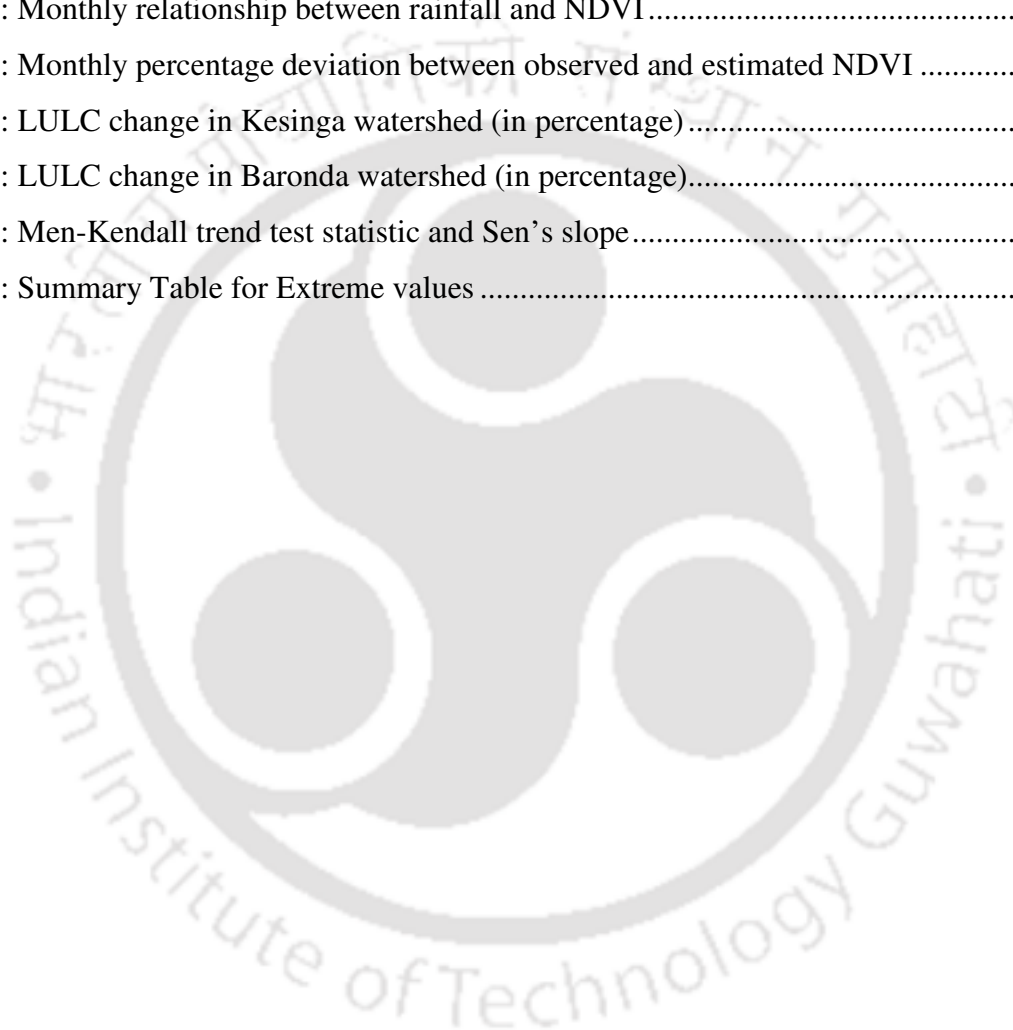
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INTRODUCTION

Nearly 73 percent of total population live in rural areas in Chhattisgarh and Odisha states of India and primarily depend on agriculture for their livelihood (Census of India, 1991). Flood and soil erosion are major threat usually associated with agriculture which affects soil productivity and sustainable agriculture (Dagnew et al., 2016). The average crop yield in Gariaband (Chhattisgarh) and Kalahandi (Odisha) district are 430 and 590 kg/ha, respectively, which are lowest in the states due to insufficient irrigation facilities. A significant proportion of cropped area in these districts is under rainfed agriculture and, thus, drought prone in summers and flood prone in monsoon season. These districts are inhabited mostly by tribal and schedule caste population. Though a number of poverty alleviation programmes have been implemented in the area to create employment and generate income, the living standards of the people have not improved (Planning Commission of India, 1996). Many irrigation schemes launched in the area primarily to improve soil and water conservation/availability, have not yielded desired results. The development of watersheds is increasingly being emphasized in these districts. Three major watershed development projects namely; Integrated watershed development project (IWDP) (for plains), National watershed development project for rainfed areas (NWDPA) and Indo-Danish comprehensive watershed development project (IDCWDP) were launched under 8th five year plan of India. The primary objectives were to prevent land degradation, promote and balance the ecosystem, enhance capacity to retain moisture, and increase the fertility and productivity of the soil (Agrawal and Agarwal, 2015). Despite of long-term efforts to reduce the calamities, sediment concentrations have not declined at the watershed outlets. Lack of development on sediment reduction shows that runoff and erosion processes are not fully understood for these agroforestry regions. The objective of this study was, therefore, to understand runoff and erosion generation

processes by investigating plot and watershed scale rainfall-runoff-sediment relationships and to use this information to model runoff and erosion.

Past efforts to reduce flooding and soil erosion in two agroforestry watersheds viz., Baronda and Kesinga, have been less successful mainly because many of the studies carried out, implemented hydrological and soil erosion models which are not well suited or developed for sub-tropical regions. The two agroforestry watersheds considered in the present study have an average elevation about 300 m above mean sea level and characterized by steep slopes with sub-tropical rainfall patterns. Therefore, hillslope hydrological and sedimentological process are essential to understand first then way forward to watershed scale.

Hillslopes are a fundamental landscape unit for understanding runoff generation processes and a fundamental building block for many watershed models (Graham et al., 2010; Sivapalan, 2003). The hydrological behaviour of natural hillslopes controls both surface and subsurface response of hilly watersheds. The typical nature of hillslopes often cause many adverse situations like flash flooding, slope failures and slides, soil erosion, debris flow, etc. Rainfall-runoff processes in wet tropical and subtropical hilly watersheds mostly follow the theory of variable saturated area. However, infiltration excess runoff generation may also be evident in some of the cases (Sarkar et al., 2015). On the hillslope and field scale, physiographic factors such as the runoff generating areas connectivity, vegetation cover, soil properties, as well as storm characteristics are relevant for runoff generation process (Beven and Germann, 1981; Beven, 2012; Liu and Singh, 2004).

In the last few decades several researchers carried out fundamental studies to understand the hillslope hydrological processes in different parts of the world. Despite hundreds of studies, the link between forests, streamflow, sediments, and climate are poorly understood (Anderson and Burt, 1990; Latron and Gallart, 2008; Tarboton, 2003). Historically, the vegetation function, soil hydrologic processes, soil erosion, and climatic variables were examined independently, the responses between these core areas have only recently become a research priority (Berry et al., 2005). Usually, scientists dealing ecosystem processes approach the soil-plant-atmosphere-water from a one dimensional perspective, with water enters the system as precipitation and leave by evapotranspiration and runoff (Zalewski, 2000). In complex topography and land use with steep hillslopes, this model is often inadequate, as it does not consider the lateral movement of water

through subsurface or the effect of vegetation and soil moisture in generation of overland flow. Hydrologists, on the other hand, have tended to approach the hydrological processes by measuring and modelling, but the incorporation of vegetation processes into these measurements and models has been limited (Bond, 2003; Zhou et al., 2008). Certainly, water management practices have begun to shift from more hydro-technical approaches to those that integrate ecosystem attributes into hydrologic processes (Zalewski, 2000).

It is conceptualized that spatial and temporal patterns across the hillslopes may point to important hydrological controls on runoff generation. It is more manageable to investigate hydrological and soil erosion processes and patterns at the hillslope scale. Catchment scale studies often bring large differences and uncertainties (in soil depth, soil type, topographic variations, and land use) due to which hillslope dominating hydrological process understanding gets diluted. Indeed, hillslopes are complex and heterogeneous. Several past studies have revealed the complexity of vertical preferential flow, lateral soil pipes, hydraulic conductivity, effect of antecedent conditions, etc. (Graham et al., 2010; Tromp-Van Meerveld and McDonnell, 2006a). Since every hillslope appears unique, investigations at experimental hillslopes have been a common method for quantification of the runoff response to storm rainfall. Earlier studies focused mainly on the spatial and temporal dynamics of storm characteristics, soil properties, land use patterns etc. to study the runoff and sediment generation process. The importance of threshold rainfall depth and antecedent soil moisture condition in runoff generation process was noted by (Forestieri et al., 2016; James and Roulet, 2007; Martina et al., 2006; Penna et al., 2011). Nevertheless these important observations, our understanding to hillslope runoff generation process has been limited.

It is general practice to develop a hydrological model by the understanding of hillslope hydrological processes and dynamics and scale-up to the watershed level (Blöschl and Sivapalan, 1995). Model often plays an important role in hydrological and sediment yield studies at larger scale. However, this is unviable at watershed scale because most hydrological and soil erosion models are based on plot scale research only. For instance, the universal soil loss equation (USLE) can be used to estimate average annual soil losses but reliable predictions of the spatial and temporal distributions are often questionable. Agricultural Non-Point Source Pollution (AGNPS) model (Mohammed et al., 2004) and Soil and Water Assessment Tool (SWAT) (Setegn et al., 2008) are widely used hydrological models. These models that use both USLE for erosion predictions and the curve number (infiltration excess runoff) for the hydrology do not perform

satisfactorily even on a monthly basis. The Water Erosion Prediction Project (WEPP) (Zeleeke, 2000), which has a more advanced erosion prediction system tool but still used infiltration excess for runoff, performed below average in predicting the sediment yield at watershed scale. Hence, it is vital to develop an integrated hydrological and sediment yield model which is encouraged by dominating runoff and sediment generation processes at plot scale as well as watershed scale.

Experimental hillslope plots in different parts of India were considered to study the runoff and sediment generation process at hillslope plot scale. The landscapes of north-eastern states of India are mainly characterized by the mountains, along with the agriculture and forest land cover. From the hydrologic point of view, the major sources of runoff and sediment load to the outlet are the vast hillslope areas of its basin. These hillslopes generally have deep and permeable topsoil with an impermeable layer at a shallow depth (Sarkar et al., 2015; Vadivelu, 2004). Study of meteorological data of the region reveals that the area undergoes high intensity storm events quite frequently during the monsoon season (Soja and Starkel, 2007). In general, the hillslopes have dense vegetation cover with highly interconnected macropore network in the subsoil induced mainly by plant roots. A typical combination of all these factors produces less surface runoff with a dominating component of subsurface stormflow under very high intensity storm events over these hillslopes. Therefore, both the phenomena of overland flow and subsurface stormflow through preferential pathways are considered to be predominant and critical hydrological processes of the region (Beven and Germann, 1981; Beven, 2012; Liu and Singh, 2004). It is of prime importance to study the hydrological response of natural hillslopes in order to identify and analyse the controlling parameters of the most critical hydrological processes towards understanding the behaviour of hillslope hydrology at a large scale, which is a rather complex phenomenon (Graham et al., 2010; Sivapalan, 2003; Wilson et al., 1990). For proper planning of soil and water conservation practices, realistic runoff and sediment yield estimation models are needed. Since saturation excess runoff mechanisms are prevalent in the sub-tropical humid climate of India, the challenge is to develop and evaluate models that represent the spatial nature of these runoff processes.

Negi (2001) highlighted the need of micro-scale (plot scale) and meso-scale (watershed scale) studies in the mountainous regions for a better understanding of the hillslope hydrological processes. But, no detailed hydrological studies have been undertaken in agroforestry watersheds to address the interdependence of overland flow, rainfall characteristics, degree of vegetation, and

antecedent soil moisture condition. Keeping these in view, the present investigation has been taken up to explore the hydrological behaviour of agroforestry dominated natural hillslopes by combining *in-situ* experiments with hydrological modelling of agroforestry watersheds.

The likely rise in temperature probably affects precipitation variability, surface runoff, soil erosion, and sediment loads (Bates et al., 2008; IPCC, 2007). Change in rainfall pattern alters major hydrological processes in the water cycle. As a result, the spatio-temporal variation of water resources is likely to be changed. Not only that, flood and soil loss vulnerability in a watershed would also be altered. Very few studies done on the impact of climate change on sediment yield recommend an increase in sediment loads due to increased runoff and soil erosion, particularly in areas with increased runoff (IPCC, 2014). Guhathakurta et al. (2011) studied the impact of climate change on extreme rainfall events and concluded that the frequency of heavy rainfall events is likely to increase in east and north east India. Therefore, it is necessary to assess the variations in runoff and sediment load under climate change for better management plans and practices in future. In all the previous studies carried out on impact of climate change on water resources, different hydrological models were used at different spatial and temporal scales. But, the importance was given to the changes of annual peak discharge, flood volume and annual yield in almost all the cases. The future changes of monthly characteristics of the rainfall, runoff and sediment yield have not yet been addressed with its due importance in agroforestry watersheds. Based on the above facts, the present study has been taken up to investigate the critical controlling parameters for runoff and sediment generation from agroforestry dominated natural hillslope plots and watersheds by combining *in-situ* experiments and hydrological modelling. The hydrological modelling under climate change has been performed to envisage runoff and sediment yield from agroforestry watersheds.

Objectives:

The specific objectives of the present investigation are listed as follows:

- Identification of the controlling factors for surface runoff and sediment yield in hillslope plots in agroforestry watersheds.
- Assessment of seasonal-scale rainfall, runoff and sediment relations of two agroforestry watersheds using daily observed rainfall, discharge, and suspended sediment load.
- Formulation and development of a semi-distributed runoff and sediment yield model for agroforestry watersheds.

- Evaluation of the model's performance for two agroforestry watersheds in predicting runoff and sediment yield, and its comparison with the simulation results from Soil and Water Assessment Tool (SWAT) hydrological model.
- Establishment of a relationship between monthly vegetation index and monthly rainfall for the watersheds and impact assessment of the degree of vegetation on runoff and sediment yield.
- Spatio-temporal variation analysis of runoff and sediment yield of the watersheds from the year 1951 to 2060 by considering future climate projections and change in the degree of vegetation.

Organization of the Thesis

The thesis of the present study comprises of eight chapters. Chapter 1 contains a brief overview of the problem and the specific objectives taken for the study. Chapter 2 focuses towards understanding the relevant literatures to study the progress in hillslope hydrology and sediment yield modelling. A brief assessment of the hydrological investigations carried out in the study area or in other parts of the world has been made to define the possible explanation of the problem. Chapter 3 mainly documents the details of the experiments conducted in the experimental hillslope plot. With the descriptions of the study area, experimental setup and procedures, measurements, and the types of instrumentations used in the hillslope plots the chapter also discusses and summarizes the experimental results obtained from hillslope plot. Chapter 4 describes the details of the watersheds considered in the present study, their physiographical features, and hydro-meteorological data collection. The chapter also summarizes the findings on watershed scale hydrology and sediment yield. Chapter 5 outlines the mathematical concepts of the model. The details of the governing equation and solution techniques are mentioned here. The experimental results of the previous chapters have been used for theoretical concepts and calibration of the models. The chapter also presents the model simulated results, inter-comparisons, and reasoning with detailed discussions. Chapter 6 deals with hydrological and sediment yield modelling by SWAT model and inter-comparison of the results of two hydrological models. It also describes the model sensitivity towards threshold rainfall depth and degree of vegetation variation. Chapter 7 focuses towards application of the developed hydrological and sediment yield model in two study watersheds under climate change scenarios. The chapter briefs the salient findings on behavioural changes in their hydrological response. Chapter 8 finally summarizes the results and lists the major conclusions derived from the present investigation. The scopes for future investigations in line of the present study have also been discussed.

REVIEW OF LITERATURE

During the past few decades a number of researchers have contributed towards understanding of hillslope and watershed scale hydrology in different parts of the world. A number of theoretical and modelling investigations as well as field and laboratory experiments under either natural or artificial rainfall conditions have been carried out towards proper conceptualization of the hydrological behaviour of hillslopes as well as watersheds. The applicability of any hydrological and soil erosion model depends on the understanding of the processes involved in runoff and sediment generation and their transport (Ciesiolka et al., 1995). Understanding runoff and soil erosion dynamics and identification of sediment source areas are therefore important for better runoff and sediment prediction and soil and water conservation implementation (Tilahun et al., 2013). A physical based semi-distributed runoff and sediment yield model was developed in the present study considering the dominated runoff and sediment generation processes in agroforestry hillslopes and watersheds. Climate change characterized by increasing rainfall and temperature is able to affect precipitation regime and thus surface hydrology. However, the way in which suspended sediment loads respond to climate change is not fully understood yet. Hence, this chapter is focused towards a brief discussion on the relevant research works carried out on different aspects of hydrological and soil erosion modelling and its response to climate change.

2.1 Rainfall-Runoff-Sediment Relationships

Hillslopes are fundamental units of hydrologic landscape and responsible for hydrologic processes inception and act as the main filter for water transport from atmosphere to rivers/channels (Graham et al., 2010). The hydrological behavior of natural hillslopes controls runoff and sediment response of hilly watersheds. The typical nature of hillslopes often causes many adverse situations like flash

flood, slope failure, landslides, soil erosion, debris flow, etc. Rainfall-runoff processes in wet tropical and sub-tropical hilly watersheds are significantly influenced by storm characteristics, topographic characteristics, the permeability of the soil, and vegetation cover (Beven, 2012; Beven and Kirkby, 1979; Liu and Singh, 2004). Therefore, conceptualization and modelling of the physical process of runoff and sediment generation is the primary objective of the hydrologist worldwide (Sarkar and Dutta, 2015). A brief review of some of the hillslope scale studies are discussed here.

Hillslope hydrological processes highly influence the response of natural watersheds towards runoff and sediment generation. Surface runoff may be due to different generating processes, owing to the combination of intense rainfall, soil moisture and soil hydraulic properties (Marchi et al., 2010). Hydrology can claim to be one of the *oldest*, yet one of the *youngest* of the natural sciences (Rodda and Robinson, 2015) and hydrological processes observed at the hillslope scale are rich in complexity and heterogeneity (Sivapalan, 2003).

Latron and Gallart (2008) observed non-linearity between rainfall and runoff volume at daily scale during the analyses of the runoff generation processes in a small Mediterranean catchment. They examined dynamics of soil water potential and water table to identify dominating hydrological behaviour in the catchment. The dominating runoff generation processes vary with the wetness conditions or season. Runoff generated as infiltration excess runoff in low permeable areas under dry conditions whereas saturation excess runoff dominated during wet conditions. Seasonal dynamics of runoff-contributing areas studied by Latron and Gallart (2007) showed that the rainfall on saturated area contributes more in streamflow response of the catchment during wet season. Wang and Gupta (1981) observed linear rainfall-runoff transformations in large watersheds, however non-linearity increases with reduction in area of watersheds. They developed a non-linear geomorphic approach for rainfall-runoff modelling by generalization of the linear transformations. However, Caroni et al. (1986) said that non-linearity decreases with increase in storm intensity and this assumption can be used to perform flood analyses for small watersheds. Lehmann et al. (2007) used percolation theory to show that non-linear relationship between rainfall and runoff at hillslopes arises from linear response at smaller scale. They assumed that after rainstorm events the water flows along preferential flow pathways which may include macropores, bedrock valleys, and free water ponding at the bedrock. As long as these pathways are not connected the runoff at the bottom of the hillslope will be small but increases dramatically if the flow pathways become

connected. They also explored the influence of connectivity, moisture deficit and bedrock permeability on the threshold behaviour of the subsurface outflow. The initial water deficit in the soil is important for subsurface flow initiation and the responses for initially wet and dry systems were found significantly different.

Runoff generation mechanisms in steep, humid areas where topography exerts a significant role in hydrology is primarily controlled by wetness conditions (McGlynn, 2005; Sidle et al., 2000). Relatively flat areas near the streams saturates quickly than the hillslope areas, resulting in fast runoff response. Whereas, soil water stored in hillslopes released only during wet soil conditions when flow pathways get connected. Experimental studies in mountainous and agricultural catchments indicated that riparian zones have a tendency to respond differently from upslope hillslope zones (Penna et al., 2011). James and Roulet (2009; 2007) examined the relationship between runoff response and hydrologic connectivity in a temperate forested watershed with varying antecedent soil moisture conditions. They observed non-linear relation between runoff response and antecedent soil moisture which was not evident in riparian zones. Hydrologic response observations showed that runoff coefficient increases considerably after a mean soil moisture threshold. They explained the complexity of antecedent moisture conditions and catchment morphology impact on spatial patterns of storm runoff generation in headwater forest systems. Penna et al. (2011) investigated the role of soil moisture on threshold runoff generation from a hilly watershed. Their study was focused on deriving the soil moisture-runoff relationship, effect of topography on this relationship, temporal dynamics of soil hydrological parameters in wet and dry periods, and the effect of antecedent soil saturation condition and rainfall amount on runoff generation processes. A strong seasonal threshold soil moisture was observed above which hillslope runoff response starts. They also observed opposite hysteretic behaviour in the soil moisture-streamflow relationship during dry and wet periods. Nikolopoulos et al. (2011) assessed the sensitivity of rainfall variability and initial wetness conditions towards runoff generation during a major flash flood event. They applied a distributed hydrological model over a range of sub-basins to simulate hydrologic response for different soil moisture conditions and rainfall forcing resolutions. They found that both the parameters are quite sensitive to peak flow and runoff volume.

Rainfall and runoff response observations on a hillslope over a period of five years showed strong relation of runoff generation to storm event rainfall threshold (Ries et al., 2017). Runoff in semiarid

area was generated by saturation excess overland flow whereas arid runoff response indicated the runoff generation process dominated by Hortonian overland flow. They found that linear relationship between storm event rainfall depth and catchment runoff response becomes strong as the rainfall depth exceeds a certain threshold. Tromp-Van Meerveld and McDonnell (2006b) explained threshold by fill and spill theory assuming that water flows through hillslopes follows the subsurface topography. They observed the spatial and temporal variations of soil saturation of 147 storms at soil bedrock interface to propose the hypothesis. They showed that during storm events smaller than the threshold, water table develops in parts of hillslope until bedrock depressions and subsurface saturated areas became connected. The subsurface stormflow initiates when connectivity is achieved. They showed a distinct threshold of 55 mm rainfall amount required for subsurface stormflow. Penna et al. (2015) investigated hydrometric, isotopic, and electrical conductivity data and found significant seasonal variability in runoff generation processes related to storm rainfall duration and antecedent moisture conditions. Two component hydrograph separation revealed that stormflow in summer season generated due to direct channel precipitation and some saturated overland flow from the riparian zone. However, groundwater and hillslope soil water predominantly contributes the streamflow response during wet season. They found existence of a threshold of summation of antecedent soil moisture index and precipitation for runoff generation and the summation is related to the stormflow by a linear regression equation above threshold. Western et al. (2004) characterized the behaviour of soil moisture at several small humid and sub-humid catchments and found soil moisture variability related to spatial mean soil moisture, the variability was associated to seasonal changes in spatial mean soil moisture at different study sites. They also tried to explore the relationship to defined dominant spatial hydrological processes. Tromp Van Meerveld and McDonnell (2005) argued that soil moisture is only an indicator to estimate subsurface stormflow processes and the relation between hillslope average soil moisture and subsurface flow is often strong and highly nonlinear. The development of transient saturation is not associated to the soil moisture variability on the hillslopes. Zehe et al. (2010) observed a very strong correlation between antecedent soil moisture and runoff coefficient at the forested watershed by statistical and geo-statistical analyses of distributed time series of vertically averaged soil moisture data. Many experimental studies showed that overland flow generation processes are strongly controlled by antecedent soil moisture conditions and total rainfall amount.

Distinct threshold rainfall and runoff behaviour were observed in previous studies (Mosley, 1979; Ries et al., 2017; Tani, 1997; Tromp-Van Meerveld and McDonnell, 2006a; Whipkey, 1965). However, experimental studies that relate observations of spatio-temporal soil moisture dynamics at the field scale to observed overland flows are very few (Zehe et al., 2010). Martina et al. (2006) used rainfall threshold and soil moisture initial conditions to provide flood warnings. They commented that the conventional technique for flood alarms used rainfall threshold values which was not associated with soil saturation conditions which leads to false alarms. They argued that estimation of rainfall threshold is not possible without consideration of soil moisture conditions. They analyzed joint probability density function for precipitation, soil moisture, and discharge to obtain the rainfall threshold for different soil moisture conditions. Many methods were employed to determine the rainfall threshold curves including Bayesian, Entropy, and deterministic methods. Sharafati and Zahabiyou (2014) commented that deterministic rainfall inputs and constant parameter values are the main drawback in rainfall runoff model. They estimated rainfall threshold curves by using Monte Carlo simulation on the uncertainties in the rainfall pattern and model parameters.

Norbiato et al. (2008) evaluated threshold based flash flood warning method by considering climatic and physiographic conditions of 11 basins located in Italy and France. They used probability distributed moisture based rainfall-runoff model to estimate the threshold runoff and to evaluate the threshold based approach. They suggested that representation of hydrological system dynamics for the initial soil moisture conditions should be improved to enhance the performance of flash flood guidance (FFG) system. Carpenter et al. (1999) employed Geographic Information Systems (GIS) and digital elevation database to determine threshold runoff for flash flood warning system. They estimated the runoff threshold values under the assumption that catchments respond linearly to rainfall excess. The threshold runoff values were also attributed to the rainfall duration and watershed morphometric parameters. Georgakakos (2006) estimated flash flood threshold runoff as a function of soil moisture deficit by using Sacramento soil moisture accounting model for the determination of surface runoff. Miao et al. (2016) proposed a method to estimate flood warning rainfall threshold by using frequency analysis and binary classification. They showed that threshold rainfall value decreases with increasing antecedent soil moisture in humid areas because the runoff generation is dominated by saturation excess in these areas. Forestieri et al. (2016) tried to derive the flash flood rainfall threshold using a hydrological model. Different initial soil moisture conditions estimated through hydrological model were considered

to avoid the uncertainties in non-linear rainfall-runoff relationship. Montesarchio et al. (2009) addressed the sensitivity of basin size and time of concentration towards flood warning approach. According to them, flood warning can be made on the basis of runoff and water levels for large basins ($> 10000 \text{ km}^2$) where the time of concentration is higher than 12 hr., for basins smaller than 10000 km^2 the flood warnings should be issued only on the basis of rainfall measurements. They proposed a methodology to estimate rainfall threshold for flood warnings based on the observed rainfall, initial soil moisture conditions, and the hydrologic response of the basin. Rainfall thresholds specify the precipitation amount that generates a critical discharge in a given cross section and flooding is expected.

Marchi et al. (2010) analyzed 25 extreme flash flood events which were selected based on intensity of triggering rainfall and flood response. They analyzed the storm events that produced flash floods and categorized them on the basis of rainfall duration and rainfall amount. Antecedent saturation condition seasonality effect was also observed in flash flood occurrence. On the basis of analysis of storm event rainfall and flood characteristics, they defined a minimum storm rainfall duration required to trigger a flash flood. Higher runoff coefficients estimated for Mediterranean flash floods were due to the flood generating storm event characteristics especially rainfall amount. The wide spectrum of runoff coefficient over the range of rainfall amount were attributed to the variability in initial soil moisture conditions. Numerous studies showed significant impact of initial soil moisture conditions on runoff generation process during flash floods (Borga et al., 2007; Gaume et al., 2003; Sturdevant-Rees et al., 2001).

Li et al. (2016) identified that seasonality of climatic variables have a distinct impact on flood peaks. They proposed an event-based joint probability approach by incorporating seasonality using the hybrid causative events (HCE) approach. They incorporated seasonal variation in soil moisture and extreme rainfall in HCE to model the flood frequency distributions. They analyzed cumulative distribution functions of seasonal daily rainfall and soil moisture to demonstrate the need to include the seasonality in runoff modelling framework. Sinha et al. (2016) examined the spatio-temporal variation of runoff generating mechanisms through the analysis of daily rainfall-runoff data. They also explored the inter-annual variation of runoff generation mechanisms and runoff coefficients on seasonal basis as well as for individual storms. A semi-distributed hydrological model was then used to identify the source of runoff generation. The low runoff coefficient found in humid and forest areas was due to macropore dominating pathways which

leads to the high infiltration capacity. Western and Grayson (1998) investigated the spatial variability of soil moisture pattern and its impact of seasonal runoff coefficient. They observed surface runoff is a threshold process controlled by soil moisture. The soil moisture and hydraulic conductivity is low in summer season; therefore lateral redistribution is insignificant. Whereas, wet areas are well connected to the catchment outlet in the wet pattern in winters (Detty and McGuire, 2010a). Detty and McGuire (2010b) investigated the runoff generation mechanisms and rainfall-runoff response pattern during summer and rainy season. They tried to correlate the storm flow depth to two soil moisture indices and found a threshold existence. Catchment runoff was generated mainly in near stream zones for the storm events below the threshold, whereas the contributing area expanded laterally towards hillslopes for storm events above threshold possibly due to preferential flows through macropore networks. A non-linear relationship was found between storm runoff and antecedent soil moisture index or precipitation. A clear threshold relationship was proposed between the sum of antecedent wetness and gross precipitation and storm runoff: below the threshold total runoff was minimal whereas total runoff was linearly correlated with the pair of antecedent soil moisture and rainfall above threshold (Detty and McGuire, 2010a, 2010b).

2.2 Effect of Vegetation on Runoff and Sediment

Soil erosion by water is a major environmental threat to the sustainability and productive capacity of agriculture in many tropical and sub-tropical regions of the world (Mullan, 2013). Kirkby et al. (2002) identified land use, soil and topography as the factors which influence the runoff threshold. The bare land has the lowest runoff threshold. They recommend to include seasonal variation of the factors causing runoff in hydrological modelling framework. Fu et al. (2003) analyzed the impact of land use land cover on soil moisture profile by intensive monitoring at 26 locations and five land uses in space and time. They observed that land use and its spatial distribution along with rainfall, topography, and soil properties significantly contributes to the soil moisture variations. The mean soil moisture profile for shrubland was considerably different from other land use structures and shows different runoff response. Land use often controls the spatial and temporal variations of soil moisture by influencing infiltration rates, runoff and evapotranspiration (Niu et al., 2015).

Yeshaneh et al. (2015) analyzed decadal trends of runoff and soil loss in Ethiopia by a physically based distributed model. They found that soil loss has increased 1.5 times in past 50 years due to the decrease in the amount of vegetation cover. Wang et al. (2013) developed a new sediment rating curve considering effect of vegetation cover to estimate land cover change effect on the sediment load. They criticized the application of conventional sediment rating curve which are based only on runoff volume and ignore the vegetation dynamics. It was pointed out that different type and extent of vegetation cover have different effect on soil erosion process and transport capacity of runoff. They used NDVI to incorporate the vegetation cover factor into the new sediment rating curve. An inverse relationship was found between NDVI and suspended sediment concentration.

Xinxiao et al. (2006) analyzed the correlation and multi-variable regression relationships between sediment production by erosion, water indexes, precipitation factors and vegetation cover. They concluded that the contributing ratios of vegetation cover to soil erosion changes are greater than the precipitation changes. Ouyang et al. (2010) evaluated the spatial-temporal interaction of land cover status with soil erosion characteristics in China using Soil and Water Assessment tool (SWAT). Their SWAT simulation results revealed that the annual soil erosion and sediment yield showed similar spatial distribution patterns, but the monthly variation fluctuated considerably. They showed that NDVI has a significant impact on sediment formation and transport. The higher NDVI vegetation areas prevented sediment transport, but at the same time contributed significant soil erosion. They also found an exponential correlation between monthly basin NDVI and corresponding sediment yield.

Xin et al. (2011) analyzed sediment yield and its control variables in the China's Loess plateau based on a multi-year dataset from 180 gauging stations to understand and predict the variations in sediment yield. They observed a critical threshold of precipitation and vegetation cover among the relationships of sediment yield, precipitation, and vegetation cover.

2.3 Hydrological and Soil Erosion Models

The applicability of any hydrological and soil erosion model depends on the understanding of the processes involved in runoff and sediment generation and its transport (Ciesiolka et al., 1995; Pandey et al., 2016). Several models exist for the estimation of runoff, sediment yield and about their processes from the catchments. However, these models differ significantly in terms of their

inputs requirements, scale of application, complexity, processes involved and the deliverables. In general, models may be categorized into three types, depending on how the physical processes is being simulated by the model: empirical, conceptual, and physical based. Empirical models are generally based on the observations. The input data requirement of these type of models are usually less than the other two. These models are often criticized due to their unrealistic physical assumptions, ignorance of heterogeneity of the inputs (Chow et al., 1988). Though, empirical models are used frequently by the researchers worldwide as the models can be implemented with limited data inputs. On the other side, conceptual models are based on the representation of catchment flow paths as a series of internal storages (Merritt et al., 2003). These models include the description of catchment processes without inclusion of specific process interactions. The parameter values for conceptual models are identified by using observed runoff and sediment concentration record. The third type of model is physical based model which are based on the mathematical explanation of fundamental physical equations with large number of parameters describing runoff and sediment generation from the catchment. Most of the parameters involved in physical based models are quantifiable or can be calibrated with the observed data. The commonly used algorithms in physical based sediment yield models are the steady state sediment flux equation (Merritt et al., 2003). These algorithms are basically based on sediment transport capacity which is widely used in recent models (Prosser and Rustomji, 2000). Prosser et al. (2001) emphasized that the sediment transport capacity relationship should be chosen wisely to predict actual sediment load. A brief review of the few widely used hydrological and sediment yield models are presented in this section.

Variable Infiltration Capacity model (VIC)

Variable Infiltration Capacity model (VIC) is a macroscale, semi distributed grid based hydrology model developed at the University of Washington in 1994 which uses both energy and water balance equations (Liang et al., 1994). VIC requires meteorological forcing variables, daily time series of land cover information, elevation bands and soil properties as input data requirements. Surface runoff is generated by both infiltration excess and saturation excess overland flow mechanisms. The model parameterizes the effects of sub-grid heterogeneity of soil properties in a very simple way. It considers 3 soil layers where top layer allows quick soil evaporation, middle layer represent dynamic response of soil to rainfall events and lower layer is used to characterize behaviour of soil moisture. The model basically estimate three parameters: an infiltration

parameter, an evaporation parameter and a base-flow parameter. A unit hydrograph based routing model is used to derive runoff flow.

Hydrologic Simulation Program, Fortran (HSPF)

The Hydrologic Simulation Program, Fortran (HSPF) was developed to simulate watershed hydrology and water quality parameters including suspended sediment. HSPF is conceptual catchment scale model where water, sediment and chemical fluxes are calculated separately for different homogeneous land segments of catchment. The model produces runoff through effective rainfall as a set of storages. The input requirements are: rainfall, evaporation, air and water temperature, solar radiation, sediment grain size distribution, point source discharge volume, and water quality data. The extensive input data requirement makes the model more complex and depending much on calibration (Cheung and Fisher, 1995).

MIKE-11

MIKE-11 is a one-dimensional dynamic river model developed by Danish software company (DHI). It simulates hydrology, water quality and sediment transport in rivers. MIKE-11 is a hybrid of conceptual and physical based model in which runoff estimation is based on conceptual models and flow routing is conceptualized using physical based St Venant's equations. The basic modules are a rainfall-runoff component, a hydrodynamic module, a water quality module, and a sediment transport module (<http://www.dhisoftware.com/mike11>). Erosion and deposition are derived as source or sink terms in an advection dispersion equation. The advection dispersion component is based on the 1-dimensional equation of conservation of mass of suspended materials. The large data requirement and detailed parameterization of the model makes it too complex and complicated to use.

TOPMODEL

It is a semi distributed conceptual rainfall-runoff model which uses topographic information to estimate runoff generation. But according to Beven and Kirkby (1979), the TOPMODEL can be considered as a physical based model as its parameters can be measured theoretically. Alternatively, it may be defined as a variable contributing area conceptual model. The major factors considered in the model are the topography and soil transmissivity. The main objective is to compute storage deficit which is a function of compound topographic index (Dutta and Zade,

2003). Since the index is primarily based on topography, the model give calculations only for representative values of indices. The model implies exponential Green-Ampt method (Green and Ampt, 1911) for calculating runoff. The outputs are in the form of areal maps and simulated hydrographs.

Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) is a semi-distributed, continuous-time, and physically-based river basin scale model (Arnold et al., 2012). It integrates surface and groundwater hydrology, soil properties, plant growth, weather and land management practices to model processes within a watershed (Arnold et al., 1998). SWAT is primarily used to predict the impacts of land management changes on water, sediment, and nutrient yields within a basin. Watersheds are divided into sub-basins based on junctions or outlet points along the stream network. Each sub-basin is then divided into hydrologic response units (HRUs), which are areas with homogeneous soil type, land use, slope, and management practices. Runoff, nutrient and sediment yields are calculated for each HRU and routed to outlet as sub-basin outputs. HRUs are not spatially defined within the subbasin; although they represent percentages of total subbasin area. Hence, SWAT includes both spatially distributed parameterization at the subbasin scale and lumped parameterization at the HRU scale (Gassman et al., 2007). Water balance is the primary driving force behind the plant growth, sediments and nutrients processes in SWAT. Penman-Monteith, Priestly-Taylor and Hargreaves methods are used for the estimation of evapotranspiration. SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to predict the sediment yield. The large number of input parameters are required such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, relative humidity, cropping, management practices, etc., which complicates model parameterization and calibration.

Sediment River Network model (SedNet)

The Sediment River Network model developed by CSIRO Land and Water, is a steady-state model to estimate sediment generation and deposition from hillslopes, gullies and riverbanks in a river network (Bartley et al., 2004). The model is capable to calculate the mean annual suspended sediment from each river link, the depth of sediment accumulated, contribution of sediment from surface, gully and bank erosion processes. The model requires digital elevation model (DEM), mean annual rainfall, soil erodibility, crop management factors and management practice grids.

SedNet uses simple conceptual and empirical models of sediment detachment, transport and deposition to describe long term sediment loads in river reaches. Transport capacity of the bed-load sediment fraction is estimated by sediment transport capacity discharge. Stream bank erosion, floodplain deposition and sediment transport capacity models are used to simulate sediment transport through the river reaches. SedNet also applies USLE for hillslope erosion estimation. SedNet incorporates most of the catchment sediment processes, although in a lumped manner.

Watershed Erosion Prediction Project (WEPP)

The Watershed Erosion Prediction Project (WEPP) is a physically based, distributed parameter, continuous simulation, erosion prediction model developed in the United States in 1980s for the simulation of the hydrologic and erosion processes on small watersheds (Flanagan et al., 2007). WEPP includes erosional processes, hydrological processes, plant growth and residue processes, water use processes, hydraulic processes and soil processes. Effective rainfall is estimated by Green-Ampt infiltration equation and peak runoff rate calculation is carried out by kinematic wave overland flow routing method. WEPP consider sheet erosion, rill erosion and erosion where detachment is due to hydraulic shear as erosion processes. However, sediment detachment and deposition is simulated using sediment continuity equation. Watershed configuration, channel geometry, soil and management data and channel hydraulic properties are the basic requirements of the model. The large data requirements of the model limit its applicability in areas where data is sparse. The watershed version of WEPP involves individual hillslope scale models being ‘summed up’ to the catchment scale, increases the complexity and data requirements.

Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) is an empirical average annual soil loss model developed in 1970s by the United States Department of Agriculture (Wischmeier and Smith, 1978). Although primarily developed for application to small hillslopes, USLE is widely used worldwide into catchment scale erosion and sediment yield modelling applications. The input data requirement of the model is very minimal compared to other models. The USLE cannot be applied to predict soil loss for a storm event as it does not consider the rainfall runoff processes as well as the heterogeneities in inputs such as vegetation cover and soil types. The upgraded versions of USLE are Revised USLE (RUSLE) and Modified USLE (MUSLE) (Ganasri and Ramesh, 2016; Zhang et al., 2009). RUSLE retains the basic structure of the USLE, although all equations used

to derive the factor values have been modified. Whereas, MUSLE provides a more complex representation of erosion processes than the USLE as it directly considers the effect of runoff on erosion with changes to the R factor.

Agricultural Non-Point Source model (AGNPS)

The Agricultural Non-Point Source model (AGNPS) is a non-point source pollution model developed by the USDA-ARS to predict the water quality of runoff from rural catchments (Young et al., 1989). AGNPS is a hybrid type of model which includes both empirical and physical based components. The catchment morphology, land use map and precipitation time series are required as input to the model. SCS curve number method is used in the model for runoff estimation and MUSLE for soil loss predictions.

Griffith University Erosion System Template (GUEST)

The Griffith University Erosion System Template (GUEST) is a process-based model developed by Griffith University to predict event based sediment concentration fluctuation from bare soil. The relationship between runoff, rainfall, soil properties, topographical parameter and sediment concentration is used to model the variations in sediment concentration in single erosion events. Two types of erosion processes are considered in GUEST model, those due to rainfall impact and those due to overland flow shear stress (Hairsine and Rose, 1992a, 1992b). Shear stress due to overland flow is calculated by discharge-depth relationship. Threshold stream power, calculated by shear stress and flow velocity is then applied to estimate sediment transport.

2.4 Effect of Rainfall on Vegetation

There are several different studies that have analyzed the influence of temperature, precipitation, atmospheric circulation, etc. on vegetation dynamics and biomass at high latitudes. Eklundh (1998) attempted to establish relationship between Normalized Difference Vegetation Index (NDVI) and rainfall at different time scales. Monthly NDVI was found to lag behind rainfall by 0-3 months (most frequently 1 month), reflecting the delay in vegetation development after rain. They also demonstrated a linear relationship between NDVI and precipitation when annual precipitation is less than 1000 mm. Yuan and Roy (2007) examined the relationships between local level atmospheric elements (rainfall and temperature) and NDVI for summer months in the state of Minnesota. Rather than using Ordinary Least Squared (OLS) regression analysis, they applied

Geographically Weighted Regression (GWR) and spatial interpolation techniques to establish the relationships. Dissimilar nature of relationships across the land uses were observed. However, highest correlation between NDVI and rainfall was found in forested areas.

Nightingale and Phinn (2003) assessed the relationships between precipitation and satellite-derived vegetation index (NDVI). The association of the NDVI response to precipitation was examined for different land uses viz. forest, scrubland, shrubland, woodland, and grassland. A strong relationship was observed between precipitation and NDVI both spatially and temporally within the forest formation. Damizadeh et al. (2001) investigated the relationship between NDVI and rainfall at 10-day and monthly scales. They observed that the association of vegetation index to rainfall is better at monthly scale compared to 10-day interval. They concluded that the monthly NDVI time series was significantly correlated with monthly rainfall and the best relationship was obtained when the preceding two months rainfall was included in the analysis.

Di et al. (1994) developed a model relating vegetative response to rainfall in geographic regions where rainfall is the predominant variable for vegetation growth. to estimate the lag duration of NDVI response to rainfall event for vegetation under water-limited growth conditions. They found that the peak vegetative response to a rainfall event shifts from about 14 days after the rainfall event at the beginning of a growing season to 25 days at the late stage of the season, and then shifts back to 12 days at the end of the season. Their study also showed that NDVI correlated well with two or three month cumulative rainfall. Usman et al. (2013) applied the Geographically Weighted Regression (GWR) to find the spatial relationship between climatic variables (rainfall, temperature) and NDVI derived from NOAA/AVHRR and Aqua/ Moderate Resolution Imaging Spectroradiometer (AQUA/MODIS) satellite sensors. A significant relationship between the NDVI and climate variables (*Rainfall*, T_{max} and T_{min}) was found that often vary as a function of geographical region and other environmental factors.

Zoungrana et al. (2015) implemented correlation analysis to measure the relationship between vegetation indices and rainfall indicators. A comparative analysis of the sensitivity of NDVI and EVI to rainfall indicators was also carried out for different land use land cover. They found NDVI more sensitive to rainfall than EVI. Comparing different land covers response to rainfall, they concluded that NDVI is best correlated with the total rainfall for the current and two preceding months. Ding et al. (2007) discussed about the relationship between NDVI and precipitation on

the Tibetan Plateau. Monthly maximum NDVI and monthly rainfall were considered to analyze the seasonal changes, while annual maximum NDVI, annual effective precipitation and growing season precipitation were used to investigate the inter-annual variations. They found a good relationship between NDVI and rainfall in the meadow and grassland with medium vegetation cover.

Leilei et al. (2014) analyzed the spatial-temporal distribution of 16-day composite NDVI, rainfall and land surface temperature, and also discussed about the relationships among three factors in Tibet. They concluded that vegetation cover was more influenced by the rainfall compared to the land surface temperature from April to October in Tibet. Concerning the response of NDVI to rainfall, maximum correlation for lag of one month and three months cumulative rainfall have been reported by several researchers.

2.5 Impact of Climate Change on Water Resource

Flood casualties and damages are increasing in many parts of the world due to the social and economic development bringing pressure on land use (Marchi et al., 2010). Flash flood hazards are likely to increase in frequency and severity due to the impact of climate change on storm characteristics and river discharge conditions. It was reported by Barredo (2007), that 40% of the water related casualties occurred in Europe in the period from 1950 to 2006 were due to flash floods. Changes in precipitation and temperature patterns impact plant biomass production, infiltration rate, soil moisture, land use and crop management, etc. and hence affect runoff and soil erosion (Li and Fang, 2016).

In India, rainfall is considered as the primary source of water resources, hence, planning and development of water resource projects are often based on the historical trends of water availability and demand. Rainfed agriculture plays a major role in India's food security and sustainable economic growth as rain-fed agriculture supports nearly 40 % of India's estimated population of 1210 million in 2011 (Sharma, 2011). Rainfall is an important hydro-climatic variable and trends of rainfall extremes over a long period is often considered as a crucial indicator of climate change. These extreme rainfall events have predominant effect on floods in the lower reaches of a river basin. Hence, detection of trends and variation in rainfall has profound social and economic significance (Jena et al., 2014). Inter-Governmental Panel on Climate Change has reported that the earth's temperature has increased by 0.74°C between 1906 and 2005 due to increase in greenhouse

gases emissions. By the end of this century, temperature is likely to increase by 1.8 - 4.0°C which may lead to more frequent hot extremes, floods, droughts, cyclones and gradual recession of glaciers (Aggarwal, 2008). Over the last few decades, a warming trend has initiated to rise over South Asia, particularly in India (Kumar et al., 2010). A new set of scenarios of Representative Concentration Pathways (RCPs), including RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, was also published in the IPCC report (IPCC, 2014). The radiative forcing level in year 2100 of RCP 8.5 is assumed to be the highest while that of RCP 2.6 being the lowest. Global temperature is likely to rise by 1.5 °C for all RCPs except for RCP2.6. The change in rainfall is likely to impact soil erosion directly, in terms of rainfall amount, intensity, and spatiotemporal distributions. Several recent studies combined the change in rainfall distributions with land use change. For example, if the timing of rainfall changes to coincide with planting dates, or if the rainfall amount increases during winters when vegetation cover is lower, soil erosion is likely to be increased owing to less protection and increased rainfall force (Li and Fang, 2016).

Climate change impacts on soil erosion have been observed over the world, and recent studies suggest that the rainfall is the most direct influencing factor (Bookhagen et al., 2005). Lu et al., 2013 indicated that every 1% change in precipitation has led to a 2% change in sediment loads and a 1.3% change in water discharge. Maeda et al. (2010) recommended that the uplands should be given priority for soil and water conservations, because rainfall is likely to increase significantly in uplands and may cause severe soil erosion. Higher rainfall amount is generally linked to more runoff and soil loss (Zabaleta et al., 2014), due to increase in rainfall, subsequently soil moisture, soil sealing and crusting is likely to increase, with likely decrease in infiltration capacity, and therefore increase runoff amount and the vulnerability to erosion. Mondal et al. (2015) estimated the impact of climate change on soil erosion by using the Universal Soil Loss Equation (USLE) in part of Narmada River basin, India. The application of the LSSVM (Least-square support vector machine) and SDSM (Statistical Downscaling model) models for downscaling the GCM dataset to estimate the future annual precipitation and its effect on soil erosion was also examined.

Bhatt and Mall (2015) briefly reviewed the model based projections made for the some of the major river basins of the world. They emphasized the need to assess the future runoff projections based on multi-model ensemble approach especially in Indian River basins. There have been only a limited number of studies conducted for tropical region for predicting the impacts of climate change on floods. In a recent study, Ghosh and Dutta (2012) investigated impact of climate change

on flood characteristics in Brahmaputra basin using macro-scale distributed hydrological model. The study used RCM simulated rainfall as input for the distributed hydrologic model developed for the basin. The analysis revealed that although the number of flood events would decrease in future (2010–2100), the peak discharge and duration of the floods would increase. Mirza (2002) used climate change scenarios from four GCMs as input into hydrological models for predicting the change in discharges of Ganga, Brahmaputra and Meghna rivers of India. The results of the study demonstrated a substantial increase in mean peak discharges in the rivers of Ganges–Brahmaputra basin. Prudhomme et al. (2011) estimated the mean seasonal flow by using semi-distributed hydrological model for 30 years baseline and future climatic data assuming no change in the catchment behaviour due to the vegetation change. They found a significant decrease in flow in the summer almost everywhere in Britain. Apurv et al. (2015) analyzed the changes in the magnitude and frequency of extreme floods in north-eastern part of India in the near future using the CMIP5 decadal precipitation predictions. They adopted Nested Bias Correction (NBC) technique to correct the GCM dataset. They observed that GCM's underestimates high rainfall events and slightly over simulates low rainfall events during monsoon season. In place of the usual approach of hydrological model simulations to estimate the impact of climate change, they developed empirical relationships between the storm rainfall features and the flood wave characteristics for selected monsoon storms and used them to estimate the changes in the flood characteristics in future. Jena et al. (2014) analyzed the severity of floods in Mahanadi River basin as a result of extreme precipitation events. They evaluated the trends of extreme rainfalls in relation to the trends of peak floods. Shivam et al. (2017) analyzed changes in the maximum and minimum temperature over the Subansiri River basin for different climate change scenarios using Mann-Kendall non-parametric test and Sen's slope estimator. They observed a significant increase in annual maximum temperature and annual minimum temperature for all the selected RCP scenarios.

A hydrological model was simulated using three downscaled precipitation and potential evapotranspiration scenarios to assess the impact of future climate change on seasonal hydrological regimes by establishing statistical relationships between three indices of atmospheric circulation, daily catchment precipitation, and potential evapotranspiration. Analysis of extreme events suggested significant increases in the frequency of both high- and low-flow events (Pilling and Jones, 2002). Devkota and Gyawali (2015) assessed the temporal changes in the hydrological regime of the Koshi River Basin under climate change scenario using the Soil and Water Assessment Tool (SWAT) model. They have corrected the biasness of future precipitation against

observed historical data by comparing the mean, variance, and a range of quantile values. They observed a shift of the peak monthly flow from August under baseline conditions to July under projected future conditions.

Essou et al. (2016) highlighted the application of gridded dataset over observed weather station data for hydrological modelling. They mentioned the required observed meteorological parameters are not always available due to the low spatial density and shortfalls in many weather station networks. They compared four different interpolated precipitation and temperature datasets on the basis of their statistical characteristics. They later applied a lumped hydrological model to examine the applicability of the climatic datasets. The hydrological performances was found statistically similar for most of the watersheds in United States, even with the different interpolated precipitation and temperature inputs. Cherkauer and Sinha (2010) simulated large-scale hydrology model to examine the impact of climate change on spatial distribution of total runoff and river flow in Michigan. Climate projection from three future climate scenario and two climate models were disaggregated and bias corrected before forcing them in hydrological model. They observed that annual streamflow and flashiness (R-B Index) is likely to increase in all River basins by the end of this century.

Shrestha et al. (2016) evaluated the uncertainty in flow and sediment projections with three Global Climate Models (GCMs), three Representative Concentration Pathways (RCPs) and three model parameter (MP) sets using the Soil and Water Assessment Tool (SWAT). They found that GCM and MP were the major sources of uncertainty, whereas RCPs had less of an effect for seasonal and annual flow projections. However, the uncertainty due to RCPs are large for annual sediment load projections compare to the uncertainty in flow projections. They also cited that most of the previous studies were generally focused on flow and there is still limited knowledge about the uncertainty in sediment projection due to future climate scenarios. Uncertainty in land use change was not included in the study by (Shrestha et al., 2016, 2013). Mehdi et al. (2015) evaluated the impact of climate change and land use change on streamflow and water quality parameters in agricultural watershed in Bavaria, Germany. They observed that the nitrate and phosphorus loads in streamflow significantly increased when the climate change simulations were combined with the land use change scenarios. The potential trajectories of agricultural change in the region for the next 30 years were prepared based on farmers and local stakeholder's questionnaire.

Several studies were carried out on pattern of extreme rainfall in India (Ghosh et al., 2011; Goswami et al., 2006; Patra et al., 2012; Rajeevan et al., 2008; Rakhecha and Soman, 1994; Roy and Balling, 2004; Stephenson et al., 1999). Goswami et al. (2006) reported a significant increasing trend of rainfall frequency and magnitude over central part of India during the monsoon period. Rakhecha and Soman (1994) analyzed long term annual extreme rainfall events of 1–3 days duration and found that the rainfall trend is insignificant in most of the Raingauge stations. However, Guhathakurta et al. (2011; 2010) reported that intensity of extreme rainfall over and near Indian east coast has increased during last two decades and the frequency of heavy rainfall events are decreasing in major parts of the central and north India while increasing in the peninsular India, east and north east India. Though many studies on variation of extreme rainfalls in India have been carried, very few researchers have made an attempt to correlate the trends and variation of extreme rainfall pattern and the resulting streamflow in a basin. This study focuses on the analysis of temporal trends of extreme rainfall and peak discharges in the flood prone Mahanadi river basin in eastern India. The Mahanadi river basin is selected as it is expected to be the worst affected river basins in India in terms of the increase in intensity of floods due to climate change (Gosain et al., 2006).

Zhang and Nearing (2005) evaluated the potential impacts of climate change on soil erosion, surface runoff, and wheat productivity using monthly precipitation and temperature projections. The Water Erosion Prediction Project (WEPP) model was implemented to predict average annual soil loss projections. Cousino et al. (2015) implemented SWAT model to model the effect of climate change on water, sediment, and nutrient yields from the Maumee River watershed. Mullan (2013) assessed the future soil erosion rates using the Water Erosion Prediction Project (WEPP) model across six hillslopes in Northern Ireland. They determined the vulnerability of the changing soil erosion rates by considering number of scenarios depends on precipitation, sub daily rainfall intensity and land use change. Routschek et al. (2014) investigated the changes in soil erosion rate due to climate change. Four soil erosion models and future scenarios were considered based upon land use, soil management due to changed crop rotation and shifted harvest date to estimate the soil erosion in two future periods. Analysis of future precipitation dataset revealed that the total number of rainstorms with intensities greater than 0.1 mm/min is likely to decrease in future while rainfall intensities are increasing and periods of heavy rainstorms will mostly shift from summer to autumn. They found significant increase of soil loss by 2050 and a partial decrease by 2100. Li and Fang (2016) reviewed and summarized the studies of the impacts of climate change (change

in rainfall, vegetation cover, and land management) on water erosion. They recommended the need of detailed study integrating climate change models with climate scenarios and land use models with hydrologic/erosion models to accurately predict climate change impacts.

Some recent studies coupled land use models or dynamic vegetation models with GCMs and hydrologic/sediment models to establish an integrated modelling system (Maeda et al., 2010; Paroissien et al., 2015). Land use land cover plays a key role in affecting hydrological and sedimentological behaviour. However, most hydrologic/sediment models consider the vegetation as a state variable, neglecting the vegetation dynamics. Quevedo and Francés (2008) developed a dynamic vegetation-soil model that can be coupled with other hydrological models to simulate the transformed hydrological cycle. It should be noted that this model is developed for arid and semiarid zones and it may not be suitable for a tropical climate area. Ruiz-Pérez et al. (2016) implemented a dynamic vegetation model using satellite products and used it to reproduce the dynamics of vegetation. Although many studies were carried out on the impact of climate change on water resources, but researches concerning the impact of climate change on sediment load of rivers were limited (IPCC, 2014, 2013, 2007). Therefore, an integrated modelling system considering climate-induced land use/cover changes is urgently required to predict climate change impacts more realistically and accurately.

2.6 Conclusions

From the above discussions on the available literatures related to different aspects of hillslope and watershed hydrology it was clear that the rainfall depth, antecedent soil moisture and vegetation have significant control on both surface runoff and sediment generation processes in hillslopes under sub-tropical conditions. For better assessment of the short- and long-term hydrological impacts it is extremely important to identify the dominating processes at the plot level to have more clarity in understanding. Considering the large spatial and temporal variability of the runoff and sediment generation features and the extent of physical complexity of the controlling processes, it is difficult to conceptualize and model these processes to full satisfaction. Most importantly, from the studies conducted in different parts of the world for the past few decades it has been quite clear that in general the dominance and extent of runoff and sediment processes are threshold driven and show wide spatial and temporal variations. Therefore, understanding runoff

and soil erosion dynamics and identification of critical controlling factors are essential at plot scale as well as watershed scale.

Over the past decades, the soil and water conservation practices on Indian highlands were not effective and as the permissible limit of soil loss are often exceeds in Indian river basins and sediment concentration has not decreased. Several studies have been carried out on plot, field and watershed scales in India in order to reduce soil erosion and control flooding. Watershed scale studies involves the use of hydrological models which are primarily developed for temperate regions and encouraged by plot scale studies such as SCS-CN method for runoff and USLE for soil loss. It was found from previous studies that SCS-CN and USLE methods could predict average annual runoff and erosion well, but failed to predict the distribution of these processes in the watershed. Moreover, both the methods are empirically developed and fails to represent the watershed scale processes in which upslope flow saturates downstream areas where erosion becomes more prominent. Numerous studies showed that seasonality affects the runoff and sediment generation process due to the variability of vegetation cover and soil saturation.

Due to climate change, variations in precipitation and temperature patterns impact plant biomass production, infiltration rate, soil moisture, land use and crop management, etc. and hence affect runoff and soil erosion. The literature survey shows that no detailed hydrological investigation has been carried out in the sub-tropical agroforestry watersheds to assess the influence of soil moisture and degree of vegetation on runoff and sediment generation processes. Therefore, the present study has been taken up in natural hillslope plots and agroforestry watersheds in Mahanadi river basin with the specific objectives mentioned in the previous chapter to experimentally establish and model the hydrologic and sediment response evident from vegetated hillslope plot and watersheds under sub-tropical climate. The assimilation of dominating controlling factors into the hydrological modelling framework has enhanced the overall understanding on runoff and sediment dynamics of agroforestry watersheds.



RAINFALL, RUNOFF AND SEDIMENT RELATIONSHIP ANALYSIS AT PLOT SCALE

3.1 Introduction

Recent developments in hydrology recognize different physical mechanisms of runoff and sediment production. For instance, Horton's overland flow occurs when rainfall intensity exceeds the infiltration capacity of the soil surface. Subsurface flow happens when infiltration capacity is high, and saturation excess overland flow takes place once soil saturation reaches the ground surface upwards (Chow et al., 1988). The challenge faced by watershed hydrology is the discontinuity between the processes observed at plot or hillslope plot scale and the integration of these processes at watershed scale. Linking observed runoff and sediment generation processes with the observed responses at the watershed outlet is of prime importance for the development of the rainfall-runoff-sediment model (Detty and McGuire, 2010b). The conventional models suggest that a combination of runoff and sediment generation processes expressed as a variable source area model are primarily responsible for watershed responses. However, different ecology and geomorphology characteristics of the watershed area respond differently to runoff and sediment yield response.

Several types of research have been done to identify the critical controlling factor and nonlinear behaviour for runoff and sediment response of a hillslope plot, and there remains a question of linkage of these factors/processes to watershed response. Recent researches (Lehmann et al., 2007; Sivapalan, 2003; Tani, 1997; Tromp-van Meerveld, 2004; Tromp-van Meerveld et al., 2008) suggest that identification of the primary nonlinear controls on runoff and sediment generation

may help to reduce the scaling issues challenged by watershed modelling. Therefore, it is prime importance to understand the physical processes occurring at hillslope plot scale before describing the overall watershed behaviour. Keeping these in view, the present investigation has been taken up to explore the hydrological behaviour of natural hillslope plots representing different land use classes by combining *in situ* natural storm event observations.

This chapter presents a description of the study hillslope plots with specific instrumentation and methodologies adopted for data collection. The typical characteristics of the hillslopes, climate, and physiographical conditions prevailing in the region have been elaborated to justify the assumptions in the analysis carried out. The observed/acquired field data and the results obtained from the investigations have been discussed in detail to draw suitable inferences about the hydrological response of the hillslope plot.

3.2 Material and Methods

3.2.1 Experimental Plot Description

The present study considers six experimental plots representing different land use / land cover classes. Out of six, four plots are located in part of Brahmaputra River Basin, Guwahati, Assam; one in Dehradun, Uttarakhand and one is located in Kandhamal, Odisha, India. Table 1 briefly enlists the experimental plot locations and data availability.

Table 3.1: Experimental Plot Locations and Data Availability

Plot Name	Location	Plot Size (m ²) / Slope (%)	Land Use / Land Cover Class	Soil Type
Plot A	Guwahati, Assam	108 / 45	Grasses and Shrub	Sandy Loam
Plot B		90 / 15	Deciduous Broadleaf Forest	Sandy Loam
Plot C		90 / 25	Bamboo	Sandy Clay
Plot D		90 / 20	Shrub	Sandy Loam
Plot E	Dehradun, Uttarakhand	150 / 60	Evergreen Forest	Loam
Plot F	Kandhamal, Odisha	50 / 2	Agriculture	Loam

The physical characteristics of the hillslopes, climate, and physiographical conditions prevailing in the region where experimental hillslope plots are situated, have been discussed location wise in the following paragraphs.

Four plots (say, plot A, B, C and D) are located in part of Brahmaputra River Basin of northeast India (Figure 3.1). The region is dominated by densely vegetated hillslopes and river floodplains. The climate of the study area falls under humid sub-tropics with average annual rainfall is 1611 mm. Majority of the annual rainfall in the region concentrated in the monsoon season (July-September) (Singh et al., 2004; Soja and Starkel, 2007). From a hydrological point of view, the basin is largely unexplored due to its challenging terrain and limited research facilities.

For continuous monitoring of the rainfall and runoff processes, an *in-situ* experimental hillslope plot (plot A) of 108 m² area was selected near Guwahati, Assam, India (Figure 3.1). The plot geographically lies at 26°12' N and 91°42' E with an elevation of 55 m above mean sea level. The experimental plot has thick layers of coarse sandy loam soil. Soil samples have been tested for texture analysis, bulk density, porosity and saturated hydraulic conductivity. The soil texture was investigated by dry and wet sieve analysis method (Kettler et al., 2001) on top soil layer (0-40 cm) samples for determination of sand, silt and clay percentages. The average sand, silt, and clay percentages were found to be 70, 18, and 12, respectively. Whereas, the average bulk density and saturated hydraulic conductivity were 1.14 gm/cc and 62.5 mm/hr, respectively. It was observed that upper soil layer with a top organic layer of approximately 10 cm depth stores the soil moisture for the growth of vegetation. The depth of impermeable layer below the ground surface was found to be about 1 m. Such type of formations are known to be highly favourable for rapid subsurface flow generation under saturated conditions (Chouksey et al., 2017).

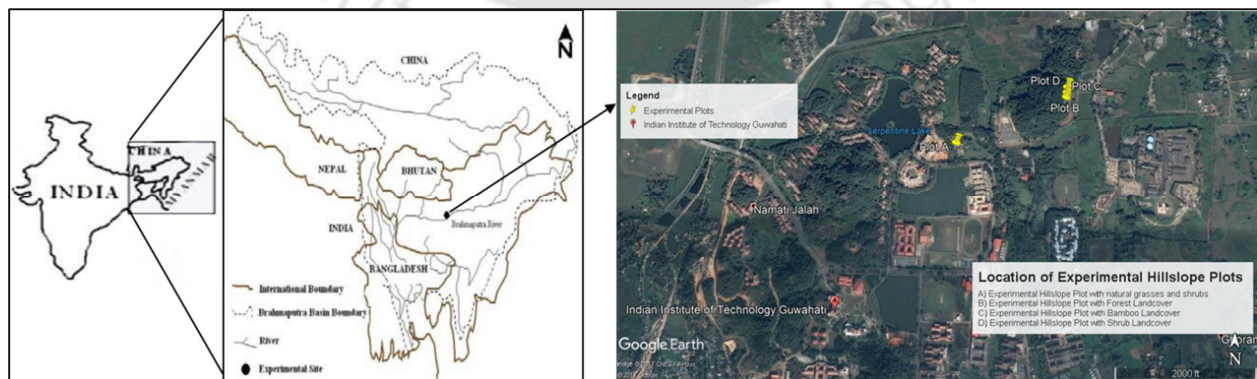


Figure 3.1: Location of the experimental hillslope plots (Plot A, B, C and D) in northeast India

Additionally, three experimental hillslope plots were prepared in the vicinity of Plot A, representing three different land use / land cover (LULC) classes (Table 3-1). The three plots, namely Plot B, Plot C and Plot D were covered with deciduous broadleaf forest, bamboo and shrub, respectively (Figure 3.2 a, b, c). The vegetation condition over the plot varies seasonally and can be classified as sparse, moderate, and dense natural vegetation including grasses and shrubs. The undisturbed vegetation condition over the experimental plots A-D typically represents the dominating land use / land cover class of the hillslopes in the northeast Indian region (Sarkar et al., 2015). To quantify topographic characteristics of the hillslope plots, a detailed topographic survey was conducted with a uniform grid of 0.25 m, using a total station (model: S5; make: Trimble; accuracy ± 2 mm + 2 ppm). The average slope of the plots in sloping direction is about 25 percent whereas the mean coefficient of variation of the slope is 11.65 % within the plots A, B, C and D. Therefore, the micro-topographic variations within the plot can be considered insignificant.

Apart from these four plots in Guwahati region, one experimental hillslope plot (Plot E) was designed in Dehradun district of Uttarakhand state, India. The setup is planned (Figure 3.2 d) keeping in view the natural hillslope conditions prevailing in the North-western Himalayas, India where high intensity rainfall events occur frequently.

The experimental hillslope site is located in Indian Institute of Remote Sensing, Dehradun, India campus at an elevation of 435 m above mean sea level. The average annual rainfall of Dehradun is about 2000 mm, and the monsoon starts during the end of June and continues until September. Around 70% of annual rainfall occurs in the period of monsoon months (Chouksey et al., 2017). To observe the runoff response to rainfall, an experimental plot of 5 m X 10 m was designed. A detailed topographic survey of the experimental plot at a uniform grid of 0.05 m has been done using the same technique as done for plots mentioned above. The soil properties such as bulk density and soil texture of two soil layers (0-10 cm and 20-30 cm) were analyzed in the laboratory. The region is found to have loamy sand texture on the top soil surface and hard rock layer at varying depths starting from a depth of 0.5–1.2 m below the ground surface. The experimental plot is mainly covered with small shrubs throughout the year. Figure 3.2 d shows the photograph of the experimental setup of hillslope plot E.

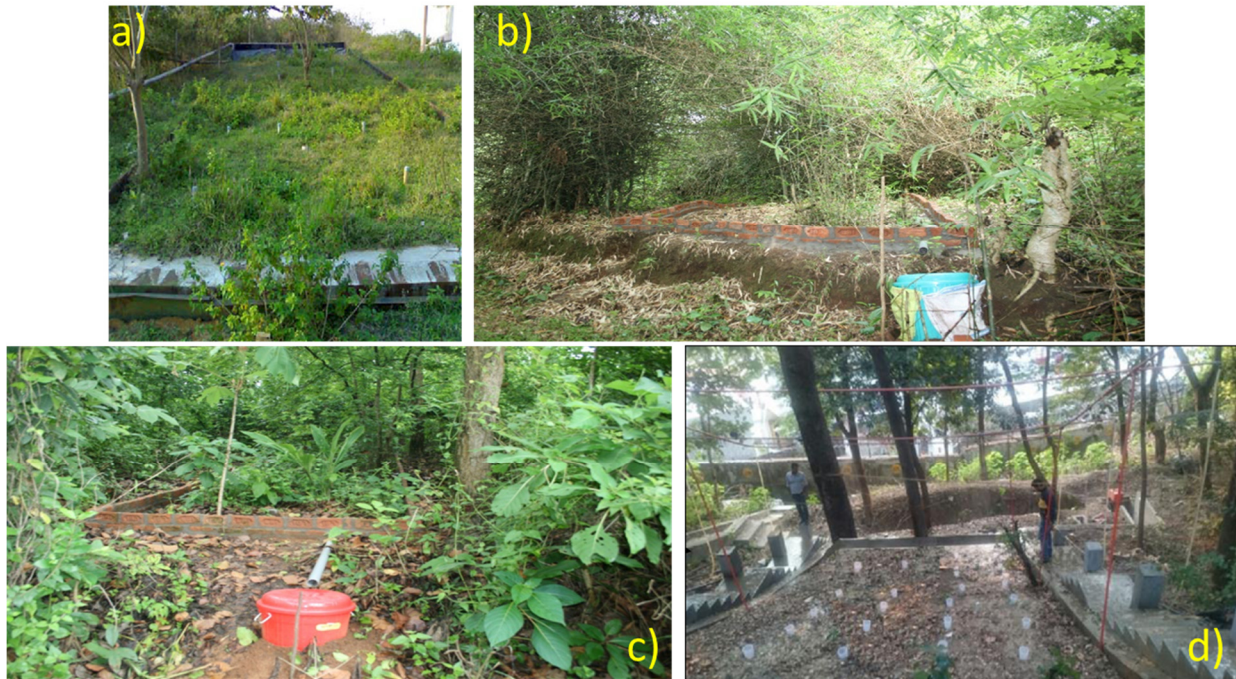


Figure 3.2: Photographs of Experimental Hillslope Plots. a) Plot A, b) Plot B, c) Plot C, and d) Plot E.

To quantify the runoff and soil loss at plot scale, an agricultural plot (Plot *F*) located at $20^{\circ} 28' 46.9596''$ N, $84^{\circ} 13' 59.3328''$ E near Phulbani, Kandhamal district, Odisha, India was considered. The experimental plot was prepared and maintained under All India Coordinated Research Project to analyse the behaviour of different cropping pattern on runoff and soil loss from an agricultural plot (Subudhi and Senapati, 2016). The dimension of plot *F* was 25 m X 2 m with two percent slope. The region lies under Agro-Climatic Zone VII with an average annual rainfall of 1100 mm and maximum rainfall intensity lies in the range of 70-100 mm/hr. The soil is mostly mixed grey soil (Inceptisols) which is porous having organic matter content. Due to the porous soil, it has reduced moisture retention capacity and is subject to heavy runoff and soil erosion. The dominated land use / land cover class of the region is kharif agriculture and mixed forest. Major crops are cereals, pulses, oilseeds, fibre crops and spices (Sarangi, 2016).

3.2.2 Rainfall-Runoff-Sediment Observational Setup and Instruments

To identify the rainfall characteristics of the region where plot *A*, *B*, *C* and *D* are located, daily rainfall time series of 50 years (1951-2000) was analyzed. The 50 years rainfall data was provided by National Climate Centre, India Meteorological Department (IMD). The daily data was supplied

in a binary gridded format having a grid size of $0.25^\circ \times 0.25^\circ$. The 50 years (1951-2000) rainfall data for Guwahati region was extracted and analysed for average monthly rainfall depth. The analysis of long-term rainfall data was carried out to identify the period in which majority of rainfall occurs.

Table 3.2: Data availability for experimental plots

Plot Name	Location	Observation Period	Parameters
Plot A	Guwahati	2008 to 2012	Rainfall, Runoff Depth, Soil Moisture
Plot B, C, D		2012 (June – August)	Rainfall, Runoff Depth
Plot E	Dehradun	2016 (September-November)	Rainfall, Runoff Depth, Soil Moisture
Plot F	Kandhamal	2007 to 2009	Rainfall, Runoff, and Sediment Load

The natural rainfall-runoff response from the experimental hillslope plot A was monitored over a period of five years from 2008 to 2012 (Table 3-2) (Sarkar et al., 2015). The rainfall observations were taken using an automatic rainfall recorder. The rainfall recorder has tipping bucket type rainfall sensor (make: virtual electronics company) with an accuracy of 0.025 mm (Sharma, 2016a). The tipping bucket sensor includes a rain collecting funnel and two carefully calibrated “buckets” mounted on a fulcrum, and an electronic switch for counting of the tips as shown in Figure 3.3 a. Each tip volumes equal to 0.2 mm. The recorder assembly includes inbuilt data logger, solar panel, and power supply unit. The rainfall data can be downloaded from the recorder by data shuttle provided along with the data logger. The data shuttle transfers the data to a computer by data cable. The rainfall was recorded at 5 min log interval.

The overland runoff from the hillslope plot A was collected into a collection pit by diverting the flow to the downstream channel of the plot. The dimension of collection pit is 0.62 m width and 0.72 m length. The schematic diagram of the experimental hillslope plot and data collection system is shown in Figure 3.4. The collected water level from plot A was monitored using a digital water level recorder based on the float counterweight type sensor. The float type digital water level recorder (DWLR) has an enclosed box which contains a data logger, pulley mechanism, and power supply (Figure 3.3 b). The DWLR also equipped with a solar panel to keep the battery charged throughout the year and facilitated unattended continuous logging. The float was installed inside the pit which is attached to the data logger by aluminium string through pulley mechanism.

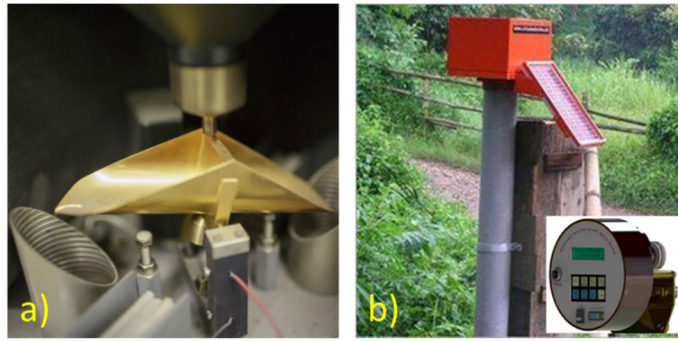


Figure 3.3: (a) Tipping bucket type rain gauge and (b) Digital water level recorder assembly (source: (Sharma, 2017, 2016b))

The data logger measures the variations in water level in the pit by float level rise/fall. The log interval and time for DWLR was kept synchronized with rainfall recorder. The recorded rainfall and runoff data were downloaded and analyzed every month to identify the runoff generation patterns of the hillslope plot A under natural storm events. The 16-day composite Normalized difference vegetation index (NDVI) at 250 m spatial resolution and top 10 cm soil moisture at a spatial resolution of 0.25° was obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) (Didan, 2015) and NASA Global Land Data Assimilation System (GLDAS), respectively for plot locations at Guwahati region.

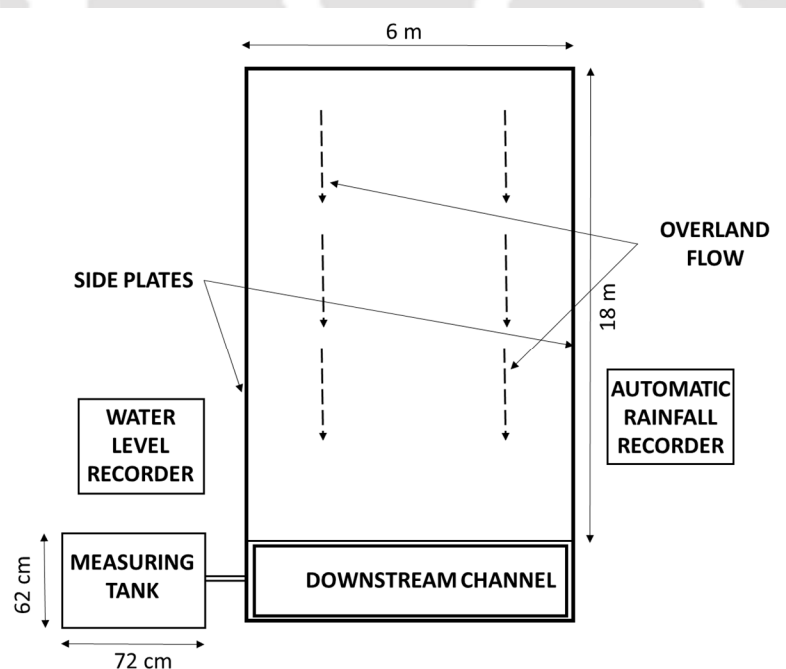


Figure 3.4: Schematic diagram of experimental hillslope plot A

Further, overland flow from plot *B*, *C* and *D* was collected manually over a period of three months from June to October 2012 (Table 3-2). To prevent the lateral flow infiltration/exfiltration from the experimental plots, the plots were enclosed by brickwork upto a depth of 30 cm. The surface runoff generated from the plot area was carefully diverted to a common outlet and collected in a container of diameter 0.7 m as shown in Figure 3.2 b, c. The collected runoff volume was then measured by measuring cylinder and then converted to runoff depth by dividing runoff volume from the plot area.

The rainfall and runoff measurement at plot *E* was carried out by using an artificial rainfall simulator and digital water level recorder, respectively (Chouksey et al., 2017). The intensity of rainfall was controlled with the help of pressure gauges installed at rainfall simulator. Soil moisture sensors were also installed at different depths and locations to monitor the soil moisture variability before, during and after the rainfall simulation experiments. A schematic diagram of the experimental plot and digital elevation model of the experimental plot is shown in Figure 3.5 a, b. The digital elevation map was prepared by using the total station topographic survey to identify the micro-topographical variations of the hillslope. A portable rain gauge was also installed at the experimental plot to monitor the rainfall intensity from simulator continuously. The observations were taken from 15 rainfall simulation experiments carried out during September to November 2016.

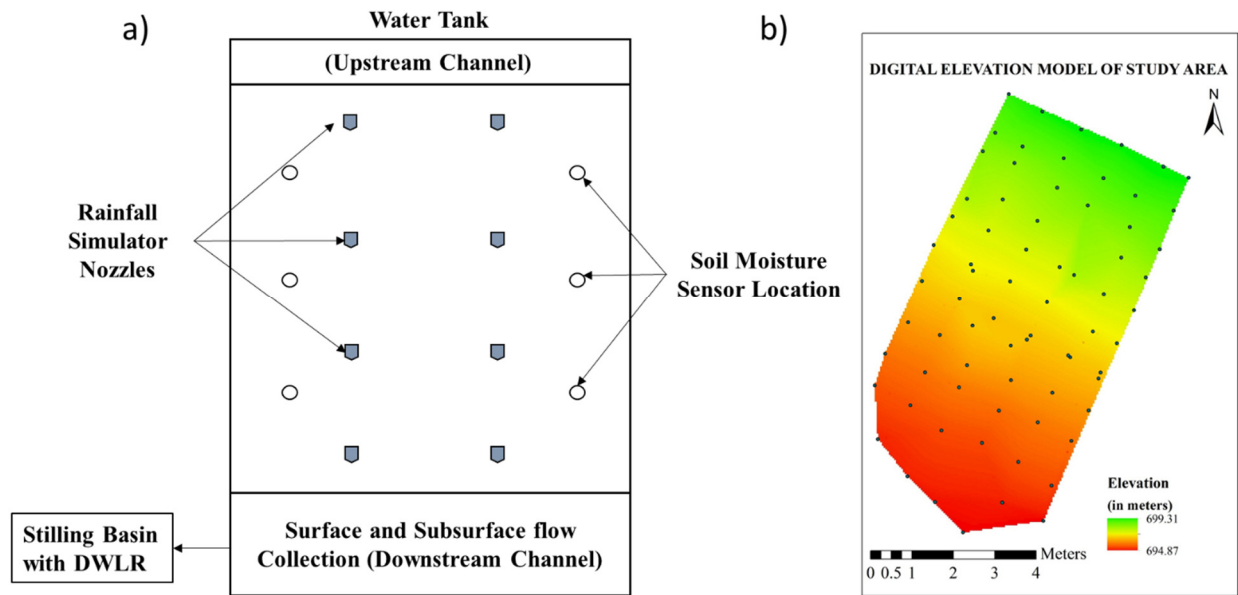


Figure 3.5: (a) Schematic diagram of the experimental setup; (b) Digital elevation model (DEM) of the E. Digital water level recorder (DWLR).

Rainfall, runoff and sediment loss data for plot *F* was acquired by Subudhi and Senapati (2016) for the period from 2007 to 2009. The runoff volume was collected manually, and suspended sediments were measured by oven dry method.

3.2.3 Runoff and Sediment Response from the Experimental Plots

In northeast India, the climate is considered as humid and short duration; low-intensity frequent rainfall events are common in the region during monsoon season (Soja and Starkel, 2007). The main parameters responsible for runoff generation over hillslopes are storm event rainfall depth (P), storm duration (t), rainfall intensity (i), five days antecedent precipitation index (API) (Marchi et al., 2010; Wang and Gupta, 1981). Rainfall data collected over five years for plot *A* was used to identify the critical controlling parameter for runoff generation at plot scale. All storm events with total rainfall depth greater than 5 mm and isolated by at least one hr., were only considered for the analysis given significance in runoff generation process (Penna et al., 2015, 2011; Zehe et al., 2010). The recorded rainfall and runoff data were analyzed for all four dominating parameters. The observed storm events were then classified as runoff generating and non-runoff generating events. Scatter plot analysis was attempted to identify the critical controlling parameter for runoff generation at plot scale.

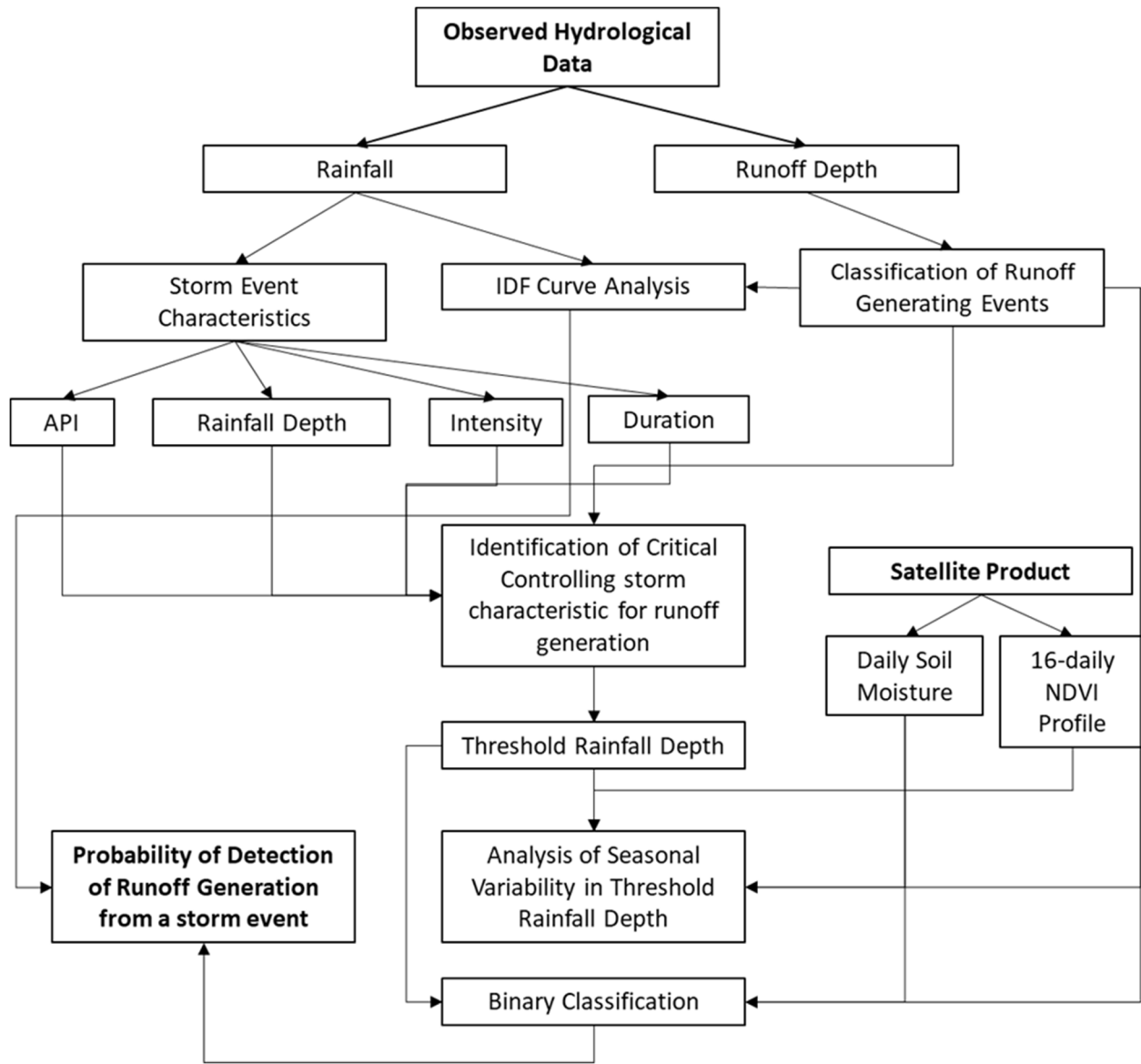


Figure 3.6: Methodology Flowchart for the runoff generation analysis for plot A

To verify the range of observed rainfall intensity and duration of the majority of storm events, intensity-duration-frequency (IDF) equation for Guwahati area (Narayana, 2002) was referred as given in Equation 3.1.

$$i = \frac{7.206 T^{0.1557}}{(t + 0.75)^{0.9401}} \quad (3.1)$$

where, i is rainfall intensity of the storm event in mm/hr., t is the duration of a storm event in minutes, and T = return period (frequency) of the storm event in years. The runoff generating events with more than 3% runoff coefficient were considered significant for the analysis of the probability of detection of storm event observations with IDF curve.

The probability of detection (POD) (Miao et al., 2016) of runoff generating storm event was calculated by Equation 3.2.

$$POD = \frac{R}{R + N} \quad (3.2)$$

where, R denotes the number of runoff generating event falls true with decision criteria, otherwise False (N). The scatter plot between runoff coefficient and storm event rainfall depth was also illustrated to explain the linear runoff response to the rainfall depth. The runoff coefficient was calculated using Equation 3.3 (Goel, 2011).

$$Runoff\ Coefficient = \frac{Runoff\ Depth\ (mm)}{Rainfall\ Depth\ (mm)} \quad (3.3)$$

To determine the variability of rainfall threshold depth and effect of land use / land cover class on runoff response, scatter plot analysis was attempted for rainfall-runoff observation of plot B, C and D. The relationship between storm rainfall depth and surface runoff depth for three land use / land cover classes were established by regression analysis. The curve number was also estimated for plot B, C, D and F by Soil Conservation Service-Curve Number (SCS-CN) method (SCS, 1972; USDA-SCS, 1985). Further, to identify the relationship between runoff depth and sediment concentration at plot scale, regression analysis was attempted for plot F.

16-day composite Normalized Difference Vegetation Index (NDVI) data and top 10 cm soil moisture data were obtained for five years (2008-2012). Temporal variation of NDVI along with the scatter plot of storm event rainfall depth was analyzed to detect the effect of vegetation on runoff generation mechanism over hillslope plot A. The soil moisture data was used to determine the threshold rainfall and soil moisture for the classification of runoff generating events for plot A and E. The storm event observations were categorized into two groups' viz. runoff generating events and non-runoff generating events. Soil moisture depth (θ) was converted to the degree of saturation (S) by dividing the soil moisture to saturated soil moisture (θ_s) (Equation 3.4).

$$S = \frac{\theta}{\theta_s} \quad (3.4)$$

To determine the threshold, least mean square algorithm also referred as, the Windrow-Hoff algorithm (Miao et al., 2016) was applied. The linear discriminant function $d(x)$ is defined in Equation 3.5.

$$d(x) = w_1p + w_2s + w_3 = wx \begin{cases} \leq 0, & \text{runoff generating events,} \\ > 0, & \text{non-runoff generating events} \end{cases} \quad (3.5)$$

where, $x=(p, s, 1)$ represents a value pair of rainfall depth and degree of soil saturation and $w = (w_1, w_2, w_3)$ is the pending coefficient. Then, $d(x) < 0$ indicates runoff generation. The technique is also referred as binary classification technique. The probability of detection for runoff generating and non-runoff generating events was then calculated by dividing the number of detected events by the total number of storm events as given in Equation 3.2.

3.3 Results and Discussions

3.3.1 Rainfall characteristics and Runoff Generation

Northeast India has been considered as a sub-tropical humid climatic region where summers are very hot with fewer rainfall events, and most of the rainfall occurs between July and September (Climate of India, 2016). Long-term (50 years) rainfall data were analyzed to identify the rainfall characteristics of the region. Figure 3.7 shows the average monthly distribution of rainfall obtained from 50 years (1951-2000) rainfall record analysis. It was observed that the average maximum monthly rainfall for July is 586 mm with a mean rainfall of 345 mm. It was also noted that during 1951 to 2000, daily maximum storm rainfall depth was 94 mm. In view of a typical pattern of monsoonal rainfall in northeast India, the rainfall and runoff observations from plot A was analysed for April to October months for all five years from 2008 to 2012.

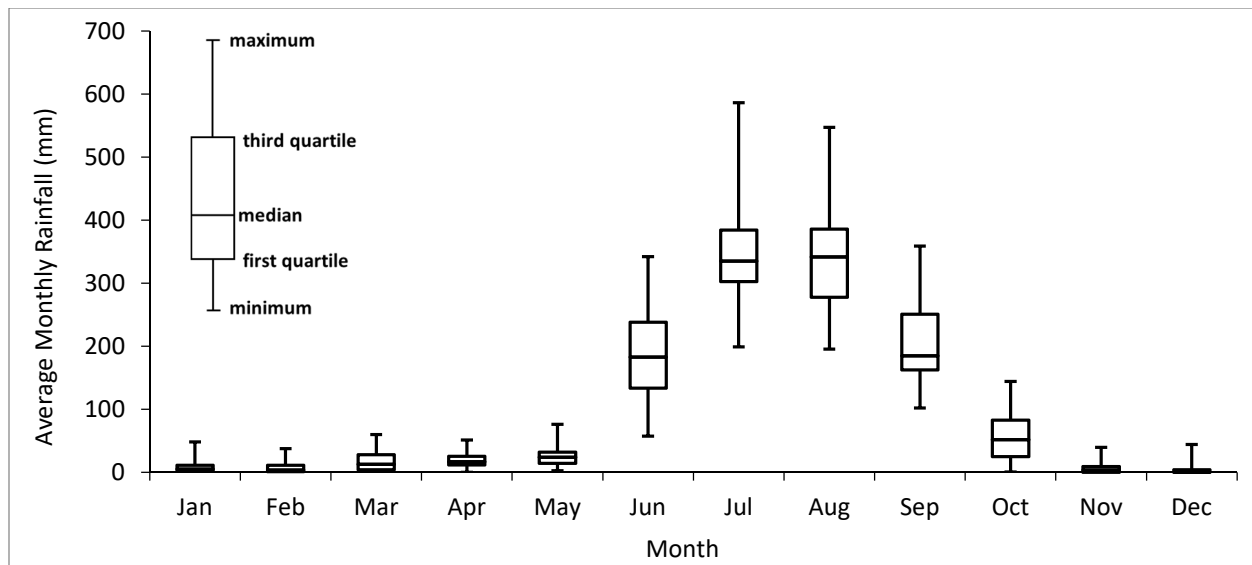


Figure 3.7: Average monthly rainfall distribution at Guwahati

The observed rainfall and runoff response from experimental hillslope plot for five years from 2008 to 2012 are shown in Table 3.3-3.7. Compared to the typical monsoon rainfall pattern of Northeast India, the year 2008 and 2009 observed relatively dry monsoons. In the year 2008, there were total 16 significant storm events occurred. Out of these only six storm events generated overland flow runoff from hillslope plot (Table 3.3). It may be noted that the maximum rainfall intensity of these runoff generating events was in the range of 57-250 mm/hr. Out of these six runoff generating events, two events responded high runoff coefficients with lower API compared to others. The runoff generation from these two low API rainfall events was due to their prolonged storm durations (190 and 215 minutes). In the year 2009, there was seven runoff generating events occurred out of total 18 significant storm events (Table 3.4). The runoff coefficient of runoff generating events was in the range of 0.02-0.22. The total rainfall depth and maximum rainfall intensity for runoff generating events were in the range of 19.5-63.7 mm and 27.43-189 mm/hr., respectively. It can also be observed that an intense rainfall event (maximum intensity 189 mm/hr) on 20-04-2009 of small duration (10 minutes) generated significant surface runoff from the plot even under the dry antecedent condition and lower depth of storm event rainfall. The year 2010 is comparatively wet than the previous two years. During April to October 2010, seven storm events generated surface runoff out of total 24 storm events (Table 3.5). The rainfall depth for runoff generating events lies between 19.5-44.7 mm. These seven runoff generating events have antecedent precipitation index (API) in the range of 18-100 mm. It may be noted that the runoff

coefficient of an event of 04-07-2010 is 0.06 under dry antecedent condition. During the year 2011, 14 storm events generated surface runoff out of total 33 significant storm events. The rainfall depth for runoff generating events was in the range 12-92.3 mm. It can be witnessed that a lower depth of event rainfall on 08-08-2011 produced significant runoff under dry antecedent condition (Table 3.6). Total 20 storm events occurred during April to October 2012, out of which 12 storm events generated surface runoff (Table 3.7). It may be noted that event rainfall 16 mm on 15-06-2012 under dry antecedent condition produced surface runoff due to prolonged storm duration which may lead to saturation excess overland flow generation. It is very complex to understand the runoff generation mechanism from hillslope plot. From the natural rainfall runoff observations, it can be said that a favourable combination of rainfall depth, storm duration, maximum intensity, and antecedent conditions control the runoff generation process from the hillslope plot.



Table 3.3: Observed Rainfall-Runoff Response for the year 2008

Date	Event Rainfall (mm)	Duration (min)	Maximum Rainfall Intensity (mm/hr)	5 Days API	Runoff coefficient
31-May	6.6	57	30.48	0	0
2-Jun	28.19	64	101.6	8.38	0
9-Aug	32.26	85	85.34	32.26	0.02
10-Aug	2.79	65	6.1	34.29	0
11-Aug	46.99	215	60.96	37.08	0.07
15-Aug	22.86	20	188.98	105.92	0
16-Aug	91.95	55	250.52	130.3	0.14
18-Aug	12.19	20	67.06	146.56	0
18-Aug	88.9	30	387.1	161.29	0.14
19-Aug	26.42	25	152.4	249.68	0
19-Aug	14.73	45	67.06	276.1	0
22-Aug	13.72	115	21.34	286.26	0
28-Aug	21.08	170	36.58	69.09	0
31-Aug	29.21	70	63.53	46.48	0.03
5-Sep	10.16	160	6.1	54.1	0
9-Sep	50.29	190	57.91	25.91	0.11

Table 3.4: Observed Rainfall-Runoff Response for the year 2009

Date	Event Rainfall (mm)	Duration (min)	Maximum Rainfall Intensity (mm/hr)	5 Days API	Runoff coefficient
20-Apr	19.558	10	188.98	0.00	0.22
5-May	28.956	25	115.82	0.00	0
9-May	35.052	35	146.30	37.34	0.04
3-Jun	20.574	65	57.91	3.81	0
2-Jul	9.144	140	6.10	18.26	0
28-Jul	32.512	395	27.43	26.16	0.02
28-Jul	15.24	95	27.43	26.16	0
30-Jul	19.558	55	42.67	65.28	0.04
31-Jul	12.446	25	67.06	65.28	0
4-Aug	63.754	60	149.35	42.42	0.11
8-Aug	23.368	35	73.15	68.33	0.06

13-Aug	19.304	115	39.62	31.24	0.02
16-Aug	6.096	50	24.38	32.26	0
17-Aug	16.51	75	27.43	40.89	0
7-Oct	4.572	60	9.14	16.26	0
7-Oct	20.574	90	48.77	18.29	0
8-Oct	10.668	140	12.19	38.86	0
8-Oct	47.244	280	48.77	54.10	0

Table 3.5: Observed Rainfall-Runoff Response for the year 2010

Date	Event Rainfall (mm)	Duration (min)	Maximum Rainfall Intensity (mm/hr)	5 Days API	Runoff coefficient
05-Apr	3.048	20	12.19	0	0
12-Apr	9.906	15	57.91	6.86	0
17-Apr	12.7	55	42.67	36.07	0
17-Apr	25.654	255	54.86	67.56	0
17-Apr	22.098	35	91.44	101.60	0
19-Apr	13.97	30	70.10	165.10	0
16-May	21.08	65	48.77	80.77	0
01-Jun	12.95	60	36.58	30.48	0
02-Jun	19.558	25	51.82	55.37	0.04
03-Jun	26.162	100	48.77	100.58	0.02
04-Jun	18.03	55	39.62	79.50	0
07-Jun	20.32	25	76.20	158.24	0
26-Jun	10.414	75	24.38	29.97	0
28-Jun	40.386	180	51.82	54.61	0
04-Jul	40.132	160	73.152	18.542	0.06
10-Jul	30.734	270	79.248	48.768	0
11-Jul	17.526	50	27.432	37.592	0
12-Jul	30.48	60	57.912	55.118	0.20
12-Jul	28.194	90	57.912	86.106	0.10
19-Jul	44.704	80	80.772	38.608	0.04
20-Jul	36.576	120	67.056	52.832	0.07
29-Jul	6.1	80	10.67	15.49	0
13-Aug	14.73	70	25.91	2.54	0

18-Aug	28.448	220	47.244	27.686	0
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Table 3.6: Observed Rainfall-Runoff Response for the year 2011

Date	Event Rainfall (mm)	Duration (min)	Maximum Rainfall Intensity (mm/hr)	5 Days API	Runoff coefficient
7-May	9.10	45	33.21	0.20	0
14-May	14.11	55	27.13	17.90	0
16-May	6.72	30	19.05	33.17	0
20-May	13.54	50	47.52	23.21	0
22-May	11.05	65	33.44	32.90	0
28-May	24.15	90	76.30	25.85	0
10-Jun	12.60	70	58.43	6.58	0
11-Jun	20.03	85	72.60	26.38	0
12-Jun	11.20	40	45.12	51.18	0
15-Jun	16.32	90	35.06	70.79	0
24-Jun	17.80	35	120.05	1.78	0.02
27-Jun	24.32	75	43.02	22.11	0
29-Jun	25.00	40	86.78	67.45	0
1-Jul	18.40	55.00	67.05	89.40	0
6-Jul	16.40	30.00	97.10	43.55	0
9-Jul	15.10	45.00	105.20	32.51	0
15-Jul	16.60	20.00	143.75	8.30	0.03
18-Jul	9.43	120.00	12.39	17.25	0
17-Jul	42.17	65.00	52.08	33.78	0.02
19-Jul	88.04	125.00	160.58	75.95	0.03
23-Jul	73.69	95.00	172.08	36.85	0.03
27-Jul	92.30	140.00	109.41	137.68	0.05
29-Jul	53.55	105.00	97.36	115.39	0.02
3-Aug	33.02	85.00	65.07	0.76	0
31-Jul	67.60	80.00	151.25	129.63	0.02
2-Aug	23.41	65.00	51.34	142.82	0.02
4-Aug	41.55	50.00	121.05	96.23	0.02
5-Aug	29.06	90.00	106.70	79.09	0.02
8-Aug	12.00	25.00	87.56	14.15	0.05

14-Aug	32.34	45.00	135.30	12.40	0.04
18-Aug	27.32	75.00	79.05	58.20	0.02
21-Aug	22.50	60.00	64.17	33.10	0
24-Aug	18.16	95.00	57.24	33.40	0

Table 3.7: Observed Rainfall-Runoff Response for the year 2012

Date	Event Rainfall (mm)	Duration (min)	Maximum Rainfall Intensity (mm/hr)	5 Days API	Runoff coefficient
28-Apr	10.922	35	19.30	26.67	0
1-May	18.034	95	32.51	38.10	0
7-Jun	17.018	290	5.08	116.84	0.03
15-Jun	16.764	800	3.05	10.16	0.05
25-Jun	9.144	10	36.58	2.54	0
26-Jun	80.01	455	70.10	13.46	0.09
27-Jun	12.192	20	79.25	93.22	0.16
27-Jun	16.256	135	18.29	93.22	0
9-Jul	19.304	55	64.01	9.14	0.05
15-Jul	27.94	80	51.82	21.84	0.04
17-Jul	5.08	55	12.19	38.61	0
20-Jul	13.208	30	39.62	44.20	0.03
21-Jul	15.494	140	18.29	58.42	0.04
31-Jul	9.652	45	30.48	3.56	0
1-Aug	7.112	65	18.29	13.46	0
5-Aug	8.128	50	18.29	27.43	0
6-Aug	24.892	45	94.49	37.59	0.05
10-Aug	14.732	60	27.43	43.43	0.10
11-Sep	103.886	115	131.06	13.46	0.16
2-Oct	21.59	85	79.25	12.45	0.02

To identify the critical controlling parameter for runoff generation at the hillslope plot scale (*for plot A*), four variables namely, total storm event rainfall depth, average rainfall intensity, maximum rainfall intensity, and five days antecedent precipitation index (API) were considered. The observed storm events were classified as runoff generating and non-runoff generating events. Figure 3.8 shows the scatter plot of rainfall depth, API, average intensity, and maximum intensity for runoff generated and non-runoff generated storm events for the

year 2008. It was observed from the plots that there is no distinct runoff generation pattern in case of average intensity, maximum intensity and the antecedent precipitation index. In Figure 3.9 b-d, the storm event no. 5 of August 11, 2008, generated significant surface runoff with runoff coefficient 0.07 has API, average intensity, and maximum intensity as 37 mm, 13 mm/hr. & 60 mm/hr., respectively. However, the event no. 6 of August 15, 2008, did not generate any surface runoff in spite of wet antecedent condition and high maximum intensity (189 mm/hr.). But, the surface runoff generating events are distinctly clustered in an upper region of Figure 3.8a and shows a significant control of rainfall depth over runoff generation. The threshold rainfall depth was estimated as 29 mm for surface runoff generation from experimental hillslope plot for the year 2008.

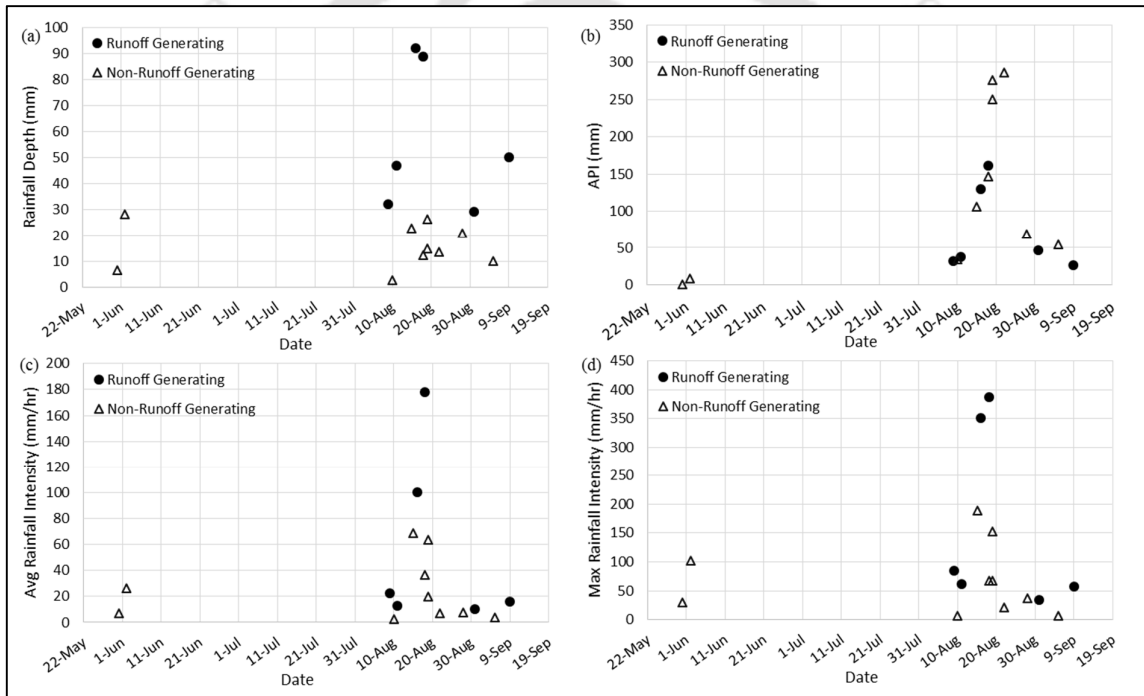


Figure 3.8: Influence of (a) Rainfall depth, (b) API, (c) average intensity and (d) maximum intensity on runoff generation from experimental hillslope plot for the year 2008

It was further observed that during the years 2008-2012 a total of 111 major storm events occurred over experimental hillslope plot. Out of these 111 rainfall events, 46 events (6 in 2008, 7 in 2009, 7 in 2010, 14 in 2011 and 12 in 2012) generated significant surface runoff volume. Runoff coefficients for these 46 events were very low in the range of 0.02-0.20. Figure 3.9-3.12 shows the scatter plot of the influence of rainfall depth, API, average intensity and

maximum intensity on runoff generation from experimental hillslope plot for the year 2009-2012.

It was noted from observed rainfall-response for all five years that the runoff generation processes largely depend on rainfall depth as well as to a lesser extent on antecedent conditions. In Figure 3.9, all runoff generated events have rainfall depth more than 19 mm. In the year 2009, for exceptional two storm events which occurred on May 5, 2009, and June 3, 2009, did not generate any surface runoff even with high total storm rainfall depth. The antecedent precipitation for these two events was very low (0 mm and 3.8 mm, respectively). While in other scatter plots in Figure 3.9, no distinct threshold of API, average rainfall intensity and maximum rainfall intensity was found. Similarly, in Figures 3.10-3.12, rainfall depth was found to be a critical factor responsible for runoff generation and threshold rainfall depth for the year 2010, 2011 and 2012 were identified as 20 mm, 20 mm and 16 mm, respectively. Few events occurred in the year 2010 with rainfall depth more than 20 mm did not generate any surface runoff. It was also observed in Figures 3.11 and 3.12 that surface runoff was not produced in few cases in the year 2011 and 2012 where storm events are having more than threshold rainfall depth, sufficient wetness condition, and moderate to high rainfall intensity. The reason for non-generation of runoff from these exceptional events could be the seasonal effect in rainfall threshold depth which is explained further in the following section.

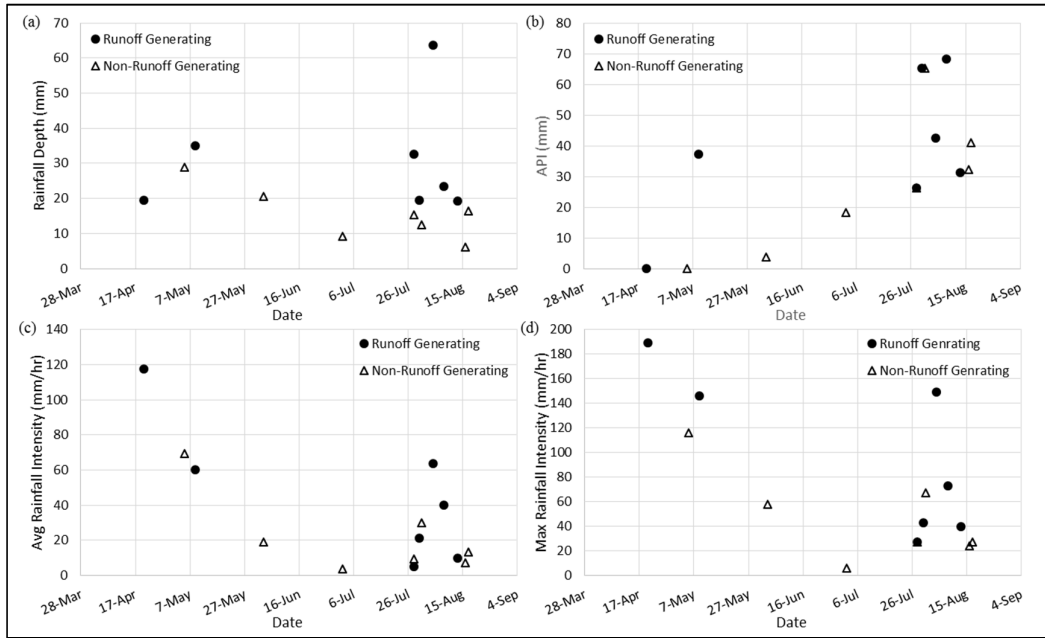


Figure 3.9: Influence of (a) Rainfall depth, (b) API, (c) average intensity and (d) maximum intensity on runoff generation from experimental hillslope plot for the year 2009

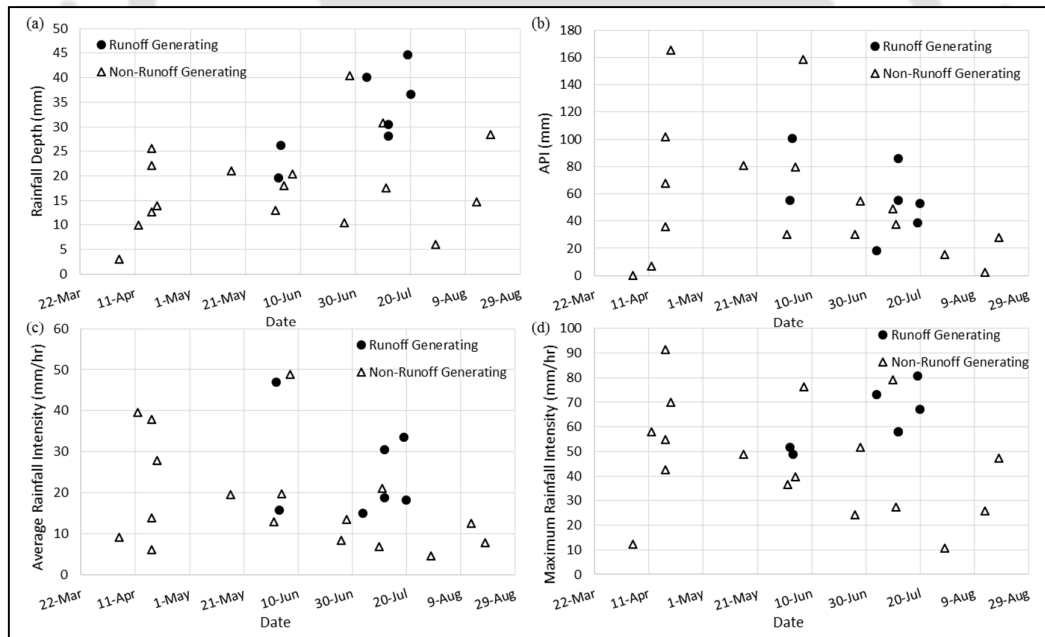


Figure 3.10: Influence of (a) Rainfall depth, (b) API, (c) average intensity and (d) maximum intensity on runoff generation from experimental hillslope plot for the year 2010

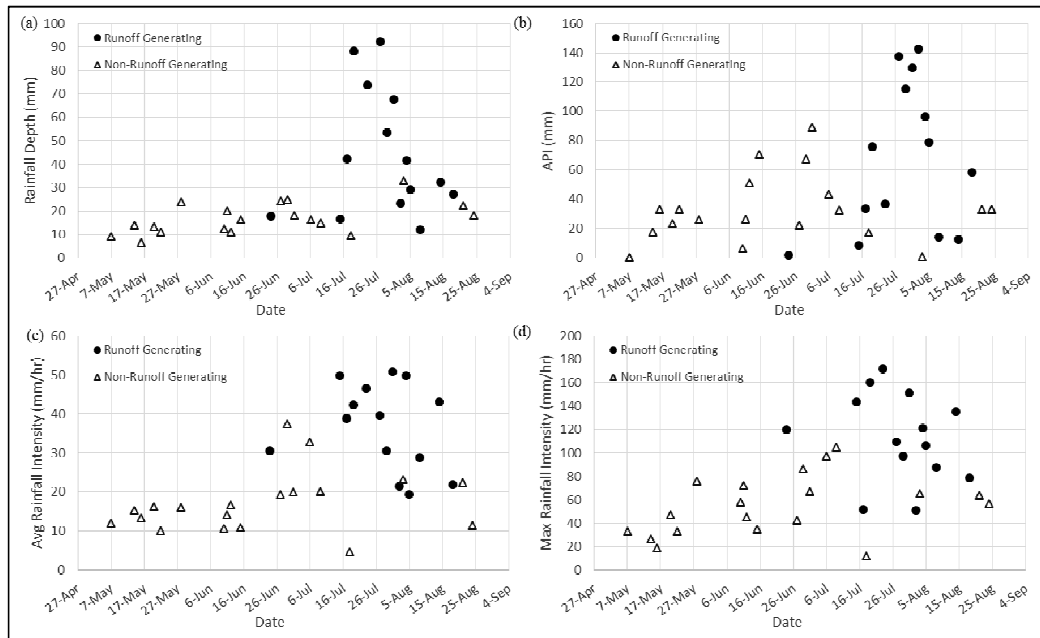


Figure 3.11: Influence of (a) Rainfall depth, (b) API, (c) average intensity and (d) maximum intensity on runoff generation from experimental hillslope plot for the year 2011

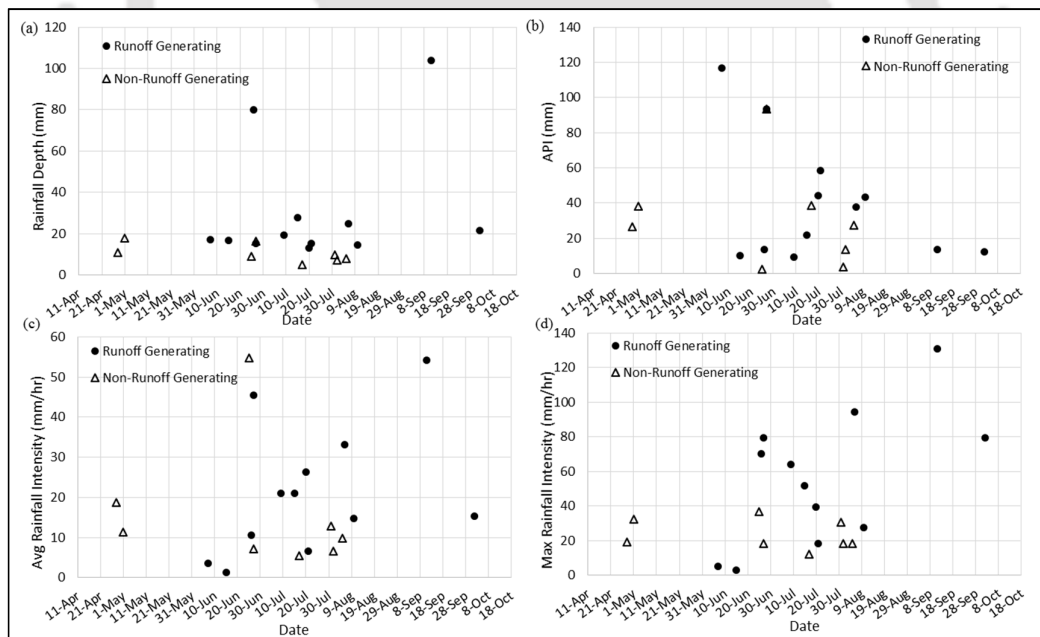


Figure 3.12: Influence of (a) Rainfall depth, (b) API, (c) average intensity and (d) maximum intensity on runoff generation from experimental hillslope plot for the year 2012

3.3.2 Threshold Rainfall Depth in Hillslope Plots with Different Land Use / Land Cover

To study the effect of land use / land cover (LULC) on runoff generation process, three hillslope plots were selected which represents three different LULC classes. Based on the rainfall and runoff observation of 3 months at plot B, C and D, scatter plot between rainfall depth and runoff coefficient was drawn (Figure 3.13). The plot shows the existence of a linear relationship between rainfall and runoff depth based on fitted regression equation. The coefficient of determination of the regression line for deciduous broadleaf forest, shrub, and bamboo was found to be 0.828, 0.633, and 0.84, respectively. The threshold depth for hillslope plots with different land use / land cover was also identified as 9 mm, 13 mm, and 16 mm for the forest, shrubs, and bamboo plots, respectively. The estimated linear relationships between rainfall depth (P) and surface runoff depth (q) are given below in Equations 3.6-3.8, where subscripts f , s , and b denotes forest, shrub, and bamboo, respectively.

$$q_f = 0.034 P_f + 0.392 \quad (3.6)$$

$$q_s = 0.0245 P_s + 0.415 \quad (3.7)$$

$$q_b = 0.0297 P_b - 0.2362 \quad (3.8)$$

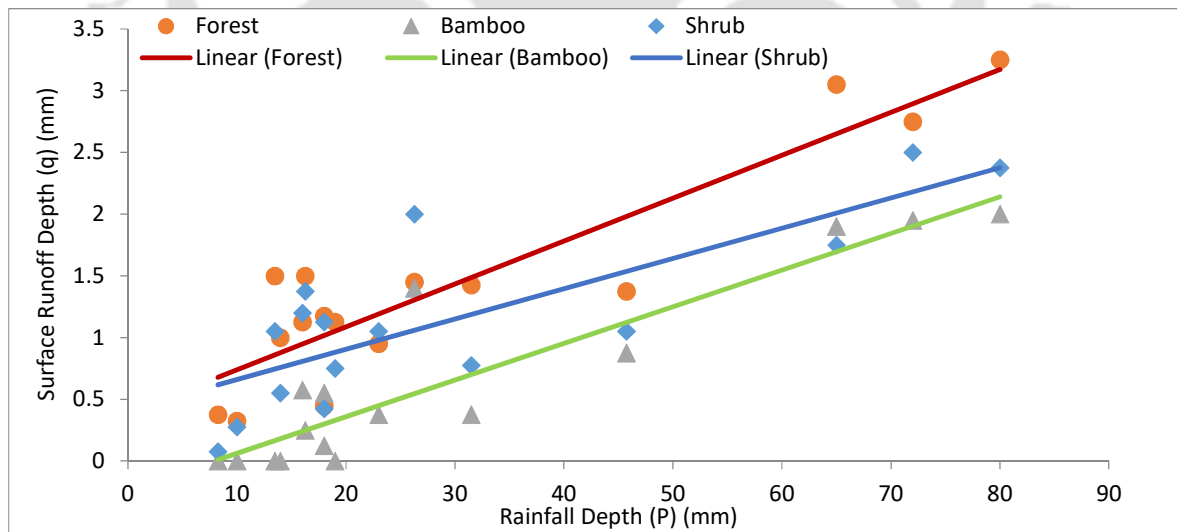


Figure 3.13: Scatter plot between rainfall depth and runoff depth of natural hillslope plots under different land use classes for 2012 monsoon season with linear regression lines

To verify the range of observed runoff coefficient and to estimate curve number of hillslope plots, Soil Conservation Service-Curve Number (SCS-CN) method (SCS, 1972, USDA-SCS,

1985) developed by United States Department of Agriculture and Soil Conservation Service (USDA-SCS) to estimate surface runoff was used. Curve number values for forest, shrub, and bamboo land cover class were determined based on the observed data as 37, 34, and 30, respectively (USDA-SCS, 1986). The runoff depth (q , in mm) can be estimated by Equation 3.9.

$$q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad (3.9)$$

where, P is rainfall depth in mm, I_a is initial abstraction in mm, and S is potential maximum retention in mm. The potential retention for different LULC class can be estimated by using curve numbers (CN) as in Equation 3.10.

$$S = \frac{25400}{CN} - 254 \quad (3.10)$$

The value of initial abstraction (I_a) was kept same as threshold rainfall depth (Figure 3.13). The observed rainfall and runoff depth were used in Equation 3.9 to calculate the potential retention (S) and subsequently average CN . The runoff depth was again estimated by the Equation 3.9 and 3.10 keeping the estimated curve number value for different land use classes. The runoff coefficient was estimated from runoff depth obtained by SCS-CN method. The estimated and observed runoff coefficient were then plotted in Figure 3.14. It was observed that the observed runoff coefficients were in the range and it was also noted that the rainfall-runoff response follows the linear relationship which can be used in runoff estimation model. Further, the linear rainfall runoff relationship was also observed between rainfall depth and runoff coefficient of runoff generated events in monsoon season from experimental hillslope plot A (Figure 3.15) and plot F (Figure 3.16). The lower curve number indicated that the tropical hillslope region has high retention capacity and subsurface storage. The threshold rainfall depth and curve number was estimated for plot F as 15 mm and 12, respectively. The lower curve number may be due to the water retention capacity is high in agriculture fields.

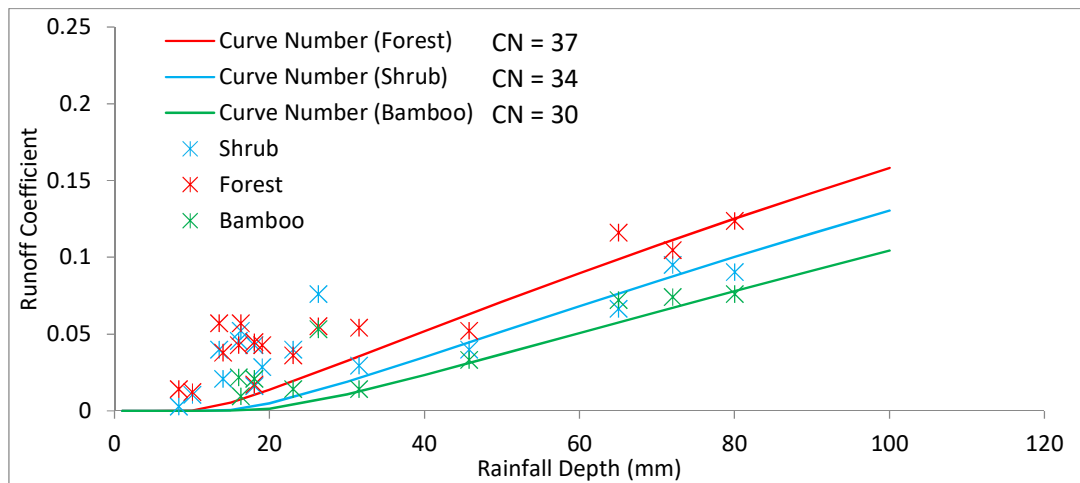


Figure 3.14: Rainfall depth and runoff coefficient regression analysis for different land use / land cover plots (B, C and D)

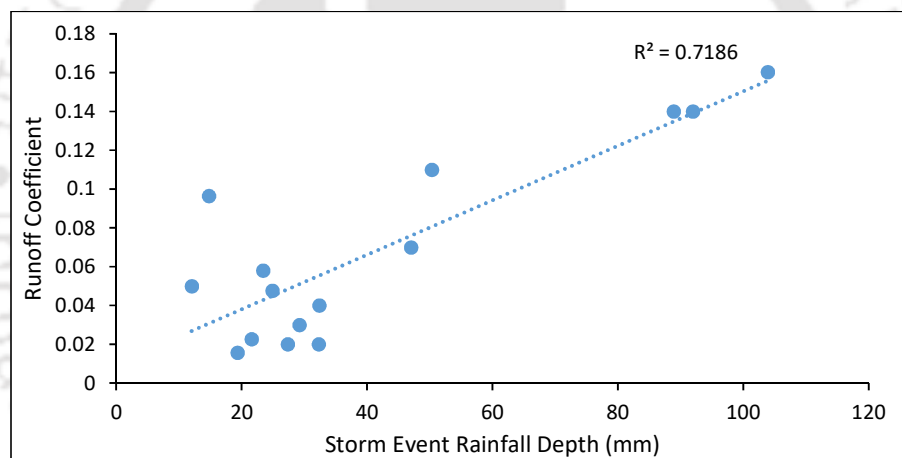


Figure 3.15: Scatter plot between rainfall depth and runoff coefficient of runoff generated events from experimental hillslope plot in monsoon season

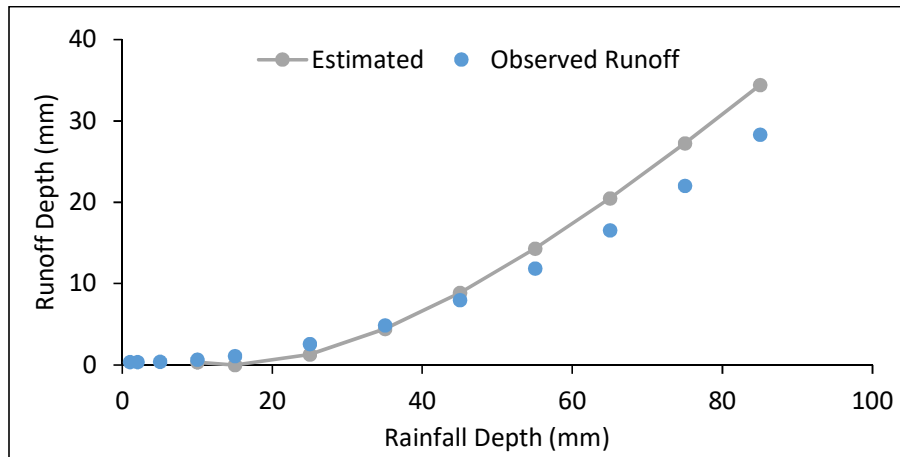


Figure 3.16: Scatter plot between rainfall depth and runoff depth from experimental hillslope plot F (Grey points shows the estimated runoff depth by CN method with the best fit)

3.3.3 Intensity Duration Frequency Curve (IDF) Analysis

An IDF curve is often used to determine the expected rainfall intensity of a given duration of the storm having a desired frequency of occurrence. The runoff generating and non-runoff generating events observed from plot A were draped over IDF curve derived by Equation 3.1. It was observed that out of 26 significant runoff generating events 18 storm events were having more than 0.25 year (3 months) return period (Figure 3.17).

The probability of detection with 0.25 year return period for generation of surface runoff from experimental hillslope plot comes as 0.69. The same was calculated for 0.5 year return period as 0.23. However, the probability for non-generation of surface runoff comes out as 0.94 for 0.25 year return period (Figure 3.18). Therefore, it can be concluded that runoff generating events probability may also be predicted based on IDF curve and rainfall characteristics in case of sparse rainfall runoff observations.

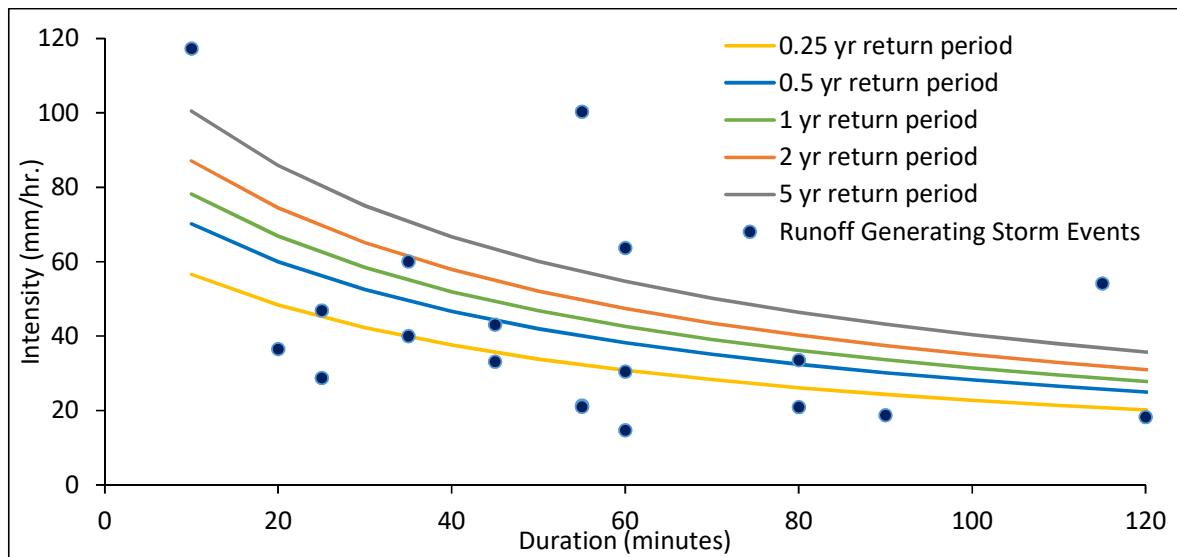


Figure 3.17: Intensity-duration-frequency curve and runoff generating storm events

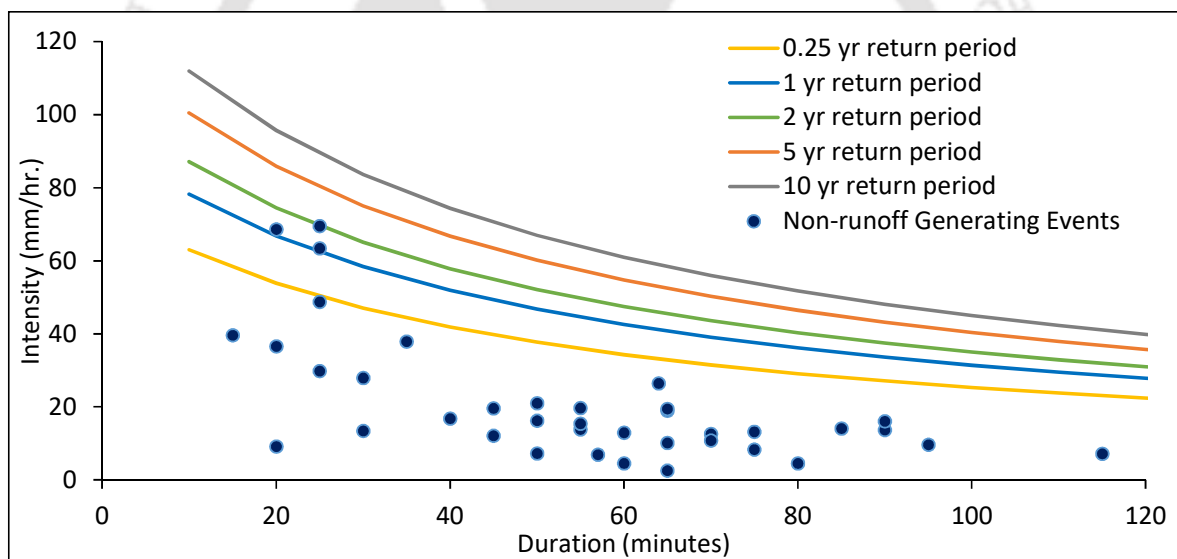


Figure 3.18: Intensity-duration-frequency curve and non-runoff generating storm events

3.3.4 Seasonality in Runoff Generation as an Effect of Vegetation and Soil Moisture

The runoff generation depends on antecedent states, the pattern of intensities, size of the area being considered and other factors (McDonnell, 2013). It is not necessary that all storm events with rainfall depth above threshold rainfall value produce runoff. Tromp-Van Meerveld and McDonnell (2006) analyzed 147 storms to derive a threshold relationship between storm total precipitation and total flow, total matrix flow, and total pipe flow and found a strong seasonality in the runoff coefficients produced by storm events. To classify the runoff generation

mechanism, a hypothesis was adopted in the present study that the runoff generation process primarily depends on the threshold rainfall depth which varies with season. To prove the hypothesis, five-year observations of rainfall and runoff from plot A were combined in a single scatter plot to identify the variation, if any in threshold rainfall depth (Figure 3.19). It was observed that small storm event rainfall depth events generated significant runoff in monsoon months while contradictorily high rainfall depth storm events did not generate surface runoff in summer months (April – June). To identify the effect of vegetation on runoff generation process, 16-day composite NDVI data was plotted with the observed rainfall-runoff response. It was well reported in recent studies (Leilei et al., 2014; Nightingale and Phinn, 2003) that hillslope vegetation depends on rainfall and soil saturation condition. The 10-daily average soil moisture depth of wet (the year 2010) and dry year (the year 2011) was plotted against five years (2008-2012) average NDVI (Figure 3.20). On the basis of variation of NDVI, soil moisture and runoff generation pattern, runoff generation mechanism can be categorized in two ways considering seasonal variability:

- (i) It was noted that NDVI increases in May in comparison to April and June months while soil moisture remains unsaturated due to dry antecedent condition (Figure 3.20: the year 2011). Due to unsaturated conditions, the infiltration rate used to be very high during the summer season. Therefore, the probability of runoff generation reduces in this condition even at the high rainfall depth storm event.
- (ii) However, in monsoon season NDVI increases due to frequent rainfall storm event in this region. Consequently, soil moisture also increases. It was observed from Figure 3.19 that the soil moisture remains near saturation level throughout the monsoon season. In this scenario, even less rainfall depth storm event generated surface runoff.

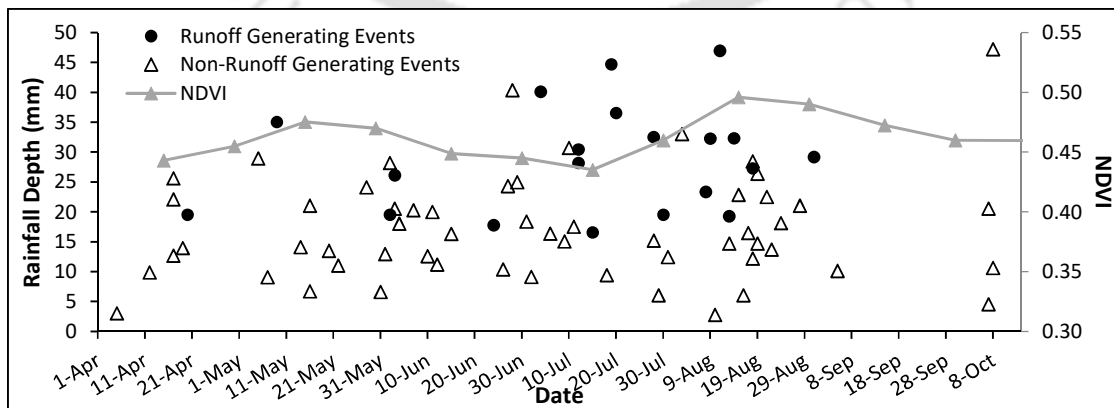


Figure 3.19: Scatter plot of storm event rainfall depth and NDVI variation

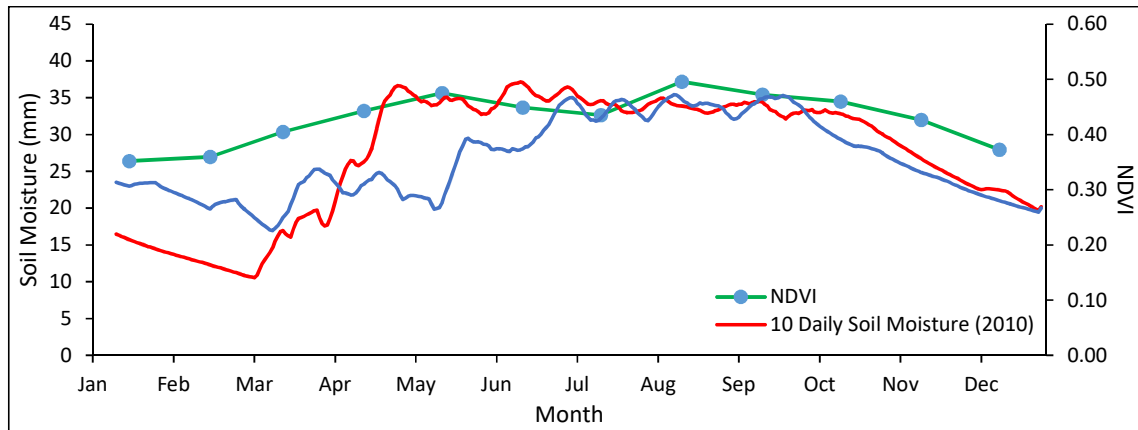


Figure 3.20: Variation of 10-daily soil moisture for dry and wet year with 5-year average NDVI

It can be concluded from the observations of rainfall depth, runoff response, NDVI and soil moisture variations that the probability of runoff generation is a function of the degree of vegetation and soil saturation conditions. To determine the rainfall threshold depth for the classification of runoff generating and non-runoff generating events for plot A, linear binary classification technique was applied (Miao et al., 2016). Value pairs of storm event rainfall depth and degree of soil saturation were used in the binary classification technique. The rainfall depth was plotted against the soil saturation. Then, pairs that correspond to runoff generating events were grouped into pattern-1 (marked as red dots in Figure 3.21), while the non-runoff generating pairs were grouped into pattern-2 (marked as green dots). To determine the discriminant function to minimize the classification errors, least mean square algorithm was applied. The probability of detection for runoff generating events and non-runoff generating events were found to be 0.75 and 0.8, respectively.

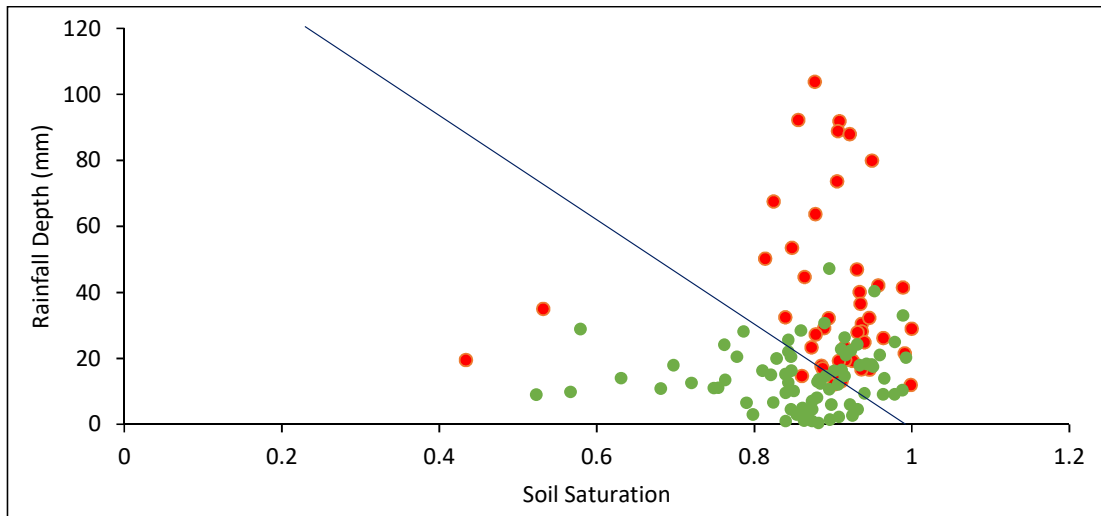


Figure 3.21: Binary classification of storm event rainfall depth and soil saturation for plot A; (red: runoff generating events, green: non-runoff generating events)

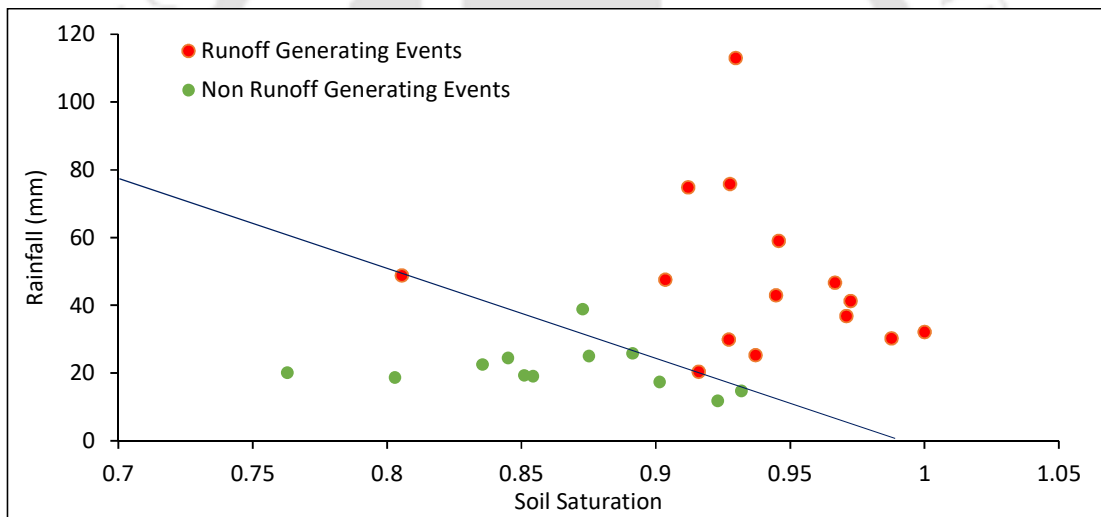


Figure 3.22: Binary classification of storm event rainfall depth and soil saturation for plot E; (red: runoff generating events, green: non-runoff generating events)

Similarly, binary classification technique was applied for observed rainfall-runoff response and soil moisture for plot E (Figure 3.22). The probability of detection for runoff generating events and non-runoff generating events was found as 0.86 and 0.9, respectively. The threshold storm event rainfall depth for runoff generation for plot A was estimated as 17 mm, whereas 20 mm for plot E.

The probability of detection of runoff generating events was further enhanced based on the seasonality in the degree of vegetation (NDVI). NDVI increased few days after the start of the monsoon season. A significant rise in soil saturation and vegetation growth were considered to start from August. Therefore, all storm events were partitioned into two groups based on the NDVI variation. Storm events occurred before 1st August were placed in the first group (Figure 3.23a), while remaining storm events were kept in the second group (Figure 3.23b).

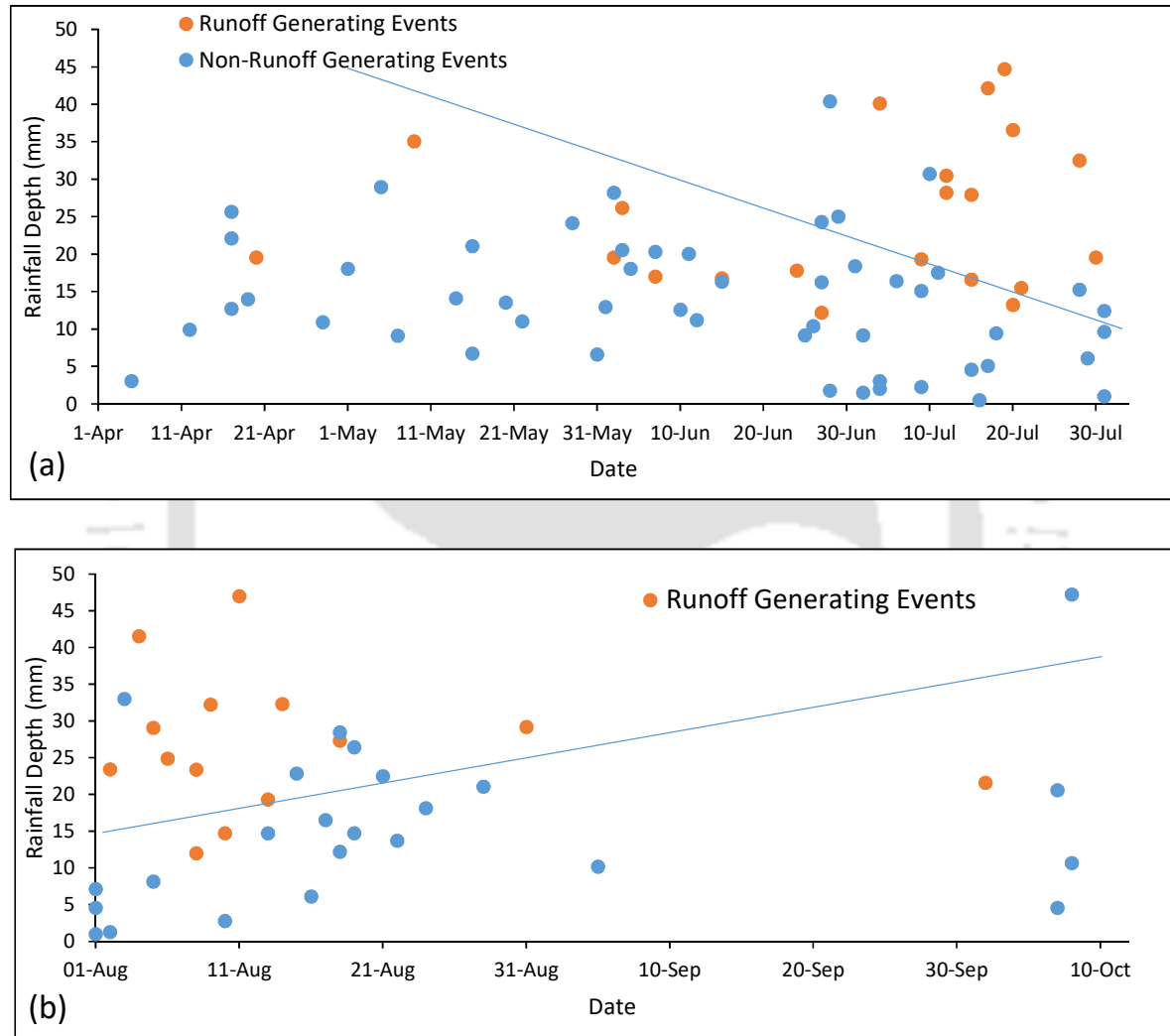


Figure 3.23: Scatter plot for the natural storm events during 2008-2011 (a) March – July; (b) August- October

Table 3.8: Probability of detection of runoff events for plot A

	Number of Runoff Generating Events	Number of Events Detected	POD
Group 1	24	16	0.70
Group 2	22	19	0.86
	Number of Non-Runoff Generating Events	Number of Events Detected	POD
Group 1	47	41	0.87
Group 2	29	23	0.80

The revised probabilities of detection for runoff generating and non-runoff generating events at plot A is given are given in Table 3.8.

3.3.5 Sediment response to Runoff

To identify the relationship between runoff and sediment loss at plot scale, the regression analysis was attempted. The sediment data was available only for plot F. A power relationship was observed between runoff depth and sediment concentration similar as observed by Guzman et al. (2013) with a coefficient of determination 0.87.

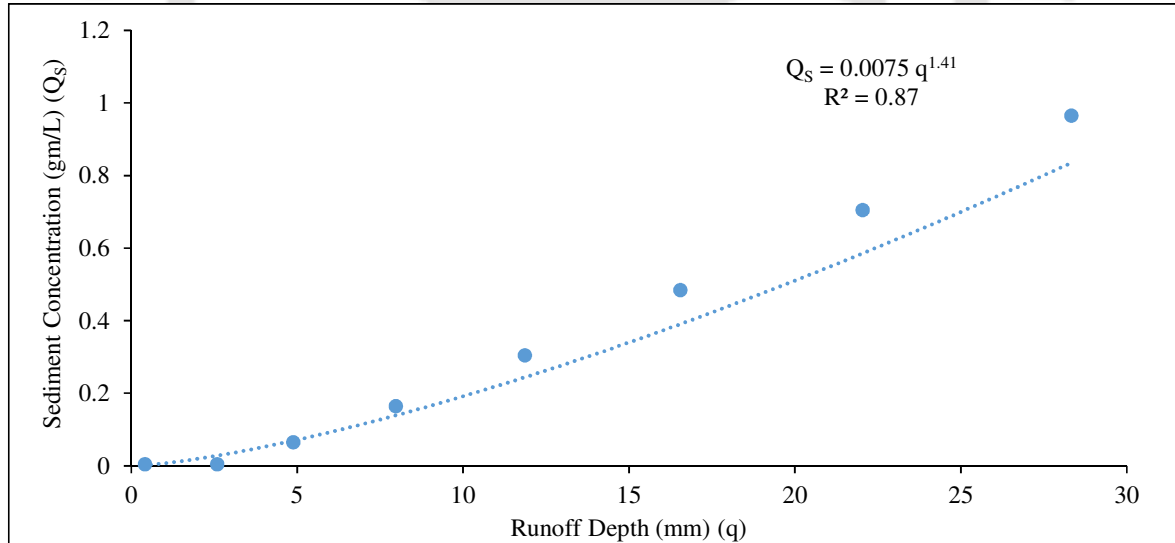


Figure 3.24: Relationship between runoff and sediment concentration at plot scale

3.4 Conclusions

The study described in this chapter suggests that the runoff generation is a threshold driven phenomenon and is not limited to a particular region and may be widespread phenomena. A

linear relationship, especially during monsoon season was identified between rainfall and runoff response of the hillslope plots. Four rainfall characteristics were considered to identify the critical controlling parameter for runoff generation. The storm event rainfall depth was found to be the primary controlling parameter for runoff generation. Threshold rainfall depths were identified for all hillslope plots representing different land use / land cover class. It suggests that there are site-specific differences in the threshold amount and the runoff coefficient after the precipitation threshold. It was also observed that the threshold rainfall depth for runoff generation depends on the land use / land cover/NDVI and the season of analysis which can be represented by antecedent soil saturation. In regions with limited observed data, the probability of runoff generation may be estimated by IDF curve analysis of the region. A power relationship between runoff and sediment was also established from the observed runoff and sediment loss data for plot *F*. This study shows that runoff and sediment responses are not proportional to the given rainfall input across the year. It is now argued that the identification of an apparent threshold, linear response and vegetation dependent behaviour of runoff generation process may be a way forward for the integration of the plot processes to watershed scale.



RAINFALL, RUNOFF, AND SEDIMENT RESPONSE AT WATERSHED SCALE FROM HYDRO-METEOROLOGICAL DATA

4.1 Introduction

The understanding of runoff generation mechanisms is essential as they act as a fundamental driving force in sediment, nutrient and pollutant transport from a catchment/watershed. Several field scale efforts to predict runoff and erosion processes have enhanced our understanding of the physical processes underlying on a field scale. Scaling up plot-level estimates to larger scale invariably leads to overestimation or underestimation at the outlet. Savenije (2010) writes on discharge predictions “physically based small scale basic principles (such as the Darcy, Richards, and Navier-Stokes equations) with detailed distributed modelling, leads to equifinality and high predictive uncertainty, mostly because these methods ill account for heterogeneity, preferential pathways and structural patterns on and under the surface”. Estimation of runoff and sediment in Indian conditions has often been hampered by application of such models that have been developed for temperate regions and do not perform well in the monsoon climate prevailing in India. Therefore, further research is desirable on a watershed scale to understand the runoff and sediment dynamics. With this objective, this chapter describes the rainfall, runoff and sediment relationships at watershed scale. A detailed description of the study watersheds with their physiographical characteristic, data availability and the outcomes obtained from the analysis have been discussed in detail. The effect of soil moisture and vegetation cover on runoff and sediment dynamics have been examined.

4.2 Material and Methods

4.2.1 Watershed Description

In this study, two watersheds were selected to identify the rainfall-runoff response characteristics at the watershed scale. The study watersheds include the Baronda watershed (with a drainage area of 3025 km² and mean annual rainfall of 1200 mm) and the Kesinga watershed (with a drainage area of 11112 km² and mean annual rainfall of 1360 mm). The detailed description about both the watersheds is given in the following sections.

4.2.1.1 Baronda Watershed

Baronda watershed, situated in the Mahanadi River Basin was selected for the analysis of rainfall-runoff response and runoff-sediment response at the watershed scale. The Baronda watershed, a part of Pairi tributary, extends over an area of 3025 km². The Pairi joins Mahanadi River near Rajim, where gauge and discharge are being measured daily by the Central Water Commission (CWC), Burla, Orissa. Figure 4.1 shows the location of Baronda watershed in the Chhattisgarh state of India.



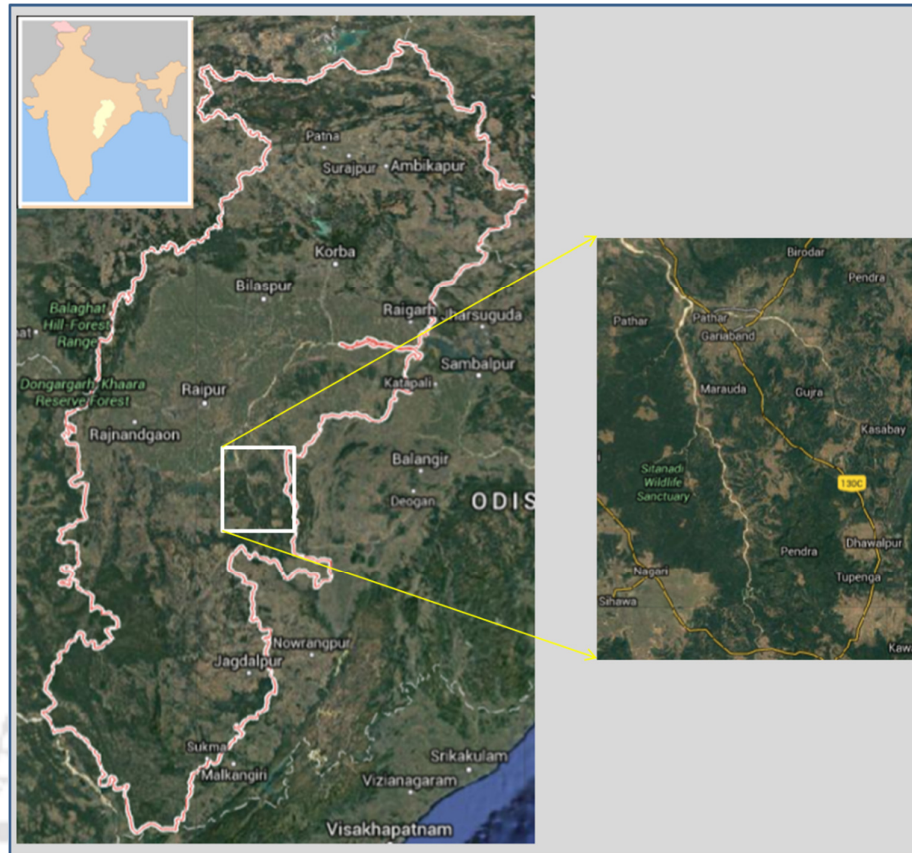


Figure 4.1: Location of the Baronda watershed in Chhattisgarh, India

The region has a tropical climate with average annual temperature is 26.8 °C, and average annual rainfall is about 1200 mm (climate-data.org, 2016). The watershed receives around 80% of annual rainfall during the monsoon season (July to September), and the maximum precipitation falls in July with an average of 414 mm. Figure 4.2 shows the digital elevation model of the watershed. A major part of the watershed lies between 270 to 500 m above mean sea level. Table 4.1 enlists the data availability and their sources which were used during the analysis.

Table 4.1: Data availability and their Sources for Baronda watershed

Data types	Data source	Period
Digital Elevation Model	Shuttle Radar Topography Mission (SRTM); resolution 30 m	—
Land Use / Land Cover Map	Derived from Landsat ETM+ satellite imagery; resolution 30 m	2005
Soil Map	NBSS&LUP; 1:250,000 scale	1985
Discharge and Sediment Data	Central Water Commission (CWC), Burla, Mahanadi Division, Orissa	1990-2000

Rainfall Time Series Data	IMD & CWC	1990-2000
Normalized Difference Vegetation Index (NDVI)	Global Inventory Modeling and Mapping Studies (GIMMS)	1990-2000

Land Use / Land Cover (LULC) Classification

The LULC classification was done by maximum likelihood supervised classification technique in ERDAS Imagine using multispectral satellite data obtained from Landsat 7 ETM+ satellite imagery for the year 2005. The satellite data was provided with training signatures of predetermined LULC classes by delimited polygons around the representative land cover site. After selection and evaluation of training samples, the maximum likelihood algorithm was then applied for supervised classification of the image (Lillesand and Kiefer, 1994). The watershed was classified into six major LULC classes viz. agriculture, forest, barren, urban settlements, waterbody and river (Figure 4.3).

The classified land use / land cover image was assessed for its accuracy by the technique mentioned by (Lillesand and Kiefer, 1994). 30 random pixels from each of the LULC classes were selected from the classified image and compared with the reference land use / land cover map. In the present study, the Google earth natural colour composite was considered as reference for accuracy assessment of prepared LULC map. The error matrix generated through the process is shown in Table 4.2. The error matrix indicates overall accuracy, user's accuracy, and producer's accuracy. The overall accuracy was computed as the ratio of correctly classified pixels and the total number of sample pixels. Producer's accuracy is the ratio of the number of correctly classified pixels in each class to the number of reference pixels. Whereas, the user's accuracy is the ratio between the number of correctly classified pixels in each class and the total number of pixels classified in that class. Kappa test statistic was then applied to assess the independence of test data and final accuracy of the classified image.

Table 4.2: Error matrix and Accuracy for land use / land cover image classification

	Reference Data								
Classified Data	Agriculture	Forest	Urban	Barren	Waterbody	River	Classified Total	User's Accuracy	Producer's Accuracy
Agriculture	27	2	2	1	1	0	33	0.82	0.90
Forest	2	26	1	2	0	0	31	0.84	0.87
Urban	0	1	24	1	1	0	27	0.89	0.80
Barren	1	0	3	25	0	1	30	0.83	0.83
Waterbody	0	0	0	1	28	2	31	0.90	0.93
River	0	1	0	0	0	27	28	0.96	0.90
Reference Total	30	30	30	30	30	30	180		
	Overall Accuracy						0.87		
	Overall Kappa Statistic						0.85		

The user's and producer's accuracy were found in the range of 0.80 to 0.96, which is quite satisfactory. The overall accuracy and kappa statistics were estimated as 0.87 and 0.85, respectively.

The 16% of the watershed area is under rainfed paddy cultivation, whereas major remaining area lies under forest land cover class as shown in Figure 4.3. The soil in the region is mainly red sandy soil and sandy loam.

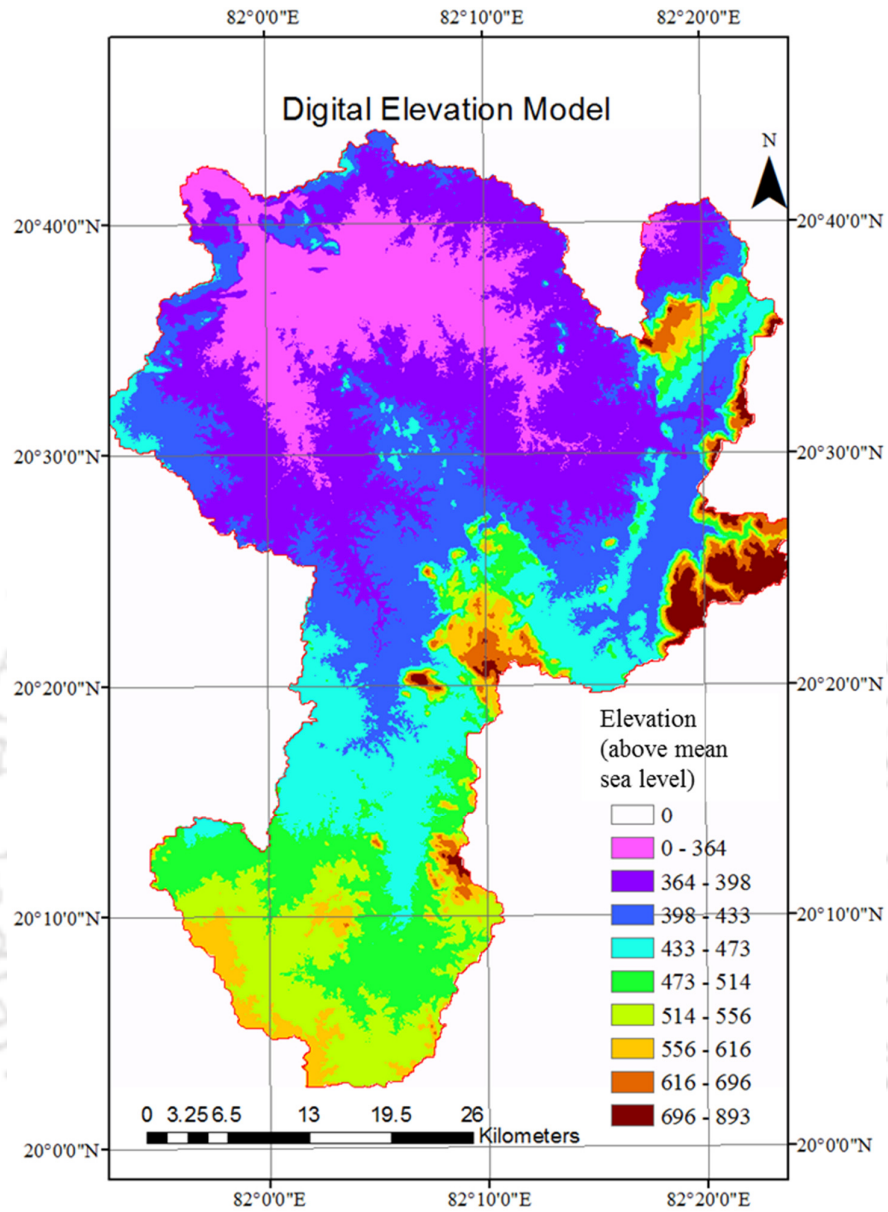


Figure 4.2: Digital Elevation Map

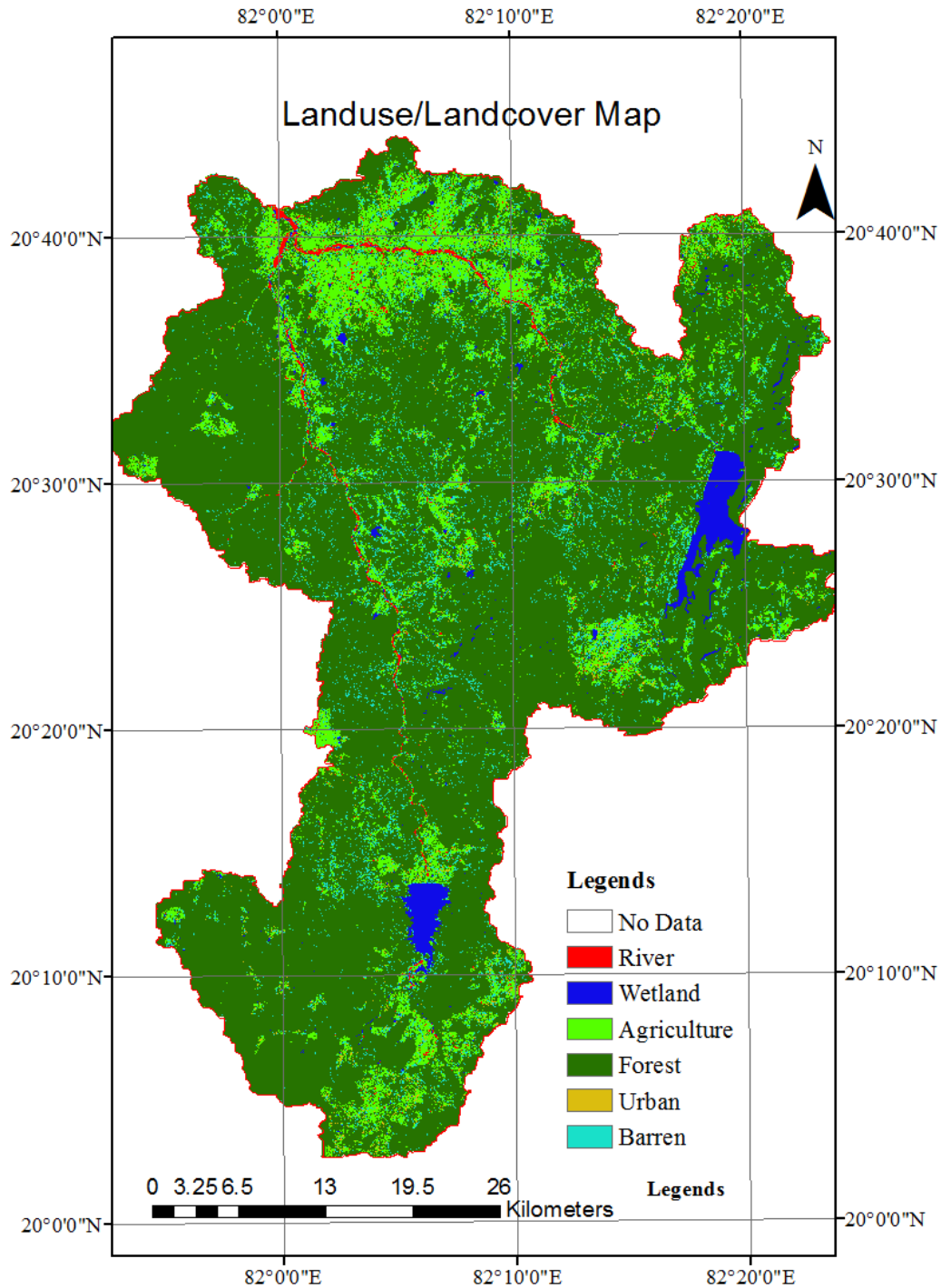


Figure 4.3: Land use / Land cover Map of Baronda

The rainfall, discharge and sediment data for 11 years (1990-2000) was collected from India Meteorological Department (IMD) and Central Water Commission (CWC), Orissa. It was

observed that monsoon period (July to September) contributes around 75% of rainfall over the total year (Table 4.3).

Table 4.3: Rainfall Characteristics of Baronda Watershed

Year	Annual rainfall (mm)	Monsoonal rainfall (mm)	Monsoonal period contribution, %	Maximum daily rainfall (mm)	No. of Rainfall days (>10mm)
1990	881	698	79.25	49	25
1991	1306	866	66.31	94	30
1992	967	837	80.68	107	21
1993	1112	880	79.15	70	27
1994	1569	1100	70.11	82	32
1995	1115	859	77.05	89	24
1996	931	755	81.09	92	26
1997	1185	886	74.77	72	25
1998	735	496	67.54	35	16
1999	777	622	80	59	19
2000	815	574	70.48	50	20

4.2.1.2 Kesinga Watershed

Mahanadi River, among the major rivers of India, travels around 851 km and drains into the Bay of Bengal. The drainage area of Mahanadi River basin is about $1.42 \times 10^5 \text{ km}^2$ which majorly covers two states of India viz. Madhya Pradesh and Orissa (Figure 4.4). The main tributaries of Mahanadi River are Jonk, Hasdeo, Mand, Ib, Ong, and Tel.

The Tel River originates from Koraput district of Orissa, India and spread across the districts of Koraput, Kalahandi, Balangir, and Phulbani join Mahanadi at Sonapur (Mishra, 2003). The basin mainly covers its path through mountains and deciduous forest. The total drainage area of the Tel River is about 22,818 km^2 , in which 11112 km^2 lies up to Kesinga, and 19600 km^2 lies up to Kantamal gauging stations shown in Figure 4.5 (CWC, 1997). The Kesinga gauging station ($20^\circ 11' 51'' \text{N}$ $83^\circ 13' 30'' \text{E}$) was selected as outlet location for delineation of Kesinga watershed in the present study. The region falls under sub-tropical climatic zone where the wet season is shorter and mostly receives rainfall during monsoon months (July-September) through southwest monsoon (Kneis et al., 2014; Mishra and Nagarajan, 2012). The mean annual rainfall is about 1360 mm.

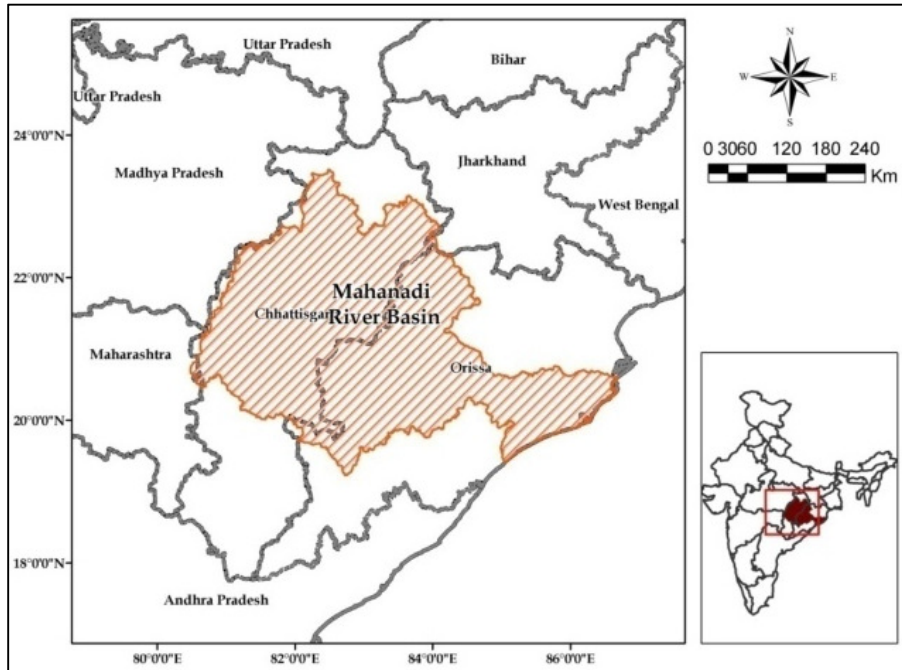


Figure 4.4: Location of Mahanadi River Basin (source: Mahanadi Basin Newsletter, 2014)

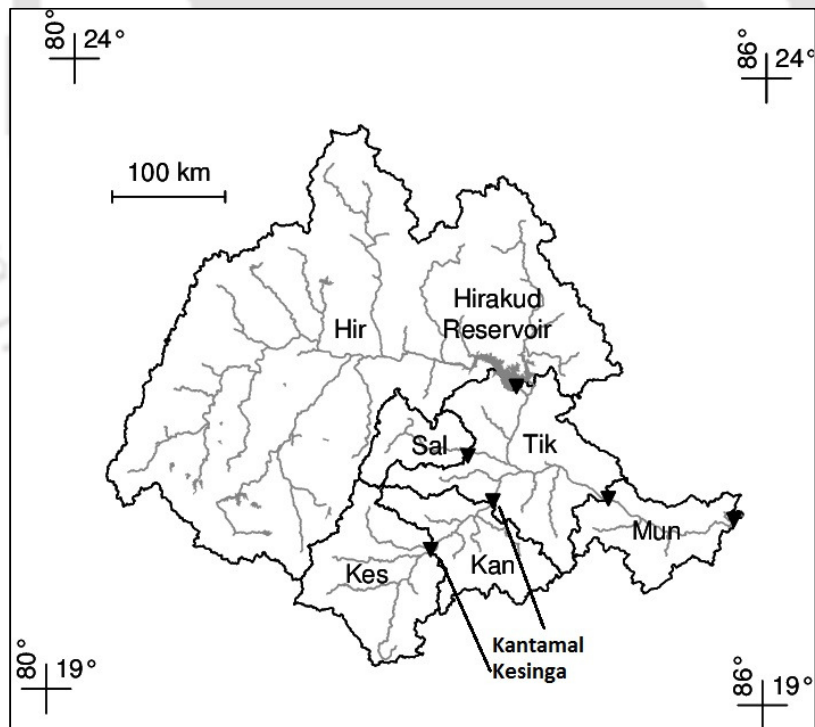


Figure 4.5: Location of Kesinga and Kantamal Gauging stations in Mahanadi River Basin

The watershed lies between 82°50'E 19°20'N and 83°20'E 20°30'N with an average elevation of about 240 meters above mean sea level (Figure 4.6). Table 4.4 briefs the data used in the present study for Kesinga watershed.

Table 4.4: Data availability period and their source for Kesinga watershed

Data types	Data source	Period
Digital Elevation Model	Shuttle Radar Topography Mission (SRTM); resolution 90 m	–
Land Use / Land Cover Map	Derived from Landsat ETM+ satellite imagery; resolution 30 m	2005
Soil Map	NBSS&LUP; 1:250,000 scale	1985
Discharge data	Central Water Commission (CWC), Burla, Mahanadi Division, Orissa	2006-2011
Rainfall Time Series Data	IMD & CWC	2006-2011
Normalized Difference Vegetation Index (NDVI)	Moderate Resolution Imaging Spectroradiometer (MODIS), USGS	2006-2011
Soil Moisture	Global Land Data Assimilation System v2.1	2006-2011

Land Use / Land Cover (LULC) Classification

The LULC map was prepared using maximum likelihood supervised classification technique on Landsat 7 ETM+ satellite imagery for the year 2005. The image was classified into 10 LULC classes: Built-up (BU), Agriculture (AG), Fallow Land (FL), Plantation (PL), Deciduous Broadleaf Forest (DBF), Mixed Forest (MF), Shrub Land (SH), Water Body (WB), Barren (BR), and Wasteland (WL) (Figure 4.7). The classification accuracy assessment was then done to generate the error matrix as shown in Table 4.5.

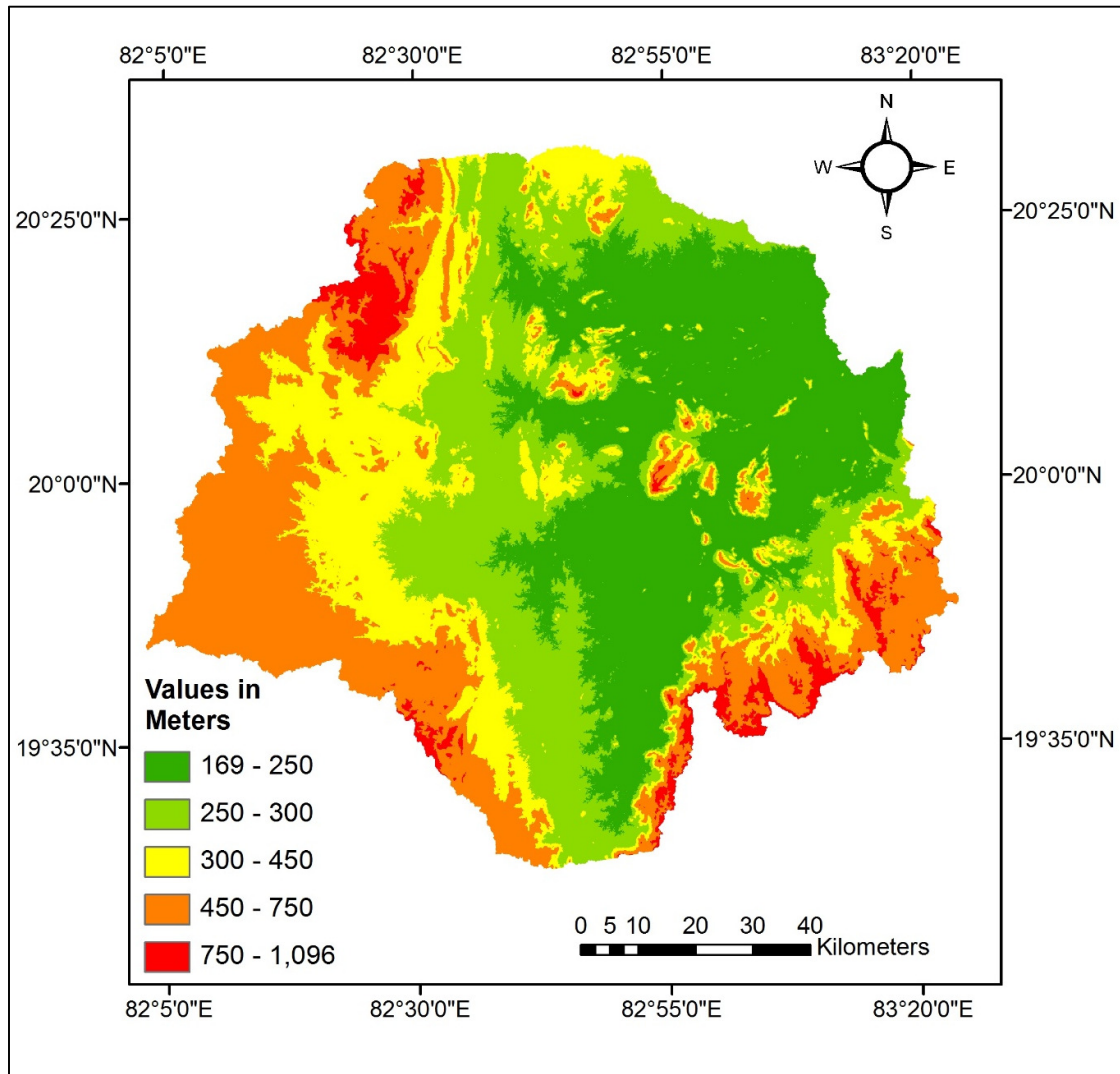


Figure 4.6: Elevation map of Kesinga watershed

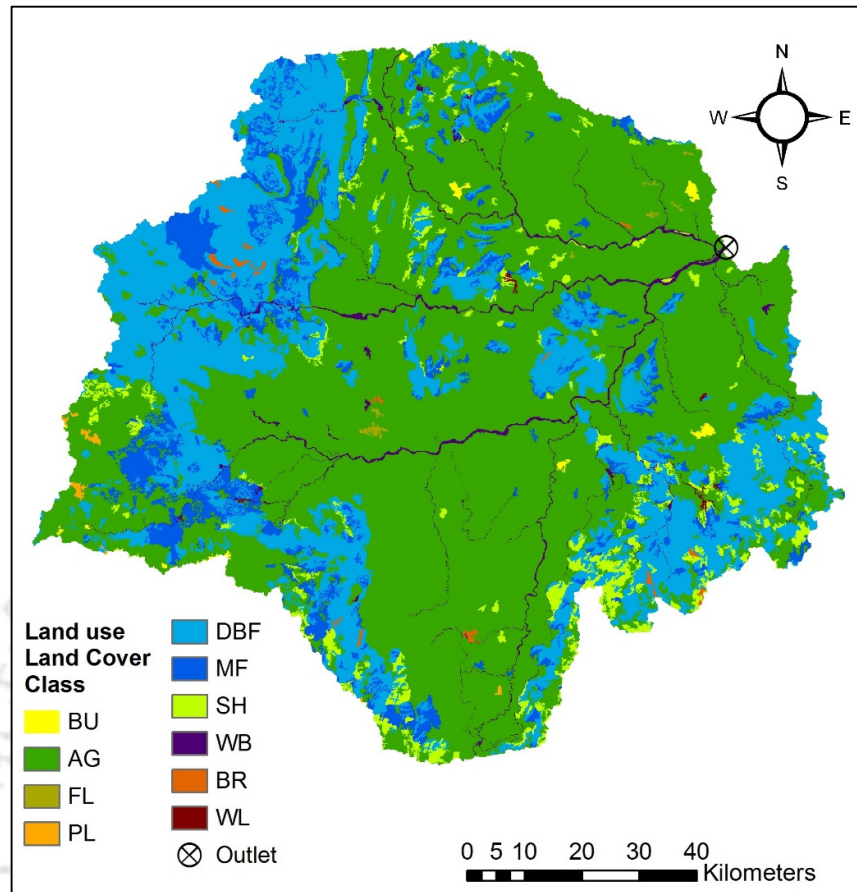


Figure 4.7: LULC map of Kesinga watershed (BU: built-up, AG: agriculture, FL: fallow, PL: plantation, DBF: deciduous broadleaf forest, MF: missed forest, SH: shrubland, WB: waterbody, BR: barren land, WL: wetlands).

Table 4.5: Error matrix and Accuracy for land use / land cover image classification

Classified Data	Reference Data										Classified Total	User's Accuracy	Producer's Accuracy
	Built-up	Agriculture	Fallow Land	Plantation	Deciduous Broadleaf Forest	Mixed Forest	Shrubland	Waterbody	Barren	Wasteland			
Built-up	22	0	0	0	0	0	0	0	0	0	22	1.00	0.73
Agriculture	1	28	1	0	1	1	1	2	0	1	36	0.78	0.93
Fallow Land	0	1	26	2	1	0	1	0	0	0	31	0.84	0.87
Plantation	1	0	0	26	0	0	0	0	0	1	28	0.93	0.87
Deciduous Broadleaf Forest	0	0	0	0	25	2	0	0	0	0	27	0.93	0.83
Mixed Forest	0	0	2	1	2	27	2	0	0	1	35	0.77	0.90
Shrubland	0	1	1	1	1	0	24	0	1	0	29	0.83	0.80
Waterbody	0	0	0	0	0	0	0	26	0	0	26	1.00	0.87
Barren	4	0	0	0	0	0	1	0	28	2	35	0.80	0.93
Wasteland	2	0	0	0	0	0	1	2	1	25	31	0.81	0.83
Reference Total	30	30	30	30	30	30	30	30	30	30	300		
Overall Accuracy											0.86		
Overall Kappa Statistic											0.84		

4.2.2 Hydro-meteorological Observations

To analyze the hydrological response to watershed scale, rainfall, runoff, and sediment concentration data were obtained from India Meteorological Department (IMD) and Central Water Commission (CWC). The hydro-meteorological data set was available for 11 years (1990-2000) for Baronda watershed and six years (2006-2011) for Kesinga watershed. Normalized difference vegetation index (NDVI) data was also downloaded for the same period for both the watershed areas. For the period from the year 1990 to 2000 the NDVI product was available at a spatial resolution of 8 km from Global Inventory Modeling and Mapping Studies (GIMMS). The NDVI product was originally derived from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR) satellite sensor series. However, for Kesinga watershed analysis, NDVI was available at a spatial resolution of 250 m from Moderate Resolution Imaging Spectroradiometer (MODIS) Terra satellite. To analyze the dependency of top soil moisture on runoff generation process, top soil moisture depth was downloaded at two locations of Kesinga watershed representing different LULC class viz. forest and agriculture. The spatial resolution of soil moisture product is $0.25^{\circ} \times 0.25^{\circ}$.

4.2.2.1 Rainfall-Runoff Response

As discussed in the previous chapter that runoff generation process varies with season, soil moisture and vegetation conditions. Therefore, the observed dataset was grouped into three categories viz. pre-monsoon, monsoon, and post-monsoon. The three months from July to September were considered in monsoon season. However, from April to June falls under pre-monsoon category and post-monsoon season means from October to December. The months from January to March were not considered in any of the analysis in the present study due to insignificant contribution to runoff in these months. The methodology flowchart of watershed scale hydrological analysis is given in Figure 4.8.

The scatter plot analysis was performed on rainfall depth and runoff depth for each observation year to identify the relationship and seasonal behaviour among them. To estimate the average curve number at the watershed scale, Soil Conservation Service-Curve Number (SCS-CN) method (USDA - SCS, 1972) developed by United States Department of Agriculture and Soil Conservation Service (USDA-SCS) was applied for both the watersheds. The upper envelope curve was estimated to capture the maximum possible runoff depth generation from rainfall storm.

As discussed in previous chapter that soil moisture conditions play a significant role in runoff generation process. Therefore, to identify the effect of soil moisture on runoff generation process, the hydrological dataset was categorized into two groups viz. runoff generating events and non-runoff generating events. Soil moisture depth (θ) was then converted to the degree of saturation (S) by dividing the soil moisture depth to saturated soil moisture (θ_s) (Equation 4.1). Value pairs of the degree of saturation and rainfall depth were then used to perform linear binary classification for the Kesinga watershed. The analysis could not be performed for Baronda watershed due to unavailability of soil moisture data.

$$S = \frac{\theta}{\theta_s} \quad (4.1)$$

Furthermore, to investigate the relationship and effect of vegetation on runoff generation and sedimentation process at watershed scale, variation of NDVI, saturation, and runoff with rainfall depth was analysed. The methodology for the analysis of response of runoff and sediment with vegetation is explained and discussed in Section 4.2.2.2, 4.3.3 and 4.3.4.

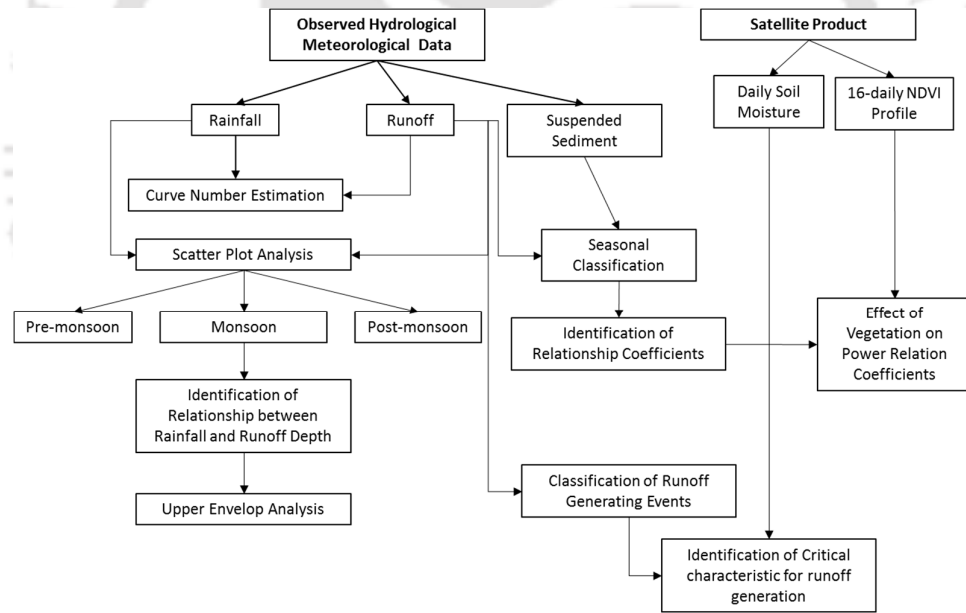


Figure 4.8: Methodology flowchart for the analysis of watershed scale hydro-meteorological data

4.2.2.2 Runoff Sediment Response with Degree of Vegetation

The sediment in rivers originates as a result of soil erosion process in the catchment area. Sediment is the output of eroded soil particles that are transported in runoff from their site of origin. Sediment production and transport processes depend on the amount of surface runoff.

It was reported that sediment concentration is a function of the amount of surface runoff (Tilahun et al., 2013). Hence, the sediment concentration (Q_s) is related to discharge (Q) by Equation 4.2.

$$Q_s = a Q^b \quad (4.2)$$

where, Q_s is sediment concentration in gm/L, Q is discharge (m^3/s), 'a' and 'b' are the variables.

The runoff discharge and sediment concentration data for the Baronda watershed were analyzed to estimate the power relationship and the values of variable 'a' and 'b'. Sediment concentration data for Kesinga watershed was available in irregular period. Therefore, the relationship between discharge and sediment concentration for Kesinga watershed could not be established. For this analysis, the discharge and sediment concentration data were categorized into three groups viz. pre-monsoon, monsoon, and post-monsoon.

Further to classify the seasonal behaviour of sediment generation process, the identified variables were plotted against the normalized difference vegetation index, and relationships among them were established (Figure 4.8).

4.3 Results and Discussion

4.3.1 Rainfall-Runoff Response

4.3.1.1 Baronda Watershed

To determine the relationship between rainfall and runoff depth at Baronda watershed, observed rainfall and discharge data were obtained from CWC for the period from 1990 to 2000. The rainfall and discharge observations were categorized into three groups depending upon the season. The observed discharge at watershed outlet includes the base flow contribution. Therefore, baseflow was separated from the observed discharge data by straight-line method (Chow et al., 1988) to obtain total surface and subsurface runoff contributed by the watershed. The direct runoff depth was calculated by dividing the runoff volume from watershed area. The rainfall depth was plotted against runoff depth for each observation year to identify the relationship and seasonal behaviour between rainfall and runoff depth. Figure 4.9 to 4.11 show the scatter plot of rainfall and runoff depth for Baronda watershed for the year 1990 pre-monsoon, monsoon, and post-monsoon, respectively. It was observed that a linear relationship between rainfall and runoff depth exists during monsoon season (Figure 4.10). However, no particular trend was identified in pre-monsoon and post-monsoon season. The

runoff depth ranges from 0 to 3 mm in pre-monsoon season, and it reaches upto 18 mm during the post-monsoon season (Figures 4.9 and 4.11).

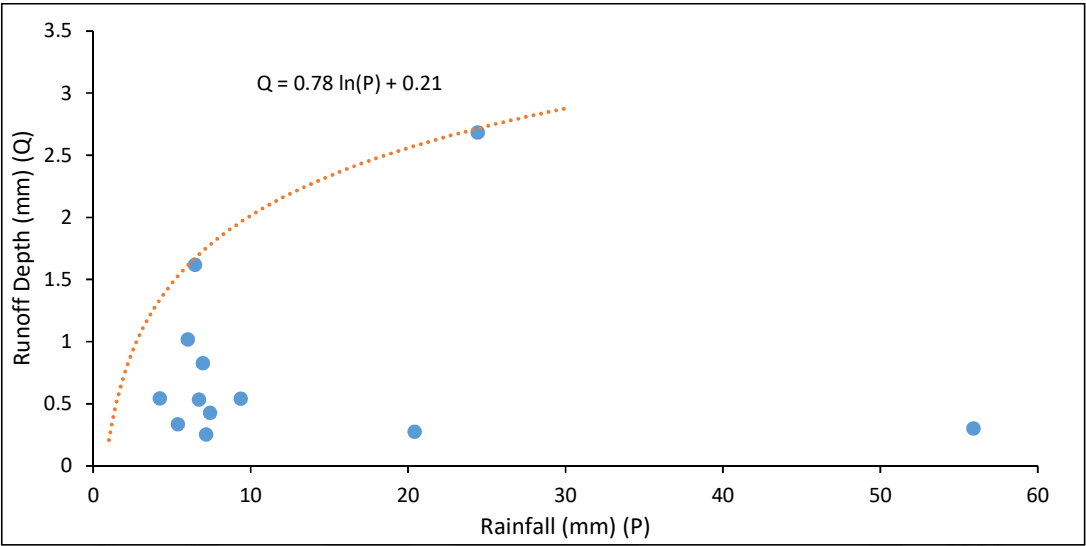


Figure 4.9: Scatter plot between rainfall and runoff depth for the year 1990 pre-monsoon season for Baronda watershed.

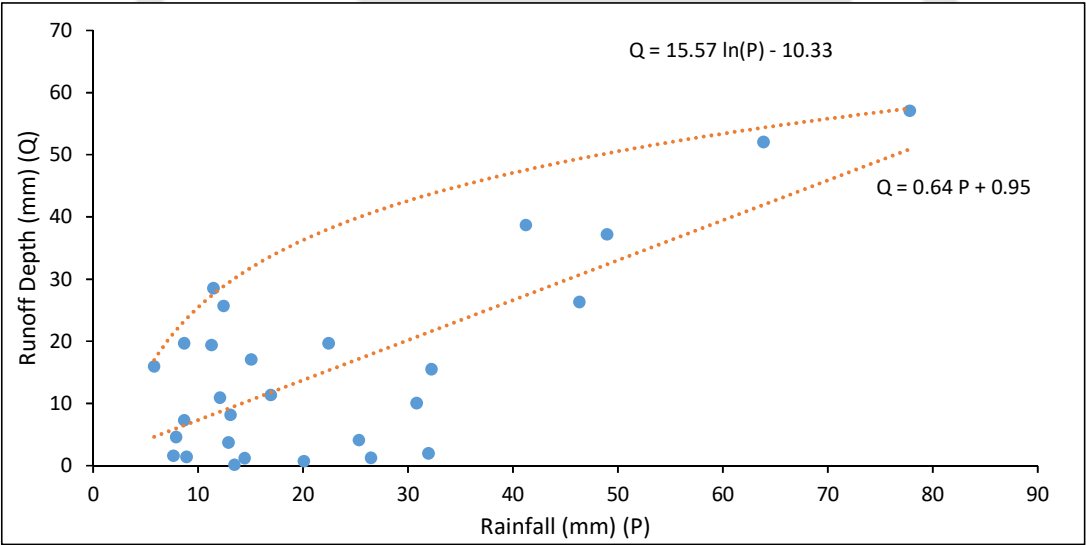


Figure 4.10: Scatter plot between rainfall and runoff depth for the year 1990 monsoon season for Baronda watershed.

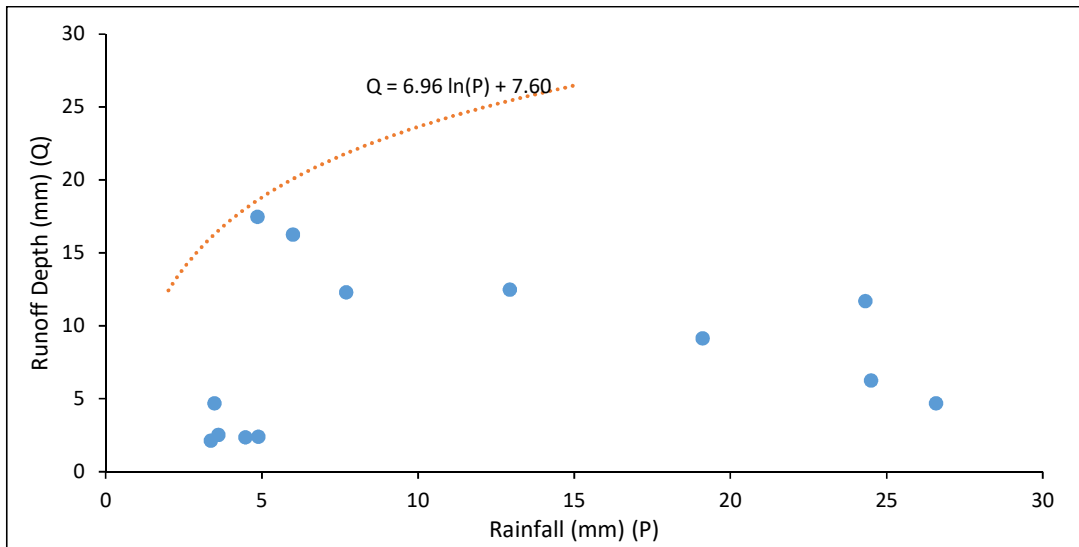


Figure 4.11: Scatter plot of rainfall and runoff depth for the year 1990 post-monsoon season for Baronda watershed.

It was also witnessed that 56 mm rainfall depth storm event on June 25, 1990, could only produce 0.3 mm runoff depth, while the same rainfall depth storm event in monsoon season produced 37 mm of runoff depth. It was noted that the seasonal threshold rainfall depth behaviour in runoff generation process exists at a watershed scale too. To capture the extreme runoff depth generation at Baronda watershed, an upper envelope curve relationship between rainfall and runoff depth was identified with 0.99 coefficient of determination.

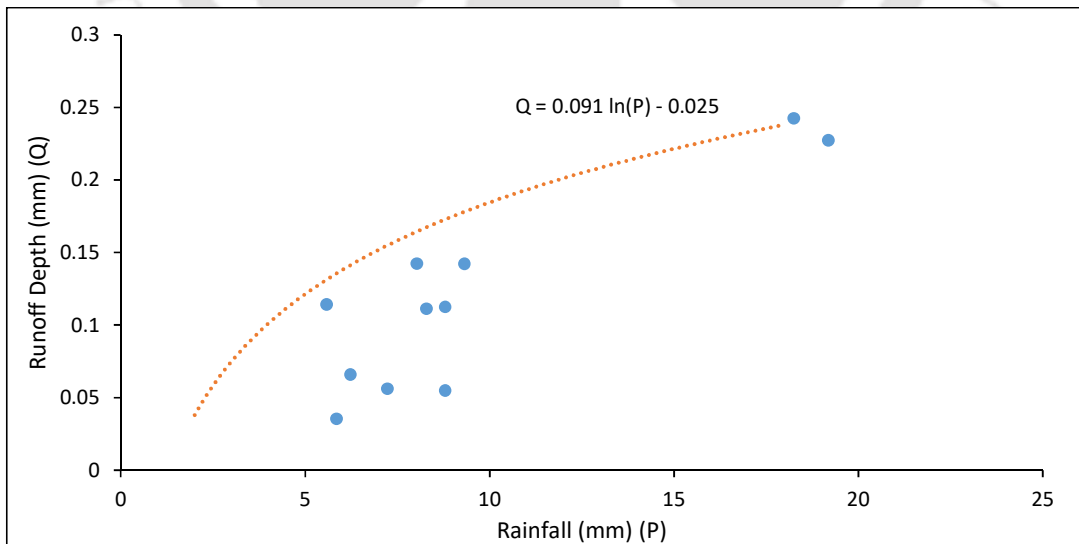


Figure 4.12: Scatter plot of rainfall and runoff depth for the year 1991 pre-monsoon season for Baronda watershed.

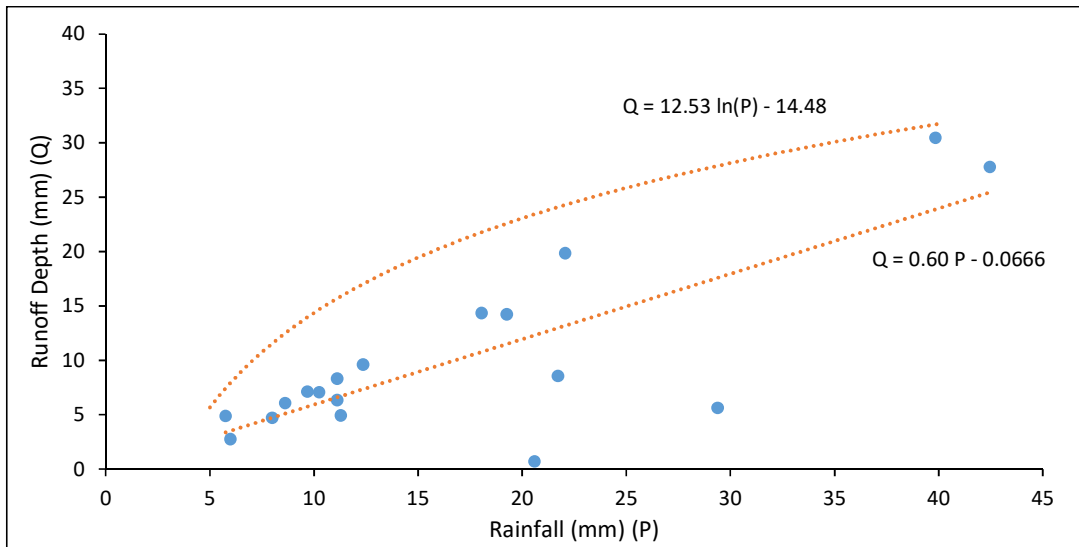


Figure 4.13: Scatter plot of rainfall and runoff depth for the year 1991 monsoon season for Baronda watershed.

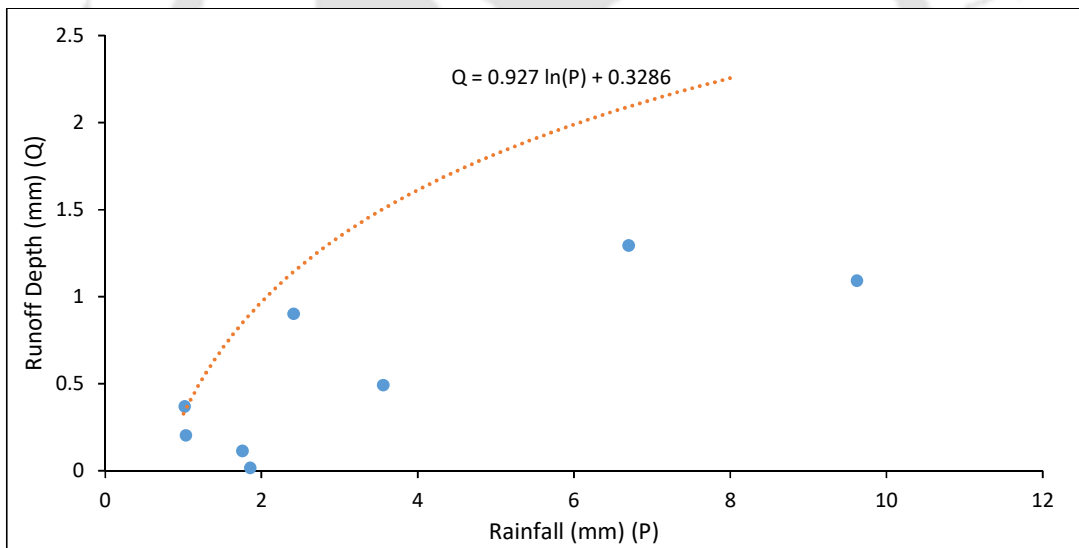


Figure 4.14: Scatter plot of rainfall and runoff depth for the year 1991 post-monsoon season for Baronda watershed.

Figure 4.12-4.14 shows the scatter plot between rainfall and runoff depth for the pre-monsoon, monsoon, and post-monsoon season of the year 1991. It was observed that runoff depth is linearly related to the rainfall depth for all the seasons of the year 1991. However, the maximum runoff depth generated during pre-monsoon and the post-monsoon season was only 1 mm. During monsoon season of the year 1991, except two storm events with rainfall depth 20 mm and 29 mm, all the rainfall storm events generated significant runoff depth with a linear

relationship. Extreme events upper envelope curve was estimated with 0.99 coefficient of determination.

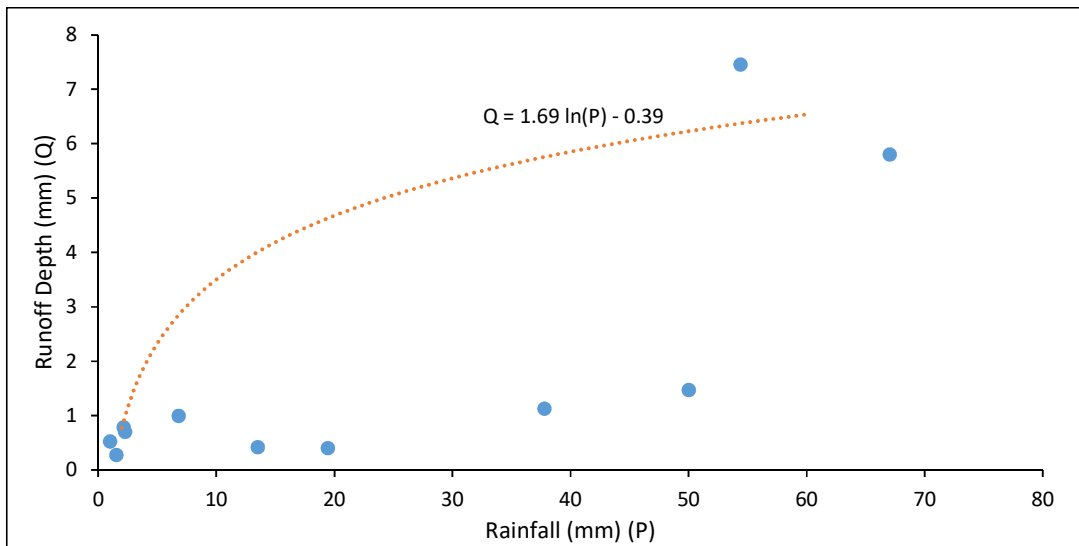


Figure 4.15: Scatter plot of rainfall and runoff depth for the year 1992 pre-monsoon season for Baronda watershed.

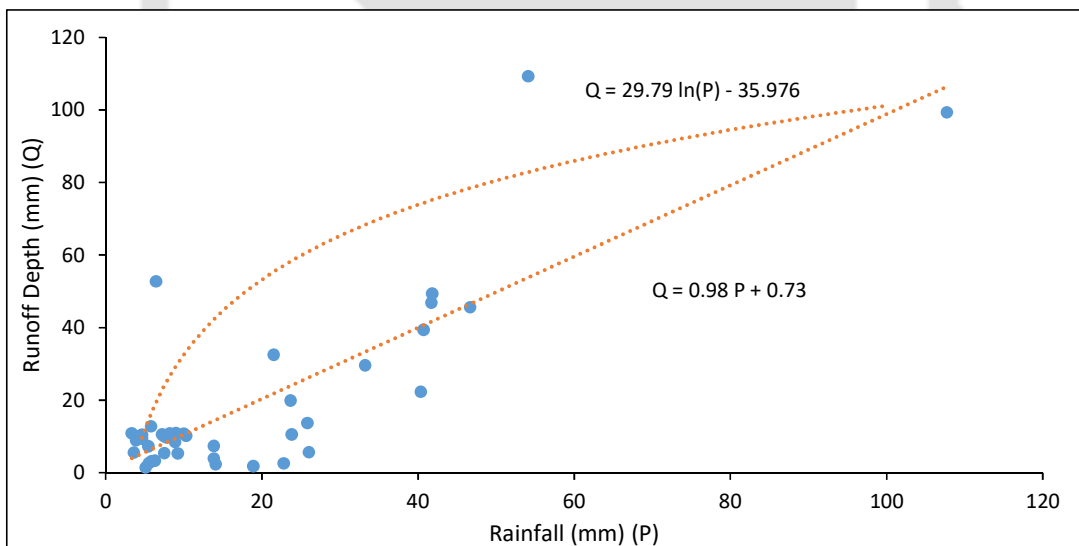


Figure 4.16: Scatter plot of rainfall and runoff depth for the year 1992 monsoon season for Baronda watershed.

The runoff depth of 80 % of storm events during pre-monsoon season of the year 1992 ranges between 0 to 2 mm. Only two high rainfall depth storm events (54 mm & 67 mm) generated significant runoff depth from the watershed (Figure 4.15). Post-monsoon season in 1992 had

only four major rainfall storm events. Therefore meaningful analysis could not be done. During 1992 monsoon season, the rainfall depth was linearly related to runoff depth with 0.66 coefficient of determination (Figure 4.16). It was noted that on July 29, 1992, the storm event rainfall depth was 55 mm. But, the storm event generated 109 mm of runoff depth due to over spilling of water harvesting structure and paddy agriculture fields. The water harvesting structures and agriculture paddy field plays a significant role in the hydrological behaviour of the watershed (Rajyalakshmi and Dutta, 2006). Scatter plot analysis, in the same manner, was done for all the years for Baronda watershed from 1993 to 2000 (Appendix A-1). The linear relationship between rainfall depth and runoff depth along with their coefficient of determination and upper envelope curve equation are shown in Table 4.6.

Table 4.6: Rainfall-Runoff Response for monsoon season of Baronda Watershed

Year	Rainfall Depth (P) & Runoff Depth (Q) Relationship (in mm)	R ²	Curve Number	Initial Abstraction (mm)	Upper Envelope Equation
1990	$Q = 0.64 P + 0.95$	0.64	92	5	$Q = 15.57 \ln(P) - 10.33$
1991	$Q = 0.6 P - 0.06$	0.85	93	7	$Q = 12.53 \ln(P) - 14.48$
1992	$Q = 0.98 P + 0.73$	0.57	89	5	$Q = 29.8 \ln(P) - 35.9$
1993	–	0.90	90	6	$Q = 4.73 \ln(P) + 3.96$
1994	$Q = 0.55 P + 0.04$	0.59	92	7	$Q = 31.1 \ln(P) - 41.77$
1995	$Q = 0.067 P + 8.20$	0.68	91	4	$Q = 2.86 \ln(P) + 7.07$
1996	$Q = 0.058 P + 7.08$	0.72	90	8	$Q = 3.96 \ln(P) + 0.611$
1997	$Q = 0.13 P + 8.5$	0.73	87	5	$Q = 8.23 \ln(P) + 1.07$
1998	$Q = 0.07 P + 8.59$	0.68	92	6	$Q = 2.25 \ln(P) + 12$
1999	–	0.64	90	5	$Q = 0.88 \ln(P) + 11.4$
2000	$Q = 0.6 P - 0.06$	0.53	91	7	$Q = 5.9 \ln(P) + 8.5$

Average curve number for Baronda watershed during the monsoon season of the year 1990 was estimated by Soil Conservation Service-Curve Number (SCS-CN) method. The initial abstraction and curve number were obtained by hit and trial method considering the observed rainfall and runoff depth. The rainfall-runoff relationship for curve number 92 and initial abstraction 5 mm was found the best fit with a coefficient of determination 0.98 for the year 1990 (Figure 4.17). In the same manner, the curve number and initial abstraction values were estimated for the Baronda watershed for years 1990 to 2000 (Table 4.6).

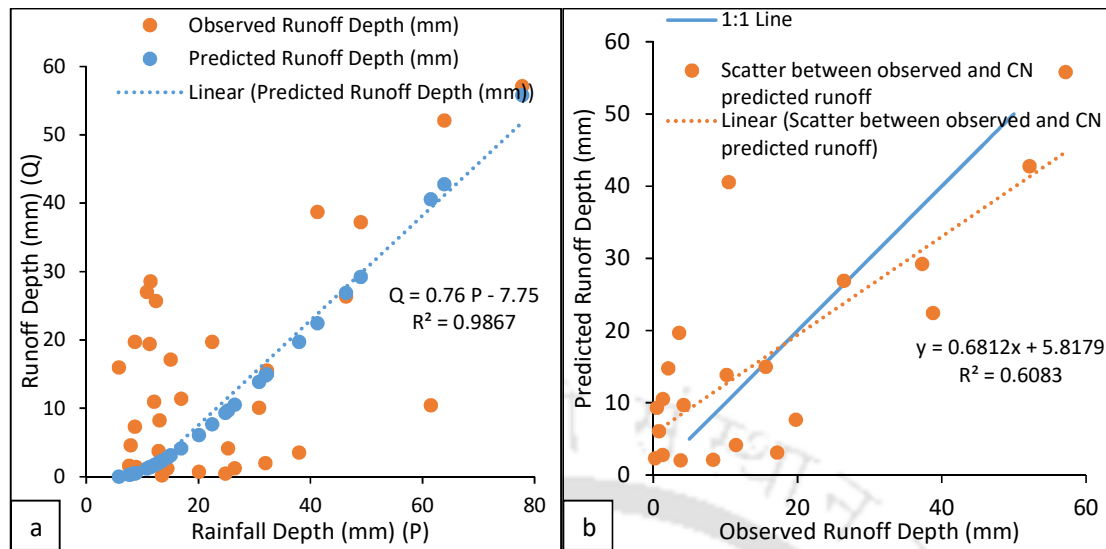


Figure 4.17: (a) Average Curve number estimation, (b) Scatter Plot between estimated and observed runoff depth in the year 1990 monsoon season for Baronda watershed

4.3.1.2 Kesinga Watershed

The scatter plot analysis of rainfall and runoff depth was done for the Kesinga watershed for six years from 2006 to 2011. Figures 4.18, 4.19, and 4.20 shows the scatter plot analysis of rainfall depth and runoff depth for the year 2006 pre-monsoon, monsoon, and post-monsoon season. It was observed that the rainfall runoff response of the watershed does not follow a linear trend in pre- and post-monsoon season. However, a linear relationship with 0.74 coefficient of determination exists between rainfall depth and runoff depth for the monsoon season of the year 2006. It was strongly noted that the same rainfall depth storm event in pre- or the post-monsoon season could not produce significant runoff depth as it generates in monsoon season. The upper envelope curve was also estimated to capture the maximum possible runoff depth generation from rainfall depth storm event (Figure 4.19).

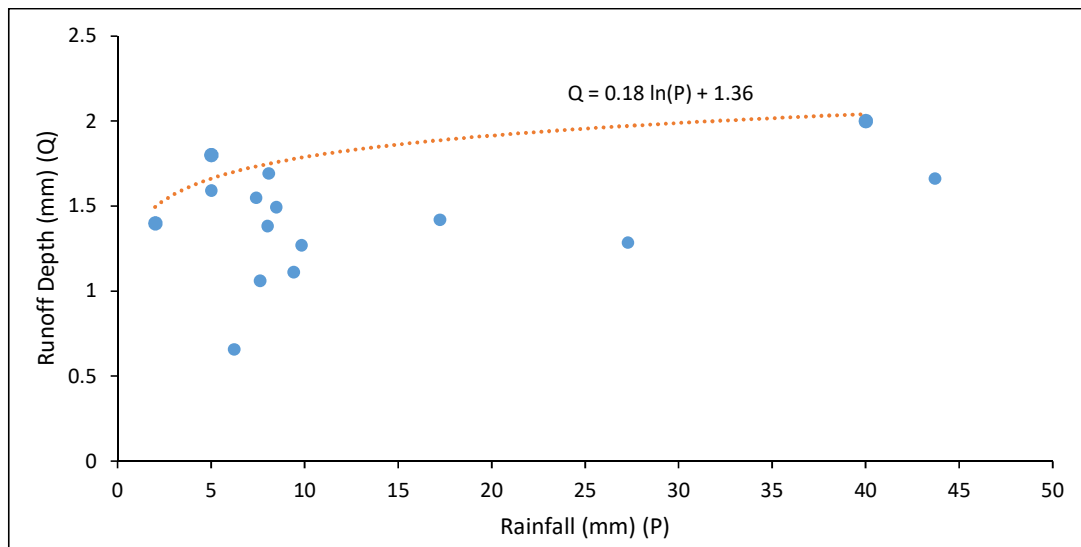


Figure 4.18: Scatter plot of rainfall and runoff depth for the year 2006 pre-monsoon season for Kesinga watershed.

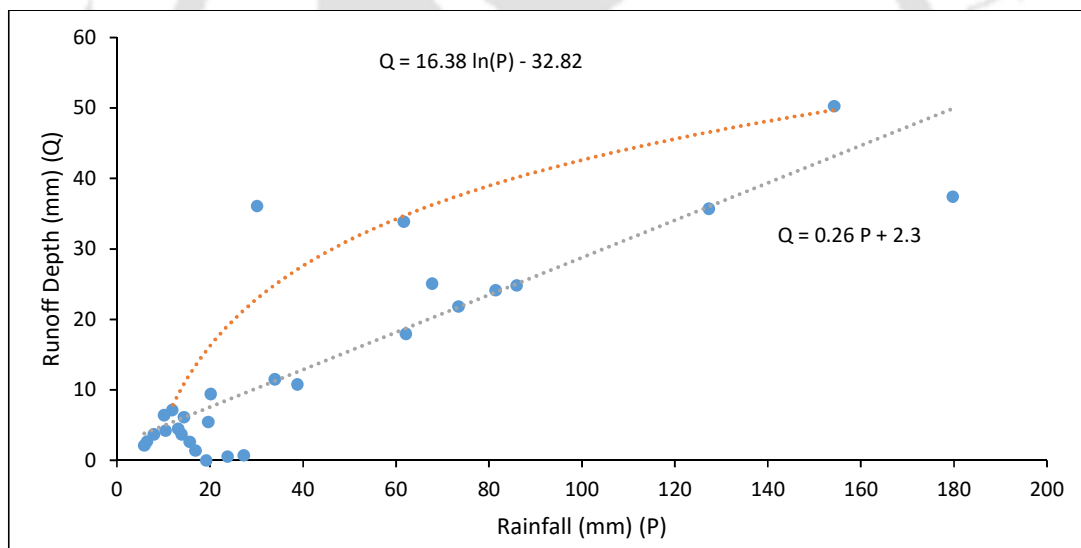


Figure 4.19: Scatter plot of rainfall and runoff depth for the year 2006 monsoon season for Kesinga watershed.

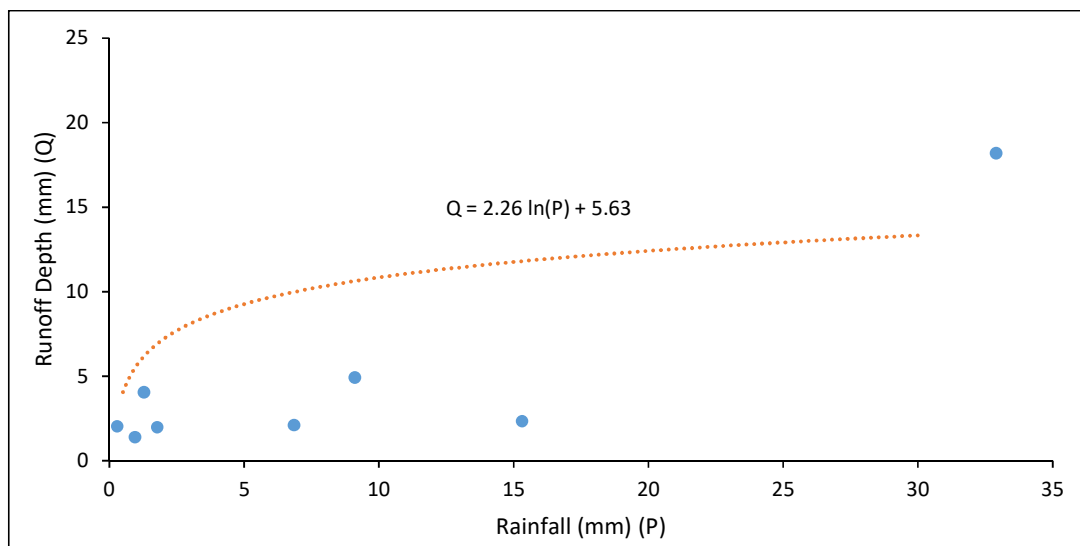


Figure 4.20: Scatter plot of rainfall and runoff depth for the year 2006 post-monsoon season for Kesinga watershed.

The similar analysis between rainfall depth and runoff depth for the pre-monsoon and monsoon season of the year 2007 was done (Figures 4.21 and 4.22). The plot for the years 2008-2011 are shown in Appendix A-2.

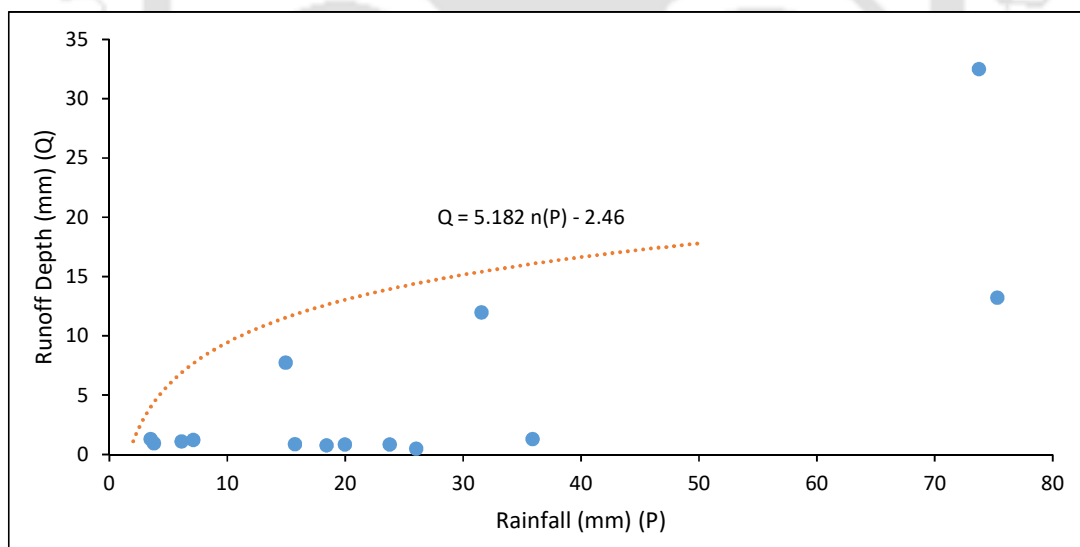


Figure 4.21: Scatter plot of rainfall and runoff depth for the year 2007 pre-monsoon season for Kesinga watershed.

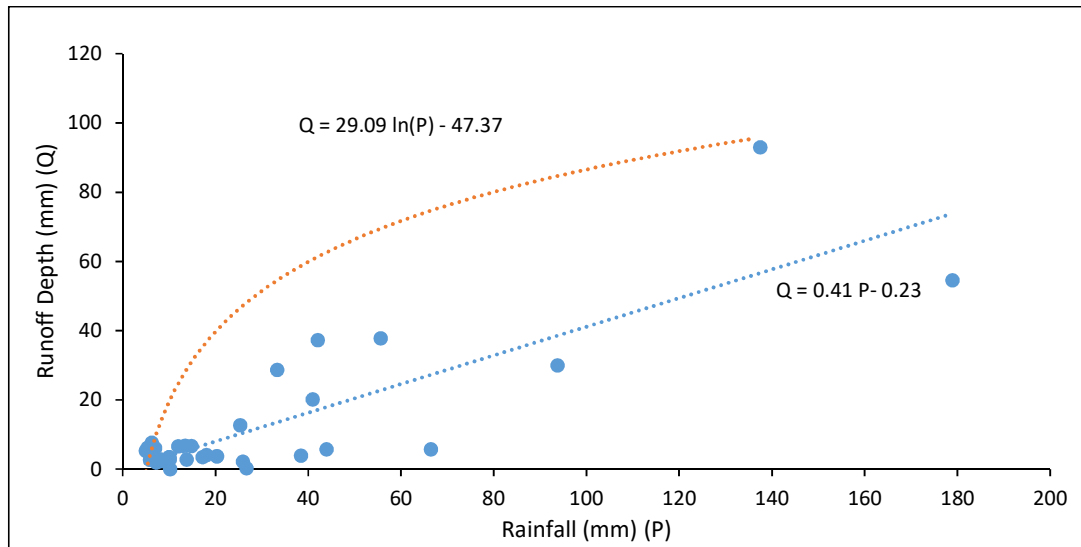


Figure 4.22: Scatter plot of rainfall and runoff depth for the year 2007 monsoon season for Kesinga watershed.

Table 4.7 shows the linear relationships between rainfall and runoff depth for the monsoon season of the observation period. The average curve number for the Kesinga watershed was then estimated by SCS curve number method. The estimated curve number ranges from 83 to 91, while intimal abstraction ranges between 5 mm to 10 mm (Table 4.7). The best-fitted curve number for the year 2010 and 2011 was found as 87 and 83, respectively. The fitted curve number curve for the year 2010 and 2011 are shown in Figures 4.23 and 4.24.

Table 4.7: Rainfall-Runoff Response of Baronda Watershed

Year	Rainfall Depth (P) & Runoff Depth (Q) Relationship (in mm)	R ²	Curve Number	Initial Abstraction (mm)	Upper Envelope Equation
2006	$Q = 0.26 P + 2.30$	0.74	84	8	$Q = 16.38 \ln(P) - 32.82$
2007	$Q = 0.41 P - 0.23$	0.69	85	6	$Q = 29.09 \ln(P) - 47.37$
2008	$Q = 0.39 P + 1.48$	0.75	88	5	$Q = 17.46 \ln(P) - 17.82$
2009	$Q = 0.25 P + 0.98$	0.64	91	10	$Q = 6.46 \ln(P) + 4.63$
2010	$Q = 0.45 P + 1.04$	0.71	87	8	$Q = 17.7 \ln(P) - 22.03$
2011	$Q = 0.31 P - 0.08$	0.67	83	5	$Q = 6.21 \ln(P) - 2.88$

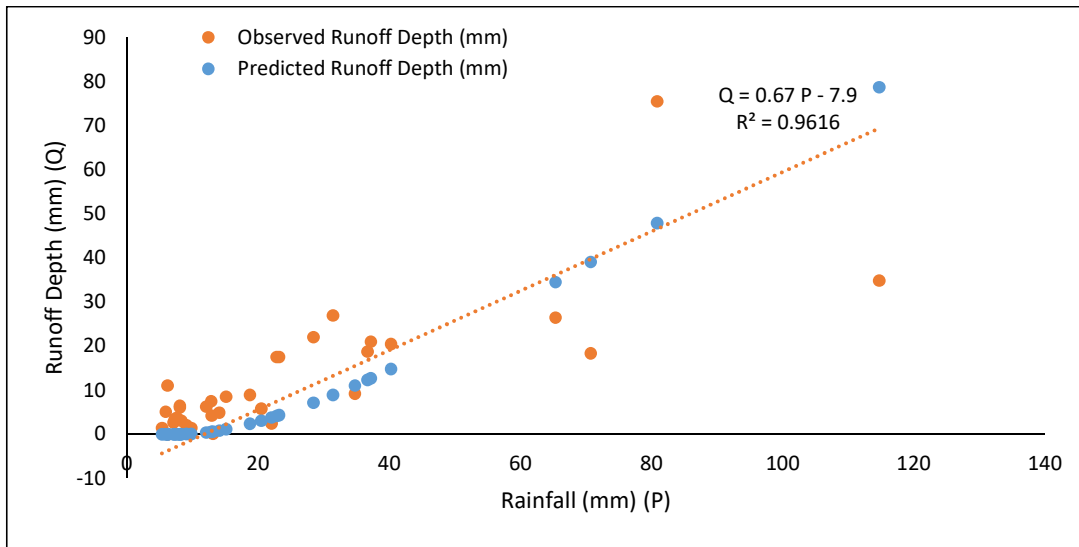


Figure 4.23: Average Curve number estimation for Kesinga watershed during the year 2010 monsoon season

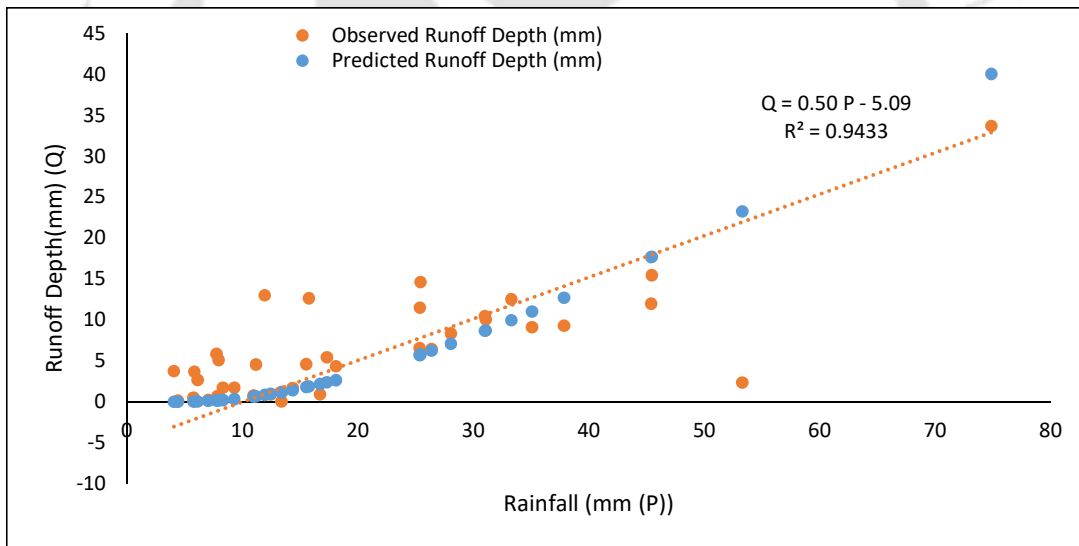


Figure 4.24: Average Curve number estimation for Kesinga watershed during the year 2011 monsoon season

As discussed in the previous chapter and evident from plot scale observations that soil moisture condition plays a major role in runoff generation process. Therefore, the soil moisture data were obtained for Kesinga watershed for the period from the year 2006 to 2011 at 0.25° spatial resolution. Hence, average soil moisture of the watershed was estimated by geospatial averaging (Jensen, 2000). To analyze the effect of rainfall depth and soil moisture condition over runoff generation, the rainfall storm events were segregated into two groups' viz.

significant runoff generating events and non-significant runoff generating storm events (say, non-runoff generating events). Value pairs of the degree of soil saturation and rainfall depth were then used for linear binary classification along with least mean square algorithm. Figures 4.25 and 4.26 show the scatter plot of rainfall depth and degree of soil saturation for the years 2006 and 2007, respectively. The plots for years 2008-2011 are shown in Appendix A-3. The straight line in the figures represents the linear determinant function. It was evident that the storm event with high soil saturation and above threshold rainfall depth generates runoff (Miao et al., 2016).

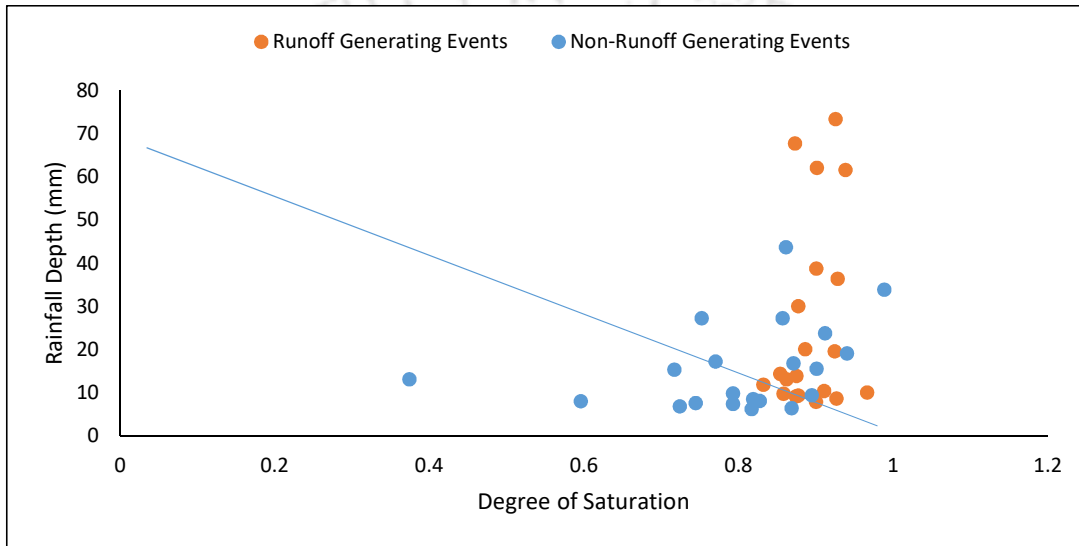


Figure 4.25: Binary classification plot of storm event rainfall depth and soil saturation for Kesinga watershed for the year 2006

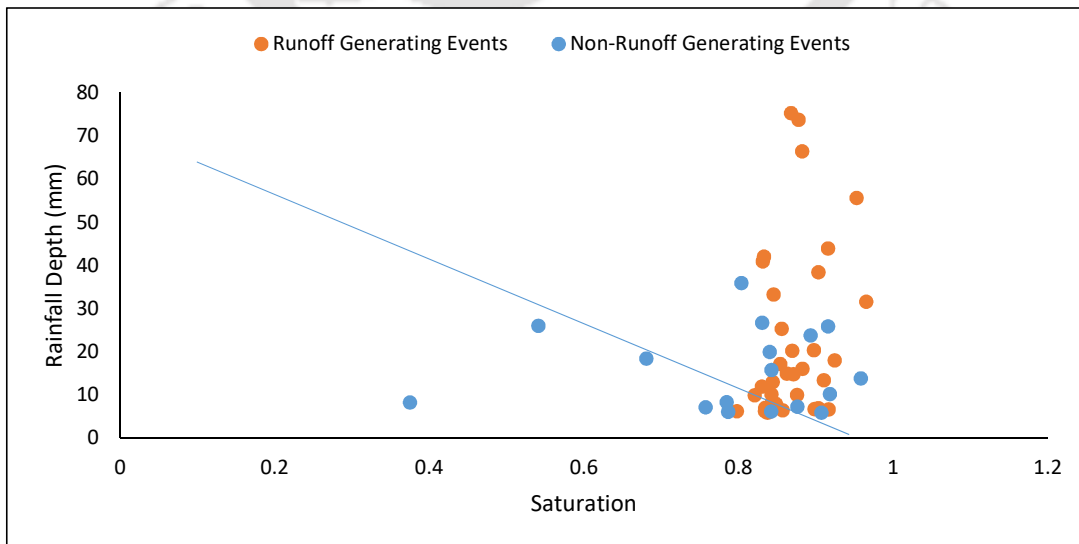


Figure 4.26: Binary classification plot of storm event rainfall depth and soil saturation for Kesinga watershed for the year 2007

4.3.2 Effect of Rainfall, Vegetation and Soil Moisture Variation on Runoff Generation

The relationships between precipitation and satellite-derived vegetation index (NDVI) was assessed in several studies (Damizadeh et al., 2001; Eklundh, 1998; Leilei et al., 2014; Nightingale and Phinn, 2003; Usman et al., 2013). Though many studies on the variation of rainfall and vegetation pattern in India have been carried, very few researchers have attempted to correlate the trends and variation of rainfall pattern and resulting streamflow as a function of vegetation conditions in a basin. Therefore, to investigate the relationship and effect of vegetation on runoff generation at the watershed scale, Figure 4.27 shows the variation of NDVI and runoff with rainfall for the year 1990 at Baronda watershed.

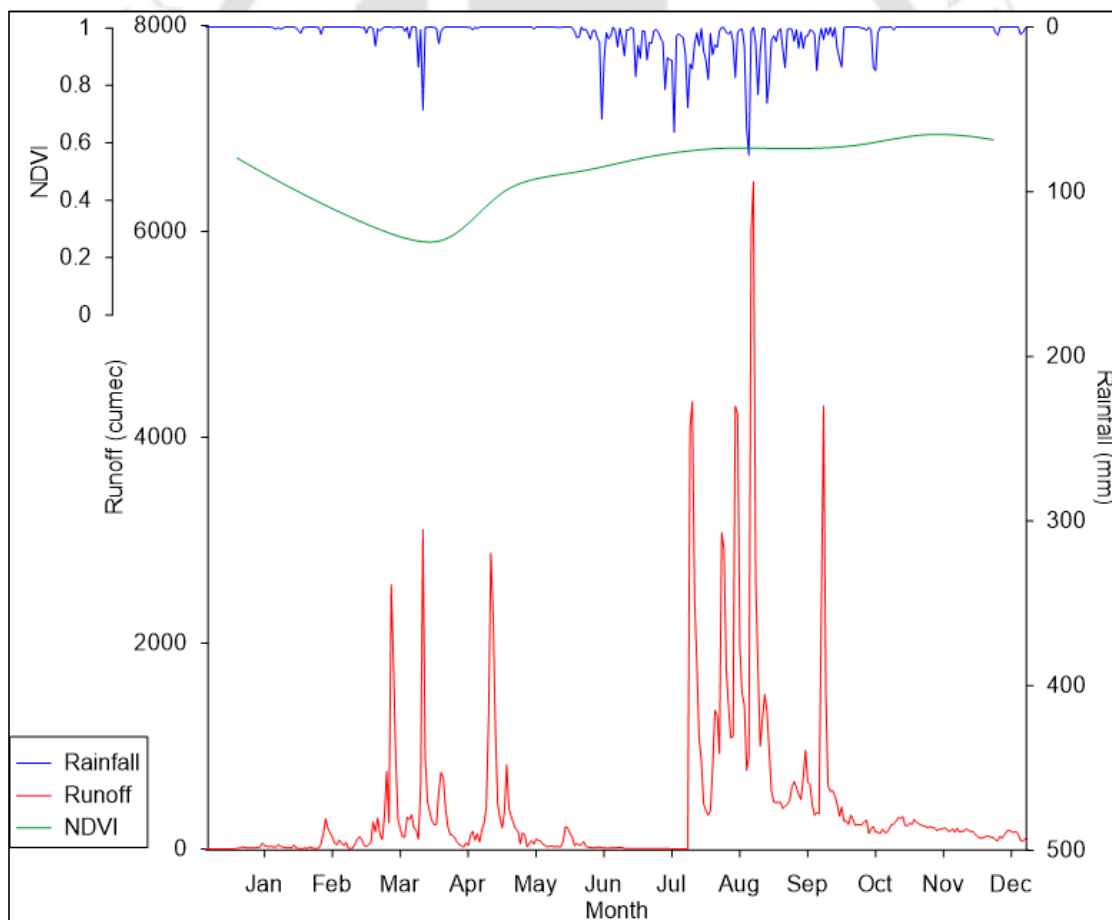


Figure 4.27: Variation of NDVI with rainfall and runoff for year 1990 at Baronda Watershed

The NDVI varies in the range of 0.24 to 0.62 throughout the year 1990 for Baronda watershed. During the start of pre-monsoon season, NDVI is minimum, and as the season proceeds, the vegetation growth starts rising due to the pre-monsoon showers.

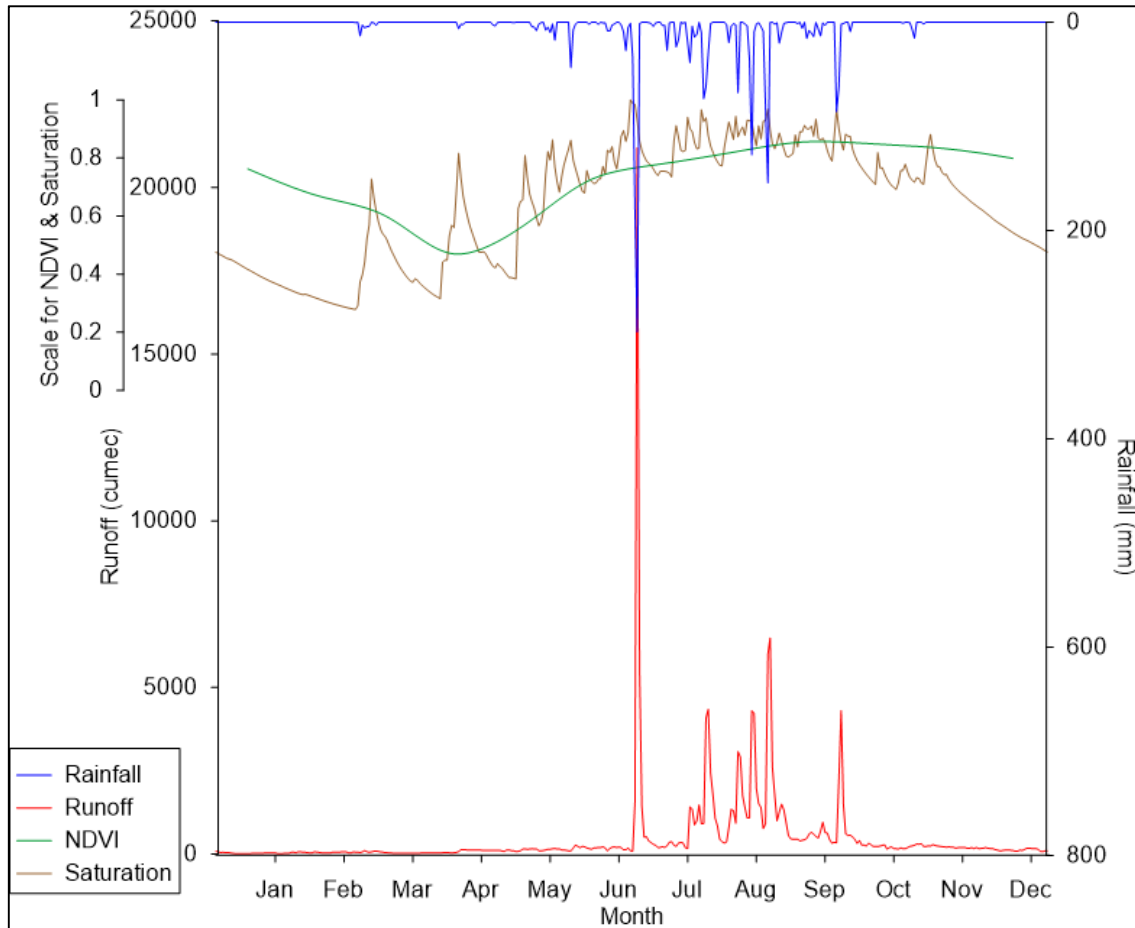


Figure 4.28: Effect of rainfall, NDVI and degree of soil saturation on runoff discharge for the year 2006 at Kesinga watershed

It was observed that a storm event of about 50 mm rainfall depth had generated a significant amount of runoff in April. An extreme rainfall event in last week of April could not be captured because of unforeseen reasons. However, it can be visible in Figure 4.27 that only high rainfall events in pre-monsoon season have generated significant runoff. While during monsoon season even smaller rainfall events has generated significant runoff. The reason for runoff generation in monsoon months could be the effect of vegetation. As the watershed is mostly covered with forest area, NDVI reaches its maximum during monsoon season and have dense vegetation cover with highly interconnected macropore network in the subsoil induced mainly by plant roots. As a result of high soil saturation and presence of preferential pathways, the

characteristics of the overland flow and preferential infiltration through the soil are interdependent and are influenced by many other factors, such as the degree of vegetation, topography, rainfall characteristics, etc. At the same time due to the presence of dense network of macropores in the soil, the magnitude of subsurface stormflow, both in vertical as well as lateral directions, can be quite significant in the hydrological response of the vegetated hillslopes. The same phenomenon was observed in case of Kesinga watershed for the year 2006 shown in Figure 4.28 and other year's data at watersheds (Appendix A-4 and A-5). Due to the agriculture-dominated watershed, the NDVI in Kesinga watershed varies between the ranges from 0.4 to 0.8. The smaller rainfall events in pre-monsoon season could not generate significant runoff. However, runoff amount varies significantly with the effect of rainfall events during the monsoon season.

4.3.3 Relationship between Discharge and Sediment Concentration

Soil erosion by water is a major environmental threat to the sustainability and productive capacity of agriculture in many tropical and sub-tropical regions of the world (Mullan, 2013). Recent developments criticized the application of conventional sediment rating curve which is based only on runoff volume and ignores the seasonal dynamics. The runoff associated sediment dynamics is enlightened by different researchers differentially by relating this with sediment depletion, vegetation cover, subsurface flow, the effect of soil moisture, etc. However, any of the model does not include the seasonal dependent sediment dynamics. Therefore, the sediment concentration and discharge relationships were analyzed seasonally shown in Figures 4.29 and 4.30 for years 1990 and 1991, respectively for Baronda watershed. It was depicted from the figures that runoff and sediment concentration strongly follows a power relationship as same as observed by (Guzman et al., 2013; Wang et al., 2013; Xinxiao et al., 2006). It can be concluded by interpretation of Figures 4.29 and 4.30 that sediment generation dynamics vary with season, i.e., it can be a function of vegetation condition or antecedent soil moisture. The similar plots for other years are given in Appendix A-6.

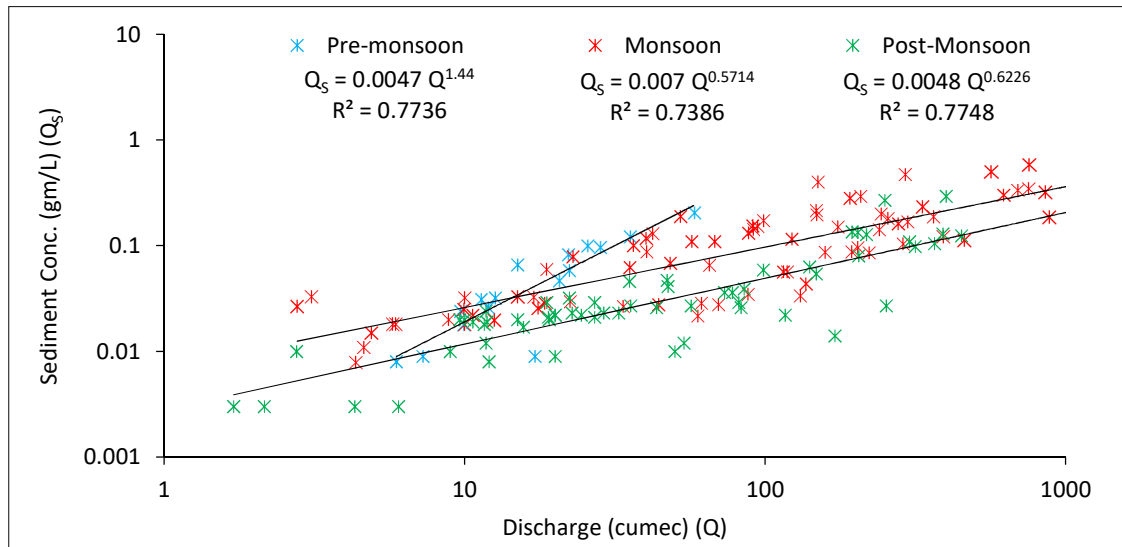


Figure 4.29: Runoff and sediment relationships at Baronda watershed outlet for the year 1990

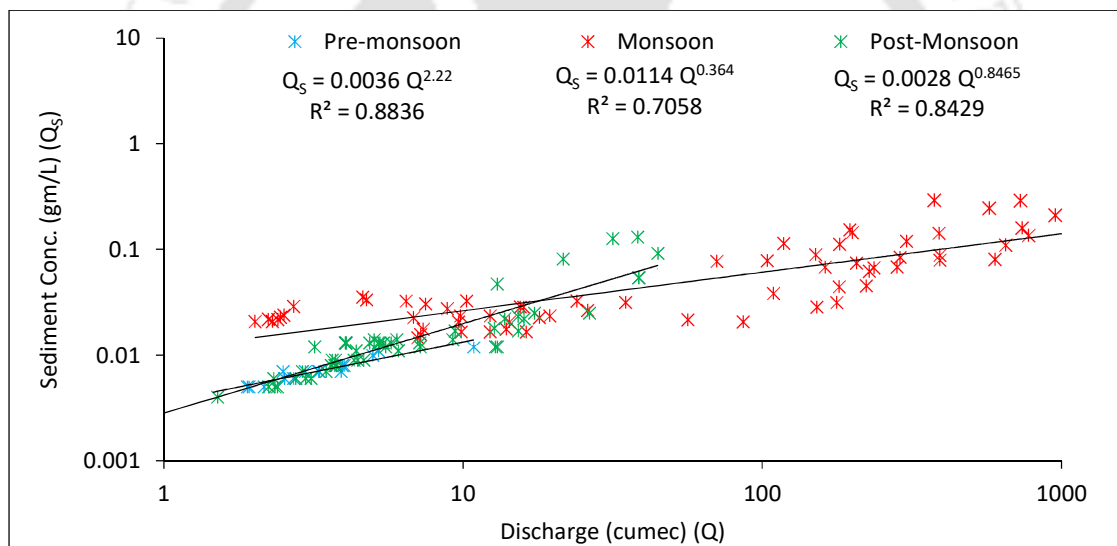


Figure 4.30: Runoff and sediment relationships at Baronda watershed outlet for the year 1991

4.3.4 Effect of Vegetation on Sediment Generation

The sediment dynamics is directly related to the soil moisture as it affects the shear strength of the soil and overland flow transport capacity (Guzman et al., 2013). But, relating soil moisture to the sediment dynamics and upscale this phenomena to watershed scale needs a lot of parameterization. Therefore, we hypothesized that sediment concentration varies with the vegetation conditions which indirectly represent the seasonal behaviour. The seasonal sediment

dynamics is explained in the previous section in which the power relation in the form of Equation 4.3 between discharge and sediment concentration was obtained in three seasons.

$$Q_s = a Q^b \quad (4.3)$$

where, sediment concentration (Q_s) is explained as a function of the runoff (Q). 'a' and 'b' are the variables. To classify the seasonal behaviour of sediment dynamics, the variables of Equation 4.3 were plotted against the NDVI and relationships among them were established. Average sediment concentration, average NDVI and power coefficient variables for pre-monsoon, monsoon and post-monsoon season are shown in Table 4.8, 4.9 and 4.10, respectively.

Table 4.8: Power Relationship Coefficient for Baronda Watershed during pre-monsoon season

Year	Qs	NDVI	'a'	'b'
1990	0.038	0.373	0.0047	1.44
1991	0.0074	0.387	0.0036	2.22
1992	0.1739	0.306	0.008	0.63
1993	0.082	0.328	0.0075	0.89
1995	0.0564	0.342	0.0087	0.91
1997	0.042	0.352	0.0082	1.11
1999	0.035	0.364	0.0048	1.89
2000	0.033	0.383	0.0037	1.76

Table 4.9: Power Relationship Coefficient for Baronda Watershed during monsoon season

Year	Qs	NDVI	a	b
1990	0.145	0.469	0.017	0.57
1991	0.097	0.398	0.0114	0.36
1992	0.117	0.454	0.0086	0.50
1993	0.061	0.305	0.0026	0.83
1994	0.1003	0.38	0.0054	0.67
1995	0.106	0.392	0.0094	0.52
1996	0.158	0.456	0.0135	0.59
1997	0.1384	0.529	0.0142	0.30

1998	0.134	0.385	0.0056	0.69
1999	0.119	0.392	0.01	0.48
2000	0.08	0.391	0.011	0.53

Table 4.10: Power Relationship Coefficient for Baronda Watershed during post-monsoon season

Year	Qs	NDVI	a	b
1990	0.045	0.609	0.0048	0.62
1991	0.021	0.654	0.0028	0.84
1992	0.033	0.587	0.0062	0.75
1993	0.025	0.613	0.0052	0.79
1994	0.021	0.629	0.003	0.65
1995	0.01	0.679	0.004	0.80
1996	0.024	0.629	0.003	0.61
1997	0.027	0.592	0.0083	0.49
1998	0.0412	0.62	0.0056	0.69
1999	0.049	0.581	0.008	0.47
2000	0.042	0.584	0.0057	0.66

Figure 4.31 shows the variation of average sediment concentration with average NDVI for pre-monsoon season. It was observed that sediment concentration and NDVI are inversely proportional to each other and are strongly related by a linear relationship. It can be illustrated as sediment concentration decreases when pre-monsoon season NDVI increases each year. It is well reported that NDVI is directly correlated with rainfall (Damizadeh et al., 2001; Eklundh, 1998; Leilei et al., 2014; Zoungrana et al., 2015). As discussed in Section 3.3.4, runoff generation is a threshold driven phenomenon, and rainfall threshold varies seasonally. The increased NDVI in pre-monsoon season can be correlated with increased rainfall, however, due to the frequent and longer dry spells during pre-monsoon season (as evident from Figures 4.27 and 4.28) the average antecedent moisture condition of the watershed during this season remains dry. The dry conditions in pre-monsoon season will induce more initial losses, resulting in the smaller amount of surface runoff and sediment concentration from the watershed. Furthermore, the increased resistance due to canopy cover reduces the transport capacity of overland flow this could be one more reason for sediment depletion with NDVI

rise. Hence, it can be concluded that NDVI is inversely related to sediment concentration during pre-monsoon season. The finding can be validated with the observations of (De Jong, 1994) in which he found a negative correlation between NDVI and 'C' factor of Universal Soil Loss Equation (USLE).

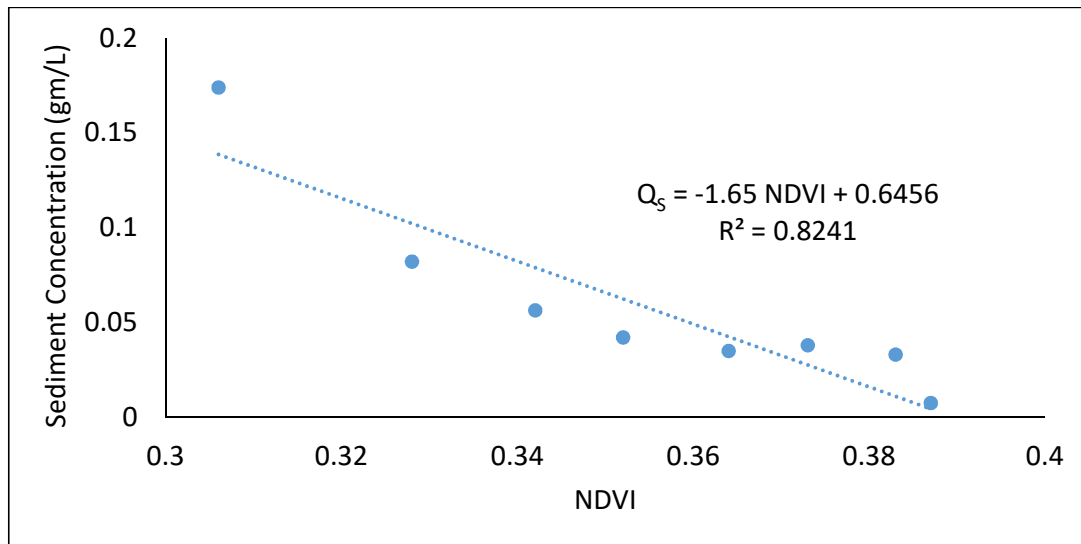


Figure 4.31: Variation of sediment concentration with NDVI for pre-monsoon season

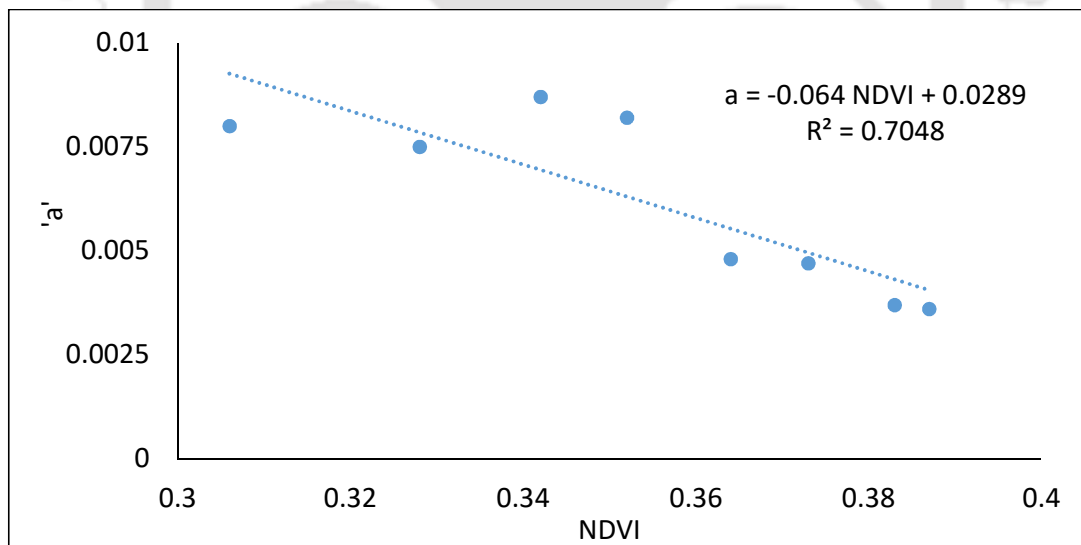


Figure 4.32: Variation of parameter 'a' with NDVI for pre-monsoon season

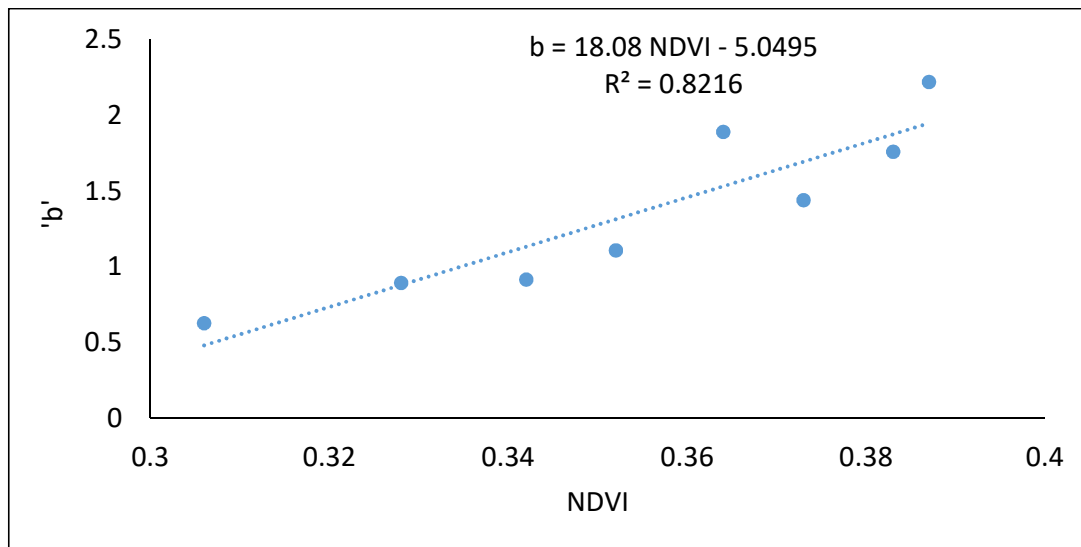


Figure 4.33: Variation of parameter 'b' with NDVI for pre-monsoon season

The pre-monsoon season runoff-sediment power relationship variables 'a' and 'b' were plotted against NDVI in Figures 4.32 and 4.33, respectively. It was observed that 'a' has a negative correlation with NDVI (R^2 0.7), while 'b' is directly correlated (R^2 0.82).

The variation of average sediment concentration with average NDVI for monsoon season for Baronda watershed is shown in Figure 4.34. It can be seen that sediment concentration increases with increase in NDVI of the season. As discussed, NDVI directly signifies the effect of rainfall. As discussed in Section 4.2.1.1, monsoon season receives around 80% of annual rainfall. It is evident from Figures 4.27 and 4.28, that this season is mostly characterised by prolonged wet antecedent moisture conditions. This will lead to considerable increase in runoff coefficient (runoff/rainfall) during monsoon season. The wet soil exposed to frequent and high rainfall events will yield higher runoff with minimum initial losses. Though the increased rainfall in the monsoon season will also increase the vegetation condition, however, the linear relation between seasonal NDVI and seasonal rainfall (Damizadeh et al., 2001; Di et al., 1994; Ding et al., 2007) saturates between mid to end of July. The excess rain above this saturation threshold will majorly contribute to runoff and sediment dynamics, due to higher antecedent moisture condition. Increased NDVI will increase resistance to the overland flow sediment transport processes. However, the adverse effect of this resistance will be turned down by frequent and intense rainfall events of the season, which will dominate the runoff and sediment dynamics. The negative correlation between NDVI and USLE 'C' factor proposed by (De Jong, 1994) is not valid for monsoon season.

The variables 'a' and 'b' for monsoon season were found to be weakly correlated with NDVI with R^2 of 0.64 and 0.47, respectively (Figures 4.35 and 4.36). It was observed that 'a' is directly associated, while 'b' has a negative correlation with NDVI.

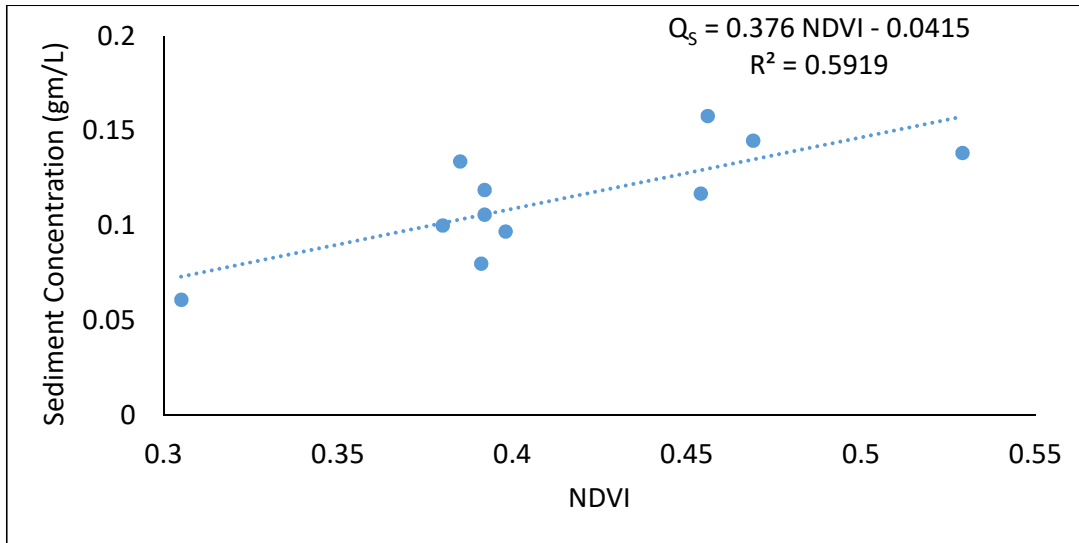


Figure 4.34: Variation of sediment concentration with NDVI for monsoon season

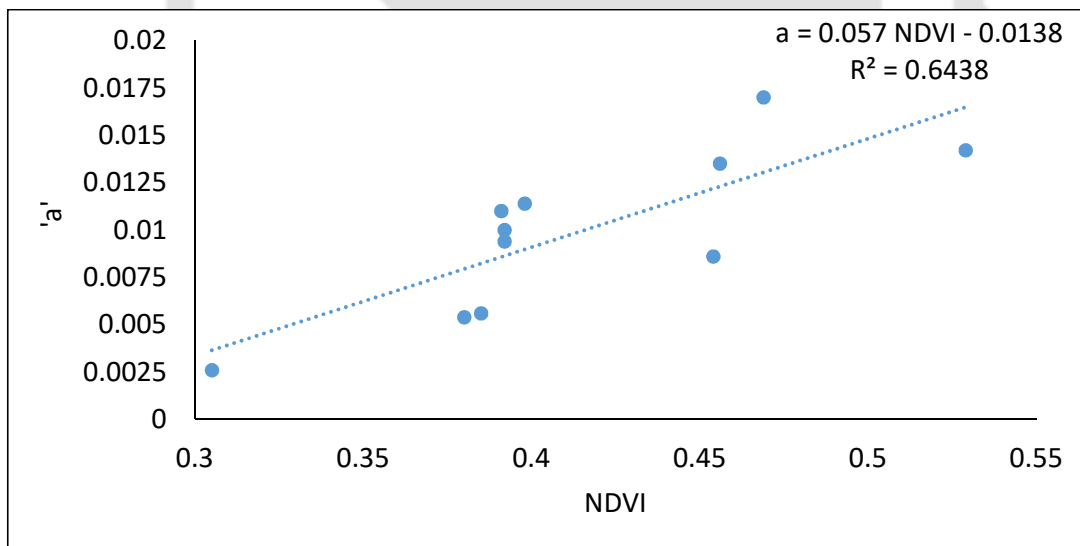


Figure 4.35: Variation of parameter 'a' with NDVI for monsoon season

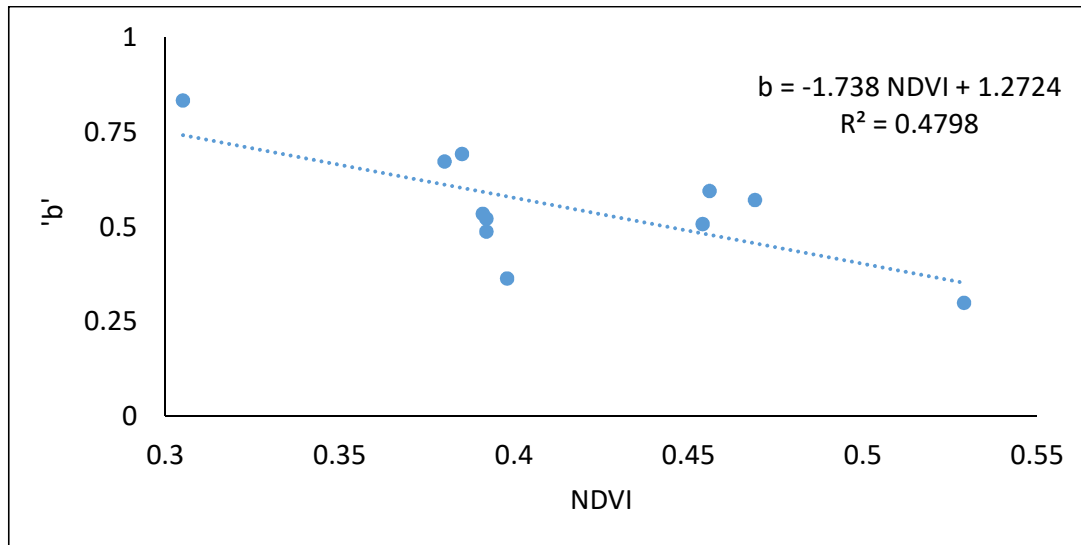


Figure 4.36: Variation of parameter 'b' with NDVI for monsoon season

The average sediment concentration for the post-monsoon season was found to be inversely correlated with the seasonal average NDVI as shown in Figure 4.37. The inverse correlation between NDVI and sediment concentration in post-monsoon season behaves similarly to pre-monsoon conditions. However, the underline factors, governing this correlation, are different in post-monsoon season. During the post-monsoon season, the NDVI reaches its maximum due to the lagged effect of monsoon season rainfall, while the rainfall magnitude and frequency reduce, as evident from Figure 4.27. The sediment concentration depletion happens due to the less runoff generation and increased vegetation resistance to sediment transport. Therefore, the average sediment concentration decreases with increase in NDVI during post-monsoon season. It is now argued that the relationship between NDVI and USLE 'C' factor established by (De Jong, 1994), which is widely used in soil erosion prediction models, is only valid for non-monsoon periods.

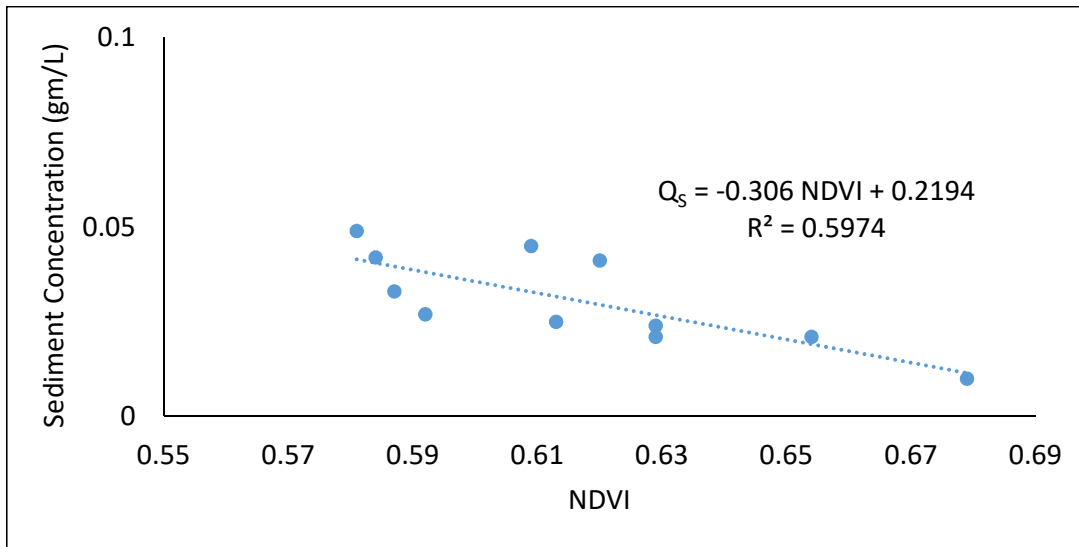


Figure 4.37: Variation of sediment concentration with NDVI for post-monsoon season

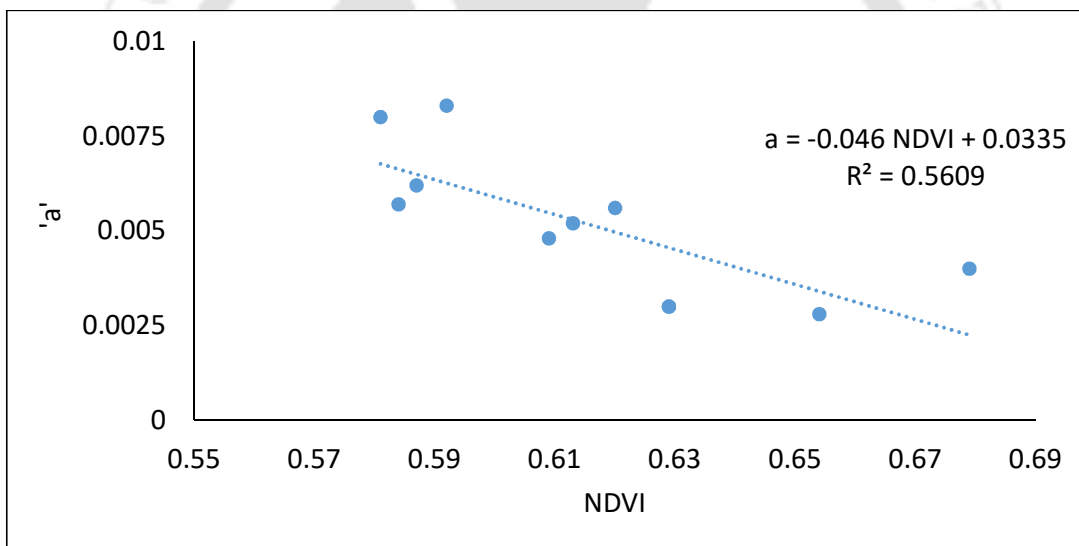


Figure 4.38: Variation of parameter 'a' with NDVI for post-monsoon season

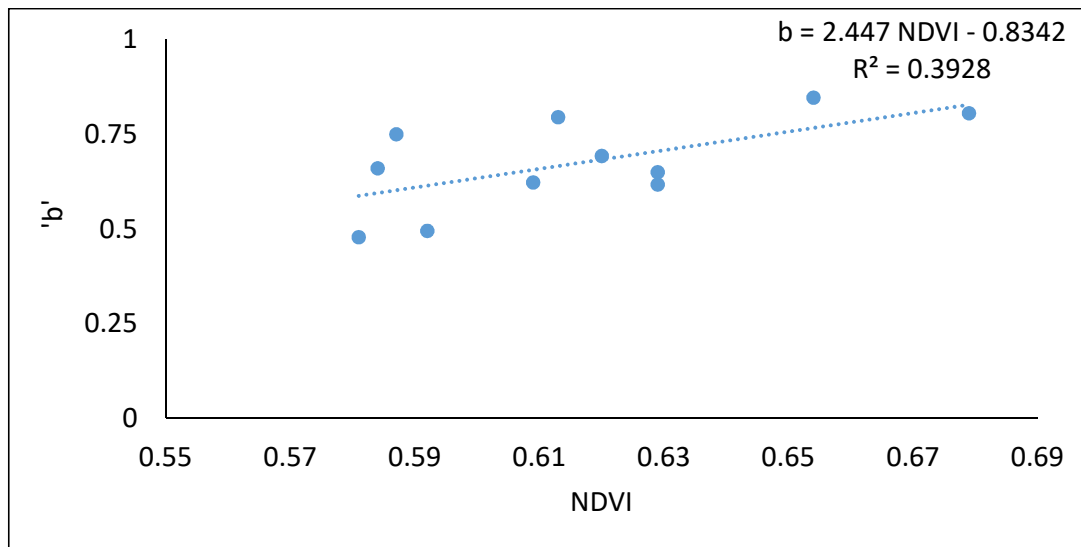


Figure 4.39: Variation of parameter 'b' with NDVI for post-monsoon season

To identify the relationship between NDVI and runoff-sediment power relationship variables 'a' and 'b' for the post-monsoon season, scatter plot analysis was performed (Figures 4.38 and 4.39). It was observed that the variables are weakly correlated with NDVI. However, they vary with NDVI as similar as in case of pre-monsoon season.

4.4 Conclusions

The study described rainfall-runoff-sediment relationships at watershed scale. Two agroforestry watersheds in part of Mahanadi river basin were selected to identify the runoff and sediment response characteristics. LULC classification reveals that Baronda watershed is mostly covered with forests, while Kesinga watershed is dominated by agricultural activities. The rainfall, runoff and suspended sediment concentration data was analyzed thoroughly for different seasons. It was found that runoff depth is linearly related to rainfall depth during monsoon season. However, there was more non-linearity found during the non-monsoon period. The curve number was estimated at about 90, which is very high at watershed scale and indicates flashiness in rainfall-runoff response in hilly tropical agroforestry watershed. To capture the extreme runoff response to rainfall, upper envelope equations were developed. The effect on rainfall depth and soil moisture was identified by the application of binary classification technique. It was found that the storm event with high soil saturation and above threshold rainfall depth generates runoff. It was observed that suspended sediment concentration and runoff are related with a power relationship, coefficients of which vary

seasonally. To derive the seasonal power relationship coefficients, the coefficients were related to degree of vegetation i.e., NDVI. It was found that monsoon season behaviour for sediment generation is significantly different from non-monsoon season. Hence, it was argued that the relationship between NDVI and USLE 'C' factor established by (De Jong, 1994) is only valid for non-monsoon periods.





FORMULATION OF HYDROLOGICAL AND SEDIMENT MODEL

5.1 Introduction

Scaling up runoff and sediment dynamics have been problematic because widely used models (e.g., SCS-CN, USLE, WEPP) were developed using small plot scale data which assumes that rainfall intensity is the main driving forces for causing runoff and sediment generation, and infiltration excess mechanism generates runoff (Tilahun et al., 2013). Even though it might be a realistic assumption for temperate regions where infiltration capacity is limited, However, in humid subtropical watersheds, runoff is produced mainly by saturation excess processes. Therefore, most of the developed models are not applicable for humid climates, where soils have a vast network of macropores, and rainfall intensities are typically less than the infiltration capacity (Dagnew et al., 2016; Guzman et al., 2013). Most of the previous models developed assume that runoff and sediment originate from all part of the watershed, while runoff is generated from saturated and degraded areas of the watersheds in humid hilly areas and runoff amount is a function of rainfall depth and antecedent soil moisture. A number of models are available now a days for the study of hydrology and soil erosion processes. However, these model often vary in terms of their input parameters, capability and complexity (Pandey et al., 2016). SWAT, WEPP, MIKE, etc. are widely accepted models according to literature. However, every model has few limitations and may not be suitable for other parts of the globe. The limiting factors depends on the intended application of their development, datasets used for their calibration and testing, For instance, SWAT model was developed for predicting the impact of management practices on hydrological behaviour of large agricultural watersheds (Arnold et al., 2012). However, it is not well suitable for event based high or low flow

simulations (Borah and Bera, 2003). WEPP is widely applicable for sediment yield estimation which requires a lot of field based parameterization (Flanagan et al., 2007). Therefore, the objective of this study is to develop a modified hydrology and sediment yield model for humid subtropical climates and evaluate its performance for two agroforestry watersheds, located in central part of India.

This chapter presents simple conceptual modelling approaches for water budgeting and suspended sediment load for an agroforestry watershed under humid sub-tropical climatic conditions. In the modified hydrology and sediment yield model, the hydrology model Rice Irrigation and System Evaluation (RISE) of (Dutta and Zade, 2003) with the erosion model of (Guzman et al., 2013) were improved and combined. The primary controlling variables affecting the hydrological and suspended sediment response of the watersheds have been identified from the experimental investigations discussed in the previous chapter. The functional relationships developed from the experimental evidence have been used in the modelling concept. Some of the physical parameters, observed from the *in situ* experiments conducted on the hillslope plot, have been used to calibrate the models.

5.2 Material and Methods

Accurate practical measurement of overland flow depth on a natural hillslope is difficult. Therefore, mathematical approximations of the overland flow governing equations and sediment generation mechanisms are considered here to characterize the processes on the landscape.

5.2.1 Model Development

Rice Irrigation System Evaluation (RISE) developed by (Dutta and Zade, 2003), is a physically based semi-distributed rainfall-runoff model which describes all the physically based processes involved in a rice agriculture and vegetated hillslope dominated watershed. The model is modified based on the functional relationships developed from the experimental evidence described in Chapter 2 and 3. Sediment model developed by (Tilahun, 2012) is also modified and combined with RISE model to conceptualize an integrated rainfall-runoff and sediment yield model for agroforestry dominated watersheds. A detailed formulation of each hydrological and sediment generation processes used in the model are described in next section.

5.2.1.1 Hydrology Model

Surface and sub-surface hydrologic processes have been conceptualized in Rice Irrigation System Evaluation (RISE) model for a watershed in tropical/subtropical regions. The model defines the dominant hydrological processes based on different distinct hydrological similarity classes (HSC) which is different than the hydrologic response unit (HRU). HRU's are the smallest spatial unit of the model, and lumps all similar land uses, soils, and slopes within a subbasin based upon user-defined thresholds which dilutes the unique hydrological behaviour of the land use /soil class. However, the delineation of the HSC approaches on unique hydrological processes based on the soil type distribution and land use / land cover type. For each HSC class, runoff generation processes have been conceptualized. For the present study, four distinct HSCs were delineated based on seven distinct type of land-use/land-cover types and soil classes. The four delineated classes are: (i) macropore dominated vegetated hillslope, (ii) paddy cultivation dominated agricultural lands, (iii) semi-impervious urban areas, and (iv) wetlands and permanent sinks. Various hydrological processes such as infiltration, overland flow, surface water budgeting, sub-surface water budgeting, and channel flow are described with physically based equations for each HSC as depicted in Figure 5.1. Macropore dominated processes have been conceptualized for HSC-1 while retention excess flow and hortonian infiltration excess overland flow have been conceptualized for HSC-2 and HSC-3 respectively. Water budgeting has been done for HSC-4. Subsurface storm flow processes are mathematically inter-coupled with infiltration processes. Lateral flow to the channel segment has been conceptualized following the steepest gradient method while the linearized channel routing process follows the kinematic wave approximation approach. In the present study, the concept of saturation excess overland flow mechanism based on the threshold rainfall seasonal characteristics is introduced in the model.

5.2.1.1.1 Infiltration Process

Macropore Dominated Vegetated Hillslope

Infiltration process in a vegetated hillslope is controlled by micropore and macropore flow mechanism in its subsoil formations (Sarkar and Dutta, 2015). However, in tropical/subtropical regions, subsurface flow mechanism is governed mainly by both the soil matrix and macropore networks as the monsoon season advances to its peak and have concentrated rainfall over a

short time span; though soil matrix flow primarily governs the infiltration rate during the onset of monsoon season.

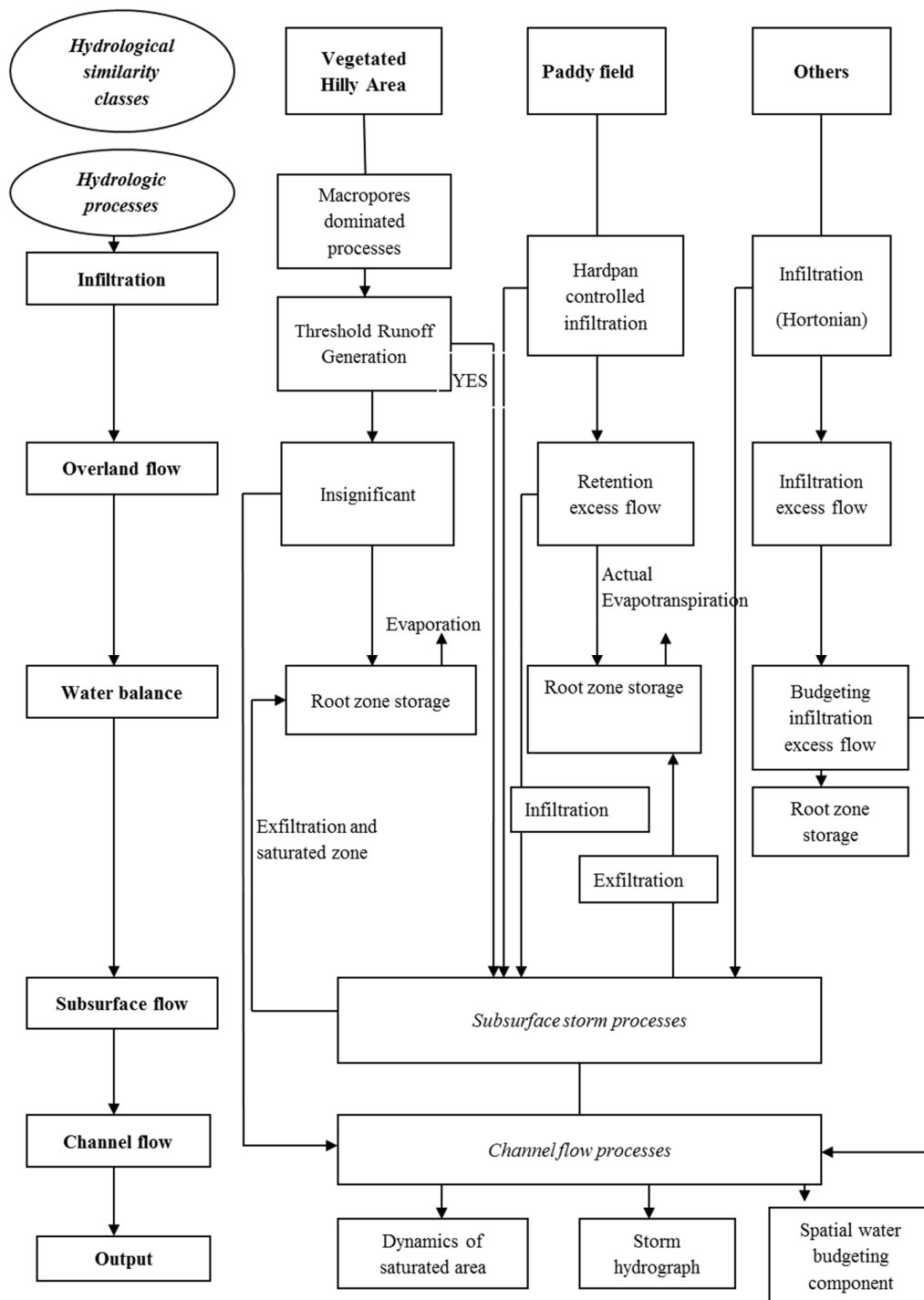


Figure 5.1: Flowchart of Water budgeting using RISE model

If the threshold rainfall depth of a vegetated hillslope is P_{thresh} , due to combined effect of micropores and macropores the resulting overland flow rate (R) can be expressed as Equation 5.1 and 5.2

$$R = 0, \text{ when } p \leq P_{thresh} \quad (5.1)$$

$$R = aP_{thresh} + b, \text{ when } p > P_{thresh} \quad (5.2)$$

where, p represents the storm rainfall depth, a and b are the coefficients derived in Section 3.3.2 for different land use / land cover classes.

Paddy Cultivation Dominated Agricultural Lands

The hardpan formation below the plow layer, typical in the paddy agricultural system, having a very low permeability (typically, 2–4 mm/h) inhibits the infiltration of ponded field water. A permeability factor has been introduced for defining this particular infiltration behaviour. If h is the retaining depth in the paddy field, h_1 and h_2 are the depth of plow layer and the depth of hardpan formation respectively, using the two-layer Green-Ampt model, the infiltration rate at the bottom of the lowest layer, i.e., the hardpan formation can be formulated as

$$f = \frac{k_1 k_2 (h_1 + h_2 + h + \psi_1)}{h_1 k_2 + h_2 k_1} \quad (5.3)$$

where ψ_1 is the suction pressure of the saturated plow layer; k_1 and k_2 are saturated hydraulic conductivities of plow layer and hard pan formations respectively. Value of k_2 can be obtained from the relation: $k_2 = k_1 / r$ where r is the degree of soil impermeability (dimensionless) due to the formation of hard pan layer.

Semi-impervious Urban Area

The dominant runoff generation mechanism in this type of area is a Hortonian infiltration excess runoff generation process. The infiltration rate for this case can be obtained by the analytical solution of one-dimensional Richard's equation for saturated soil horizon. This results in Philip's two-term infiltration equation, given as

$$f_c(t) = 0.5 S t^{-0.5} + A_0 \quad (5.4)$$

where, $f_c(t)$ is the potential infiltration rate (mm/h), S is the sorptivity and A_0 is the gravitational infiltration rate (mm/h).

5.2.1.1.2 Water budgeting

Macropore Dominated Vegetated Hillslope

The soil matrix primarily contributes storage of water in the root zone as the pore water in the macropore zone has limited resident time. If S_r be Paddy cultivation dominated agricultural

lands the subsurface storage at time t , the mass balance equation considering only evapotranspiration losses in the root zone can be expressed as

$$\frac{dS_r}{dt} = i - ET_{actual} + f_{ex} \text{ when } i \leq f_{max} \quad (5.5)$$

$$\frac{dS_r}{dt} = f_{max} - ET_{actual} + f_{ex} \text{ when } i > f_{max} \quad (5.6)$$

where ET_{actual} is the actual evapotranspiration rate (mm/h) and exfiltration rate from the soil subsurface is f_{ex} (mm/h). All the rainfall above the maximum storage capacity, S_{max} contributes to subsurface recharge.

Paddy Cultivation Dominated Agricultural Lands

The retention depth (h) of water in a paddy field can be formulated as

$$\frac{dh}{dt} = i - f - ET_{actual} - h_{ov} + f_{ex} \quad (5.7)$$

If h_{ret} is the maximum retention depth of the field the unit discharge of overspilled water in the field h_{ov} is related to the retention depth (h) as

$$h_{ov} = \frac{h - h_{ret}}{\Delta t} \text{ when } h \leq h_{ret} \quad (5.8)$$

otherwise,

$$h_{ov} = 0 \quad (5.9)$$

where, Δt is the simulation time interval. Retention depth (h) at the previous time step has been used in Equation 5.6 without any significant error in water budgeting. Thornthwaite's formula has been used to determine potential evapotranspiration from daily temperature data and subsequently multiplied by a seasonal crop coefficient, which can be taken in the range of 0.9-1 for the region, to obtain the actual evapotranspiration (ET_{actual}) for paddy fields.

Semi-impervious Urban Area

Water held in the subsurface layer of the semi-impervious zone has not been considered for water budgeting unless any exfiltration processes occurred. This is because in this area the water held in the subsurface zone is negligible.

Wetlands as permanent sinks

During monsoon season, wetlands receive precipitation and lateral subsurface flow. It loses some part of its storage as evaporation. At macro-scale hydrologic condition, it works as a locally hydrologic sink.

Subsurface Flow Component

Subsurface flow approximation given by (Beven and Kirkby, 1979) has been followed by the model to calculate the dynamics of the saturated excess zone and direct subsurface flow contribution to the channel. The soil moisture local deficit at each grid cell is expressed by the following equation for a spatially averaged recharge rate f ,

$$S_i = \bar{S} + m \left[\left(\lambda - \ln \frac{\alpha}{\tan \beta} \right) - (\ln T_0 - \delta) \right] \quad (5.10)$$

where, S_i is the local storage deficit per unit plane area (m), $\bar{S}$ is lumped storage deficit (m), m is a parameter controlling the rate of decline of transmissivity with increasing storage deficit (m), T_0 is the local saturated transmissivity (m²/s), two topographic constants λ and δ are defined as

$$\lambda = \frac{1}{A} \sum_j A_j \ln \left(\frac{\alpha}{\tan \beta} \right) \quad (5.11)$$

$$\delta = \frac{1}{A} \sum_j A_j \ln(T_0) \quad (5.12)$$

where, A is the total area of the catchment (m²), and A_j is the area associated with the point j (m²), $\tan \beta$ represents the local hydraulic gradient, is the area of the hillslope per unit contour length (m). Integration of the Equation 5.7 over the entire watershed gives the mean soil moisture deficit ($\bar{S}_t$) at time t and can be expressed as

$$\bar{S}_t = \bar{S}_{t-1} + (q_{t-1} - f) \Delta t \quad (5.13)$$

where q_{t-1} is the runoff per unit catchment area (m/s) at time $(t - 1)$, and f is the average recharge from paddy fields and vegetated hillslope (m/s), while Δt is the time interval used for the model simulation. For a particular grid exfiltration (f_{ex}) has been considered to be equal to the magnitude of S_i when the local deficit is negative.

The subsurface flow rate q_b per unit length (m²/s) to the channel is given as

$$q_b = \exp \left(-(\lambda - \delta) \right) \exp \left(-S_i/m \right) \quad (5.14)$$

The mean exfiltration rate (q_0) from saturated area can be obtained from

$$q_0 = \left(\frac{1}{A_t}\right) \int_{A_s} \{-S_i - \Delta t\} dA \quad (5.15)$$

where, A_s is the saturated area of the catchment (m^2).

5.2.1.1.3 Channel routing

Lateral Flow to the Channel Segments

The contributing area of each of the delineated channel segment is obtained based on “the steepest gradient” method from a digital elevation dataset. The total runoff generated in the contributing area of each channel segment from the three classes mentioned above reaches in the form of lateral flow to that segment. The lateral flow rate is given by

$$q_t = q_b + \frac{1}{A} \left[\int_{A_p} h_{ov} dA + \int_{A_{sm}} \left(-\frac{S_i}{\Delta t} + i \right) dA + \int_{A_{um}} R dA + \int_{A_{sh}} \left(-\frac{S_i}{\Delta t} + i \right) dA \right] + \left[\int_{A_{oh}} (i - f) dA \right] \quad (5.16)$$

where A_p , A_{sm} , A_{um} , A_{sh} , and A_{oh} are the areas of paddy fields (m^2), area in vegetated hillslopes giving saturation excess overland flow (m^2), infiltration excess overland flow area in vegetated hillslopes (m^2), saturation excess overland flow area in semi-impervious urban clusters (m^2), and infiltration excess overland flow area in semi-impervious clusters (m^2), respectively.

Linearized Channel Routing

Using kinematic wave approximation the continuity and momentum equations for a steep channel can be expressed as a second order partial differential equation, (Rajyalakshmi and Dutta, 2006) with the boundary conditions $Q(0, t) = s(t)$; $Q(x, 0) = 0$ and $Q(\infty, t) = 0$, as

$$\frac{\partial Q}{\partial t} = D \frac{\partial^2 Q}{\partial X^2} + C \frac{\partial Q}{\partial X} \quad (5.17)$$

where, Q is the discharge (m^3/s), D is the diffusion coefficient (m^2/s), C is the kinematic celerity (m/s), t is time (s), and X is the distance from the upstream end (m). If a uniformly distributed

lateral impulse enters the channel over a reach length $S = [(X = S) - (X = 0)]$, the solution of the Equation 5.12 becomes

$$Q'_i(S, t) = \int_0^S \frac{X}{2(\pi Dt^3)^{\frac{1}{2}}} \exp \left[-\frac{(X - Ct)^2}{4Dt} \right] dX =$$

$$\frac{D^{\frac{1}{2}}}{\pi t^{\frac{1}{2}}} \left\{ \exp \left[\frac{Ct^2}{4Dt} \right] - \exp \left[-\frac{(X - Ct)^2}{4Dt} \right] \right\} + \frac{c}{2} \left\{ \operatorname{erf} \left[\frac{Ct}{2(Dt)^{1/2}} \right] + \operatorname{erf} \left[\frac{S - Ct}{2(Dt)^{1/2}} \right] \right\} \quad (5.18)$$

where, erf represents an error function. The solution of Equation 5.13 at distance S , when a uniformly distributed lateral impulse of q_1 enters the channel over a reach length $\Delta X = [(X = X^*) - (X = 0)]$ with $X^* < S$, is obtained directly from Equation 5.19.

$$Q'_{f(\Delta X)}(S, t) = \frac{ql}{\Delta X} [Q'(S, t) - Q'(S - \Delta X, t)] \quad (5.19)$$

5.2.1.1.4 Input Data and Parameters

The model requires three different types of input dataset:

- i. Spatial data
- ii. Time series data
- iii. Parameters

The spatial input data includes digital elevation model (DEM), flow direction, flow accumulation, land use / land cover distribution, rainfall distribution, Macropore grid file, soil distribution, cumulative topographic index (CTI) and drainage basin map of the watershed. While, the precipitation, temperature, threshold rainfall depth, vegetation indices and power relationship coefficients are to be given as time series data. Apart from that, the model has to be provided with some input and calibration parameters defining rainfall-runoff and sediment transport processes. There are the three simulation results categories: (i) average budgeting components at the outlet of the basin, (ii) budgeting components at any computational cell location, and thus the spatial distribution can be obtained, and (iii) budgeting components for all the computational cell location at any time step to obtain the spatiotemporal distribution.

Apart from the spatial and temporal data file, some input and calibration parameters are to be given for the simulation. They are listed with their corresponding units and a brief description in Table 5.1.

Table 5.1: Input data and model parameters

Parameter type	Name	Source
Static	Topography and Basin Characteristics	SRTM, CGIAR
	Soil type distribution	NBSS&LUP, India
	Soil parameters	NBSS&LUP, India
	Land use classes	Landsat Imagery
	Average surface storage in paddy field (h)	Calibration parameter
	Degree of impermeability of hardpan formation (r)	Calibration parameter
	Minimum storing depth in macropores (S_{max})	Calibration parameter
Dynamic	Exponential transmissivity decay function (m)	Calibration parameter
	Natural logarithm of transmissivity saturated soil profile ($\ln T_0$)	Calibration parameter
	Initial saturated topographic index (TI)	SRTM, CGIAR
	Diffusion coefficient and celerity (C, D)	Computed model parameters
Time Series	Daily observed stage data	CWC, India
	Rainfall distribution	IMD, Pune, India
	Temperature data	IITM, Pune, India
	NDVI, Fraction of Vegetation cover, β	MODIS NDVI Product
	Threshold Rainfall Depth	Computed Rainfall Characteristic
	a_s, a_t	Calibration parameter

5.2.1.2 Sediment Model

The runoff generation process in hydrology model discussed in Section 5.2.1.1, is primarily modelled by seasonal threshold rainfall depth concept. Not only the storm events characteristics affect the sediment generation from the watershed landscape; surface runoff generation processes significantly control the erosion processes in watersheds. In sediment model, the sediment erosion estimation is based on variable source area concept. The source of runoff, interflow, and baseflow are identified based on the landscape topography and land cover class. In sediment module of hydrology model, the watershed is divided into three hydrological zones (Figure 5.2). First, two surface runoff zones consist of the area near stream or valley which becomes saturated during wet period and cause saturation excess runoff, and the degraded or fallow hillslopes with threshold excess runoff mechanism (the area between red and green boundary in Figure 5.3).

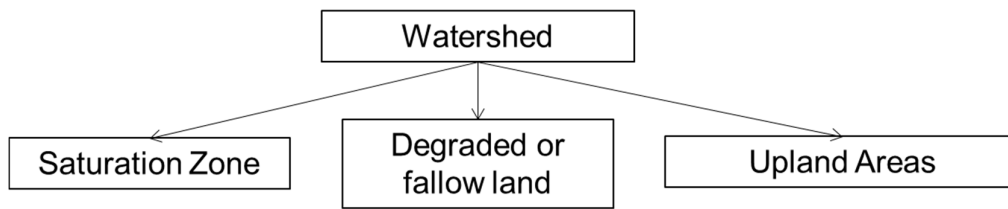


Figure 5.2: Watershed hydrological zones in sediment model

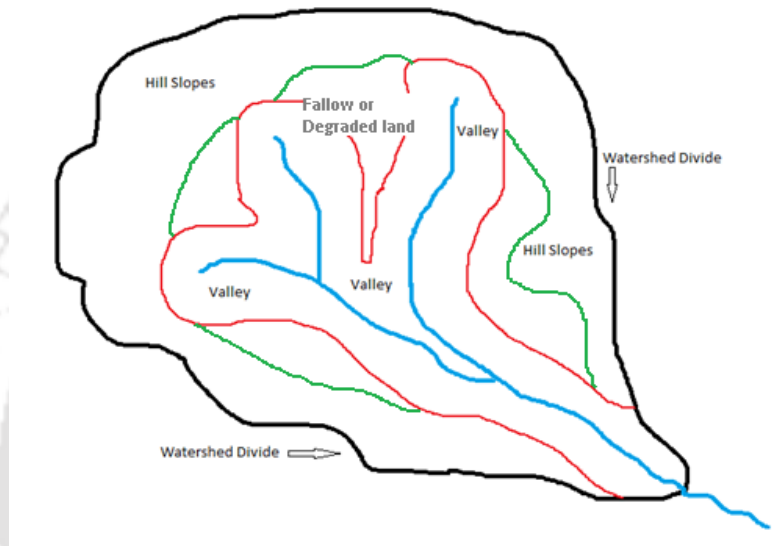


Figure 5.3: Conceptual variable source runoff generation in agroforestry watersheds

The remaining upland areas are the third zone as shown in Figure 5.3, which assumes that rainfall infiltrates and converts either into interflow or baseflow. The fluxes from the saturated area and the degraded area can be obtained from hydrology model outputs (Dutta and Zade, 2003). It is assumed that the erosion originates from only through the runoff producing zones (saturated and degraded areas). Erosion from uplands is assumed to be negligible because of insignificant surface runoff generation.

The suspended sediment concentration can be expressed as a function of surface runoff and a coefficient dependent on watershed characteristics such as slope, manning's roughness coefficient, slope length, and the sediment depositability (Hairsine and Rose, 1992a). In the sediment model, the processes are described for each runoff producing zone due to their different sediment generation and transport characteristics. Figure 5.4 shows the flowchart of the methodology adopted for soil erosion modelling.

Saturation Zone or Valley

The valley or area near the stream is likely to have variable vegetation cover throughout the year. Before the onset of monsoon, the vegetation cover is less, the maximum concentration of sediment carried by the stream is equal to the transport limiting capacity C_t (gm/L) of the runoff depth which can be obtained from Equation 5.20.

$$C_t = a_t q_{sat}^n \quad (5.20)$$

where, q_{sat} (mm/day) is the runoff depth per unit area, a_t ($\text{gL}^{-1}\text{mm}^{-n}\text{day}^{-n}$) is a calibrating parameter which depends on function of slope, manning's roughness coefficient, slope length, and sediment deposit ability. a_t becomes independent of flow rate with the increase in water depth and can be taken as a constant. n is the exponent that can be assumed as 0.4 due to a linear relationship between sediment concentration and flow velocity (Yu et al., 1997).

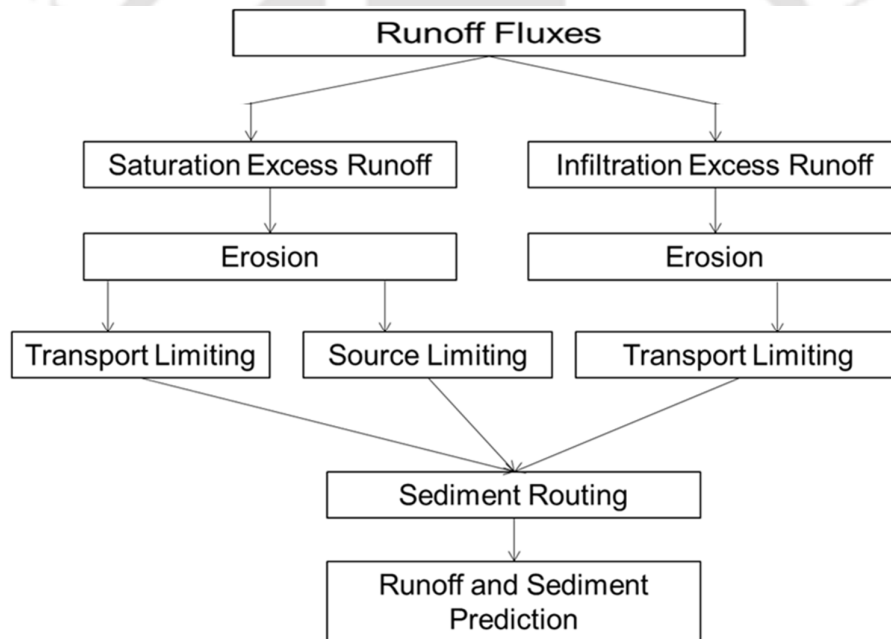


Figure 5.4: Flowchart of the processes for soil erosion modelling

As the monsoon proceeds, the vegetation cover increases in saturated zone and sediment erosion decreases due to resistance in runoff offered by the vegetation cover and less shear stress. In that case, the sediment concentration becomes source limiting, C_s (g/L), Equation 5.21:

$$C_s = a_s q_{sat}^{0.4} \quad (5.21)$$

where, a_s is the source limit and is independent of the flow rate.

Thus the sediment erosion can be modelled with the effect of vegetation cover over the saturated area which causes both transport limit and source limiting sediment concentration. H , defined as the fraction of the sediment producing area which depends on the total vegetation cover present at the time of runoff generation. H can be obtained with the help of Normalized Difference Vegetation Index ($NDVI$) (Ghorbani et al., 2012). $NDVI$ and H are dimensionless indices computed as Equation 5.22.

$$H = 1 - \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (5.22)$$

$$\left(NDVI = \frac{NIR - RED}{NIR + RED} \right)$$

where, NIR = spectral reflectance in near infrared band, RED = spectral reflectance in the red band, $NDVI_{min}$ is minimum $NDVI$ of the annual time series. Sediment erosion by combining two vegetation cover dependent processes can be written as Equation 5.23:

$$C_r = C_s + H (C_t - C_s) \quad (5.23)$$

Combining Equation 5.23 with equation 5.21 and 5.22, the concentration becomes

$$C_r = [a_s + H (a_t - a_s)] q_{sat}^{0.4} \quad (5.24)$$

The yield, Y_l ($gm^{-2}day^{-1}$) can be obtained by multiplying Equation 5.24 by relative saturated area A_l and saturated runoff volume q_{sat} as in Equation 5.25.

$$Y_l = A_l q_s [a_s + H (a_t - a_s)] q_{sat}^{0.4} \quad (5.25)$$

Degraded Area or Fallow Land

The fallow land is also likely to have a variable degree of vegetation cover. Figure 5.6 shows the effect of degree of crop contact cover on sediment concentration at transport capacity of runoff depth. To model sediment erosion for the degraded area, sediment concentration at transport capacity is computed as transport limiting from degraded area as from Equation 5.26.

The transport limit, C_t :

$$C_t = a_t q_d^{0.4} \quad (5.26)$$

Considering an exponential decay function, the parameter, β , is used as an exponent to model the trend shown in Figure 5.6 (Equation 5.27).

$$\bar{C}_t = C_t^\beta \quad (5.27)$$

By combining Equation 5.26 and Equation 5.27,

$$\bar{C}_t = (a_t q_d^{0.4})^\beta \quad (5.28)$$

The yield, Y_2 ($\text{gm}^{-2}\text{day}^{-1}$) can be obtained by multiplying Equation 5.28 by relative degraded area A_2 and degraded area runoff volume q_d as shown in Equation 5.29.

$$Y_2 = A_2 q_d (a_t q_d^{0.4})^\beta \quad (5.29)$$

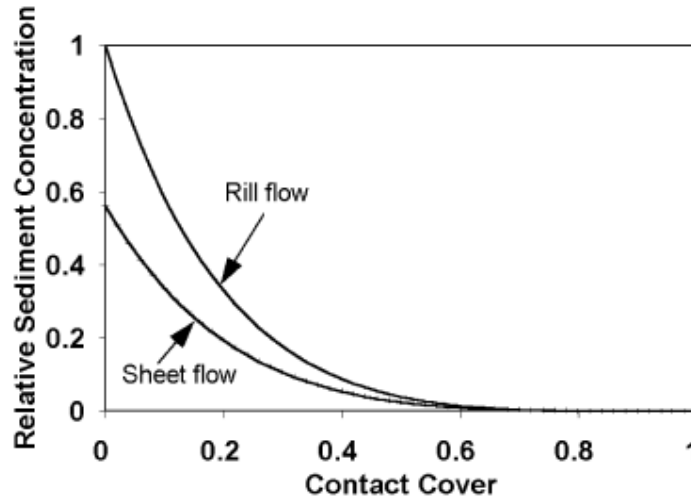


Figure 5.5: Effect of vegetation cover on sediment concentration (Source: Siepel et al., 2002)

Now, the total sediment and sediment concentration can be obtained by addition of both the sediment yields produced by the saturated and the degraded area (Equation 5.25 and Equation 5.29).

$$Y = A_1 q_{sat} [a_s + H(a_t - a_s)] q_{sat}^{0.4} + A_2 q_d (a_t q_d^{0.4})^\beta \quad (5.30)$$

Finally, the total concentration (C) may be expressed as Equation 5.31:

$$Q_s = \frac{Y}{(A_1 + A_2)} \quad (5.31)$$

5.2.2 Model Calibration and Performance Evaluation

5.2.2.1 Watershed Data

Daily discharge hydrograph and sediment concentration values have been calibrated with the hydrology model and sediment model of Equation 5.31, respectively. The location, brief description and data used in the model are summarized in Table 5.2. The data for the period from 1990-1995 for Baronda watershed was used for calibration, the period from 1996-2000 for Baronda watershed and 2006-2011 for Kesinga watershed were used for validation of the model.

5.2.2.2 Methods of calibration and validation

Five model parameters were calibrated for the hydrology model (Table 5.3). Initial values of calibrating parameters were based on (Rajyalakshmi and Dutta, 2006). These initial values were adjusted manually for the Baronda watershed. The available daily discharge and sediment concentration data for Baronda watershed at outlet Rajim has been used for this purpose. By conducting a set of trial simulations and comparisons between observed discharge hydrograph and simulated discharge hydrograph, the calibration parameters were improved to achieve the best match or goodness-of-fit between the simulated and observed flow characteristics.

In the sediment model, daily sediment load was computed by Equation 5.30 and then divided by the total area using Equation 5.31 to compute the daily sediment concentration. In the sediment model, two calibration parameters consisting of the constants for saturated and degraded areas are a_s and a_t , respectively. These constants are changed manually to match the observed and simulated daily sediment concentration as close as possible.

Table 5.2: Location, description and data used in the model for watersheds

	Baronda Watershed	Kesinga Watershed
Area Description		
Watershed Area (km ²)	3025	11112
Location	82° E and 20°40' N	83°13' E and 20°11' N
Mean Elevation (m a.s.l.)	270-500	240
Mean Annual Rainfall (mm)	1200	1360
Data Availability		
Precipitation (mm/day)	1990-2000	2006-2011
Discharge (m ³ /sec)	1990-2000	2006-2011
Sediment Concentration (gm/L)	1990-2000	-

Soil Moisture (mm/day)	-	2006-2011
NDVI	1990-2000	2006-2011

Table 5.3: Calibration Parameters, ranges and Calibrated Values for Baronda watershed

Calibration Parameter	Calibrated Value (Monsoon)	Calibrated Value (Non-monsoon)	Range
Average surface storage in paddy field (h)	0.2 m	0.2 m	0-0.5 m
Degree of impermeability of hardpan formation (r)	1200	4000	700-5000
Minimum storing depth in macropores (S_{max})	0.1 m	0.1 m	0.03-0.9 m
Exponential transmissivity decay function (m)	0.1	0.035	0.002-0.4
Natural logarithm of transmissivity of saturated soil profile ($\ln T_0$)	0.001	0.01	0-1.6
a_t, a_s (in $gm L^{-1} mm^{-0.4} d^{0.4}$)	0.008, 0.003	0.005, 0.007	0.001-0.1

During model calibration and validation period, the Nash-Sutcliffe coefficient (NSE) (Equation 5.32 and coefficient of determination (R^2) (Equation 5.33) with least square linear regression were used to evaluate the performance of the model.

$$NSE = 1 - \frac{\sum_{i=1}^n (q_{obs(i)} - q_{sim(i)})^2}{\sum_{i=1}^n (q_{obs(i)} - q_{obs(mean)})^2} \quad (5.32)$$

$$R^2 = \frac{n(\sum q_{obs} q_{sim}) - (\sum q_{obs})(\sum q_{sim})}{\sqrt{[n \sum q_{obs}^2 - (\sum q_{obs})^2][n \sum q_{sim}^2 - (\sum q_{sim})^2]}} \quad (5.33)$$

where, NSE is Nash-Sutcliffe efficiency, $q_{sim(i)}$ is simulated discharge, $q_{obs(i)}$ is observed discharge and $q_{obs(mean)}$ is average observed discharge. The NSE coefficient for the sediment concentration can be calculated similarly by replacing the discharge (q) by sediment concentration (C). Coefficient of determination (R^2) defines the degree of correlation between simulated and observed data whereas NSE determines the relative amount of the residual variance compared to the observed data difference (Moriassi et al., 2007). During calibration, parameters are adjusted and examined for that lead in R^2 values and NSE close to 1.

5.3 Results and Discussion

The simulations were performed from 1990 to 2000 for Baronda watershed and from 2006-2011 for Kesinga watershed. The model calibration was done for the period from 1990-1995 at Baronda watershed. The calibration parameters, their ranges and calibrated values are given in Table 5.3. Figure 5.6 and 5.7 shows the observed discharge hydrograph and sediment concentration for the year 1990 at Baronda watershed outlet compared with simulated discharge hydrograph and sediment concentration, respectively. The comparison of predicted and observed discharge for the Baronda watershed during other years of calibration period are shown in Appendix B-1. The goodness of fit Nash-Sutcliffe coefficient (NSE) and coefficient of determination R^2 for the hydrology and sediment prediction are presented in Table 5.4.

The hydrology model (Figure 5.6) and the sediment model (Figure 5.7) performed quite well (Table 5.4) for Baronda watershed during the calibration period. The model calibration suggests that the model has performed well in capturing the trend of hydrograph and peak discharge and sediment concentration values. The runoff response during summer season could not be captured by the model due to the missing rainfall data. The R^2 ranges in between 0.66 to 0.86 and NSE varies from 0.25 to 0.74 for discharge prediction. The low statistics for sediment model is due to the under and over-predictions in the hydrology model being transmitted to the sediment concentration simulation.

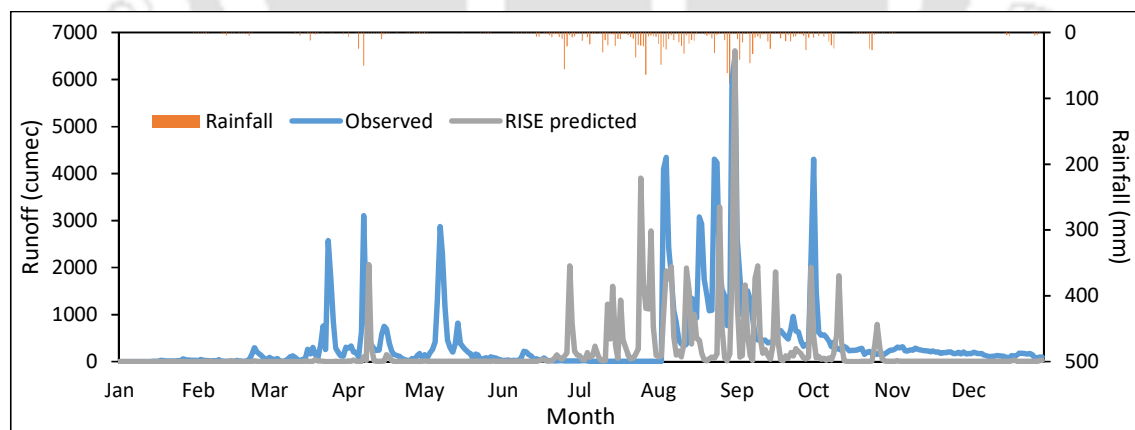


Figure 5.6: Hydrological model (RISE) simulated discharge calibration with observed discharge at Baronda watershed for the year 1990

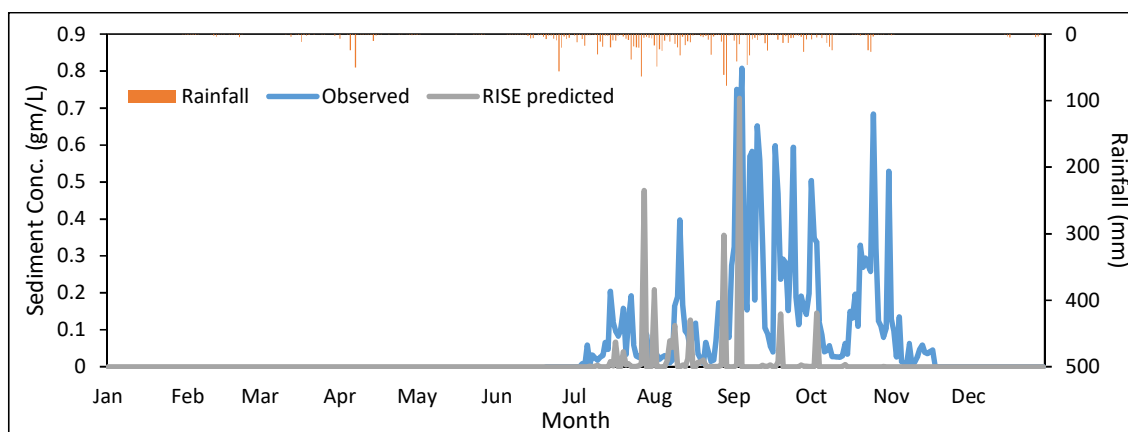


Figure 5.7: Hydrological model (RISE) simulated with observed sediment concentration during calibration at Baronda watershed for the year 1990

Table 5.4: Runoff and Sediment concentration simulation efficiency as evaluated by statistical measures for Baronda watershed during calibration

Year	Annual Rainfall	Runoff Prediction		Sediment Prediction	
	(mm)	R^2	NSE	R^2	NSE
1990	881	0.85	0.72	0.65	0.44
1991	1306	0.86	0.67	0.62	0.17
1992	967	0.85	0.74	0.35	-0.05
1993	1112	0.72	0.48	0.67	-0.99
1994	1569	0.75	0.66	0.16	0.64
1995	1115	0.66	0.25	0.37	0.6

The model was validated for the period from 1996-2000 for Baronda watershed and from the year 2006-2011 for Kesinga watershed. The sediment concentration data for Kesinga watershed was unavailable. Hence validation of sediment model was performed only for Baronda watershed. Figure 5.8 and 5.9 shows the comparison between observed and simulated discharge and sediment concentration, respectively for Baronda watershed during the year 1990. A comparison of predicted vs observed discharge and sediment concentration for the Baronda watershed for the year 1996-2000 are shown in Appendix B-2.

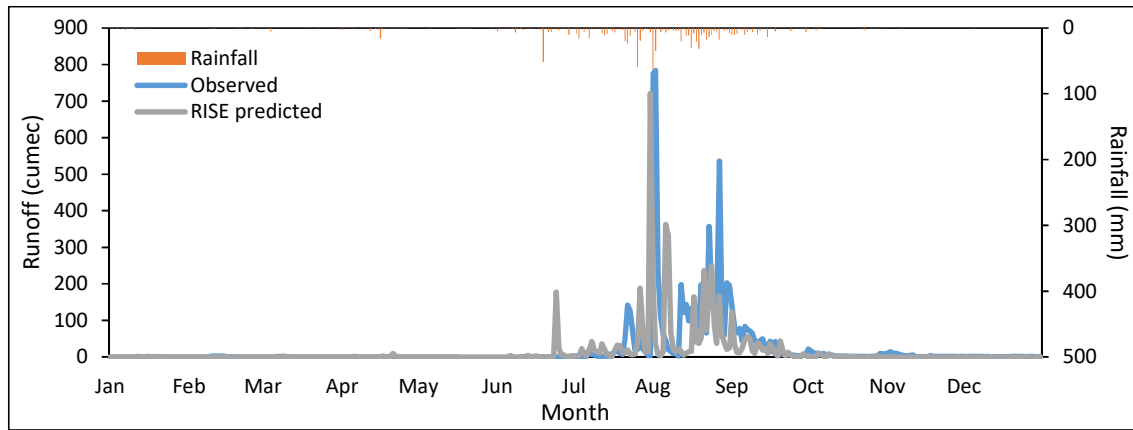


Figure 5.8: Hydrological model (RISE) simulated discharge validation with observed discharge at Baronda watershed for the year 1996

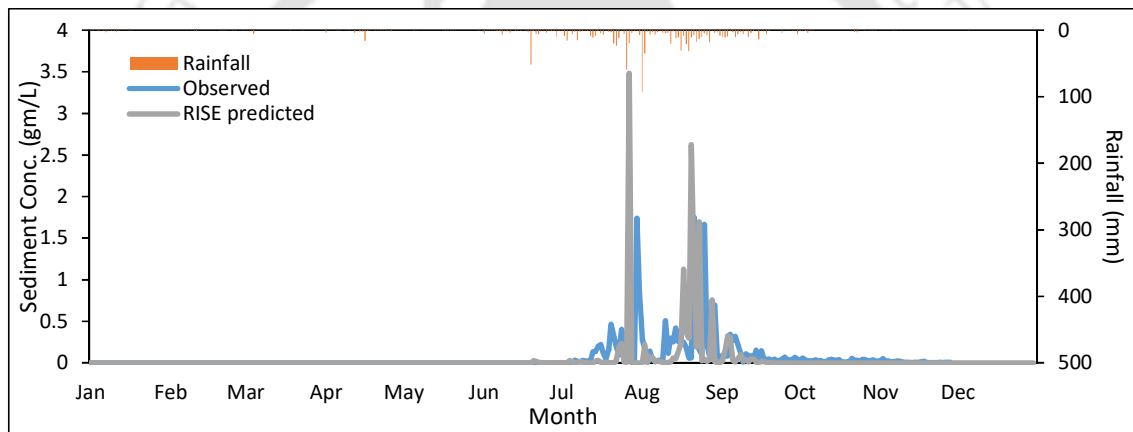


Figure 5.9: Hydrological model (RISE) simulated with observed sediment concentration during validation at Baronda watershed for the year 1996

The simulated discharge comparison with observed discharge for the year 2006 at Kesinga watershed is shown in Figure 5.10. The comparison for remaining validation years from 2007 to 2011 are shown in Appendix B-3. The goodness-of-fit in Figures 5.8, 5.9 and 5.10 was confirmed by the performance statistics.

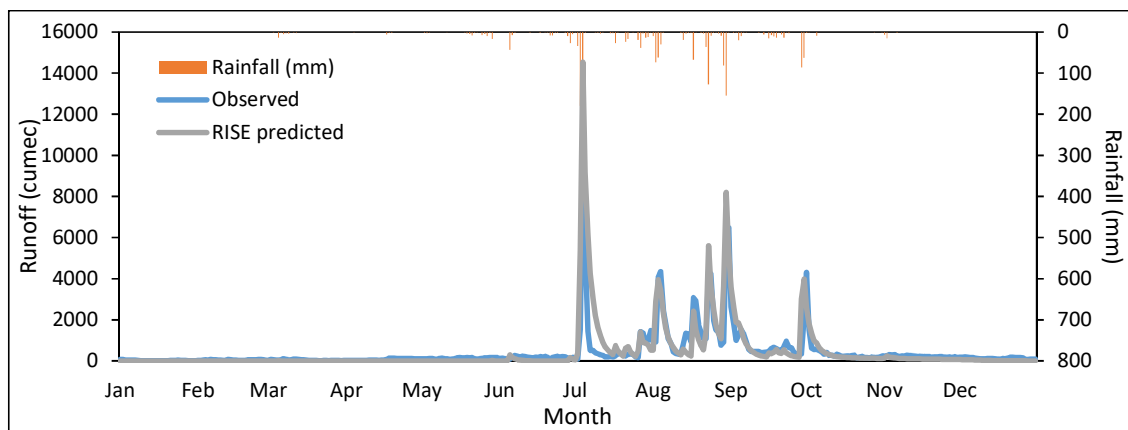


Figure 5.10: Hydrological model (RISE) simulated discharge validation with observed discharge at Kesinga watershed for the year 2006

The R^2 and NSE values for Baronda watershed for the year 1996 (Table 5.5) were 0.8 and 0.69, respectively for runoff prediction and 0.58 and 0.55 for sediment concentration, indicating that the model has reasonably captured the watershed response to rainfall. For the case of the Kesinga watershed, the R^2 and NSE values were 0.82 and 0.69, respectively for runoff prediction for the year 2006 (Table 5.6).

Table 5.5: Runoff and Sediment concentration simulation efficiency as evaluated by statistical measures for Baronda watershed during validation

Year	Annual Rainfall	Runoff Prediction		Sediment Prediction	
	(mm)	R^2	NSE	R^2	NSE
1996	931	0.8	0.69	0.58	0.55
1997	1185	0.72	0.57	0.53	0.2
1998	735	0.64	0.38	0.45	0.16
1999	777	0.84	0.59	0.1	0.31
2000	815	0.93	0.89	0.42	0.18

Table 5.6: Runoff and Sediment concentration simulation efficiency as evaluated by statistical measures for Kesinga watershed during validation

Year	Annual Rainfall	Runoff Prediction	
	(mm)	R^2	NSE
2006	1917	0.82	0.69
2007	1548	0.85	0.68
2008	1482	0.81	0.57
2009	1537	0.84	0.76
2010	1287	0.86	0.75
2011	1037	0.84	0.66

In spite of the acceptable statistics during the validation period, the model overestimated low flows and under-predicted high flows for Baronda watershed (Figure 5.8). However, the sediment concentration is over-predicted by the model (Figure 5.9). The observed low sediment concentration might be due to the bunds installed in the watershed that trapped the sediment effectively. The underestimation of peak flows is likely caused by the expansion of runoff producing areas during heavy rainfall storm events of prolonged duration. In summary, the hillslope and sediment model can simulate the discharge and sediment concentration patterns quite well in two agroforestry watersheds.

5.4 Conclusions

An integrated hydrology and sediment model was developed to simulate runoff and sediment concentrations at two agroforestry watersheds. The model was improved with the inclusion of seasonal threshold rainfall concept and functional relationship with NDVI. The model requires very limited input data such as rainfall, temperature, topographical and physiographical parameters of the watershed. The model needs very few calibration parameters and is well suited for Indian conditions where data are sparsely available. The model performed satisfactory well in capturing the variability in discharge and sediment concentrations, and the proportion of runoff and sediment source areas could also be captured using the modified *RISE* model. However, at present modified *RISE* model is incapable to adapt the spatial variations of NDVI and runoff–sediment power relationship and it is better suited for watersheds with agriculture and forest land use. Modified *RISE* model uses Thornthwaite method for the calculation of potential evapotranspiration which only considers the mean monthly temperature and represents the integrated effects of radiation and other controls (wind, humidity, vegetation, soil, etc.). Temperature based methods were developed in the mid-latitude continental region (i.e. mid-western USA) as a climatic index, not as a method for calculating ET and may include errors in estimation of actual evapotranspiration.



MODEL COMPARISON AND SENSITIVITY ANALYSIS

6.1 Introduction

Watershed models are the conceptual, simplified and efficient representation of a watershed response. The primary use of the watershed model is to simulate the complex runoff and associated processes that affect the surface and subsurface hydrology, soil erosion and nutrient transport in watersheds. Modelling framework consists of four mandatory phases. The first phase includes the data collection and its analysis; the second phase is development/selection of a model suitable for local conditions; in the third step, calibration of the model is performed; and the last phase is model validation and evaluation (Gao et al., 2016). The performance of different models can be different because of unique methods of hydrological process description and parameterization. Models are often adjusted according to the specific study area due to the lack of local data such as soil properties. Therefore, it is always desirable to choose a best suitable model for the specific study region. Due to the lack of reference hydrological modelling studies in agroforestry watersheds of central India, only a few statements on the performance of RISE model can be made. To provide more reliable and authentic statements on the performance of the developed model, this study investigates and compares the applicability of modified RISE model and SWAT model over two agroforestry watersheds located in central part of India. This chapter presents the overview of hydrological processes involved in SWAT model. The comparative analysis of hydrological and sediment response of both the models are discussed. Furthermore, the sensitivity of basic controlling parameters of the RISE model has been studied.

6.2 Material and Methods

6.2.1 Study Area and Data

Two agroforestry watersheds were considered to assess the applicability and comparison of both the models. The study watersheds include the Baronda watershed (with a drainage area of 3025 km² and mean annual rainfall of 1200 mm) and the Kesinga watershed (with a drainage area of 11112 km² and mean annual rainfall of 1360 mm). The 14% of the Baronda watershed area lies under rainfed paddy cultivation, whereas 83% area is covered under forest (Table 6.1). About 61% area of Kesinga watershed falls under agriculture land use land cover class, while 36% under forest. The detailed description of the watersheds is given in Chapter 4.

Table 6.1: Fractional area under different land use for both the watersheds. (in %)

LULC Class	Baronda	Kesinga
River	0.78	1.62
Wetland	1.93	0.11
Agriculture	13.25	61.05
Forest	83.53	36.49
Urban	0.06	0.43
Barren	0.45	0.31

Digital elevation model (DEM) of the study watersheds with a resolution of 90 m were acquired from the Shuttle Radar Topography Mission (SRTM) (www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1). Land use data with a resolution of 30 m for the year 2003 and 2005 for Baronda and Kesinga watershed, respectively were derived from the Landsat ETM+ satellite images. The soil properties for the study watersheds were obtained from SWAT database (swat.tamu.edu/software/links/india-dataset/). The rainfall and temperature data was procured from India Meteorological Department. The discharge and sediment concentration data for the study period was obtained by central water commission, India.

6.2.2 SWAT Model Overview

SWAT is a semi distributed, physically based, continuous basin scale hydrological model designed to predict the effect of land management practices on water, sediment, and water quality in complex watersheds (Arnold et al., 1998; Golmohammadi et al., 2014). The major model components comprise weather generation, hydrology, sediment, plant growth and water quality subroutines. Watersheds are divided into sub-basins based on junctions or outlet points along the stream network. Each sub-basin is then divided into hydrologic response units

(HRUs), which are areas with like soil type, land use, slope, and management practices. Surface runoff, subsurface runoff, groundwater flow, evapotranspiration, crop growth, nutrient and sediment yields are calculated for each HRU and routed to the outlet as sub-basin outputs. The hydrologic module in SWAT consist of infiltration, evapotranspiration, surface runoff, lateral flow, percolation/seepage, aquifer contribution and recharge from surface water bodies. HRUs are not spatially defined within the subbasins; although they represent percentages of total subbasin area. Hence, SWAT includes both spatially distributed parameterization at the subbasin scale and lumped parameterization at the HRU scale (Gassman et al., 2007). Water balance is the primary driving force behind the plant growth, sediments and nutrients processes in SWAT. SWAT uses the SCS-CN method for runoff estimation and Modified Universal Soil Loss Equation (MUSLE) to predict the sediment yield. A large number of input parameters are required such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, relative humidity, soil properties, crops, hydrographic properties and management practices, which complicates model parameterization and calibration. More detailed descriptions of the model processes are available in (Arnold et al., 1998). The SWAT model performance was found promising for continuous simulations in predominantly agricultural watersheds on the basis of assessment of 11 watershed scale hydrologic and nonpoint-source pollution models (Borah and Bera, 2003). Grusson et al. (2015) assessed the capability of SWAT model over an alpine watershed to simulate snow, snowmelt and streamflow. They highlighted that hydrological simulation results may be improved by setting-up of the elevation bands. Ayivi and Jha (2018) employed SWAT model to determine the effect of future landuse change on runoff and water yield. In spite of wide acceptability and application of SWAT model, evaluation and comparison of SWAT-based hydrological models was compared with twelve different modelling datasets (Asl-rousta et al., 2018).

6.2.3 Calibration and Model Performance Evaluation

Model calibration is essential to achieve better hydrological simulation results. Observed daily discharge and sediment concentration data at Baronda watershed outlet for the period of 1990 to 1995 was used to calibrate both the models. Two years data was used as a warming up period for SWAT model. The calibration of RISE model is discussed in Chapter 5. For SWAT, seven sensitive parameters were identified for model calibration based on the previous studies (Devkota and Gyawali, 2015; Ouyang et al., 2010; Shrestha et al., 2016; Zhang and Nearing, 2005).

Table 6.2: Calibrated values of the adjusted parameters for calibration of the SWAT model

Parameter	Calibrated Value	Range
Soil evaporation compensation factor	0.98	0.01-1.00
Initial soil water storage expressed as a function of field capacity water content	0.95	0.01-1.00
SCS runoff curve number for antecedent moisture condition type II	78	40-90
Manning's n value for the main channel	0.13	0-0.3
Manning's n value for overland flow	0.15	0-0.3
Groundwater revap coefficient	0.02	0.001-0.1
Surface runoff lag coefficient	0.2	0-4.0

Of these seven parameters, curve number and soil water storage is related to soil infiltration and soil moisture, surface runoff lag coefficient is related to surface runoff, groundwater revap is related to water movement from shallow aquifer into the unsaturated zone, and Manning's roughness coefficient are related to flow routing. The default range and calibrated values of these parameters are given in Table 6.2.

The performance evaluation of the models were based on the agreement of the overall shape of the time series of discharge and sediment concentration together with the peak value comparison and the value of the goodness-of-fit measures such as coefficient of determination (R^2) and the Nash efficiency (NSE) (Moriassi et al., 2007; Neitsch et al., 2009; Zhang et al., 2016).

$$NSE = 1 - \frac{\sum_{i=1}^n (q_{obs(i)} - q_{sim(i)})^2}{\sum_{i=1}^n (q_{obs(i)} - q_{obs(mean)})^2} \quad (6.1)$$

$$R^2 = \frac{n(\sum q_{obs} q_{sim}) - (\sum q_{obs})(\sum q_{sim})}{\sqrt{[n \sum q_{obs}^2 - (\sum q_{obs})^2][n \sum q_{sim}^2 - (\sum q_{sim})^2]}} \quad (6.2)$$

where, NSE is Nash-Sutcliffe efficiency, $q_{sim(i)}$ is simulated discharge, $q_{obs(i)}$ is observed discharge and $q_{obs(mean)}$ is average observed discharge. The Nash-Sutcliffe efficiency coefficient (NSE) ranges between $-\infty$ and 1. It states a perfect match between observed and predicted values when $NSE = 1$ (Equation 6.1). Values in the range of 0 and 1 indicates acceptable levels of performance, whereas values less than 0 signifies that the model's simulated values are no better than the observed mean values. A values less than 0 is not acceptable. NSE determines the relative amount of the residual variance compared to the observed data difference whereas coefficient of determination (R^2) which ranges between 0 and 1, defines the degree of correlation between simulated and observed data (Moriassi et al., 2007). Usually, $R^2 > 0.5$ is considered acceptable in hydrological studies. During calibration, parameters are adjusted and examined for that lead in R^2 values close and NSE to 1.

6.2.4 RISE model Sensitivity Analysis

The RISE model was improved by integrating with threshold rainfall depth runoff generation mechanism and effect of vegetation on runoff and sediment generation process. To analyze the sensitivity of these two complex phenomenon on runoff and sediment response of the agroforestry watersheds, two calibration parameters were selected, threshold rainfall depth and NDVI. Total ten (five for each parameter) model simulations were performed by fluctuating the calibrated values. Threshold rainfall depth was changed by 5 mm in each of 5 simulations, while keeping NDVI constant. In next five simulations, NDVI values were changed by 0.1 with unaltered calibrated rainfall threshold depth. The statistical analysis was then performed to assess the sensitivity of these parameters towards runoff and sediment response obtained by RISE model.

6.3 Results and Discussion

6.3.1 Model Performance Evaluation

Daily observed discharge and sediment data at Baronda watershed from 1990 to 1995 was used for calibration, and the remaining data from 1996-2000 at Baronda watershed outlet and from 2006-2011 at Kesinga outlet were used to validate the model performance.

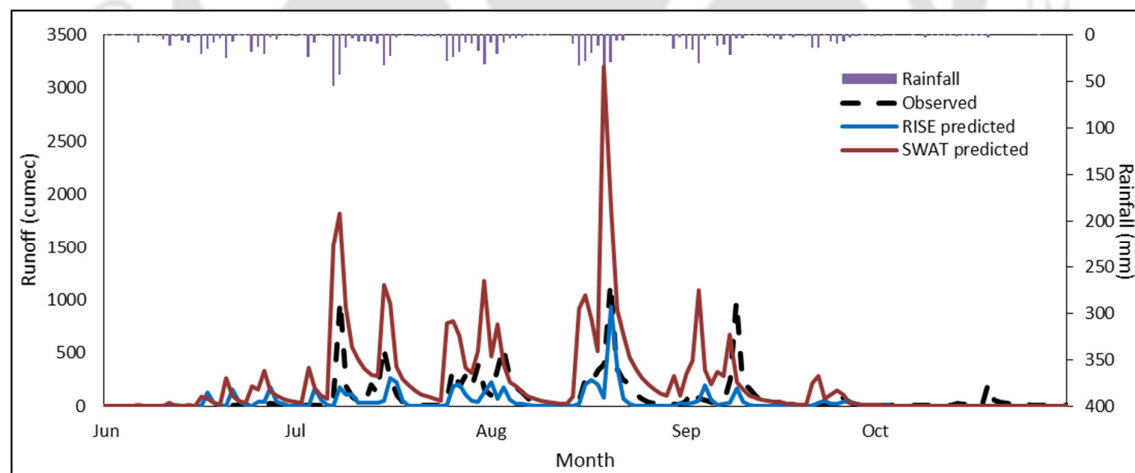


Figure 6.1: Daily observed and simulated discharge by RISE and SWAT for the calibration year 1993

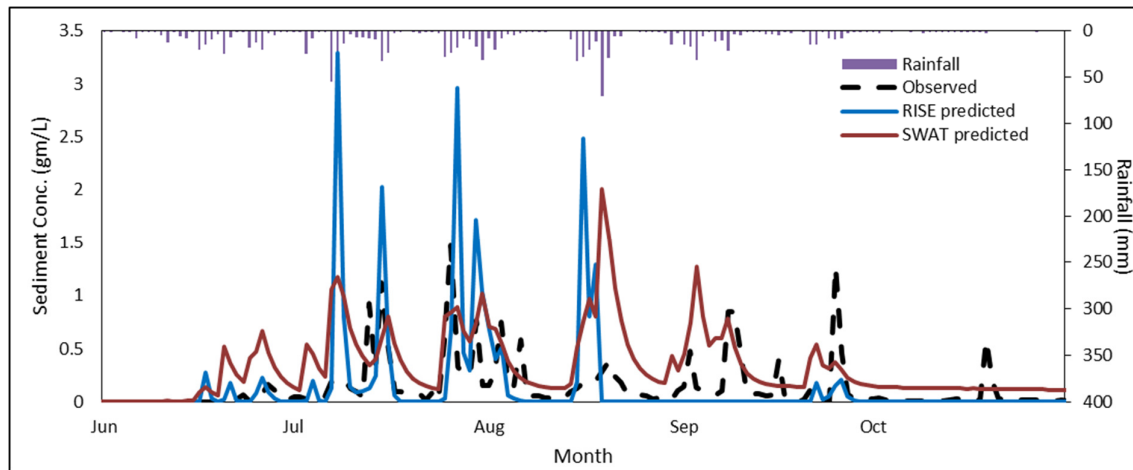


Figure 6.2: Daily observed and simulated sediment concentration by RISE and SWAT for the calibration year 1993

The scatter plots of the observed and simulated daily discharge and sediment concentration for the two models for year 1993 (2 year warm-up period in SWAT) are shown in Figure 6.1 and 6.2, respectively. Clearly, both the models showed acceptable fluctuations with the observed data. However, SWAT overestimated the discharge and underestimated the sediment concentration rate. On the basis of the visual analysis of the observed and predicted runoff and sediment concentration (Figures 6.1 and 6.2), the overall simulation results of RISE model appears to be reasonably good. SWAT outperformed RISE for peak flows for almost all the storm events. Borah and Bera (2003) reported that one of the flaws of physically-based models is the low flow prediction. While, in RISE model, the low flow variations are very well captured due to the threshold rainfall depth runoff generation concept (Figure 6.1). However, the overall sediment concentration results of RISE and SWAT model compared to observe time series appears good during calibration period. The results of RISE and SWAT were compared statistically by goodness-of-fit measures. R^2 for discharge prediction by RISE model during calibration period varies from 0.75-0.85, while for SWAT model the range was 0.25-0.75. Similarly, the R^2 values provided by RISE were better than those provided by SWAT for sediment concentration (Table 6.3).

Table 6.3: Performance evaluation of RISE and SWAT model for Baronda watershed

Year	Annual Rainfall (mm)	Discharge Prediction				Sediment Prediction			
		RISE Model		SWAT Model		RISE Model		SWAT Model	
		R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE
1990	1081	0.85	0.72	0.49	0.61	0.65	0.44	0.52	0.43
1991	879	0.86	0.67	0.75	-0.55	0.62	0.17	0.51	-0.37
1992	967	0.85	0.74	0.68	-0.69	0.35	-0.05	0.47	-10.9
1993	1112	0.72	0.48	0.58	0.36	0.67	-0.99	0.46	-1.48
1994	1569	0.75	0.66	0.67	0.26	0.16	0.64	0.43	-10.4
1995	1115	0.66	0.25	0.48	-6.1	0.37	0.60	0.59	-6.6
1996	931	0.80	0.69	0.53	0.17	0.58	0.55	0.49	-0.61
1997	1185	0.74	0.77	0.26	-2.7	0.53	0.20	0.41	-1.1
1998	735	0.74	0.38	0.53	0.11	0.75	0.36	0.44	-8.2
1999	777	0.84	0.59	0.55	0.41	0.56	0.31	0.34	-0.47
2000	815	0.93	0.89	0.61	-5.5	0.42	0.18	0.54	-8.6

The performance of the models to simulate discharge and sediment concentration was further analysed in validation period for two agroforestry watersheds. Figure 6.3a and 6.4a compare observed, RISE and SWAT discharge and sediment concentration data during the whole simulation period for Baronda watershed. The detailed plots for period June to October of year 1998 are shown in Figure 6.3b and 6.4b.

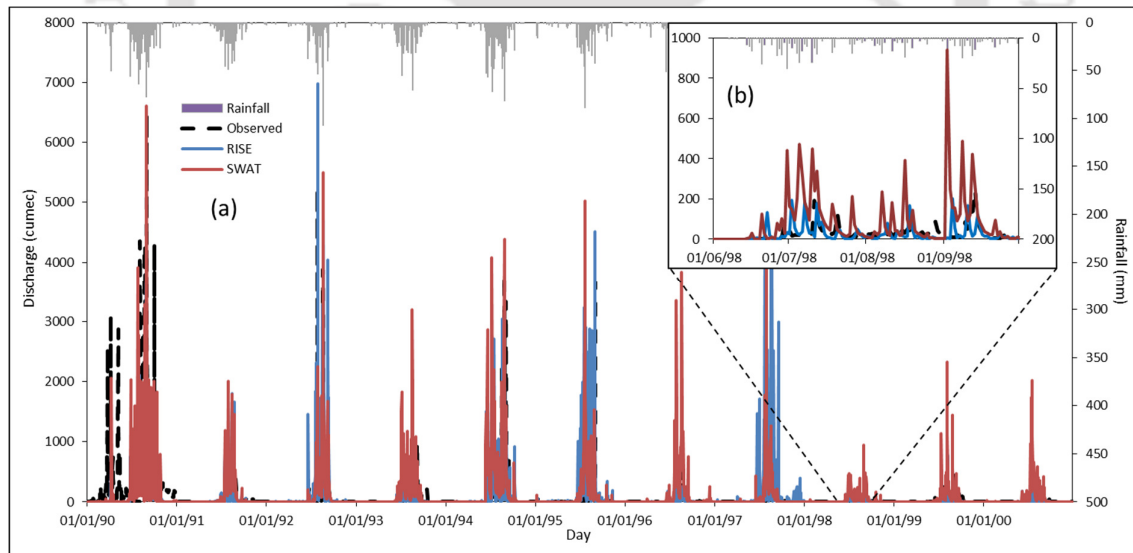


Figure 6.3: (a) Daily observed and simulated discharge by RISE and SWAT for the period from 1990-2000 at Baronda watershed, (b) Selected period from 1998

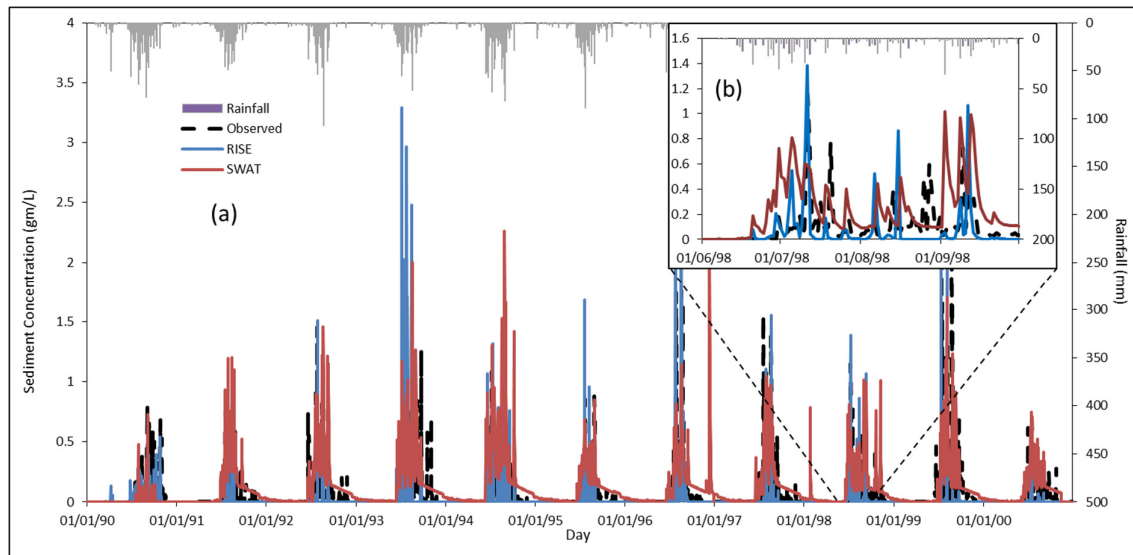


Figure 6.4: (a) Daily observed and simulated sediment concentration by RISE and SWAT for the period from 1990-2000 at Baronda watershed, (b) Selected period from 1998

The fluctuation and pattern of simulation of both the models are within acceptable range where for RISE model, R^2 ranges between 0.74-0.93 for discharge prediction and 0.42-0.75 for sediment. However, analysis showed that SWAT model slightly overestimated discharge and underestimated the sediment concentration (Figure 6.3b and 6.4b). This might be due to different runoff and sediment generation methods used in both models. MUSLE and SCS-CN method used in SWAT are empirical methods for estimating the runoff and sediment from a storm event and is not suitable for large scale watershed and when the rainfall depth is small.

Table 6.4: Comparison of observed and modelled (RISE and SWAT) peaks for Baronda watershed

Year	Annual Rainfall (mm)	Peak Discharge (m ³ /sec)			Peak Sediment Prediction (gm/L)		
		Observed	RISE	SWAT	Observed	RISE	SWAT
1990	1081	6483	6609	4030	0.8	0.72	0.54
1991	879	1467	1814	2008	0.87	0.64	1.20
1992	967	5229	6974	5497	1.45	1.5	1.45
1993	1112	1154	930	3198	1.4	3.2	2.0
1994	1569	3795	3041	4390	1.08	1.31	2.2
1995	1115	3650	4512	5020	0.8	1.68	0.85
1996	931	784	721	3831	1.75	3.5	2.0
1997	1185	4754	4276	4105	1.56	1.55	1.04
1998	735	244	200	942	1.147	1.4	1.01
1999	777	466	770	2331	3.35	2.5	1.7
2000	815	452	614	2017	0.7	0.56	0.75

The discrepancies are primarily due to the lack of detailed representation of threshold rainfall depth runoff generation process and impacts of vegetation. The study area has major area covered with forest/vegetation which has strong effects on hydrological processes in this area, especially in the monsoon and post-monsoon months. The performance evaluation measures for all years for Baronda and Kesinga watershed simulations are given in Table 6.4 and 6.5, respectively.

Table 6.5: Performance evaluation of RISE and SWAT model for Kesinga watershed

Year	Annual Rainfall (mm)	RISE Model		SWAT Model	
		R^2	NSE	R^2	NSE
2006	1917	0.82	0.69	0.63	0.17
2007	1548	0.85	0.68	0.64	0.58
2008	1482	0.81	0.57	0.45	0.25
2009	1537	0.84	0.76	0.61	0.41
2010	1287	0.86	0.75	0.60	0.13
2011	1037	0.84	0.66	0.73	0.41

The plots between observed, RISE and SWAT model simulated discharge and sediment concentration for Baronda and Kesinga watershed are provided in Appendix C. RISE model obtained good values for both calibration and validation regarding the value of R^2 and the NSE coefficient.

6.3.2 Sensitivity Analysis

To analyze the sensitivity of RISE model towards the threshold rainfall depth and NDVI, the model was simulated for year 1990 at Baronda watershed with varying threshold rainfall depth and NDVI. Sensitivity of RISE model in prediction of runoff and sediment concentration with variation in threshold rainfall depth input is shown in Figure 6.5 and 6.6, respectively. It is clear that threshold rainfall depth has a strong impact on runoff generation process and subsequently on sediment generation mechanism. As threshold rainfall depth increases, the probability of runoff generation increases. The abrupt rise in Figure 6.6 shows the flashiness in sediment generation process. Table 6.6 shows the change in annual total discharge and sediment concentration with change in threshold rainfall depth.

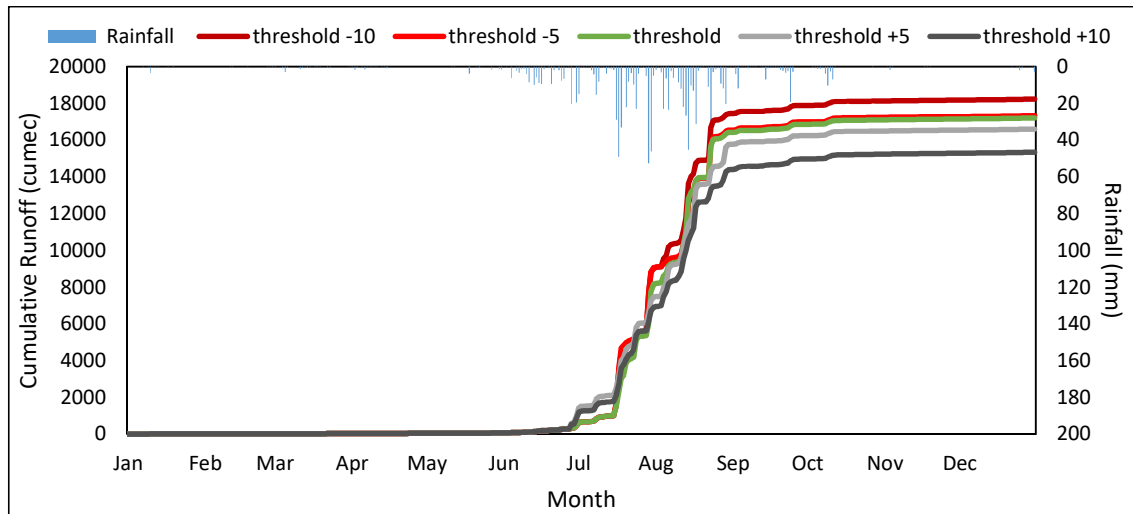


Figure 6.5: Cumulative runoff against the variation in threshold rainfall depth for year 1990 at Baronda watershed

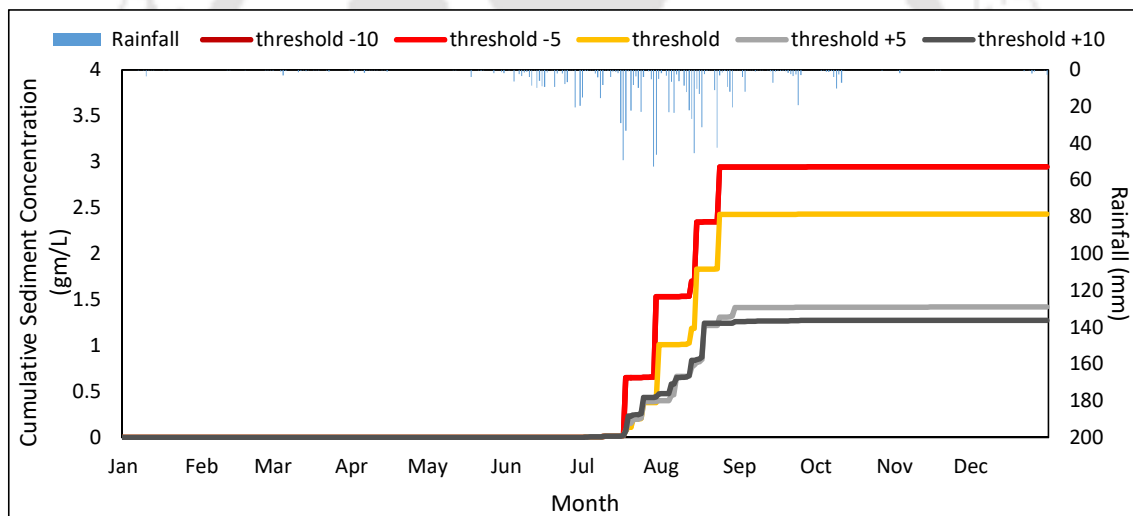


Figure 6.6: Cumulative sediment concentration against different threshold rainfall depth for year 1990 at Baronda watershed

Table 6.6: Variation in Total Annual response of watershed with threshold change

Threshold Variation (by mm)	Annual Discharge (cume)	Change (%)	Annual Sediment Concentration (gm/L)	Change (%)
-10	18225	5.98	2.95	21.07
-5	17327	0.76	2.94	21.06
0	17196	0	2.43	0
+5	16592	-3.50	1.41	-41.6
+10	15328	-10.86	1.27	-47.6

Similarly, the average NDVI of the watershed was changed by 0.1 to assess the impact of NDVI change on sediment generation process. Figure 6.7 shows the variation in cumulative sediment concentration at Baronda watershed outlet for year 1990 with change in NDVI. Table 6.7 shows the change in annual total sediment concentration with change in NDVI. It is clear that sediment concentration reduces with increase in NDVI due to the resistance offered by the vegetation to runoff flow and sediment transport process.

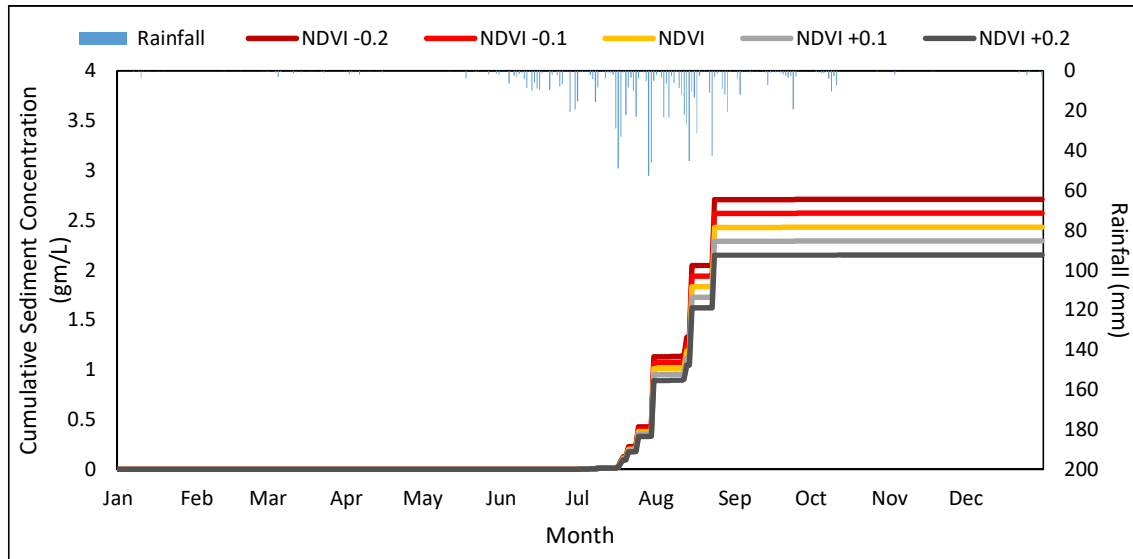


Figure 6.7: Cumulative sediment concentration against the NDVI variation for year 1990 at Baronda watershed

Table 6.7: Change in Total Annual sediment concentration with NDVI change

NDVI change by	Annual Sediment Concentration (gm/L)	Change (%)
-10	2.71	11.52
-5	2.57	5.76
0	2.43	0
+5	2.29	-5.76
+10	2.15	-11.52

6.4 Conclusions

This chapter described the overview of widely used SWAT model processes and calibration parameters. The comparative analysis of developed hydrological and sediment model (RISE) and SWAT model was performed. Runoff and sediment response of two agroforestry watershed was simulated by both the models. It was found that SWAT overestimated the

discharge and underestimated the sediment concentration peaks. On basis of goodness-of-fit measures, the overall simulation results of RISE model were found acceptable. Furthermore, the sensitivity of newly added parameters (threshold rainfall depth and NDVI) in RISE model were analyzed by varying the parameter values. It was observed that threshold rainfall depth is more sensitive towards suspended sediment concentration in comparison to runoff response of the watershed.



CLIMATE CHANGE IMPACTS ON RUNOFF AND SEDIMENT YIELD

7.1 Introduction

Climate change refers to a transformation in the state of the environment that can be recognized by variations in the mean or the change of its properties. Intergovernmental panel on climate change (IPCC) observed changes in much extreme weather and climatic events since about 1950 (IPCC, 2013). The impact of climate change on water resources indicates an escalation of global hydrological cycle affecting the water supply. Variations in total rainfall, its frequency, timing and intensity were predicted by IPCC on a global scale. However, the variations are different for all regions and have local baseline climatic effect. Several attempts by (Ghosh and Dutta, 2012; Goswami et al., 2006; Guhathakurta et al., 2011; Rajeevan et al., 2008) have been made to study the variation in extreme rainfall events and its impact on runoff over Indian basins, and studies mostly focused in central India. Whereas, very few studies were conducted on the impact of climate change on sediment transport (IPCC, 2014, 2007). Therefore, the present study attempts on analysis of temporal variation of runoff and sediment yield response of the agroforestry watersheds considering future climate change scenarios. This chapter gives the overview of data used to identify the impact of climate change on runoff and sediment yield. The monthly relationships between rainfall and NDVI are developed. Calibrated RISE model was applied for the period from 1951-2060 for two agroforestry watersheds considering future climate projections and change in the degree of vegetation. The trend analysis results and future predictions of runoff and sediment yield are discussed in detail for wet and dry conditions. A new upper envelope approach is also described to capture the extreme future runoff and sediment yield events without application of any hydrological model.

7.2 Material and Methods

7.2.1 Datasets

Daily rainfall and temperature datasets for the period from 1951 to 2060 under Representative Concentration Pathways (RCPs) 4.5 and 8.5 were obtained from National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). The freely available dataset comprises downscaled projections of daily maximum temperature, minimum temperature, and precipitation from 21 models at 0.25 degrees spatial resolution (Thrasher et al., 2012). The models differ mainly in their cloud schemes and land surface components (Dix et al., 2013). ACCESS 1.0 model developed by Centre for Australian Weather and Climate Research (CAWCR) is used in the present study. The simple statistical approach to bias correction was performed over the downscaled projected to correct the dataset for local adaptability. For that, the daily gridded rainfall and temperature data for the period from 1951 to 2005 was procured from India Meteorological Department (IMD). Table 7.1 briefs about the period of climate data used in present study for two agroforestry watersheds.

Table 7.1: Data used in present study

Future Climate Change Rainfall and Temperature Data			
Watershed Name	Historical	Future	RCPs
Baronda, Kesinga	1951-2005	2006-2060	4.5 and 8.5

7.2.2 Relationship between Rainfall and NDVI

Normalized difference vegetation index (NDVI) data obtained for the period from 1990-2000 for Baronda watershed and from 2006-2011 for Kesinga watershed was used for assessing the vegetation cover over the watersheds and correlation between rainfall and NDVI has been established. The NDVI product for Baronda watershed was available at a spatial resolution of 8 km from Global Inventory Modeling and Mapping Studies (GIMMS). The product was originally derived from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR) satellite sensor series. However, for Kesinga watershed analysis, NDVI was available at a spatial resolution of 250 m from Moderate Resolution Imaging Spectroradiometer (MODIS) Terra satellite (Didan, 2015). Bias-corrected rainfall and NDVI data sets were aggregated into monthly time series. Multiple regression analysis was then attempted to establish the relationship between rainfall and NDVI at monthly timescale (Richard and Pocard, 1998).

7.2.3 Rainfall Anomalies and Trend Analysis

Daily rainfall data (1951-2060) obtained from NEX-GDDP were aggregated into monthly (only monsoon) and annual time series. Anomalies from the long-term mean variation were analyzed along with the non-parametric Mann-Kendall (MK) test to assess the temporal variation in monthly and annual rainfall due to climate change over the two agroforestry watersheds. The MK standardised test statistic value (Maurya, 2013; Yue et al., 2002) was calculated by Equation 7.1-7.4.

$$Z = \begin{cases} \frac{S-1}{\sigma} & S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sigma} & S < 0 \end{cases} \quad (7.1)$$

where,

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{Sgn}(X_j - X_i) \quad (7.2)$$

$$\text{Sgn} = \begin{cases} +1 & S > 0 \\ 0 & \text{if } S = 0 \\ -1 & S < 0 \end{cases} \quad (7.3)$$

$$\sigma = \sqrt{\frac{n(n-1)(n-5) - \sum_{i=1}^n t_i i(i-1)(2i+5)}{18}} \quad (7.4)$$

$$p = 0.5 - \phi(|Z|) \quad (7.5)$$

$$\left(\phi(|Z|) = \frac{1}{\sqrt{2\pi}} \int_0^{|Z|} e^{-t^2/2} dt \right)$$

where, X_j and X_i are the consecutive data values, n is the number of data points, t_i is the number of ties up to sample i , and S is test statistic. The $\text{Sgn}()$ is +1, -1 and 0 when X_j is greater than X_i , X_j is less than X_i and if X_j is equal to X_i , respectively. The $\phi(|Z|)$ denotes the cumulative distribution function. The sign of Z indicates the trend (increasing or decreasing). The significance level of p -value can be estimated as Equation 7.5, where the series trend is considered significant when p -value is lower than 0.1. The magnitude of the series trend is computed by the Sen's slope (T_i) estimator (Equation 7.6).

$$T_i = \frac{X_j - X_i}{j - i} \quad (7.6)$$

where, X_j and X_i are the data values at time j and k ($j > k$).

7.2.4 Variations in Runoff and Sediment Yield under Climate Change

To assess, the impact of climate change on runoff and sediment load, calibrated RISE model was simulated for two agroforestry watersheds for the period from 1951 to 2060. Monthly temporal variations of runoff and sediment yield were analyzed for both RCPs. Five most wet and dry years were identified out of projected climate data based on annual rainfall. Impact of climate change during extreme weather conditions was investigated in detail.

7.2.5 Upper Envelope Approach to Capture Impact of Extreme Future Conditions

An approach to capture extreme weather conditions and its impact on runoff and sediment load was developed. Traditionally, empirical regional envelope curves are used to assess the upper bounds of extreme flood events in a region (Castellarin et al., 2005) as illustrated in Figure 7.1. In the present study, the upper envelope is defined as the boundary of the region occupied by the probable runoff response to rainfall of the watershed. Suppose $F = \{f_1, f_2, \dots, f_n\}$ be a set of functions where each f_i relates two parameters; rainfall and runoff. Upper envelope of F is defined as Equation 7.7.

$$U_F(x) = \max_{1 \leq i \leq n} f_i(x) \quad (7.7)$$

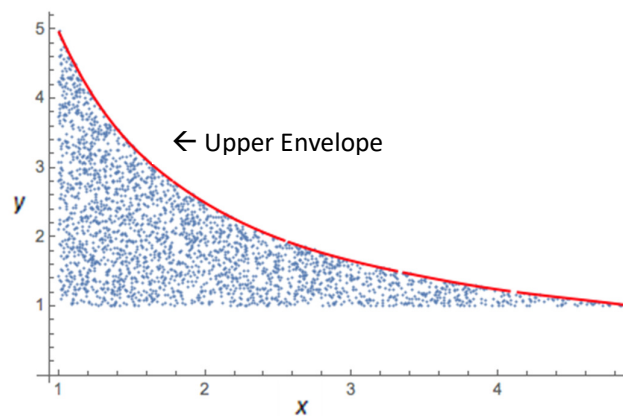


Figure 7.1: Example of upper envelope curve (red line: the upper envelope curve, blue dots: data points)

The seasonal upper envelope equations were derived for Baronda watershed in Chapter 4 for the period from 1990 to 2000. The derivation of extreme runoff and sediment response of watershed was carried out in two steps. In the first step, the extreme case of upper envelope,

out of 11 years of analysis for Baronda watershed was considered to derive the runoff response of the watershed for future climate scenarios. In the second phase, future derived NDVI data (Section 7.3.1), and regression equation established by Figures 4.31-4.33 were used to compute variables (a , b) of runoff-sediment power relationship. After computation of extreme runoff depth and variables (a and b), Equation 7.8 was employed to estimate the extreme sediment concentration at Baronda watershed for future climate scenarios. It was assumed that the relation between runoff and sediment concentration remains stationary for the study period.

$$Q_s = a Q^b \quad (7.8)$$

where, sediment concentration (Q_s) is explained as a function of the runoff (Q). ‘ a ’ and ‘ b ’ are the power coefficients.

7.3 Results and Discussion

7.3.1 Rainfall Bias Correction and Derivation of NDVI Projections

The downscaled rainfall data obtained from NEX-GDDP and IMD was aggregated in monthly time series to identify the biases. The total monthly GDDP rainfall for the period from 1951-2005 was then compared with the total monthly IMD rainfall as shown in Figure 7.2. The biases multiplication factor was then calculated as the ratio between total monthly rainfall of IMD and GDDP.

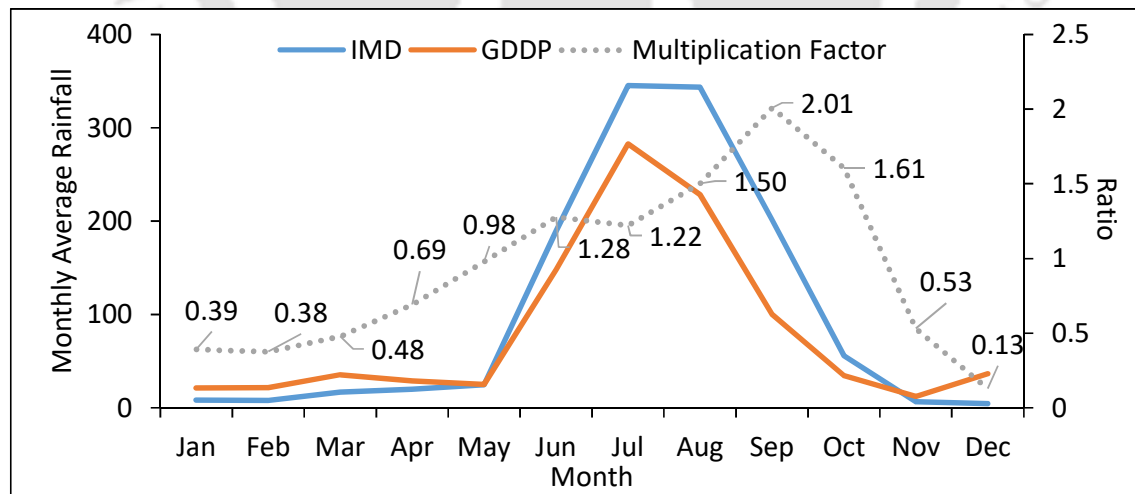


Figure 7.2: Plot of monthly IMD and GDDP rainfall and bias correction coefficient

It was observed that GDDP overestimated during November to May period and under-predicted during near monsoon season, *i.e.*, June to October. The highest correction factor was found in September (2.01), and the lowest was computed in December (0.13). This multiplication factor was then applied to GDDP daily rainfall data for the period from 1951-2060.

Multiple regression analyses were then performed between IMD observed monthly rainfall data and monthly NDVI time series for the period from 1990-2000 at Baronda watershed. It was found that rainfall and NDVI are strongly correlated at monthly timescale. However the NDVI was related to previous month's NDVI and antecedent monthly rainfall, and the rainfall response to NDVI varies for every month. The relationships between monthly averaged NDVI and preceding month's total rainfall are shown in Table 7.2. The NDVI for each month can be computed by using the developed relationships.

Table 7.2: Monthly relationship between rainfall and NDVI

Month	Relation	Coefficient of Determination (R^2)
January	$-0.15 + 0.0021 (P_{Jan}) + 1.07 (V_{dec})$	0.84
February	$0.27 + 0.0038 (P_{Jan+feb}) + 0.36 (V_{Jan})$	0.83
March	$0.07 + 0.0019 (P_{Jan+feb}) + 0.61 (V_{Feb})$	0.86
April	$0.18 + 0.0053 (P_{Apr}) + 0.43 (V_{Mar})$	0.82
May	$0.19 + 0.001 (P_{May}) + 0.56 (V_{Apr})$	0.67
June	$-0.027 + 0.00062 (P_{May}) + 1.03 (V_{May})$	0.95
July	$0.39 - 0.00037 (P_{Jun+jul}) + 0.63 (V_{Jun})$	0.83
August	$0.15 + 0.00012 (P_{Jun+jul+aug}) + 0.51 (V_{Jul})$	0.65
September	$0.43 + 0.0003 (P_{Aug}) + 0.28 (V_{Aug})$	0.635
October	$0.18 + 0.000098 (P_{Aug+sep}) + 0.83 (V_{Sep})$	0.83
November	$0.95 (V_{Oct}) - 0.039$	0.75
December	$0.66 + 0.007 (P_{Nov+dec}) + 0.03 (V_{Nov})$	0.84

(P: rainfall (mm); V: NDVI; subscript represents the respective month)

To validate the NDVI and rainfall relationships, NDVI was estimated for the period from 2006 to 2011 at Kesinga watershed using observed monthly rainfall data. The observed and predicted monthly NDVI was compared statistically as shown in Figure 7.3. The maximum deviation in mean NDVI was found in April as 13 %, whereas in maximum NDVI deviated in May by 25% (Table 7.3). Overall, the trend of NDVI statistics is acceptable for the application in water resources studies.

It was assumed that land use / land cover has not been changed from 1951 to as of now, and will remain unaltered until 2060. To justify the assumption, LULC change analysis was performed on both the watersheds. Figures 7.4a and 7.4b shows the LULC map of Kesinga watershed for the year 1972 and 2005, respectively. It was observed that the LULC change in Kesinga watershed over 33 years was maximum 5% for forest and agriculture areas (Table 7.4).

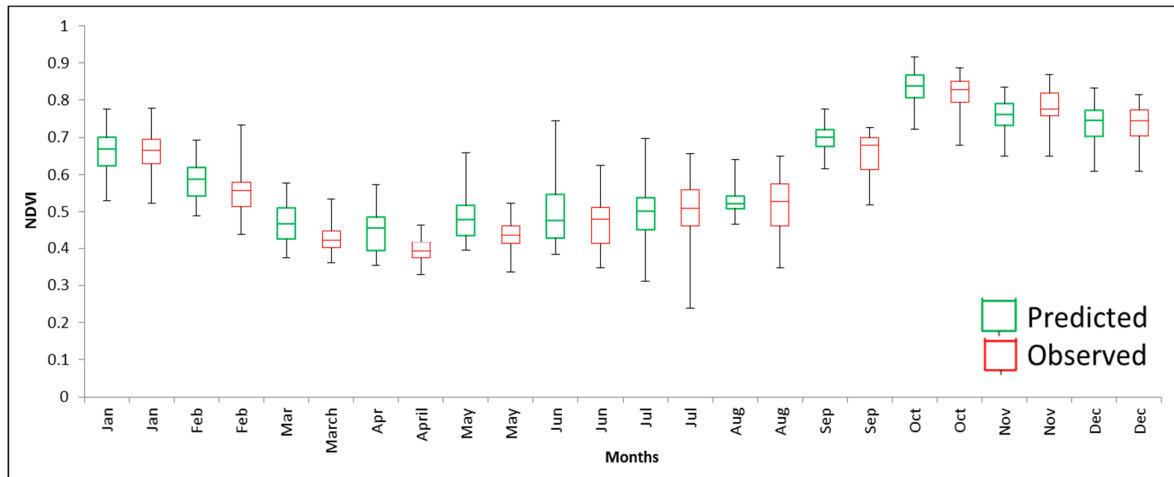


Figure 7.3: Comparison of predicted and observed monthly NDVI box plots at Kesinga watershed

Table 7.3: Monthly percentage deviation between observed and estimated NDVI

Deviation (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean NDVI	-0.24	6.11	9.25	13.09	10.63	5.53	-1.7	2.99	6.66	2.5	-2.22	-0.16
Maximum NDVI	-0.29	-5.7	7.76	23.25	25.84	19.2	6.19	-1.5	6.80	3.2	-3.8	2.33

Table 7.4: LULC change in Kesinga watershed (in percentage)

LULC Class	Change (%)
River	0.06
Wetland	0.11
Agriculture	4.78
Forest	-5.25
Urban	0.07
Barren	0.22

The land use / land cover change analysis for Baronda watershed was also performed (Figure 7.5). The LULC change of Baronda watershed was minor during past 33 years ($< 1\%$) (Table 7.5).

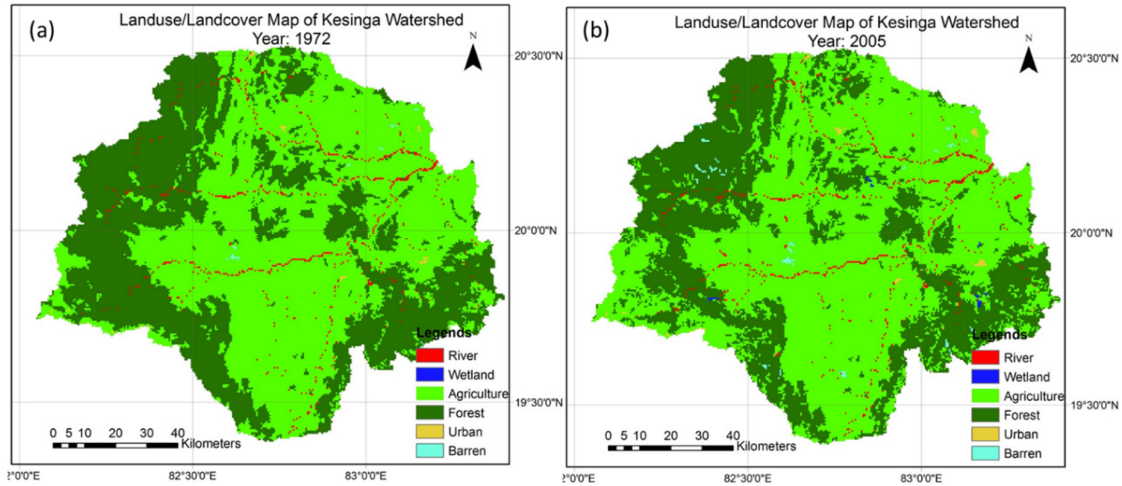


Figure 7.4: LULC map of Kesinga watershed (a) year 1972, (b) year 2005

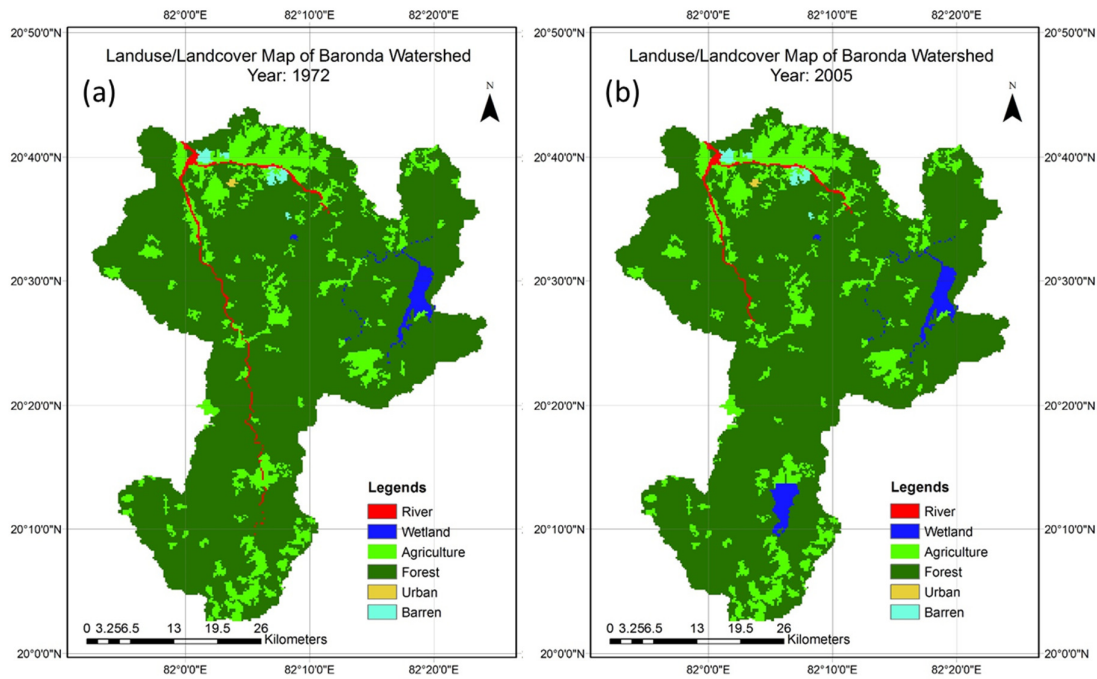


Figure 7.5: LULC map of Baronda watershed (a) year 1972, (b) year 2005

Table 7.5: LULC change in Baronda watershed (in percentage)

LULC Class	Percentage Change
River	-0.26
Wetland	0.78
Agriculture	0.01
Forest	-0.53
Urban	0.00
Barren	0.00

The time series of monthly NDVI was then estimated by developed relationships (Table 7.2) and using GDDP rainfall data for both the RCPs for the period from 1951 to 2060 at two agroforestry watersheds.

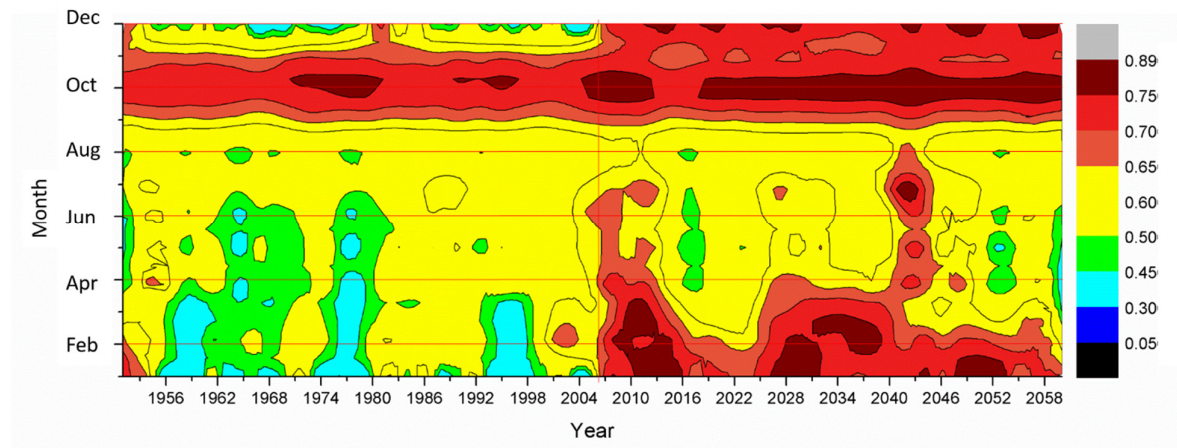


Figure 7.6: Monthly NDVI under RCP 4.5 at Baronda Watershed from 1951 to 2060

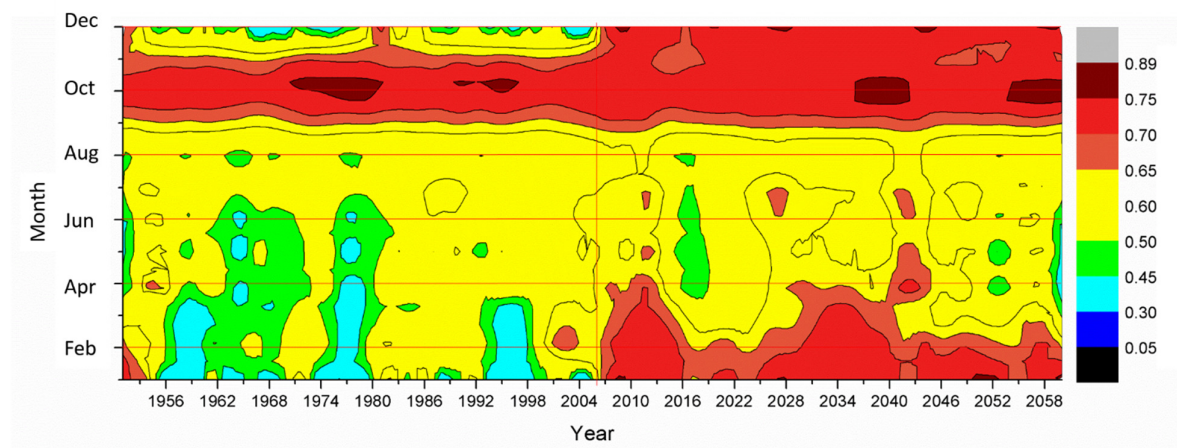


Figure 7.7: Monthly NDVI under RCP 8.5 at Baronda Watershed from 1951 to 2060

Figures 7.6 and 7.7 show the monthly NDVI variations for the period from 1951-2060 at Baronda watershed for RCP 4.5 and RCP 8.5, respectively. The difference in NDVI time series for RCP 4.5 and 8.5 was found in the range of -0.18 to 0.14. It was observed that NDVI values were higher during the period from 2004-2012 in both the RCP's compared to preceding years due to strong positive rainfall anomaly during this period (as depicted in Figures 7.10a and 7.11a). It was predicted that rainfall and NDVI are likely to be very high during 2040-2046, hence extreme wet conditions may occur which lead to severe flooding and sedimentation over the watershed. It was also predicted that the period from 2046-2056 is likely to remain dry.

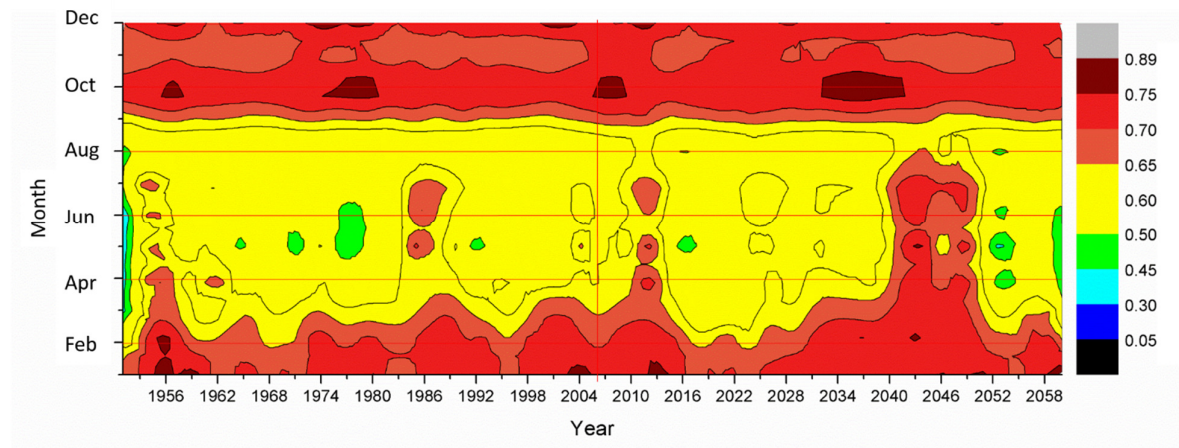


Figure 7.8: Monthly NDVI under RCP 4.5 at Kesinga Watershed from 1951 to 2060

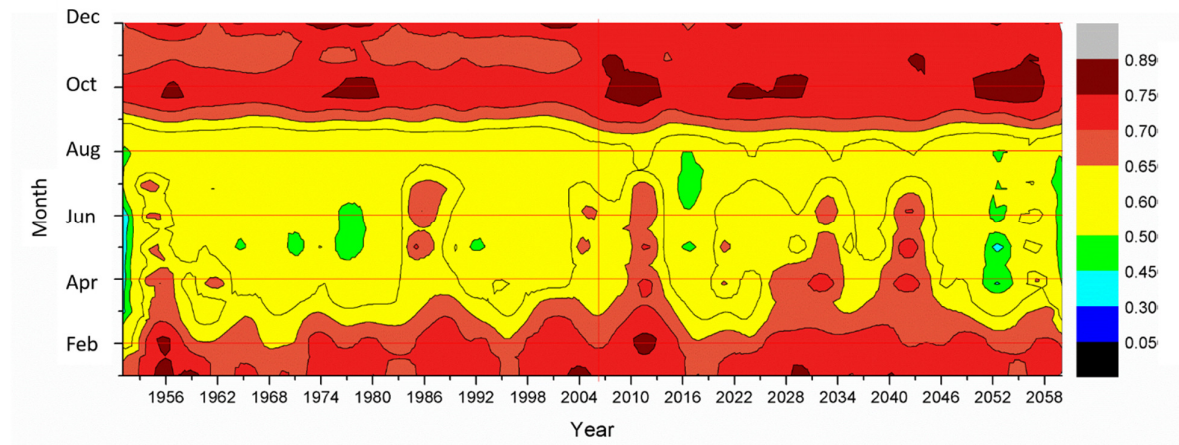


Figure 7.9: Monthly NDVI under RCP 8.5 at Kesinga Watershed from 1951 to 2060

The NDVI future projections for Kesinga watershed for both the RCP's show the similar increasing trend during the period 2040-2046 (Figures 7.8 and 7.9). (Mukherjee, 2016) reported

that Chhattisgarh and northern Orissa were most drought affected region in India during the year 1966-1969 which affected around 65 million people. Figures 7.6 and 7.7 shows this drought affected period where NDVI remained low compared to other years. Whereas, Kesinga watershed was not that much affected by drought in this time due to the proximity to the coastal area (Figures 7.8 and 7.9). The difference between NDVI for RCP 4.5 and RCP 8.5 were found in the range of -0.24 to 0.22.

7.3.2 Variations in Monthly and Annual Rainfall

Daily bias corrected GDDP rainfall data for the period from 1951 to 2060 were aggregated into monthly (only monsoon) and annual time series to analyze the anomalies and trend in variation of rainfall under climate change scenarios. Figures 7.10 and 7.11 show the long-term rainfall anomalies at Baronda watershed under RCP 4.5 and RCP 8.5, respectively. It was observed from the anomaly plots that the extreme positive (>200 mm) annual anomalies were found in years 1956, 1975, 1990, 2004, 2008, 2012, 2016, 2030, 2044 and 2056. It is realized that the extreme rainfall usually occurs after a cycle of 12-15 years. Whereas, the period from the year 2004-2016 and 1996-2003 were the wettest and driest period of the study period, respectively. It was also evident from Figures 7.10 -7.13 that year 2015 was the most severe drought year for the region, the same was also reported by India water Portal (www.indiawaterportal.org/articles/monsoon-2015-nearly-half-indian-districts-reeling-under-drought, accessed on 22/07/2017).

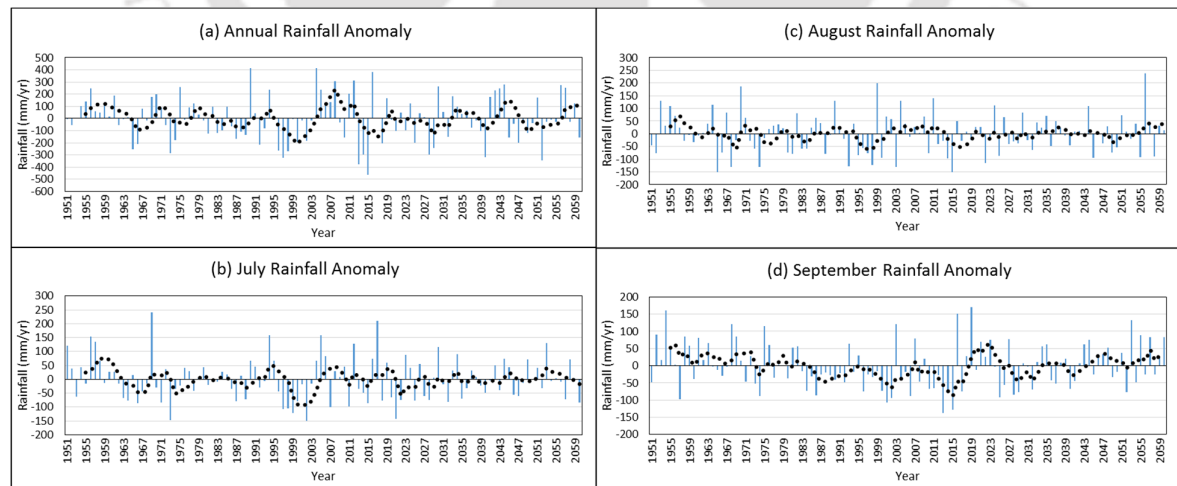


Figure 7.10: Anomalies at Baronda watershed under RCP 4.5 in (a) annual, (b) July, (c) August, (d) September rainfall (dotted line represents 5-year moving average)

The non-parametric Mann-Kendall test was performed to assess the temporal trends in monthly and annual rainfall time series for the period from 1951-2060. The p -value was found to be greater than significance level 0.1 and insignificant value of Sen's slope in all cases in Figures 7.10 and 7.11 (Table 7.6). Therefore, the null hypothesis cannot be rejected *i.e.*; there is no significant trend in the rainfall series.

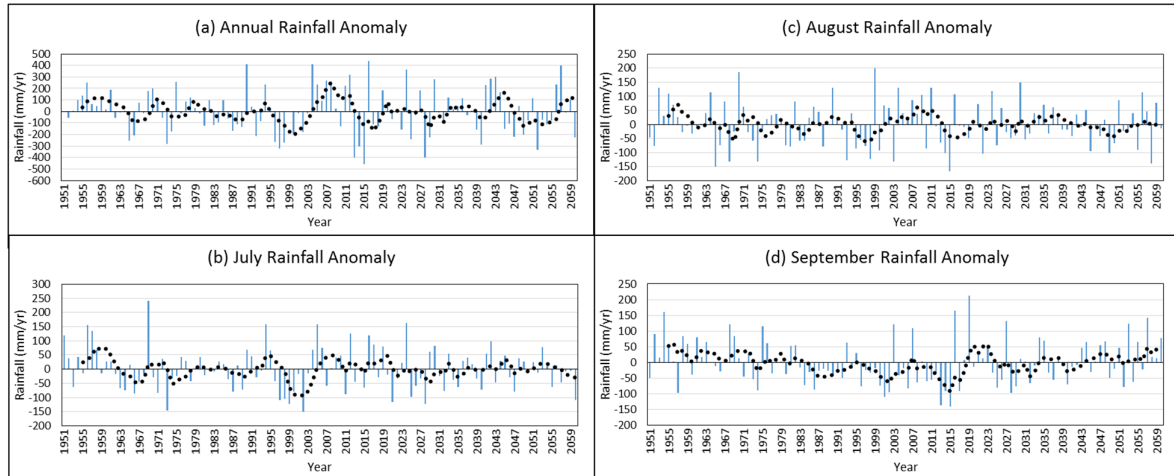


Figure 7.11: Anomalies at Baronda watershed under RCP 8.5 in (a) annual, (b) July, (c) August, (d) September rainfall (dotted line represents 5-year moving average)

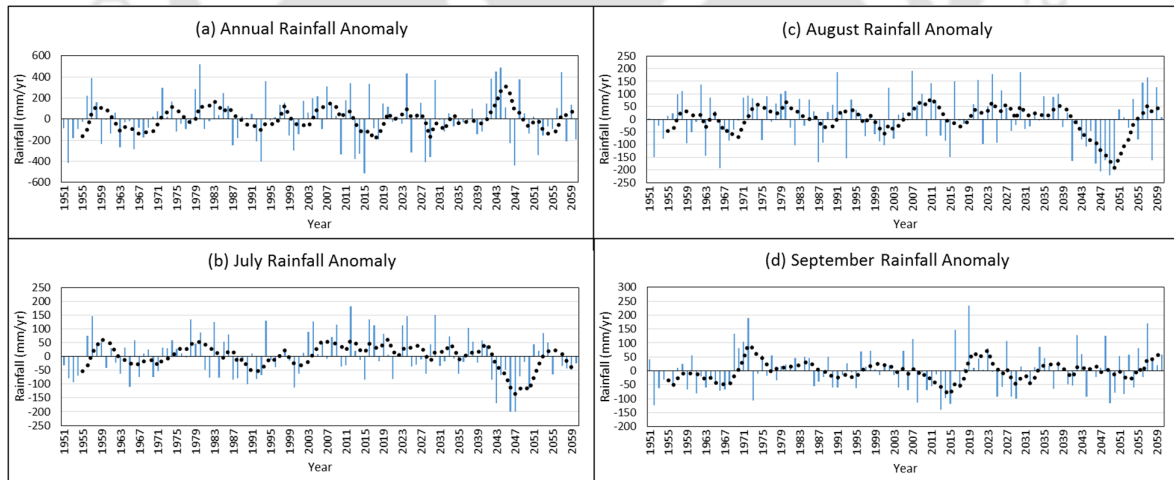


Figure 7.12: Anomalies at Kesinga watershed under RCP 4.5 in (a) annual, (b) July, (c) August, (d) September rainfall (dotted line represents 5-year moving average)

The similar analysis was performed at Kesinga watershed (Figures 7.12 and 7.13). It was found that frequent drought years is not likely to occur again until 2016. However, a frequent wet season is likely to occur during the period from 2041 to 2044. The year 2047 may be identified

as the most drier year compared to others year for Kesinga watershed until 2060, in which the annual rainfall anomaly is estimated as -440 mm and -330 mm under RCP 4.5 and 8.5, respectively. The Mann-Kendall test shows no trend for Kesinga watershed as the p-value is more than 0.1 and Sen's slope is very less (Table 7.6).

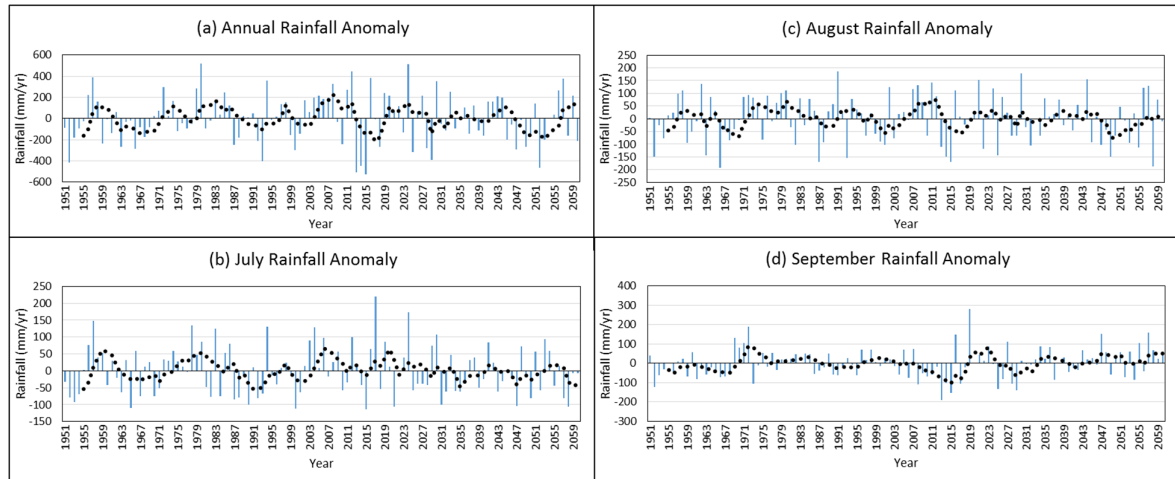


Figure 7.13: Anomalies at Kesinga watershed under RCP 4.5 in (a) annual, (b) July, (c) August, (d) September rainfall (dotted line represents 5-year moving average)

Table 7.6: Men-Kendall trend test statistic and Sen's slope

Rainfall Period	p-value		Sen's Slope	
RCP 4.5				
	Baronda	Kesinga	Baronda	Kesinga
Annual	0.597	0.785	-0.28	0.01
July	0.954	0.469	0.01	-0.28
August	0.932	0.578	-0.02	-0.01
September	0.691	0.421	-0.08	0.046
RCP 8.5				
	Baronda	Kesinga	Baronda	Kesinga
Annual	0.411	0.584	-0.46	-0.01
July	0.745	0.619	-0.06	0.01
August	0.757	0.574	-0.07	-0.02
September	0.619	0.718	-0.1	-0.08

The monthly variations of total rainfall and monthly daily maximum rainfall for both the watersheds under two RCP's are shown in Figures 7.14-7.17. The above analyses of anomalies of monthly (monsoon) and annual rainfall can be visually seen in Figures 7.14-7.17. For instance, the period around the year 2047 shows less monthly rainfall in Figure 7.14 for Baronda watershed and in Figure 7.16 for Kesinga watershed. The decade from 2040 to 2050

under RCP 4.5 scenario is likely to be most severe drought extreme for Kesinga watershed (Figures 7.16a and 7.17a). Whereas, RCP 8.5 (Figures 7.16b and 7.17b) also represents the drought but without much severity.

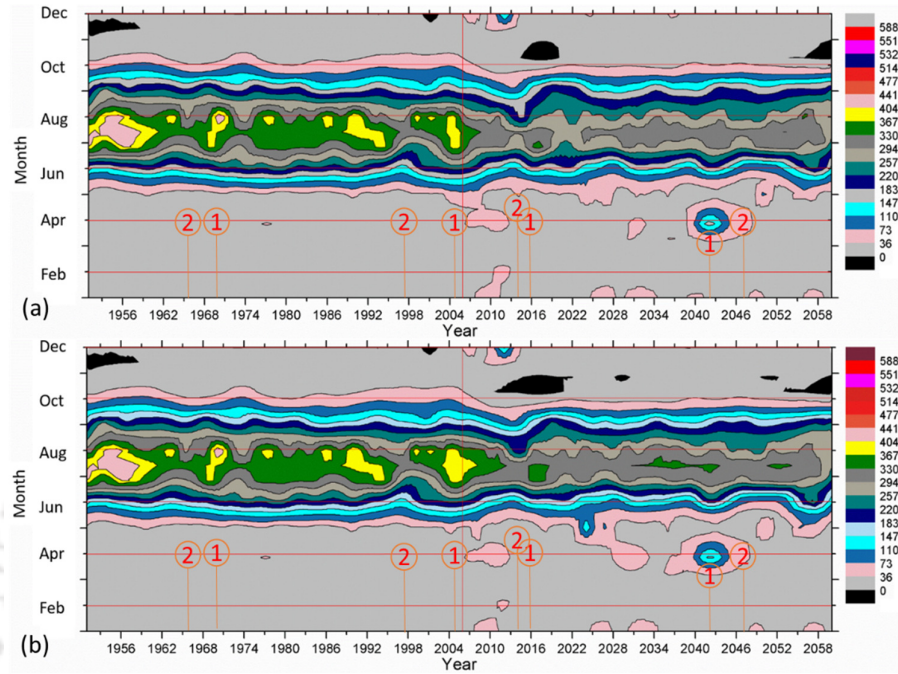


Figure 7.14: Monthly total rainfall (in mm) at Baronda watershed under (a) RCP 4.5, (b) RCP 8.5. The major hydrological events are indicated by encircled numbers: ① flood event, ② drought event

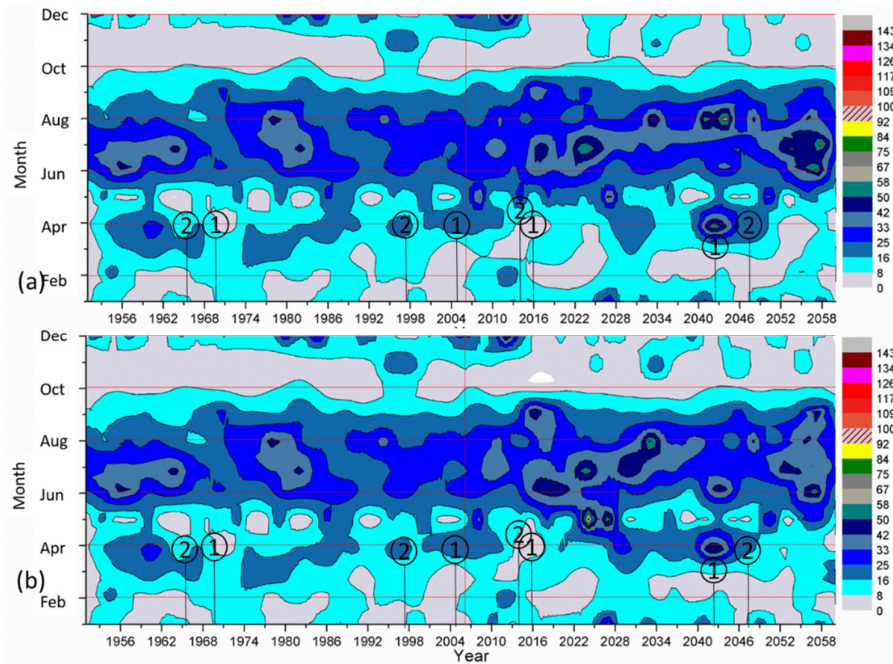


Figure 7.15: Daily maximum rainfall (in mm) at Baronda watershed under (a) RCP 4.5, (b) RCP 8.5 (① flood event, ② drought event)

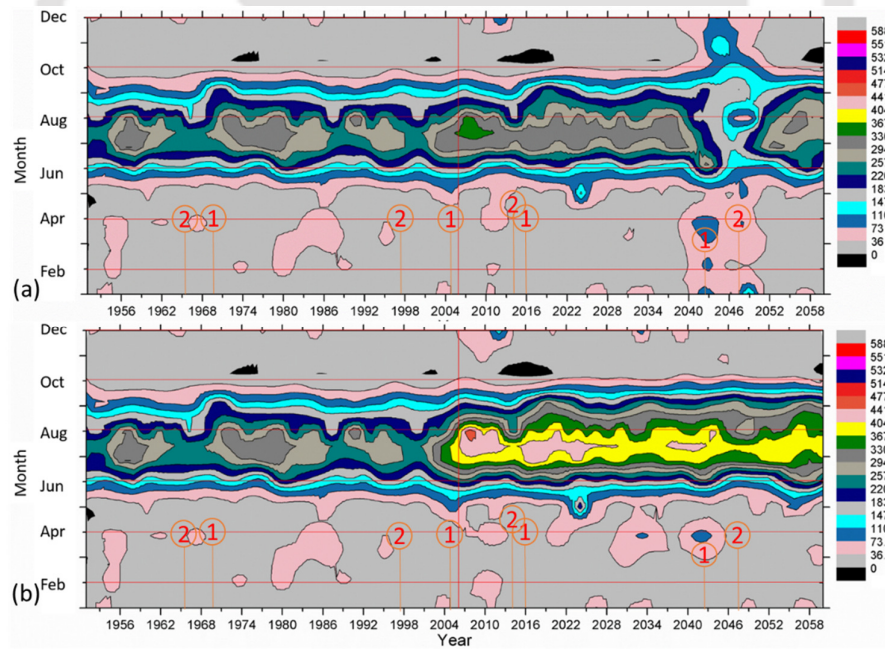


Figure 7.16: Monthly total rainfall (in mm) at Kesinga watershed under (a) RCP 4.5, (b) RCP 8.5 (① flood event, ② drought event)

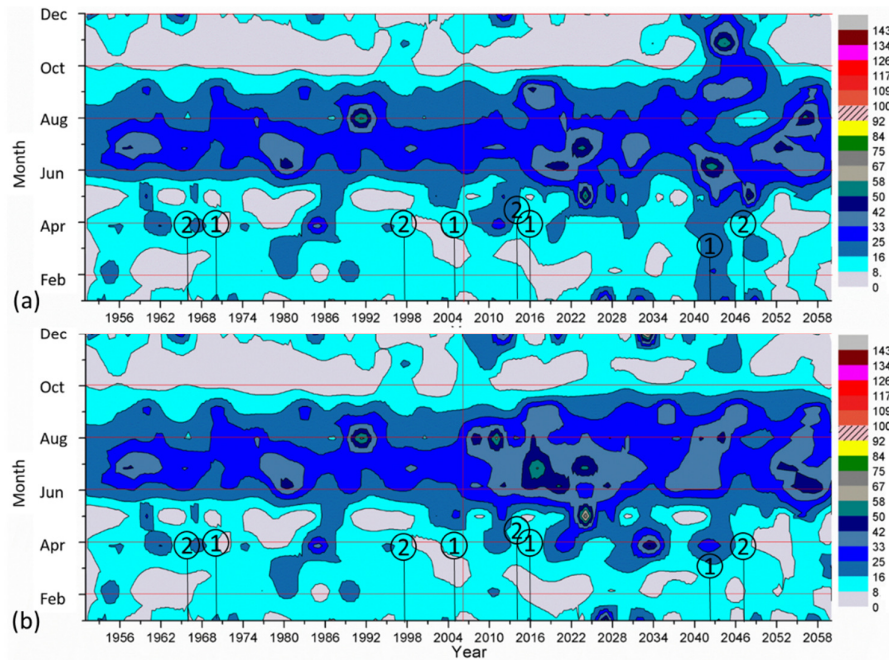


Figure 7.17: Daily maximum rainfall (in mm) at Kesinga watershed under (a) RCP 4.5, (b) RCP 8.5(①flood event, ②drought event)

7.3.3 Temperature Variations under Climate Change

The downscaled mean temperature data obtained from NEX-GDDP for the period from 1951-2005 was analysed for mean and maximum monthly temperature variation under RCP 4.5 and RCP 8.5. Figure 7.18 and 7.19 shows the monthly variation of temperature for the period from 1951-2060 for Baronda watershed. It was observed that there is no significant change in maximum and mean monthly temperature at Baronda watershed from 1951 to 2060 (Figures 7.18 and 7.19). However, RCP 8.5 climatic projections show rise of 2°C in daily maximum temperature for month of August to September between 2030 and 2040 (Figures 7.18b and 7.19b).

Figure 7.20 and 7.21 shows the monthly variation of temperature for the period from 1951-2060 for Kesinga watershed. The same trend as for Baronda watershed was observed in maximum and mean monthly temperature at Kesinga watershed from 1951 to 2060 (Figures 7.20 and 7.21).

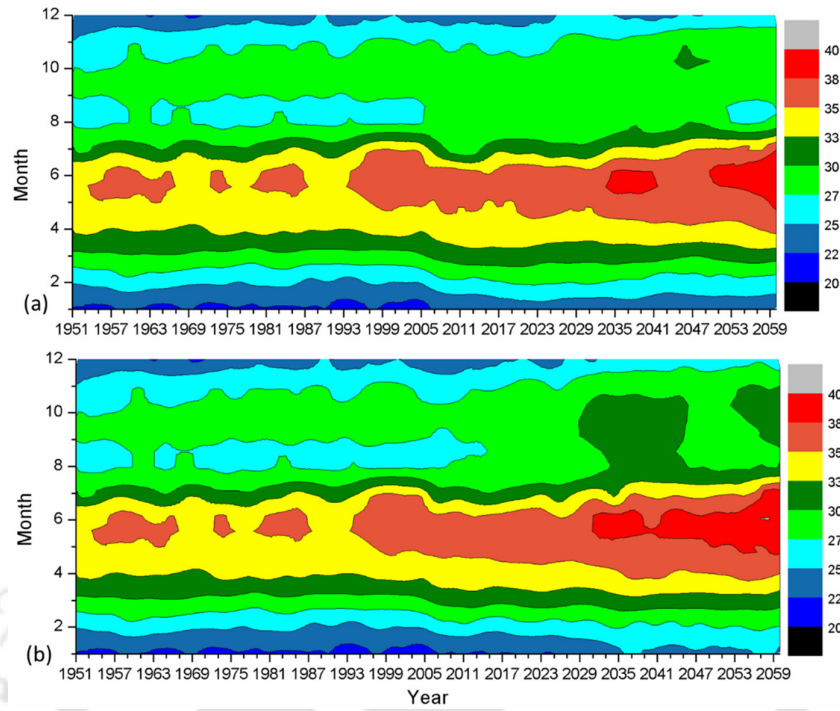


Figure 7.18: Daily maximum temperature (in °C) at Baronda watershed under (a) RCP 4.5, (b) RCP 8.5

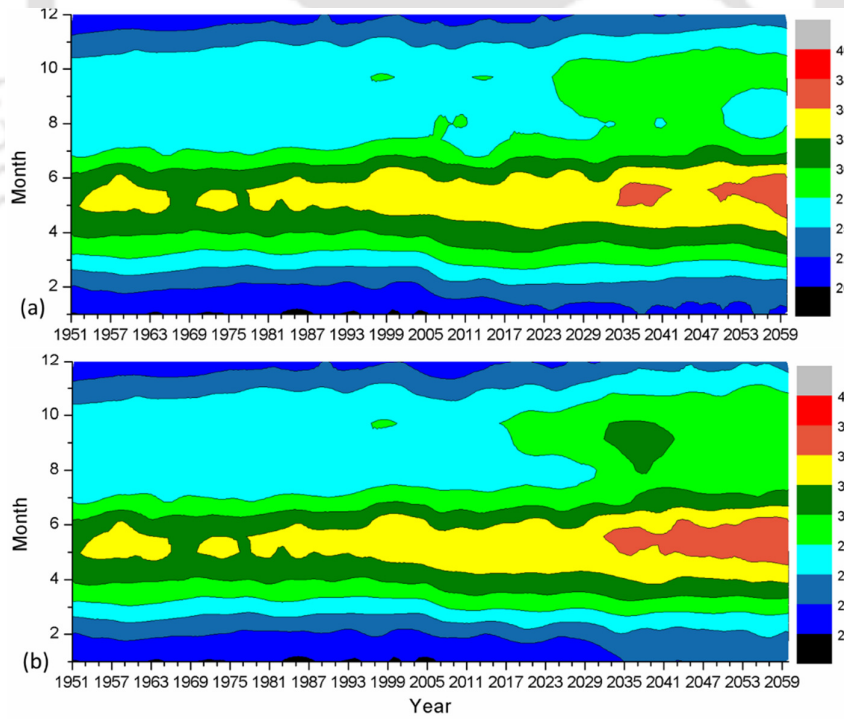


Figure 7.19: Monthly mean temperature (in °C) at Baronda watershed under (a) RCP 4.5, (b) RCP 8.5

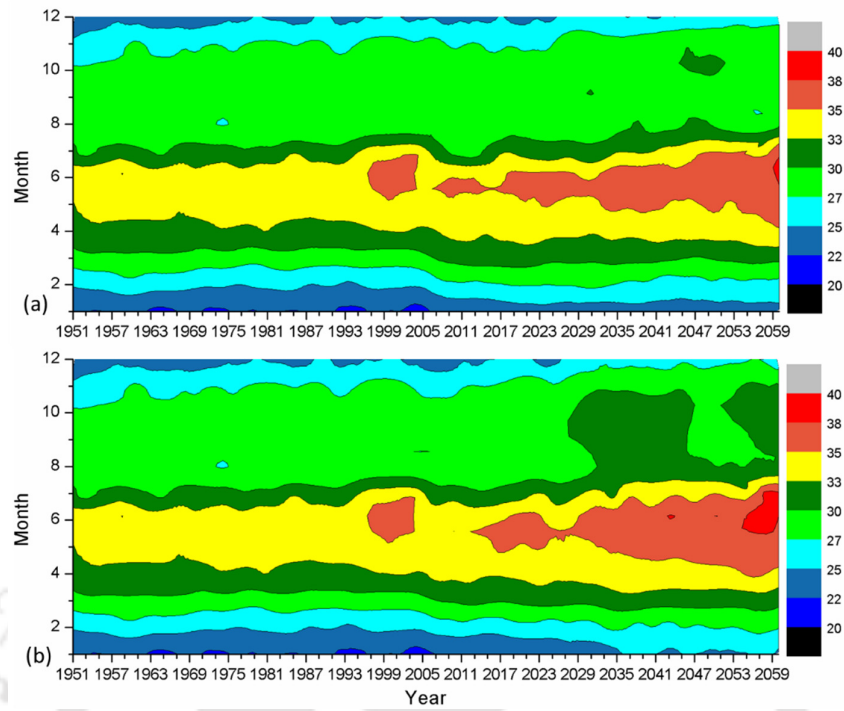


Figure 7.20: Daily maximum temperature (in °C) at Kesinga watershed under (a) RCP 4.5, (b) RCP 8.5

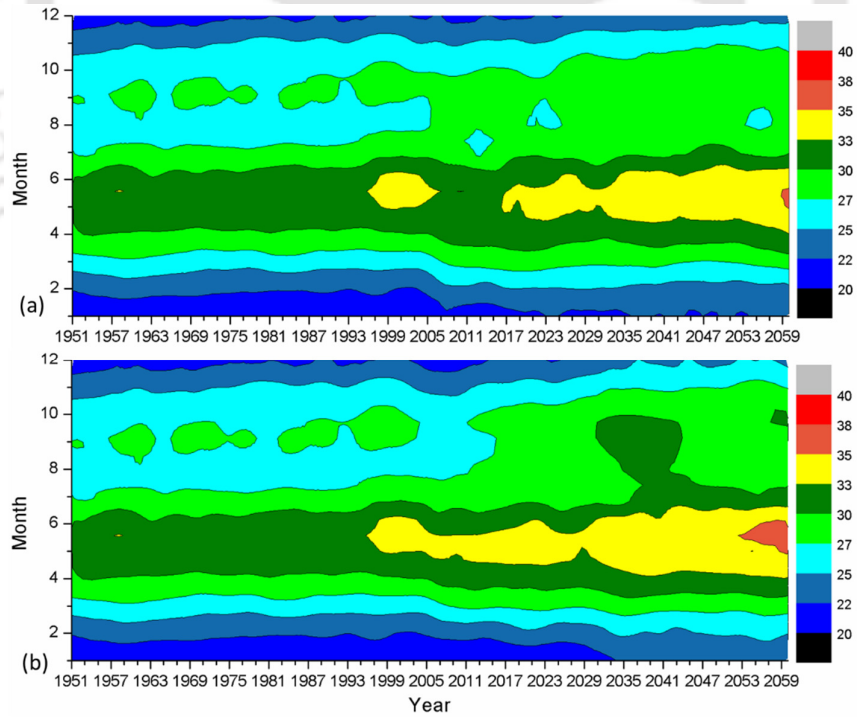


Figure 7.21: Monthly mean temperature (in °C) at Kesinga watershed under (a) RCP 4.5, (b) RCP 8.5

7.3.4 Variations in Runoff and Sediment Yield under Climate Change

To analyze the impact of climate change on runoff and sediment load, calibrated modified RISE model was simulated. The spatial inputs including DEM, LULC and soil map were kept same as discussed in Chapter 5 and 6. GDDP bias corrected rainfall and temperature data under two RCP scenarios and predicted NDVI for the period from 1951-2060 were used as time series inputs. Figures 7.22-7.25 show the runoff and sediment load response of two agroforestry watersheds under two RCP's. As shown in Figure 7.22 (a, b), the estimated maximum daily runoff volume under RCP 4.5 at Baronda watershed is 1.5 km³ in the year 1964 as a response to rainfall of 330 mm in a day in July whereas monthly runoff volume is around 3.75 km³. The flood and drought years out of 110 years of simulation were predicted based on the monthly maximum runoff volume and subsequent sediment yield (Figure 7.22 (c, d)). The maximum monthly runoff volume was captured in the year 1980 as 2.10 km³ for the historical period with maximum monthly sediment load as 12 Mt. The severe flood event under RCP 4.5 and 8.5 scenarios is likely to occur around the year 2044. The runoff response of Kesinga watershed is different for two RCPs. The maximum runoff volume captured under RCP 4.5 and RCP 8.5 is nearly 2 and 2.5 km³, respectively (Figures 7.24 and 7.25).

Similarly, the flood years were identified in the past and predicted under both RCP's scenario for Baronda and Kesinga agroforestry watersheds. The identified flood years are 1964, 1980, 2017 and 2044. The estimated drought years are 1970, 1989, 2021 and 2053 (Figures 7.22-7.25). Table 7.7 summarizes the extreme values of rainfall, runoff and sediment load in historical and future.

Table 7.7: Summary Table for Extreme values

Parameter	Baronda			Kesinga		
	Historical	RCP 4.5	RCP 8.5	Historical	RCP 4.5	RCP 8.5
Monthly Rainfall (mm)	586	514	479	424	569	614
Daily Rainfall (mm)	94	114	142	90	145	164
Monthly Runoff (km ³)	2.74	3.75	3.15	2.56	2.58	3.32
Daily Runoff (km ³)	0.92	1.15	1.06	0.27	0.58	0.48
Monthly Sediment Load (Mt)	553	884	1183	401	380	458
Daily Sediment Load (Mt)	15	18	26	12	11	16

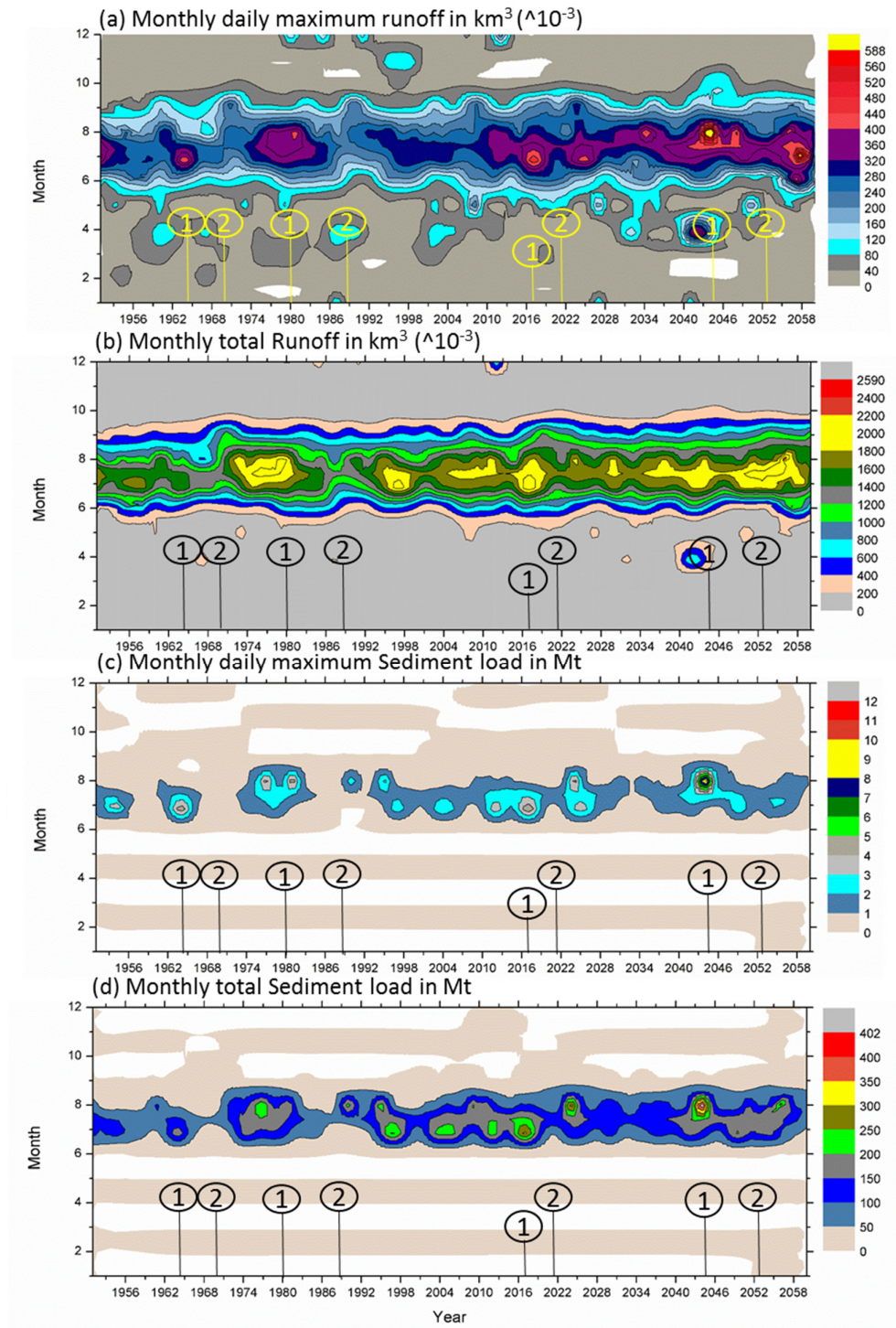


Figure 7.22: Hydrological response of Baronda watershed under RCP 4.5 (a) monthly daily maximum runoff, (b) monthly total runoff, (c) monthly daily maximum sediment load, (d) monthly total sediment load (① flood event, ② drought event)

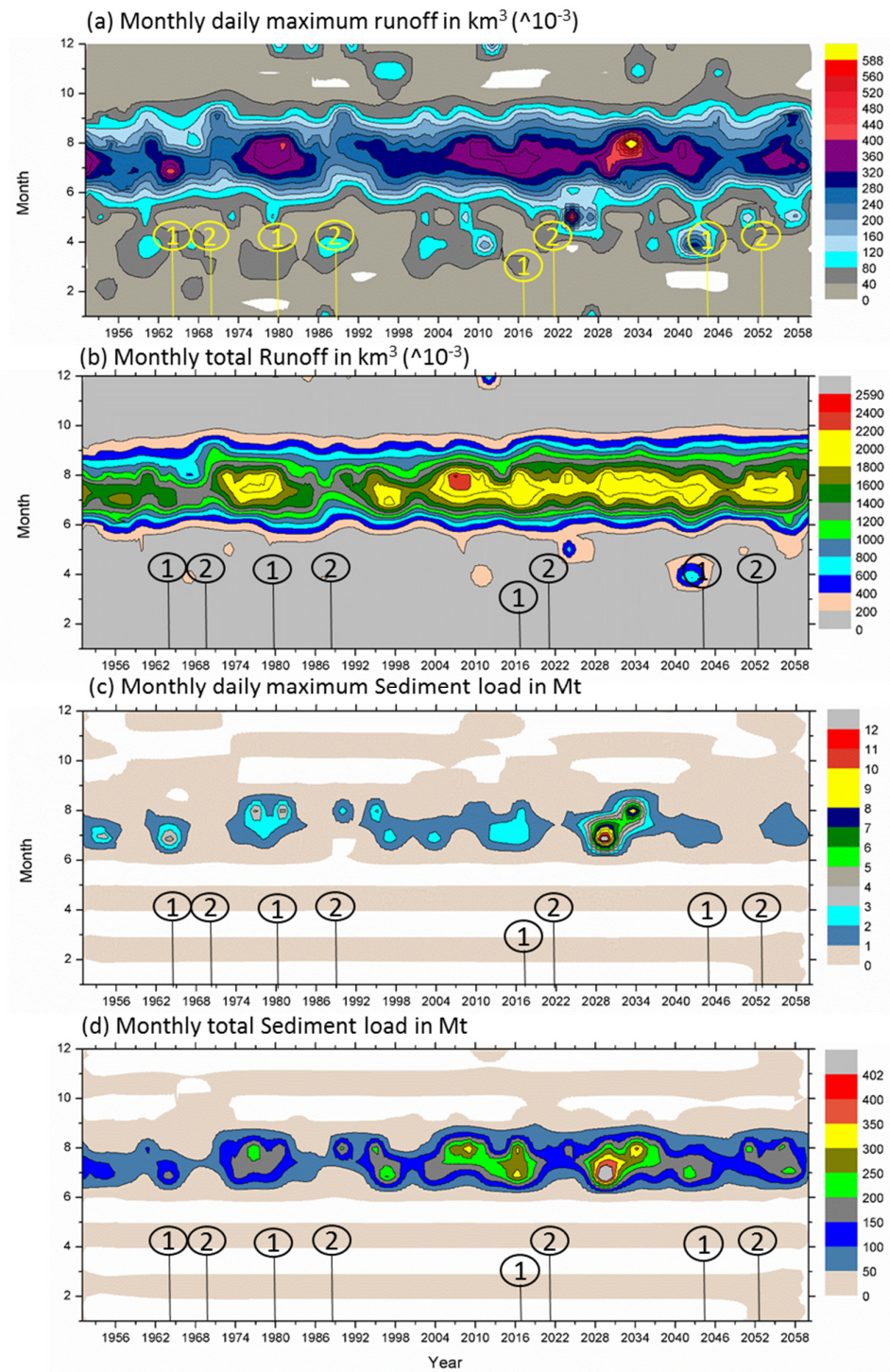


Figure 7.23: Response of Baronda watershed under RCP 8.5 (a) monthly daily maximum runoff, (b) monthly total runoff, (c) monthly daily maximum sediment load, (d) monthly total sediment load (① flood event, ② drought event)

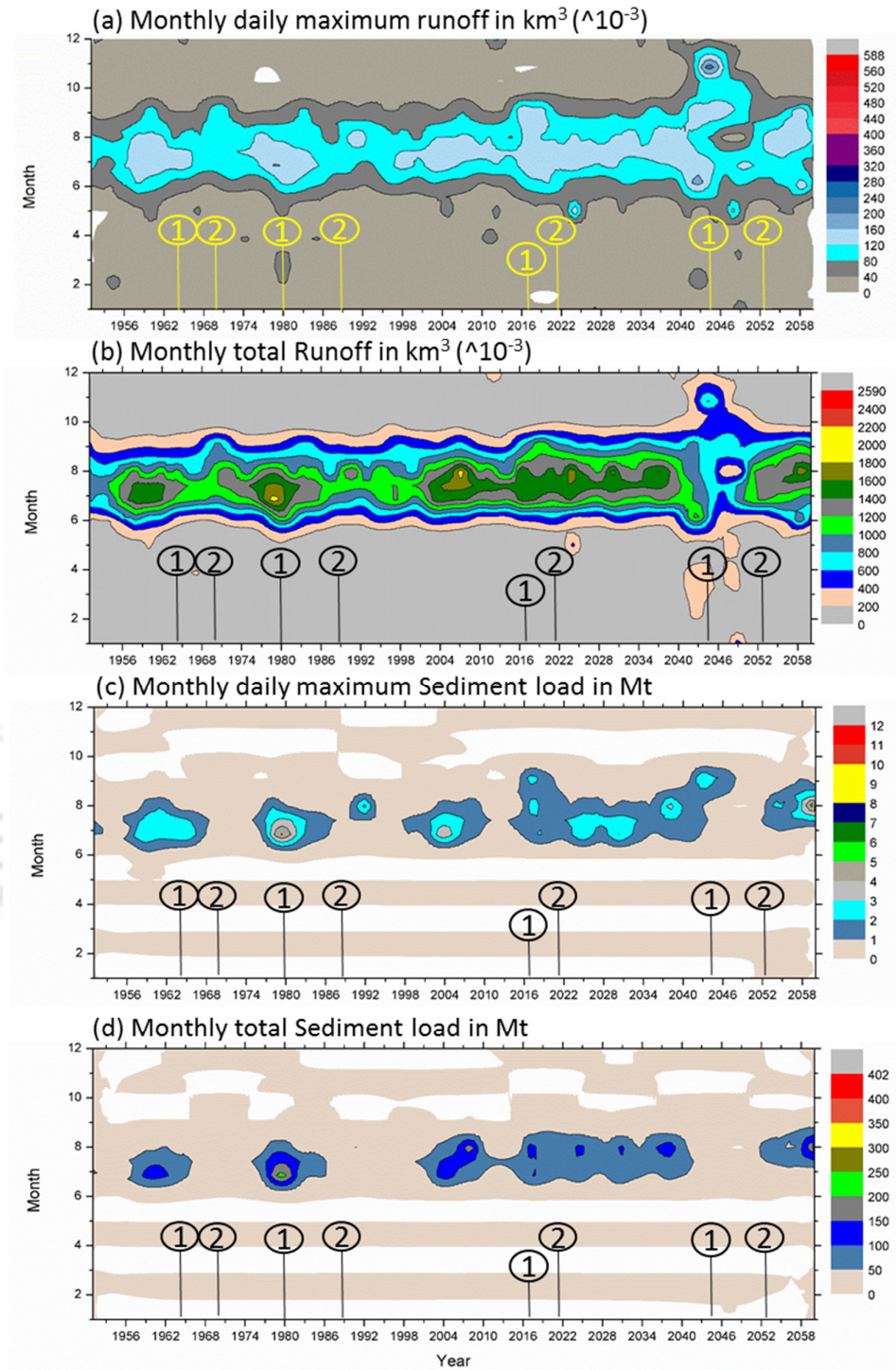


Figure 7.24: Response of Kesinga watershed under RCP 4.5 (a) monthly daily maximum runoff, (b) monthly total runoff, (c) monthly daily maximum sediment load, (d) monthly total sediment load (① flood event, ② drought event)

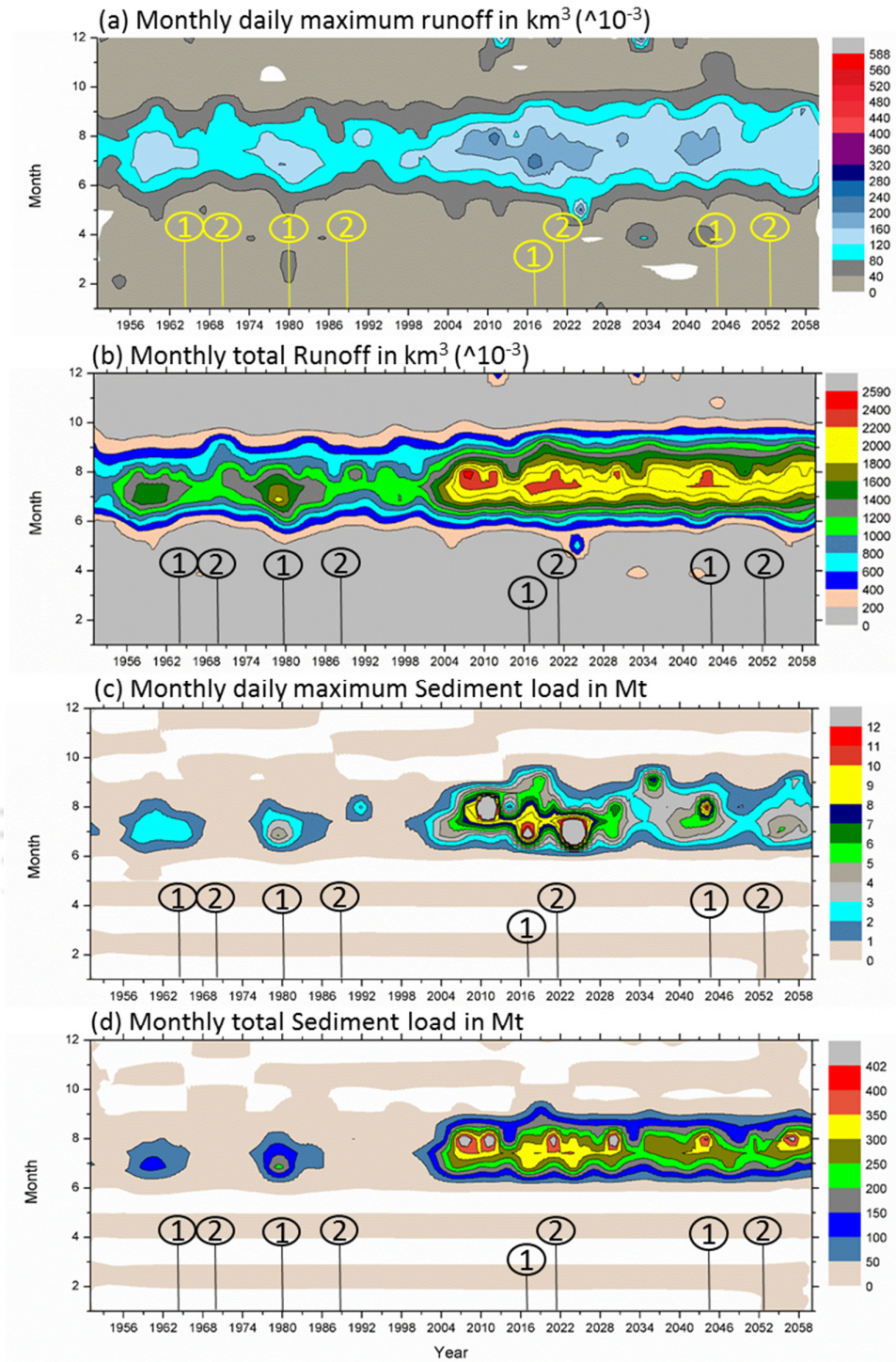


Figure 7.25: Response of Kesinga watershed under RCP 8.5 (a) monthly daily maximum runoff, (b) monthly total runoff, (c) monthly daily maximum sediment load, (d) monthly total sediment load (① flood event, ② drought event)

7.3.5 Impact of Climate Change in Extreme Conditions

To predict the extreme wet and dry conditions and their responses to runoff and sediment concentration, five most wet and dry years were identified based on annual rainfall anomalies (Figures 7.10-7.13). Impact of climate change during extreme weather conditions was investigated in detail by plotting daily cumulative runoff and sediment concentration graph. The wet years recognized for Baronda watershed are 2030, 2042, 2043, 2044 and 2057, where annual rainfall is more than 1550 mm (Figure 7.26). The maximum annual runoff and maximum annual total sediment concentration were estimated as 15.8 km³ and 47 Mt, respectively for Baronda watershed. Daily peak runoff volume and sediment load are estimated as 11.9 km³ and 32 Mt, respectively. However the minimum runoff volume (5.95 km³) and sediment load (1.45 Mt) predicted for Baronda watershed is likely to occur in the year 2028 and 2040, respectively (Figure 7.27). The annual rainfall for the year 2040 is likely to be more than 2028 annual rainfall. Despite having more rainfall, sediment load in the year 2040 is less than the year 2028. The reason behind this is monthly rainfall distribution in the year 2040 where rainfall is more concentrated towards post-monsoon season (Figure 7.27 c).

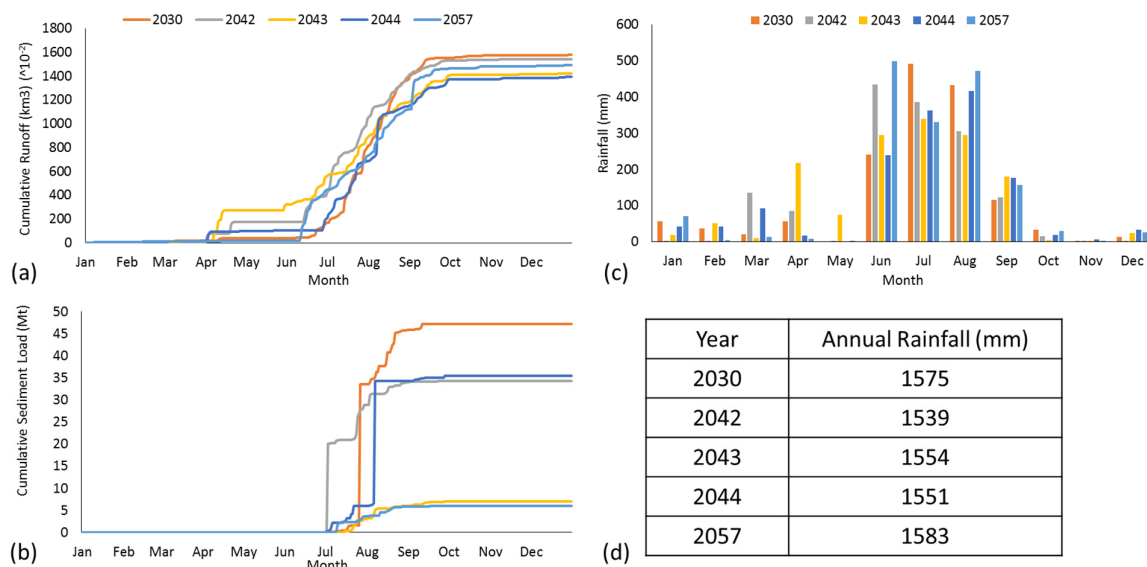


Figure 7.26: Wet years daily analysis as Baronda watershed (a) cumulative runoff, (b) cumulative sediment concentration, (c) monthly rainfall distribution, and (d) annual rainfall

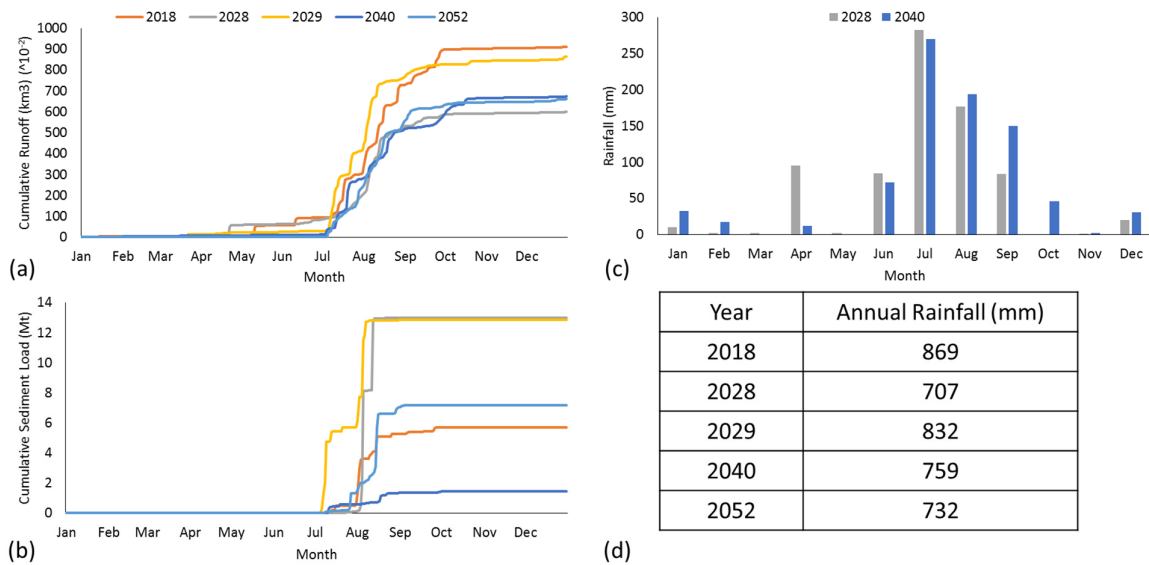


Figure 7.27: Dry years daily analysis as Baronda watershed (a) cumulative runoff, (b) cumulative sediment concentration, (c) monthly rainfall distribution, and (d) annual rainfall

The same exercise was done for Kesinga watershed also. The five most wet years in the future scenario were identified as 2030, 2042, 2043, 2044 and 2057, where maximum annual rainfall is likely to be around 1600 mm in the year 2044. The maximum annual runoff volume is likely to be 13.05 km³ for the year 2043 with daily maximum peak runoff equal to 0.54 km³. Whereas, sediment load is likely to be highest in the year 2030 with a daily peak sediment load around 2.75 Mt (Figure 7.28). The year 2047 is recognized as a driest year at Kesinga watershed (Figure 7.29). The minimum annual runoff volume and sediment load for the year are likely to be 3.71 km³ and 0.27 Mt, respectively.

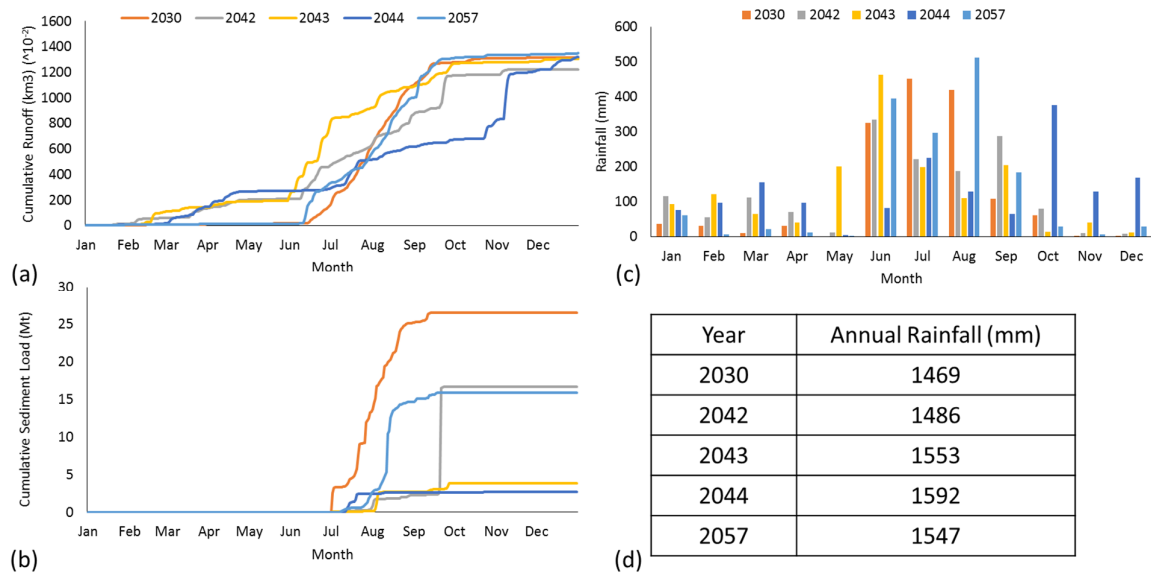


Figure 7.28: Wet years daily analysis as Kesinga watershed (a) cumulative runoff, (b) cumulative sediment concentration, (c) monthly rainfall distribution, and (d) annual rainfall

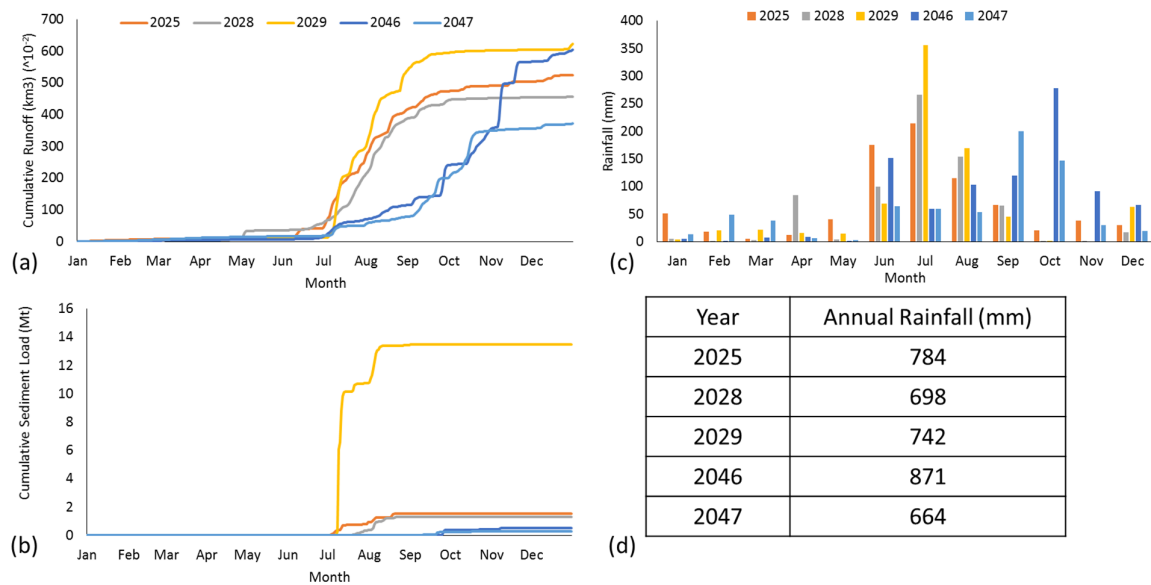


Figure 7.29: Dry years daily analysis as Kesinga watershed (a) cumulative runoff, (b) cumulative sediment concentration, (c) monthly rainfall distribution, and (d) annual rainfall

7.3.6 Upper Envelope Approach to Capture Impact of Extreme Future Conditions

Upper envelope curve approach is a traditional technique used world-wide for the estimation of discharge for high return periods or upper bounds of flood events. In the present study, a new approach using upper envelope curve is attempted to analyze the impact of rainfall on runoff and sediment load under future scenario without any modelling exercise. Figures 7.30a and 7.30b shows the RISE simulated and upper envelope approach estimated, annual monthly peak and annual daily peak runoff volume, respectively for Baronda watershed under RCP 4.5. The annual monthly peak runoff average upper bound is likely to be 3.7 km^3 , while RISE simulation shows the actual average runoff average is 2 km^3 (Figure 7.30a). The value estimated by upper envelope approach is obviously high as it shows the maximum possible runoff volume for each year for the period from 1951-2060.

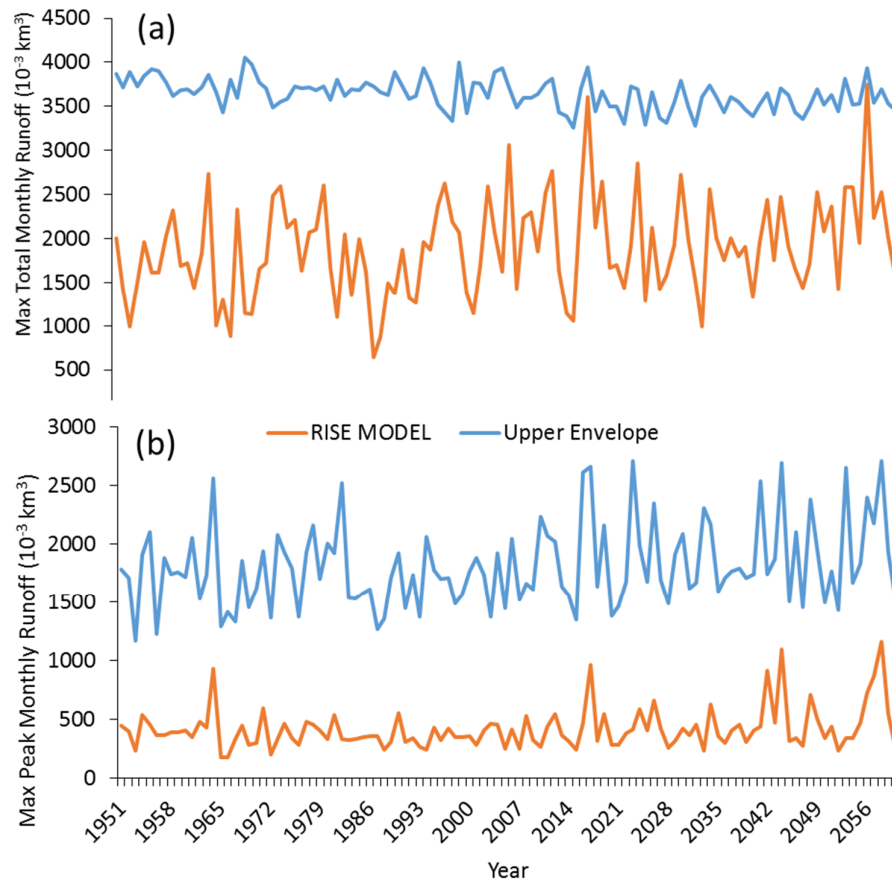


Figure 7.30: Annual (a) monthly peak, (b) daily peak rainfall under RCP 4.5 at Baronda watershed

Annual daily peak runoff estimated by upper envelope approach is averaged around 1.9 km^3 , while RISE simulated annual daily peak average is 0.53 km^3 as shown in Figure 7.30b. The estimated upper bound of peak runoff flow can be used as design discharge in water resources projects.

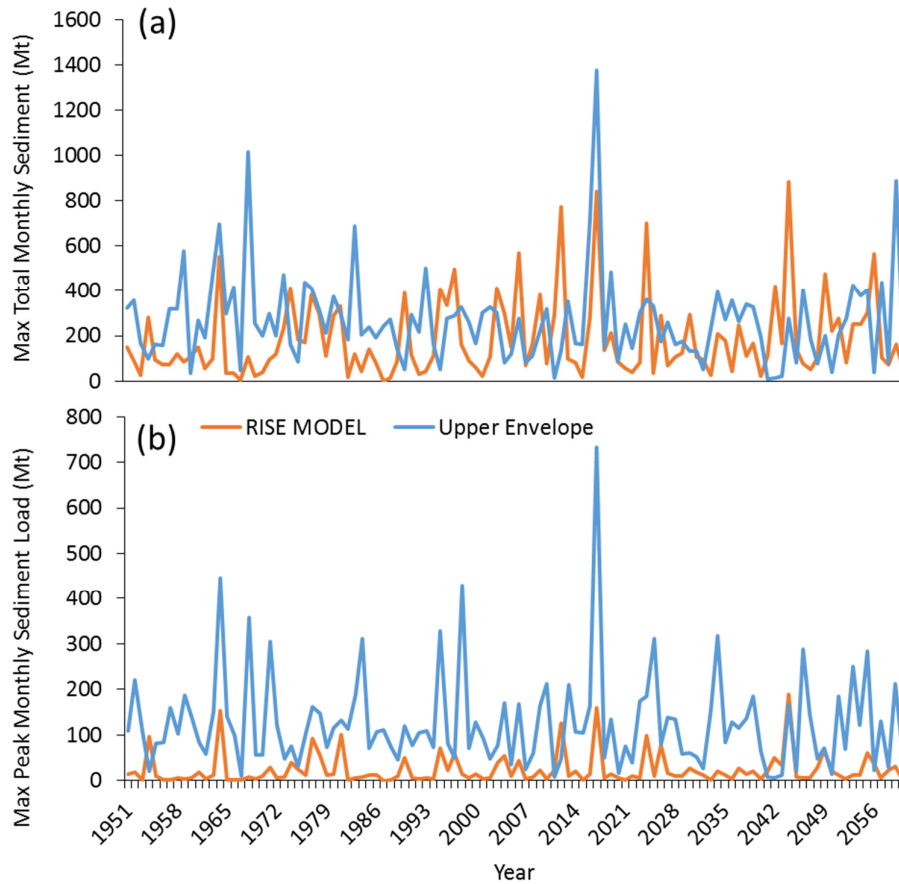


Figure 7.31: Annual (a) monthly peak, (b) daily peak sediment load under RCP 4.5 at Baronda watershed

Figures 7.32 and 7.33 show the RISE model simulated and upper envelope estimated peak daily runoff and sediment yield variation, respectively. Similarly, upper bounds of sediment load were also estimated by upper envelope approach. Figure 7.31 (a, b) shows the annual variation of daily and monthly peak sediment load for the period from year 1951-2060. The trend in Figure 7.31a for annual variation of monthly peak sediment load is analogous. However, the estimated upper bound is less than RISE model simulation peak values. Because, derivation of upper envelope curves were performed based on the rainfall data which is not directly related

to the sediment yield. But, this approach is suitable to identify/approximate maximum daily and monthly sediment load with some degree of uncertainty.

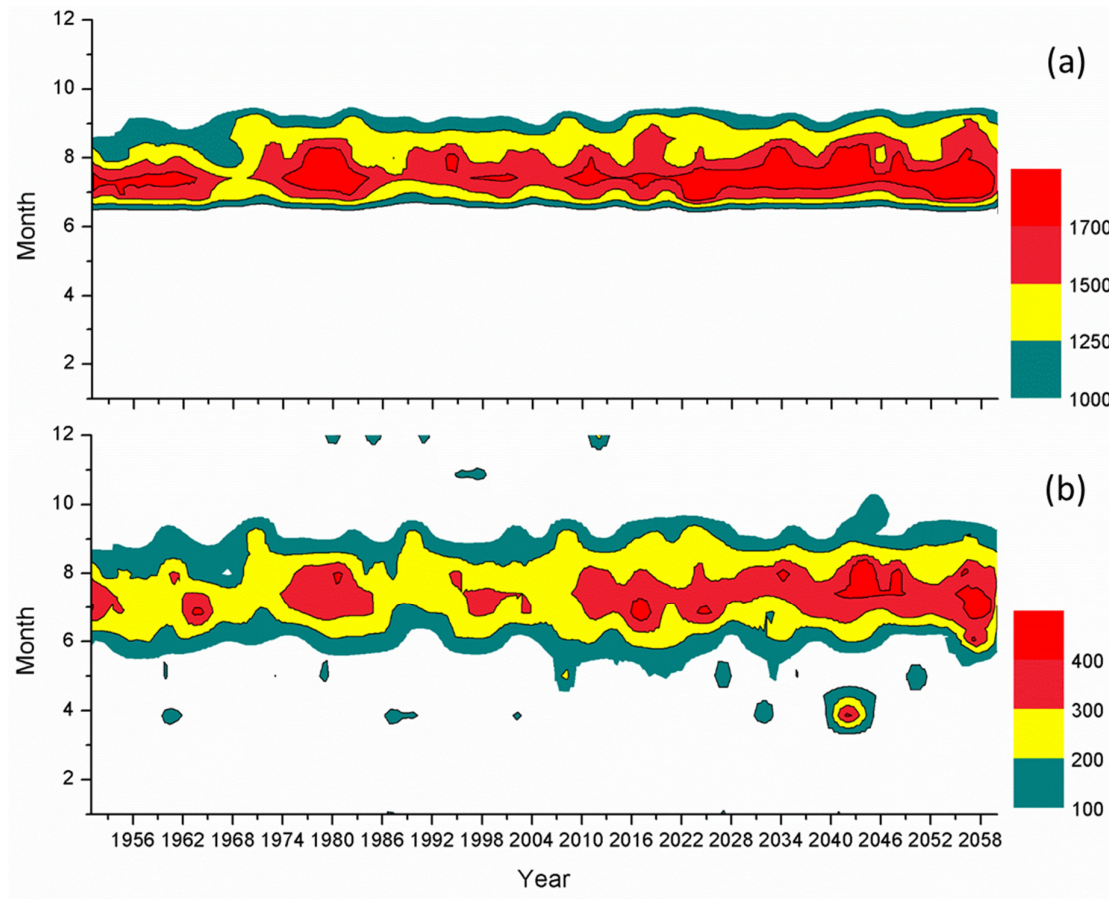


Figure 7.32: Monthly variation of peak runoff volume (in 10^3 km^3) (a) Upper envelope approach (b) RISE model simulated

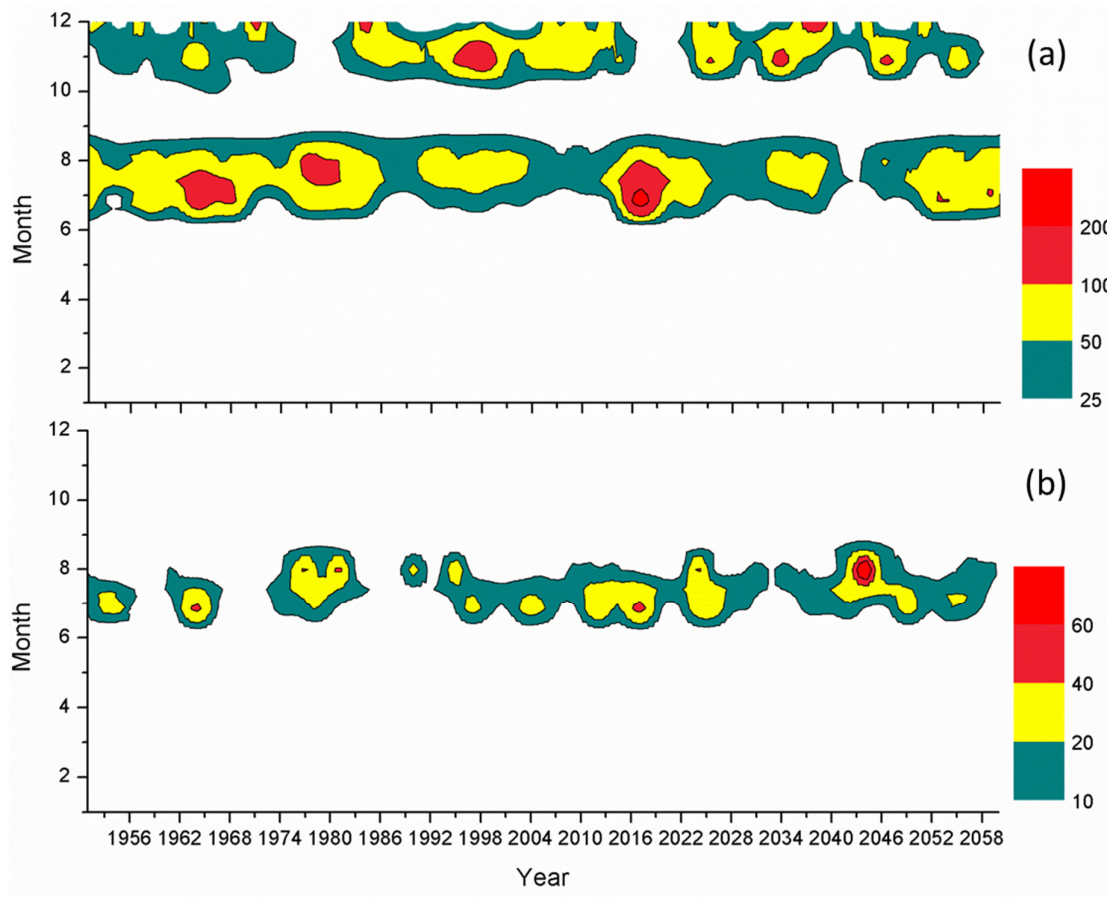


Figure 7.33: Monthly variation of peak sediment load (in 10^3 km^3) (a) Upper envelope approach (b) RISE model simulated

7.4 Conclusions

The present chapter presented a detail analysis of temporal variations of runoff and sediment yield response of two agroforestry watersheds under climate change. Two out of four RCP's recommended by IPCC were selected for the analysis. The modified RISE hydrological and sediment model was simulated for the period from 1951 to 2060 for both the watersheds by using the historical as well as future projected meteorological dataset under RCP 4.5 and 8.5. In modified RISE model, NDVI as a degree of vegetation was incorporated as discussed in Chapter 5. To derive future NDVI time series, the historical NDVI and rainfall relationship was established. It was found that rainfall and NDVI are strongly correlated at monthly time scale. After the derivation of future NDVI time series, monthly temporal NDVI variation at both the watersheds was assessed. It was depicted that NDVI values were higher during 2004-2012 in both the RCP's compared to preceding years due to high rainfall in this period. Wet

and dry years were identified based on the temporal annual and monthly rainfall anomalies from 1951-2060. It was realized that the extreme wet and dry year follows a cycle of about 12-15 years. However, there was no increasing or decreasing trend in monthly or annual rainfall time series. It was observed that there is no significant change in mean annual rainfall, maximum and mean monthly temperature at Baronda watershed from 1951 to 2060. However, RCP 8.5 climatic projections show rise of 2°C in daily maximum temperature for month of August to September between 2030 and 2040 due to the consideration of higher percentage of greenhouse gas emissions in RCP 8.5. However, annual anomalies showed that the extreme rainfall usually occurs after a cycle of 12-15 years. The modelling outputs of runoff and sediment yield were also analyzed monthly during 1951-2060 for both the watersheds under both RCP's. It was predicted that the period around year 2043/2044 is likely to have extreme runoff at Baronda watershed. The most wet and dry years were also identified based on annual rainfall. Impact of climate change on extreme wet and dry conditions were investigated for both the watersheds. Furthermore, seasonal upper envelope equations discussed in Chapter 4 were applied to forecast the extreme runoff and sediment response to future rainfall events. It was recommended that upper envelope equations may be used to estimate design discharge and sediment yield of a watershed when model input datasets are limited or absent.





SUMMARY AND CONCLUSIONS

8.1 Brief Motivation behind Objectives

The runoff generation from hillslopes depends on antecedent precipitation in semi-arid or arid regions due to the limited infiltration capacity. This may not be valid for the humid sub-tropical climates, where rainfall intensities are variable in nature and usually less than the infiltration capacity of the soil. Hydrological variables frequently found to be non-linearly related to runoff are rainfall and soil moisture. It was already reported by Penna et al. (2011) that surface runoff generation is a threshold driven process controlled by wetness conditions. Soil moisture stored in the hilly macropore zones release only during wet conditions. Therefore, the runoff generation process may be assumed a combined influence of antecedent wetness and rainfall event. It is essential to understand and identify the critical controlling factors for surface runoff and sediment generation in sub-tropical agroforestry watershed hillslopes. Can vegetation conditions be a function, on which runoff and sediment generation processes depend? If some relation among them exists, it is vital to identify and derive the relationship for hydrological modelling prospects. The sediment transport from upland hillslopes remains at the transport limit of overland flow throughout the rainy season. However, during non-monsoon season, the runoff generation becomes source limit. It may be due to the effect of vegetation and wetness conditions of watershed. IPCC reported that indirect impacts of climate change on runoff and soil erosion are related to soil and vegetation changes. Based on the above key points, six objectives were as follows:

- Identification of the controlling factors for surface runoff and sediment yield in hillslope plots in agroforestry watersheds.

- Assessment of seasonal-scale rainfall, runoff and sediment relations of two agroforestry watersheds using daily observed rainfall, discharge, and suspended sediment load.
- Formulation and development of a semi-distributed runoff and sediment yield model for agroforestry watersheds.
- Evaluation of the model's performance for two agroforestry watersheds in predicting runoff and sediment yield, and its comparison with the simulation results from Soil and Water Assessment Tool (SWAT) hydrological model.
- Establishment of a relationship between monthly vegetation index and monthly rainfall for the watersheds and impact assessment of the degree of vegetation on runoff and sediment yield.
- Spatio-temporal variation analysis of runoff and sediment yield of the watersheds from the year 1951 to 2060 by considering future climate projections and change in the degree of vegetation.

8.2 Summary of Work Done

8.2.1 Rainfall, Runoff and Sediment Relationship at Plot Scale

The present study considers six experimental plots representing different land use / land cover classes. Out of six, four plots are located in part of Brahmaputra River Basin, Guwahati, Assam; one in Dehradun, Uttarakhand and one is located in Kandhamal, Odisha, India. For continuous monitoring of the rainfall and runoff processes, an in-situ experimental hillslope plot (plot A) of 108 m² area was selected near Guwahati, Assam, India. Additionally, three experimental hillslope plots were prepared in the vicinity of Plot A, representing three different land use / land cover (LULC) classes. The three plots, namely Plot B, Plot C and Plot D were covered with deciduous broadleaf forest, bamboo and shrub, respectively. The vegetation condition over the plot varies seasonally and can be classified as sparse, moderate, and dense natural vegetation including grasses and shrubs. The undisturbed vegetation condition over the experimental plots A-D typically represents the dominating land use / land cover class of the hillslopes in the northeast Indian region. Apart from these four plots in Guwahati region, one experimental hillslope plot (Plot E) was designed in Dehradun district of Uttarakhand state, India. The setup is planned keeping in view the natural hillslope conditions prevailing in the North-western Himalayas, India where high intensity rainfall events occur frequently. To quantify the runoff and soil loss at plot scale, data from an agricultural plot (Plot F) located near Phulbani, Kandhamal district, Odisha, India was acquired. The experimental plot was

prepared and maintained under All India Coordinated Research Project to analyze the behaviour of different cropping pattern on runoff and soil loss from an agricultural plot.

The natural rainfall-runoff response from the experimental hillslope plot *A* was monitored over a period of five years from 2008 to 2012 and overland flow from plot *B*, *C* and *D* was collected manually over a period of three months from June to October 2012. The rainfall and runoff measurement at plot *E* was carried out by 15 rainfall simulation experiments carried out during September to November 2016. Rainfall, runoff and sediment loss data for plot *F* was acquired by (Subudhi and Senapati, 2016) for the period from 2007 to 2009.

The recorded rainfall and runoff data from plot *A* was analyzed for all four dominating parameters responsible for runoff generation over hillslopes such as: storm event rainfall depth (*d*), storm duration (*t*), rainfall intensity (*i*), five days antecedent precipitation index (*API*). Scatter plot analysis was attempted to identify the critical controlling parameter for runoff generation at plot scale. *IDF* curve analysis was performed to verify the range of observed rainfall intensity and duration of the majority of storm events, and to estimate the probability of detection of runoff generating events by use of *IDF* equation. To determine the variability of rainfall threshold depth and effect of land use / land cover class on runoff response, scatter plot analysis was attempted for rainfall-runoff observation of plot *B*, *C* and *D*. The curve number was also estimated for plot *B*, *C*, *D* and *F* by Soil Conservation Service-Curve Number (SCS-CN) method. The soil moisture data was used to determine the threshold rainfall and soil moisture for the classification of runoff generating events for plot *A* and *E*.

The analysis of the detailed experimental data led to some understanding of the critical hydrological processes prevailing in the hillslope. The results suggests that the runoff generation is a threshold driven phenomenon and is not limited to a particular region and may be widespread phenomena. A linear relationship, especially during monsoon season was identified between rainfall and runoff response of the hillslope plots. The storm event rainfall depth was found to be the primary controlling parameter for runoff generation. It was also observed that the threshold rainfall depth for runoff generation depends on the land use / land cover/NDVI and the season of analysis which can be represented by antecedent soil saturation/wetness. A power relationship between runoff and sediment was also established from the observed runoff and sediment loss data for plot *F*. It was argued that the identification of an apparent threshold, linear response and vegetation dependent behaviour of runoff

generation process may be a way forward for the integration of the plot processes to watershed scale.

8.2.2 Rainfall, Runoff and Sediment Relationship at Watershed Scale

For watershed scale analysis, two agroforestry watersheds in part of Mahanadi river basin were selected to identify the rainfall-runoff-sediment response characteristics. Rainfall, runoff, and sediment concentration data were obtained for the period from 1990-2000 for Baronda watershed and from 2006-2011 for Kesinga watershed. To analyze the influence of vegetation and soil moisture on runoff and sediment dynamics, satellite based NDVI and top soil moisture data for the study period was acquired.

As discussed in the Chapter 3 that runoff generation dynamics varies with season, soil moisture and degree of vegetation. Therefore, the observed watershed dataset was grouped into three categories viz. pre-monsoon, monsoon, and post-monsoon. The scatter plot analysis was performed on rainfall and runoff depth to identify the relationship among them. It was observed that runoff depth is linearly related to rainfall depth during monsoon season. However, there was more non-linearity found during the non-monsoon period. SCS curve number was also estimated at watershed scale and estimated in the range of 85-95, which indicated flashiness behaviour of rainfall-runoff response in hilly tropical agroforestry watershed. The binary classification technique was applied on soil moisture and rainfall depth to detect the threshold behaviour of runoff response. It was found that the runoff and sediment generation process depends on antecedent soil moisture, vegetation condition, and storm rainfall depth. Sediment production and transport processes depend on the amount of surface runoff and sediment concentration is a function of the amount of surface runoff. Therefore, the runoff and sediment concentration data for the Baronda watershed was analyzed to identify the power relationships among them and the values of relationship coefficient. It was found that the runoff-sediment power relationship coefficients vary with the degree of vegetation, i.e., NDVI.

8.2.3 Hydrological and Sediment Yield Model Formulation

Based on the above analysis of rainfall-runoff-sediment relationship at plot scale and watershed scale, an integrated hydrology and sediment model was developed to simulate runoff and sediment concentrations at two agroforestry watersheds. The seasonal threshold rainfall and functional relationship of sediment equation coefficients with NDVI were incorporated into RISE model. The variability of soil moisture was carried out in the model by calculation of

moisture deficit for each time step. The modified model was then simulated for both agroforestry watershed and the performance was evaluated by measures of goodness-of-fit. The model performed satisfactorily well in capturing the variability in discharge and sediment concentrations. The performance of the developed model was further evaluated and compared with the results of widely used SWAT model. It was found that both the models showed good agreement in terms of capturing the pattern of runoff and sediment concentration variation. However, peak runoff and sediment concentration were over predicted by SWAT model. The threshold rainfall depth based runoff generation mechanism is absent in SWAT model. Due to the reason, SWAT predicts the surface runoff as soon as rainfall occurs. It was also observed that SWAT uses modified universal soil loss equation for estimation of sediment load which does not consider the seasonal variability in the degree of vegetation and soil moisture. Assessment of the sensitivity of degree of vegetation and threshold rainfall depth on RISE model's performance in predicting the runoff and sediment yield was also attempted and it was observed that threshold rainfall depth is more sensitive towards runoff and sediment generation in comparison to NDVI.

8.2.4 Impact of Climate Change on Runoff and Sediment Yield

To assess and predict the runoff and sediment response to climate change, NEX-GDDP historical and projected dataset was downloaded and bias corrected for the period from 1951 to 2060. Two RCP scenarios were considered for the analysis. To derive future NDVI time series as an input to RISE model, the historical NDVI and rainfall relationship was established. It was found that rainfall and NDVI are strongly correlated at monthly time scale. The trend analysis was attempted for projected rainfall and temperature data and no particular trend was observed. However, a cycle of 12-15 years was observed for extreme wet and dry period. The model simulation was performed for both watersheds with bias corrected RCP 4.5 and RCP 8.5 climatic projected data. The modelling outputs of runoff and sediment yield were analyzed monthly during 1951-2060. It was projected that the period around year 2043/2044 is likely to have extreme runoff and sediment yield. Impact of climate change on extreme wet and dry conditions were also investigated for both the watersheds. Furthermore, seasonal upper envelope equations discussed in Chapter 4 were applied to forecast the extreme runoff response to future rainfall events. It was suggested that upper envelope equations may be used to estimate design discharge and sediment yield of a watershed when model input datasets are limited or absent.

8.3 Major Conclusions

The following major conclusions were drawn from the present investigation:

- Observation of overland flow response under natural storm events revealed that overland flow generation from the hillslope plot was a threshold dependent process. Runoff generation process was primarily controlled by storm event rainfall depth. The threshold rainfall depth varies with the seasonal vegetation and soil moisture variations.
- The evaluation of the experimentally established linear relationship between surface runoff depth and rainfall depth under natural storm events for the hillslope plots showed reasonable agreement with the estimated curve number. The low curve number indicated that the tropical hillslope regions have high retention capacity and subsurface storage.
- In absence of observed data, the probability of runoff generation can be estimated with the help of intensity duration frequency curve of the region.
- Analysis of daily rainfall depth, runoff depth, NDVI, and soil moisture data revealed that the runoff and sediment generation mechanism depends on the soil moisture and NDVI variations. The threshold value of storm event rainfall depth can be estimated by binary classification technique.
- The rainfall and runoff were linearly related to each other during monsoon season at both agroforestry watersheds. However, the relationship between rainfall and runoff during non-monsoon period was non-linear with independent trend in it. The estimated SCS curve number which ranges between 85-90 showed flashy behaviour of the watersheds.
- The upper envelop curves were developed to estimate the extreme runoff response from the watersheds.
- The runoff and sediment concentration at plot and watershed scale were related with a power relationship. It was found that sediment generation and its transport depends on the extent and variation in vegetation cover which varies seasonally. The power relationship coefficients were found influenced by the NDVI. The linear relationship pattern between power coefficient and NDVI were different for monsoon and non-monsoon period. It was argued that the relationship between NDVI and USLE 'C' factor is only valid for non-monsoon period.

- A semi-distributed hydrological and sediment yield model was developed considering the effect of vegetation, threshold rainfall depth, and soil saturation. The hydrological and sediment modelling results showed that the model captures the peak sediment and runoff very well. It may be noted that as this model is based on topography based approach, it requires less input data for calibration.
- The performance of developed model showed better results compared to the results of SWAT model.
- The hydrology and sediment yield model was more sensitive towards threshold rainfall depth in comparison to NDVI.
- By analyzing the historical rainfall and NDVI time series, relationship was established among rainfall and NDVI. The relationship was found best for monthly time scale.
- The NEX-GDDP projected data was under-predicted during monsoon season and overestimated for non-monsoon phase of the year when compared with IMD gridded rainfall data.
- Men-Kendall trend statistic test on annual rainfall from 1951 to 2060 at Baronda and Kesinga watersheds revealed that there is no particular trend of increasing or decreasing. However, a cycle of 12-15 years was observed for extreme wet and dry period.
- With the help of projected rainfall and NDVI, hydrological model simulation was performed for two agroforestry watersheds. It was observed that under climate change scenario, runoff and sediment yield is likely to increase by 30-45 %. It was projected that the period around year 2043/2044 is likely to have extreme runoff and sediment yield.
- The present investigation provides an insight to the dominating runoff and sediment generation processes, their interdependence, and their extremities in agroforestry watershed by *in situ* experiments and modeling approach under climate change.

8.4 Recommendations for Future Research

Till date very few experimental data are available to investigate such critical hydrological events of the region at the process level. Especially, the remote areas of northeast India are still not well developed from the socio-economic point of view. The process of acquiring data from these regions by installing state of art instruments remains as a great challenge to the hydrologists and researchers working in the area. Similar plot scale field experiments in

different hillslopes of the region should give better insight to the extremities of the hydrological processes. Spatial variations of NDVI and runoff–sediment power relationship may be explored in detail. The present study can be used to compare the results obtained from other locations and thus the validity range of the present experimental relationships can be further established with more confidence. The number of simplifying assumptions taken in the models can be reduced by incorporating more realistic physical definition of the complex flow domains. Efforts are also to be made to extend the modeling concept and upscale to basin scale. Landslides are often related to flashiness behavior of rainfall runoff response in hilly regions. The critical controlling rainfall characteristic for landslide occurrence and effect of vegetation can be identified based on present study. Runoff and sediment yield projections obtained in the present study may be used for planning and management of agricultural crops and forest land cover. Indirect relation of climate change to sediment yield can further be extended to water quality and nutrient studies.



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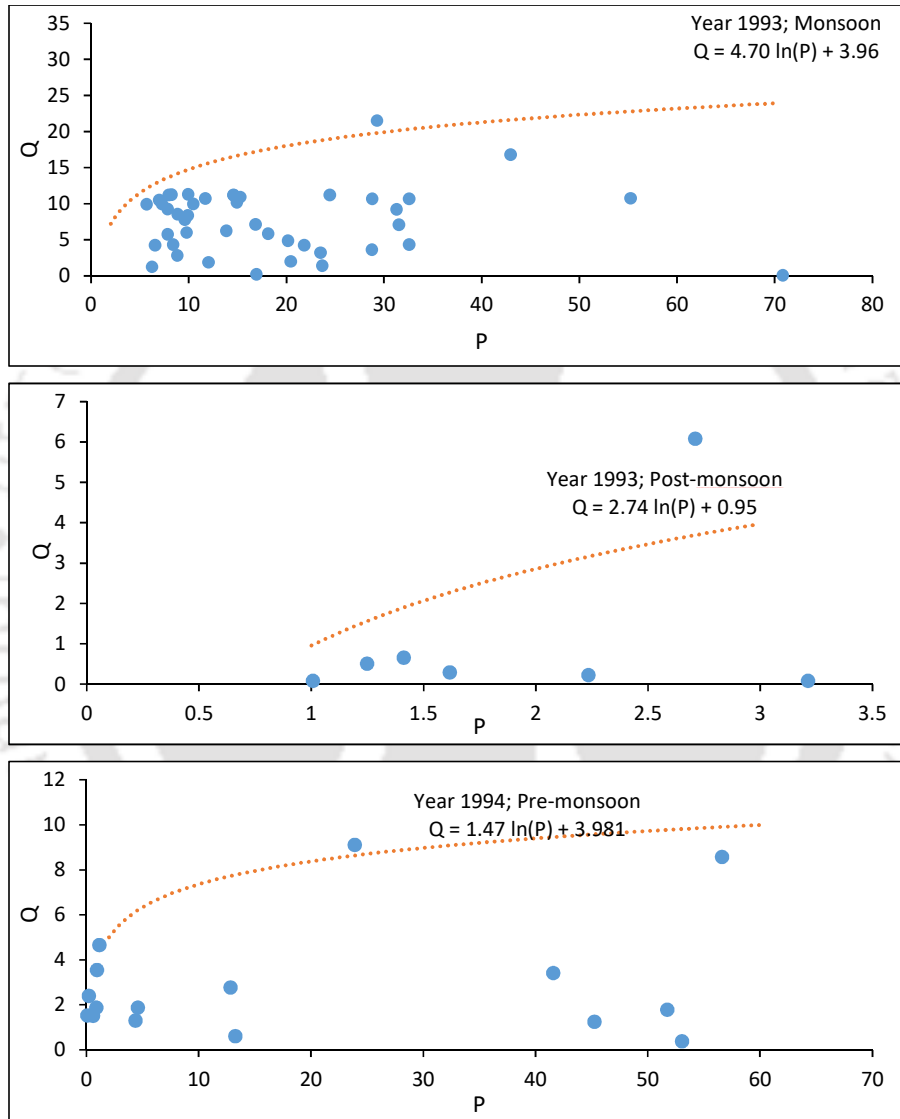
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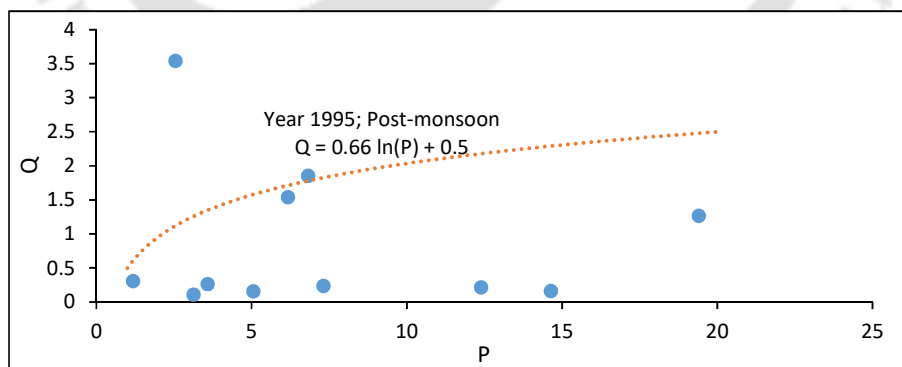
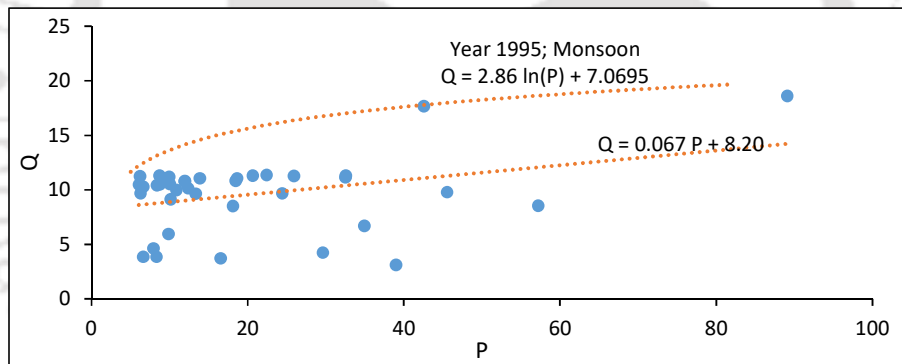
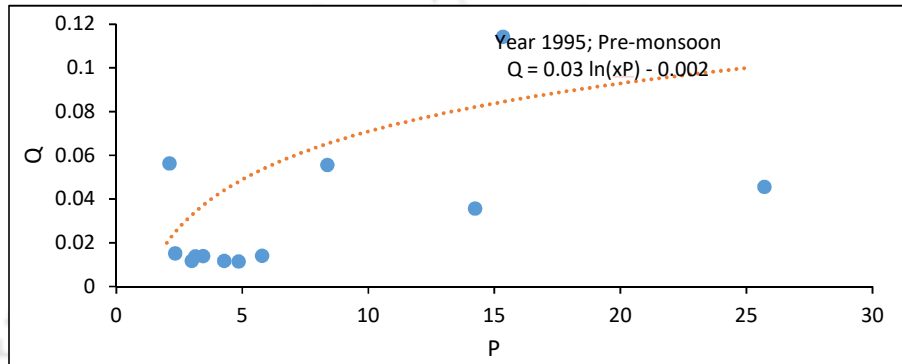
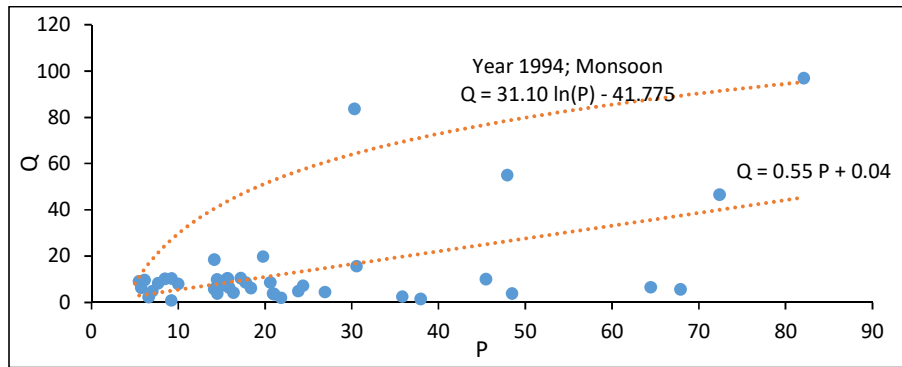
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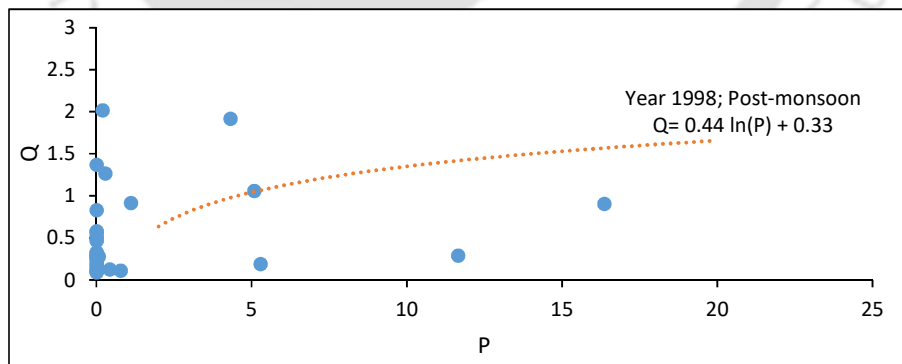
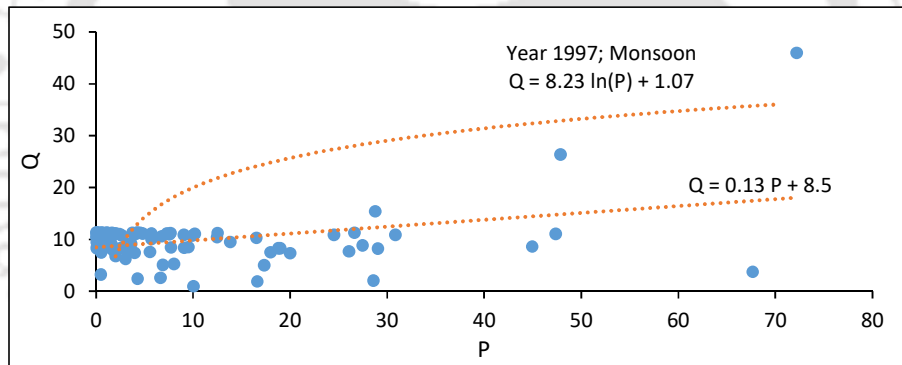
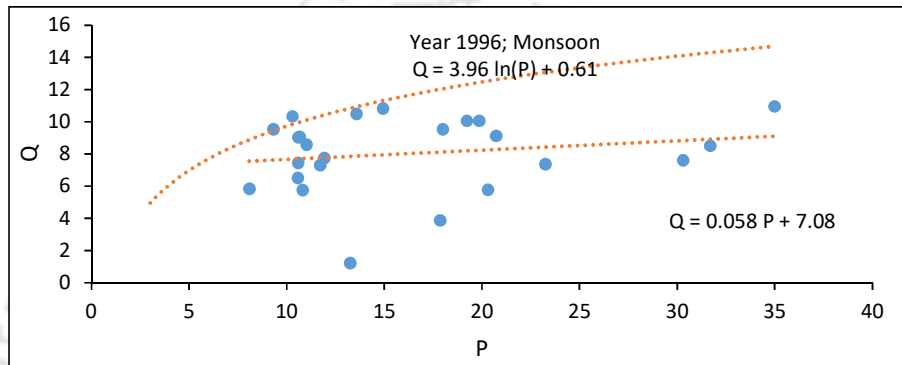
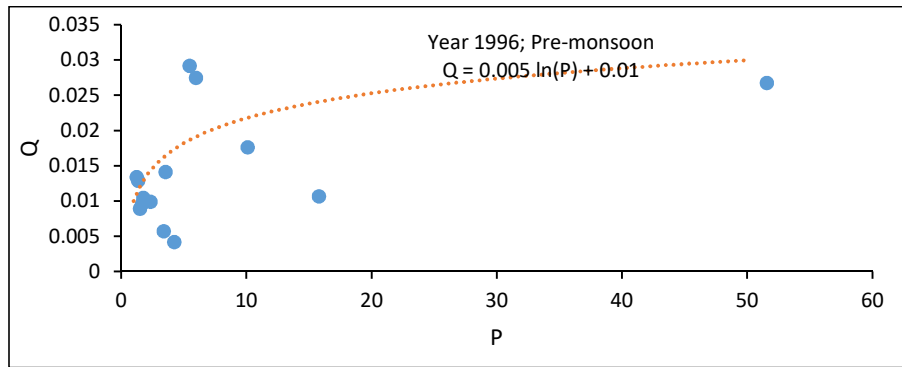
APPENDICES

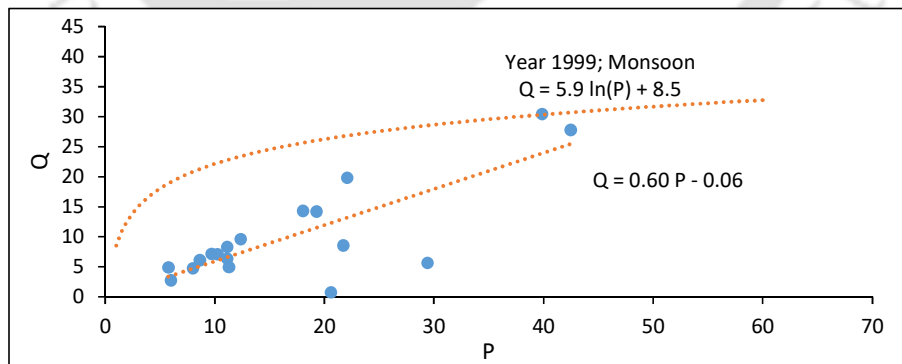
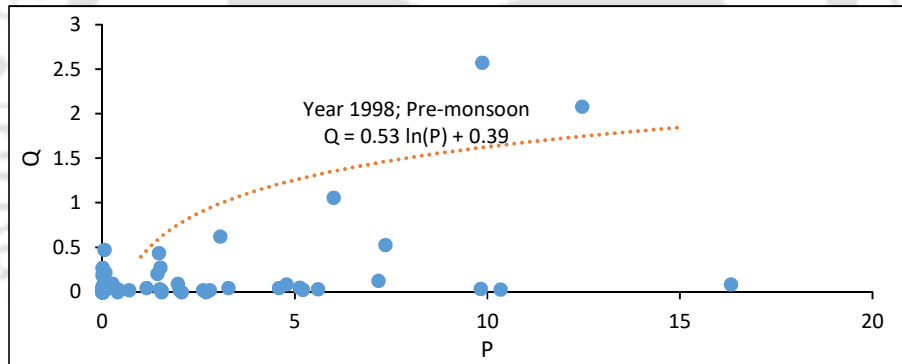
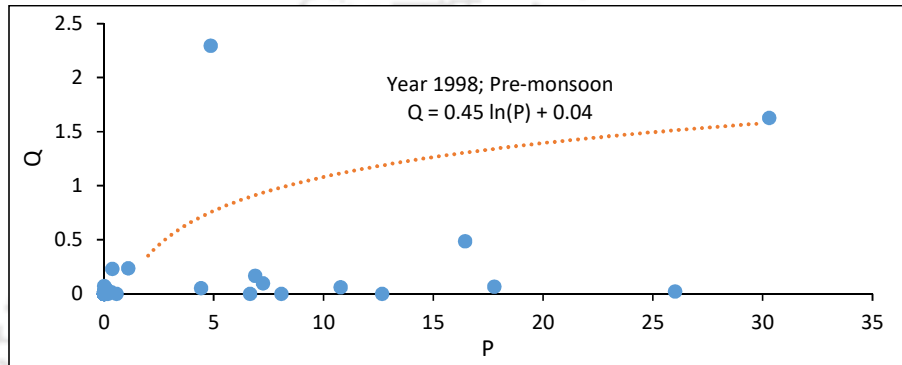
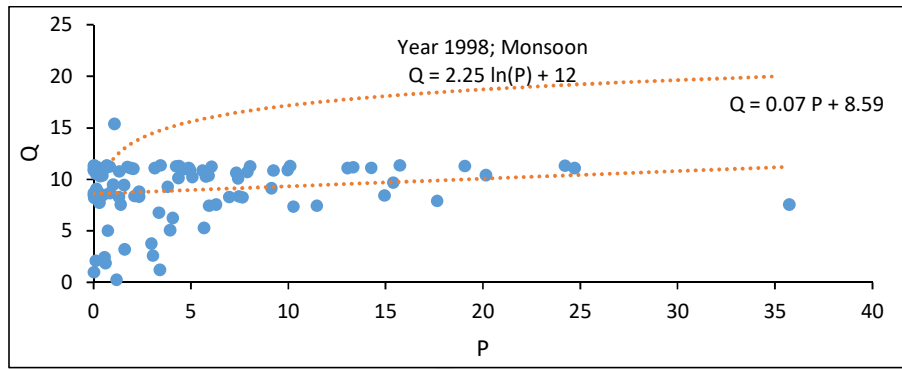
Appendix – A: Chapter Four

Appendix A1: Plots of observed rainfall-runoff response at Baronda watershed; Q: runoff depth in mm, P: rainfall depth in mm; logarithmic trend line: upper envelope

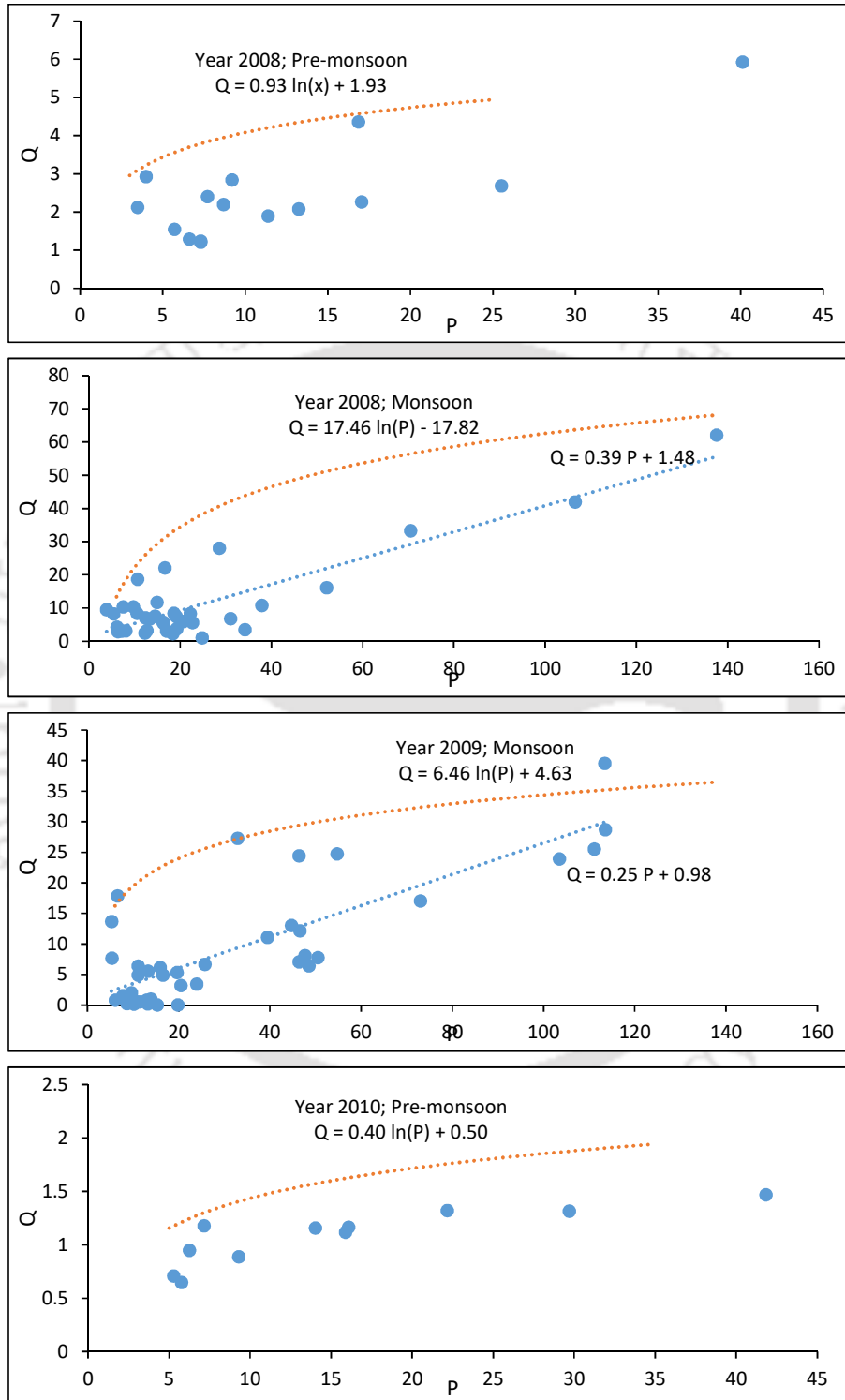


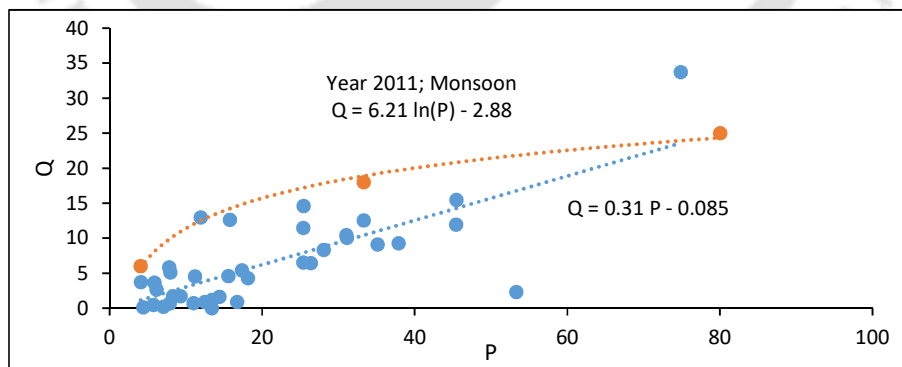
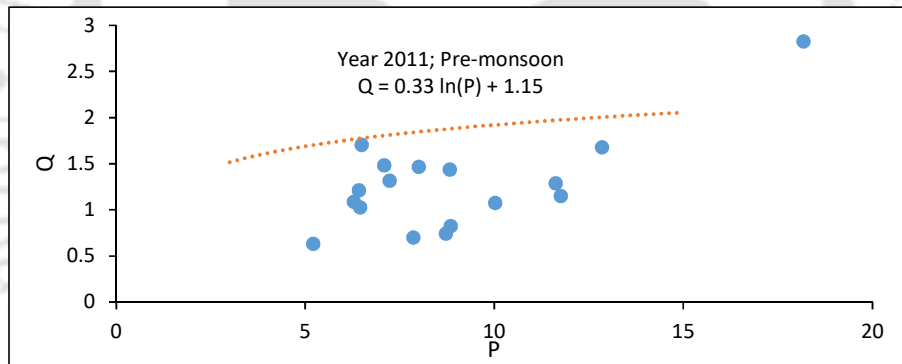
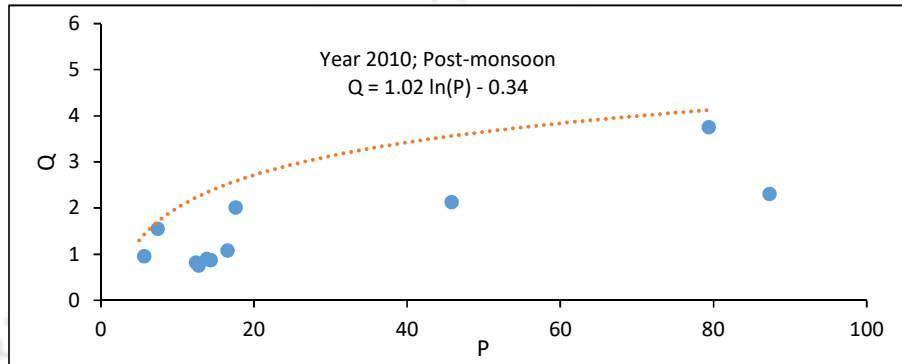
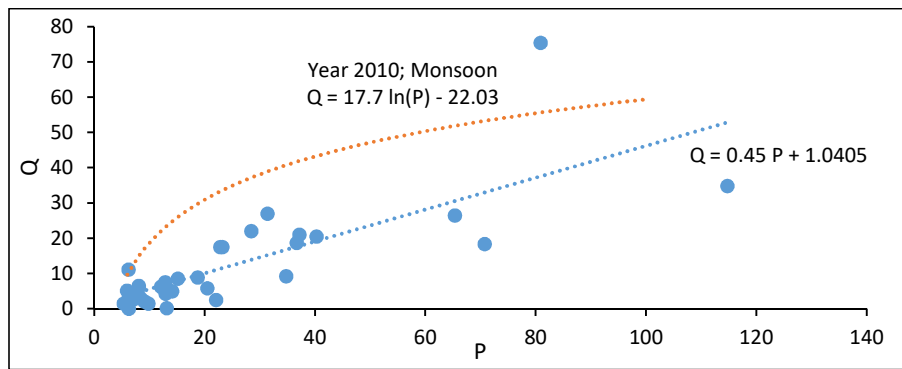




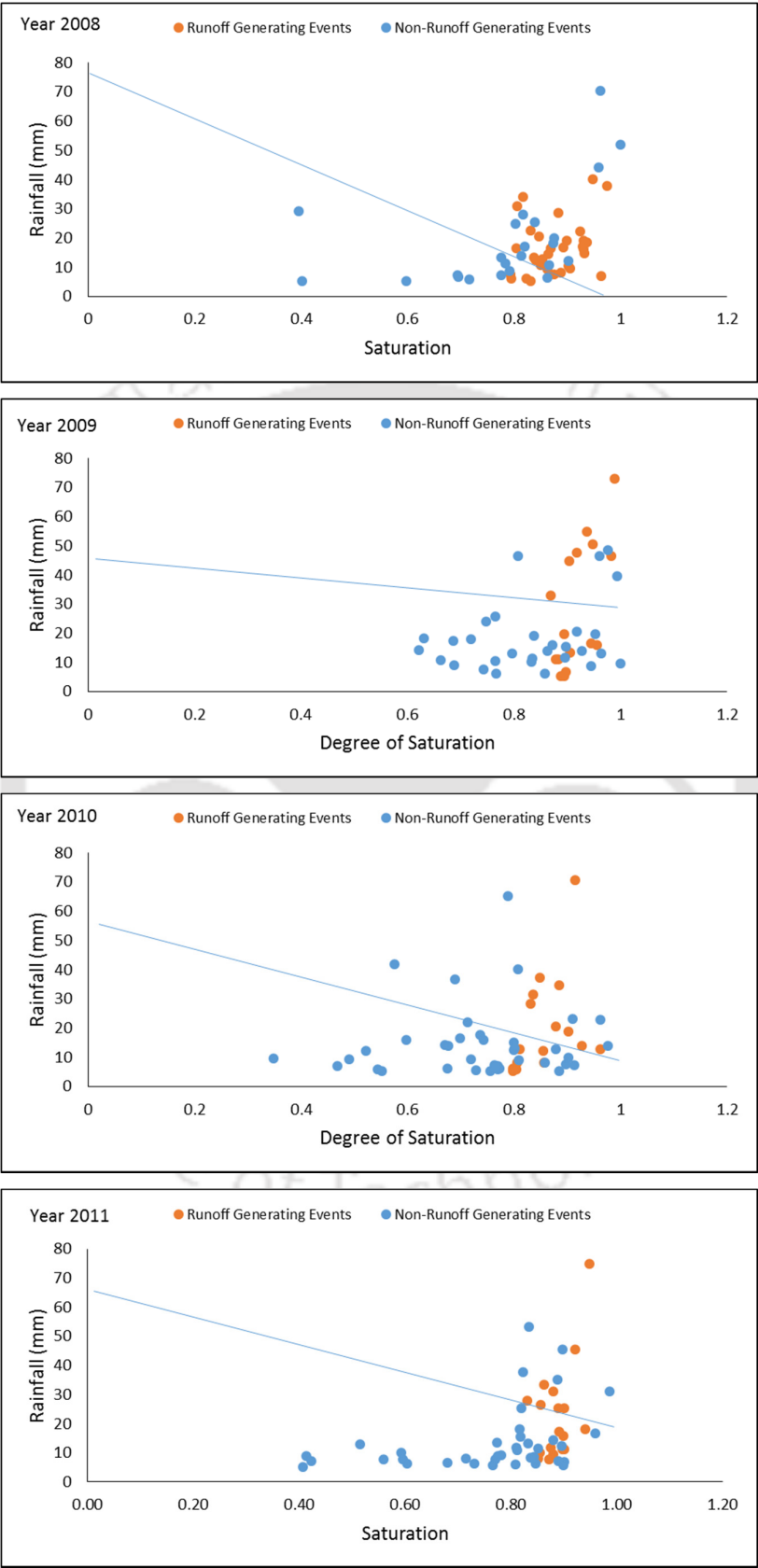


Appendix A2: Plots of observed rainfall-runoff response at Kesinga watershed; Q: runoff depth in mm, P: rainfall depth in mm; logarithmic trend line: upper envelope

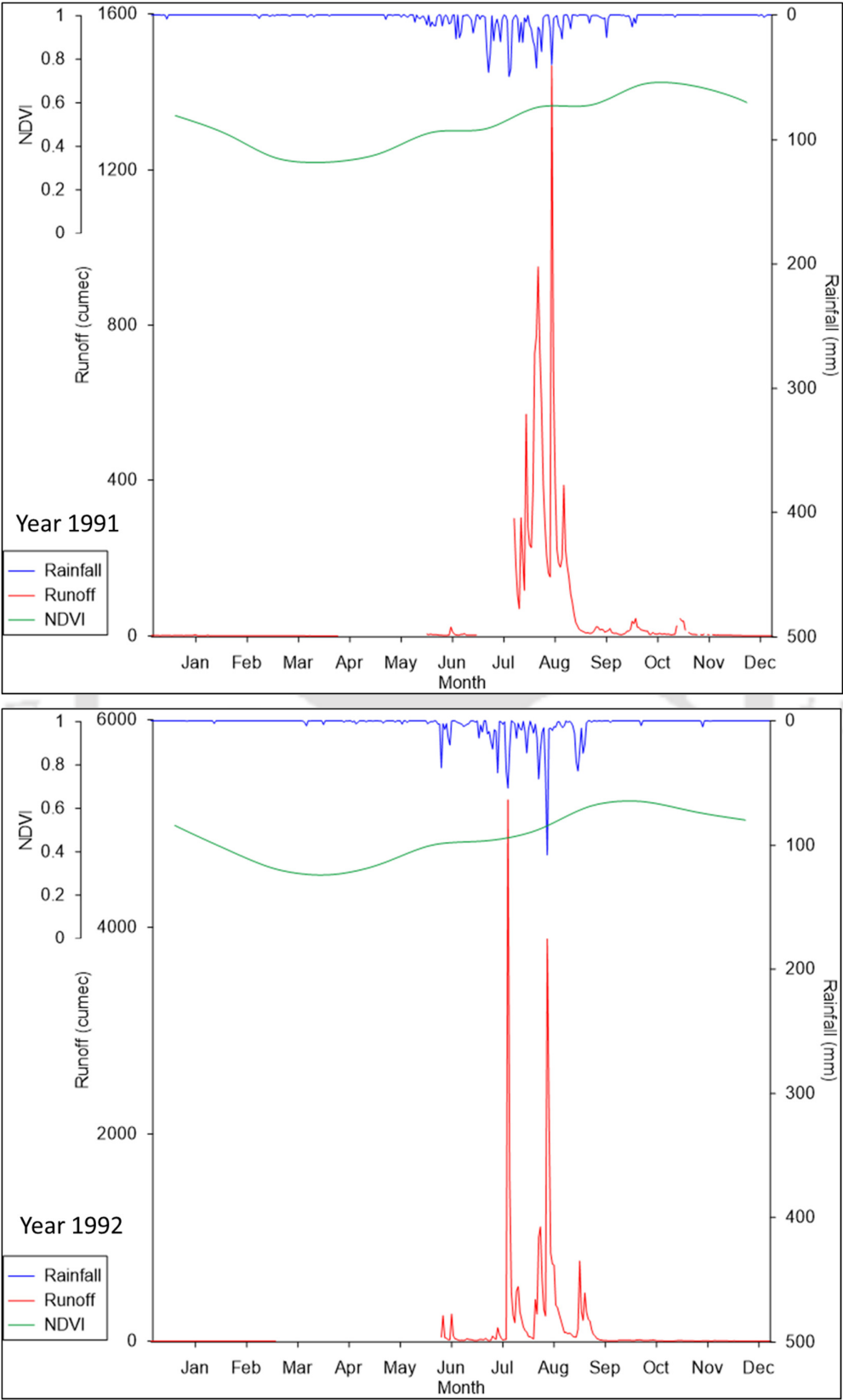


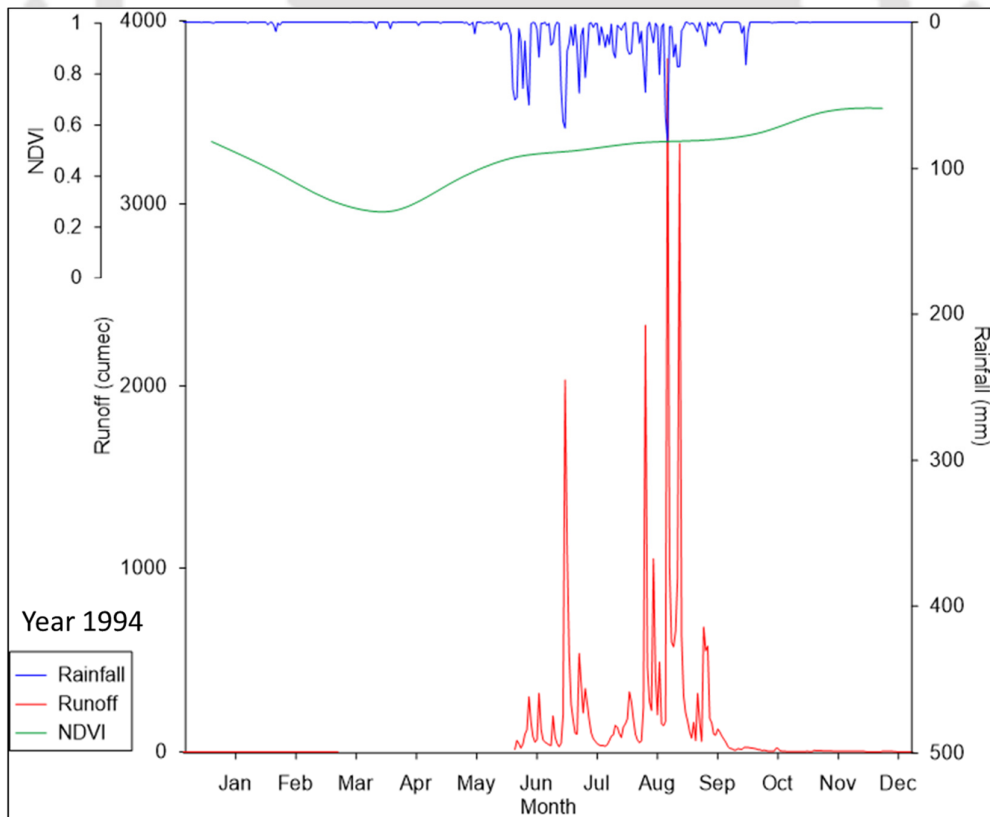
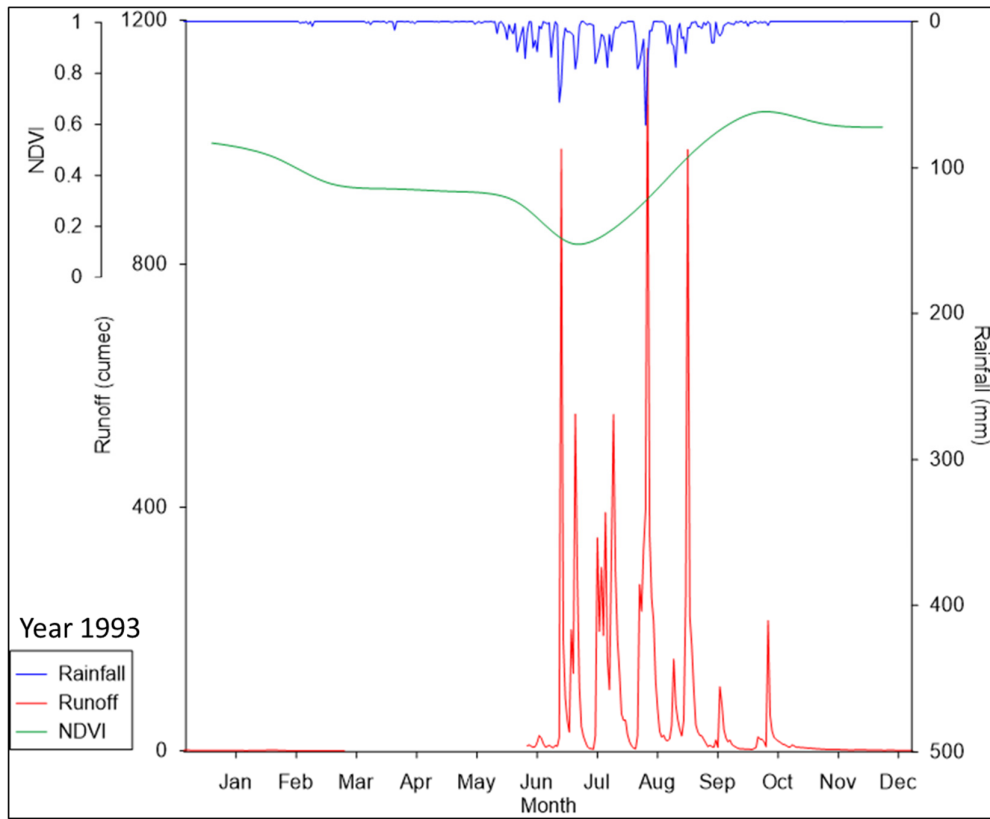


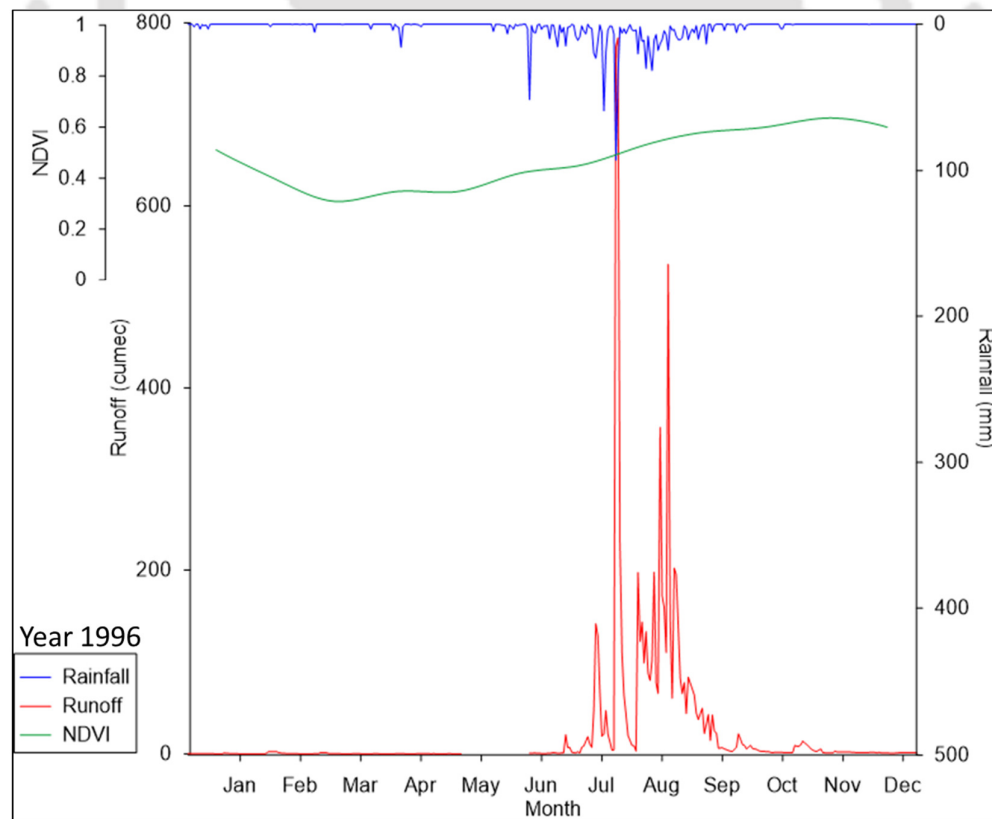
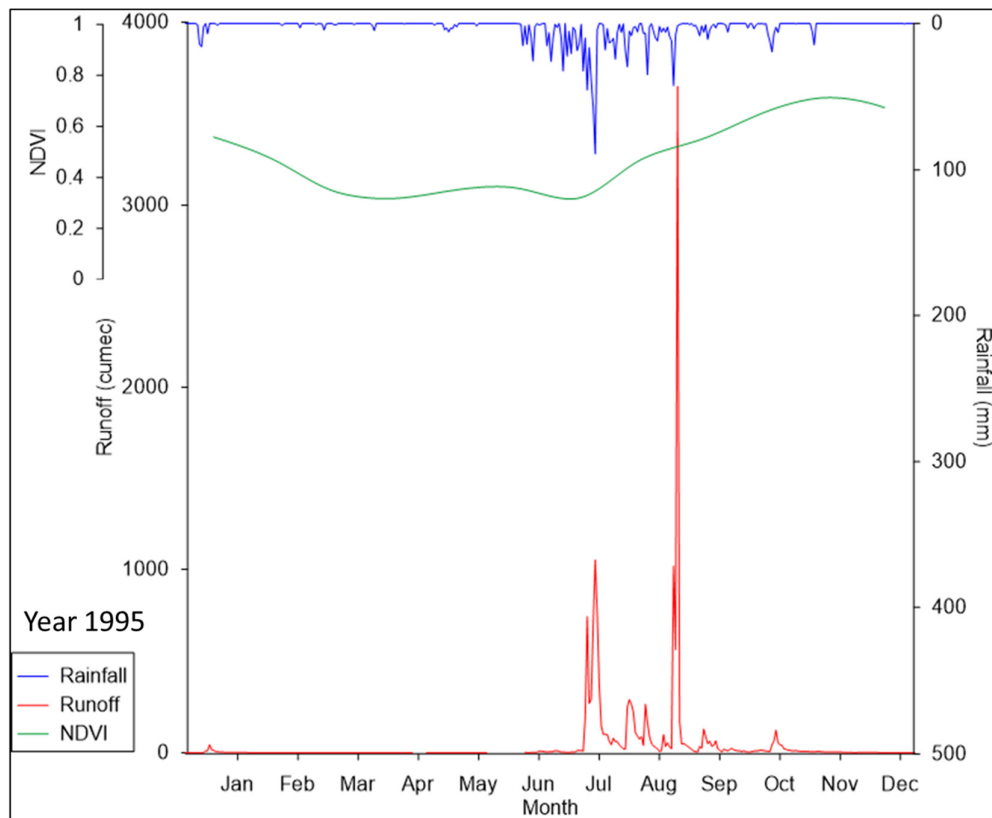
Appendix A3: Rainfall depth and soil saturation threshold for Kesinga Watershed

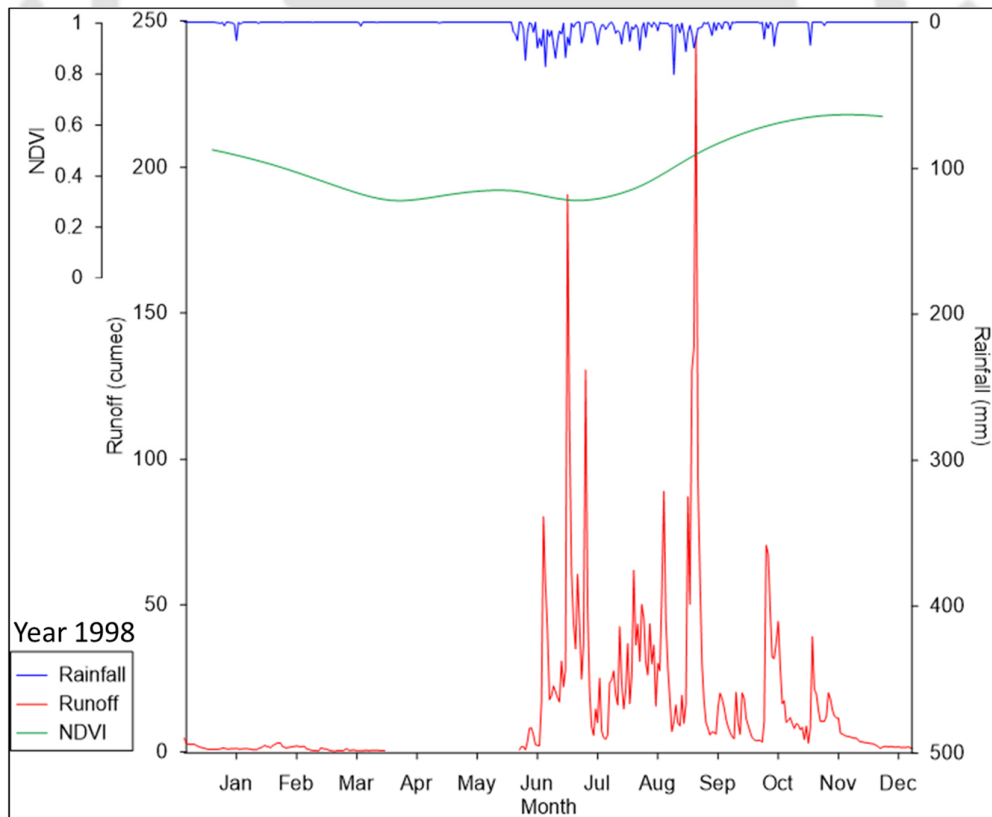
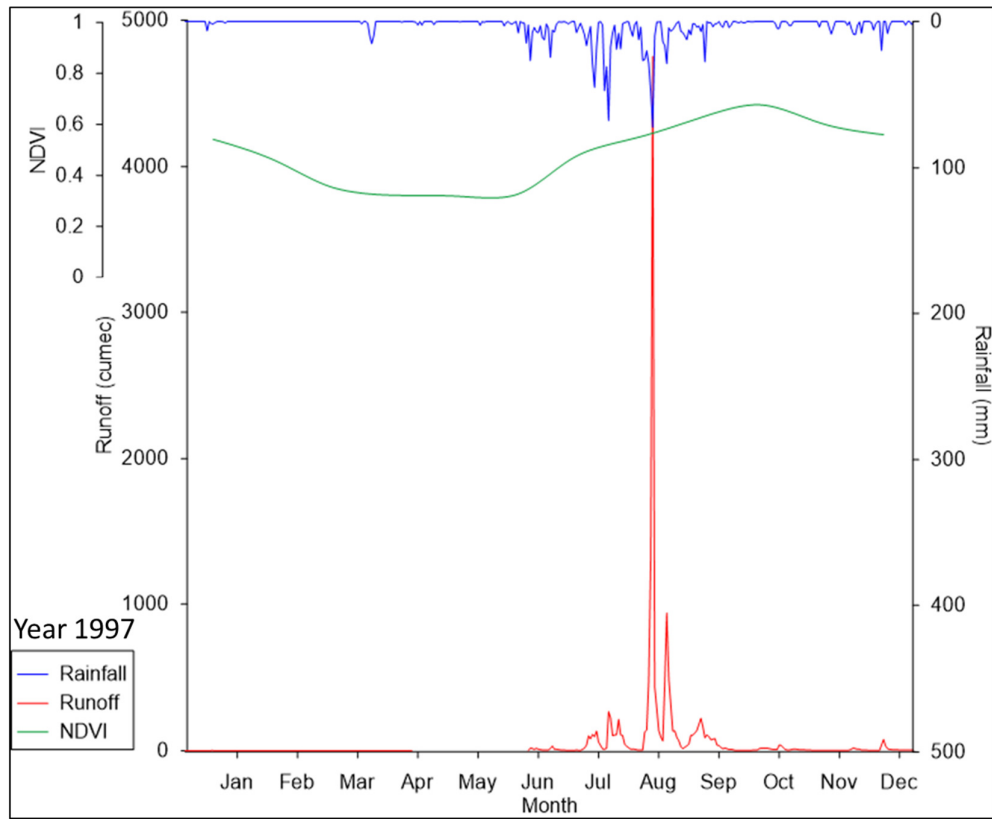


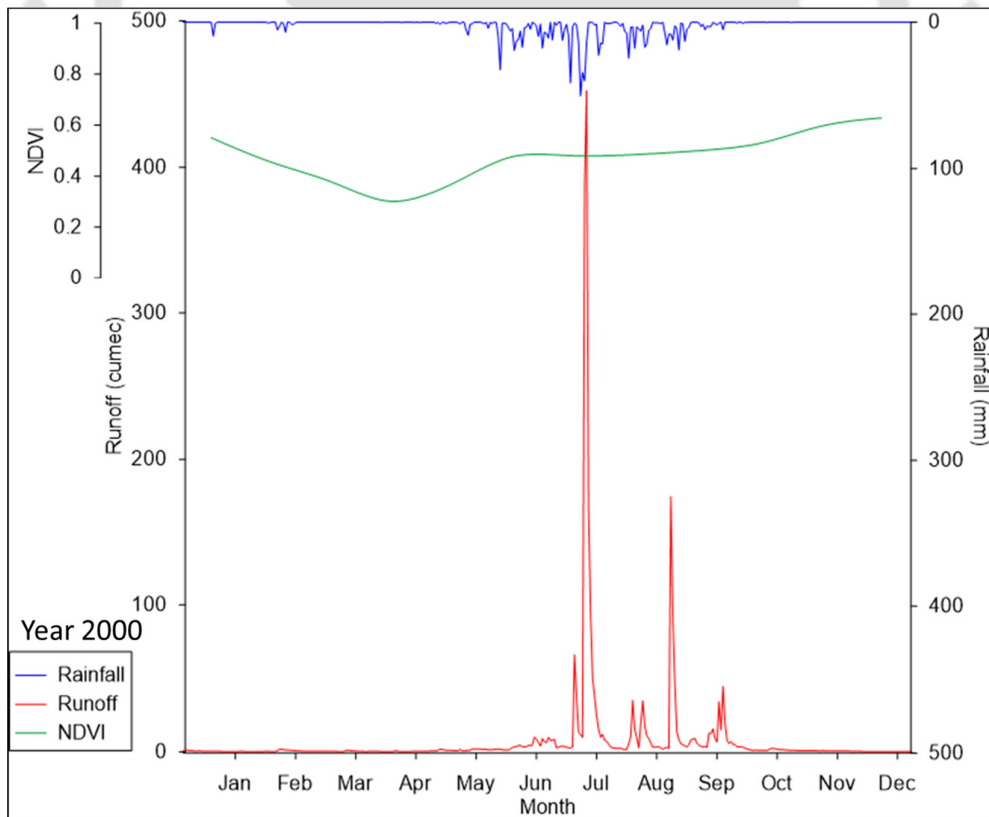
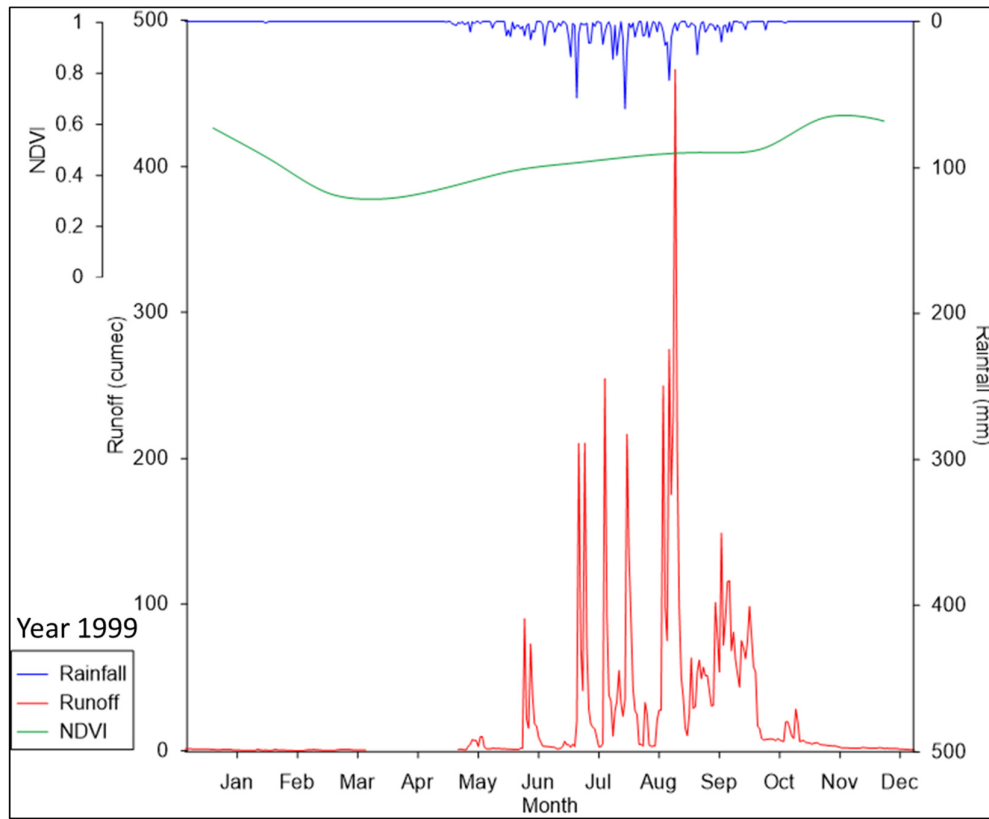
Appendix A4: Plots between rainfall, runoff and NDVI at Baronda Watershed



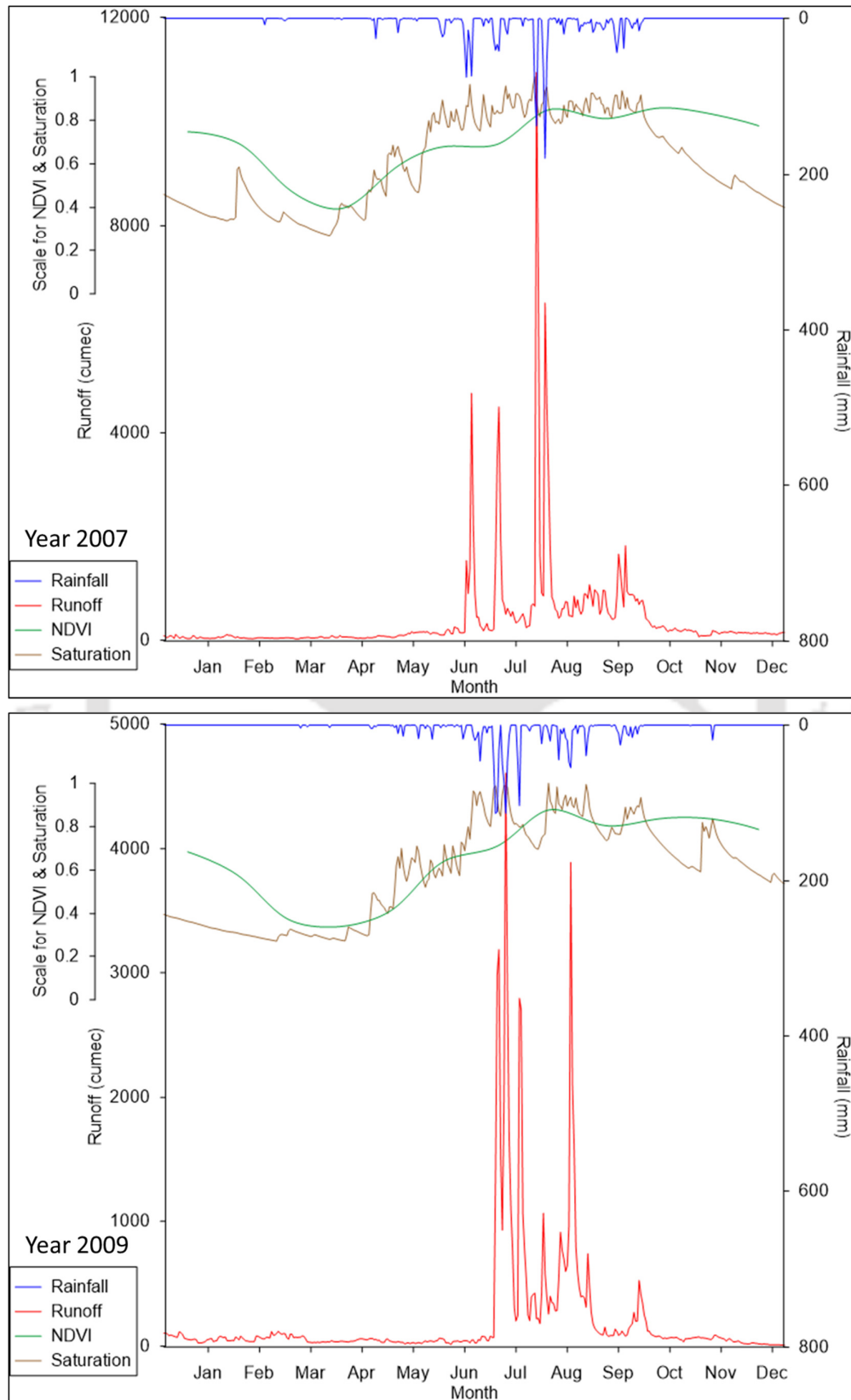


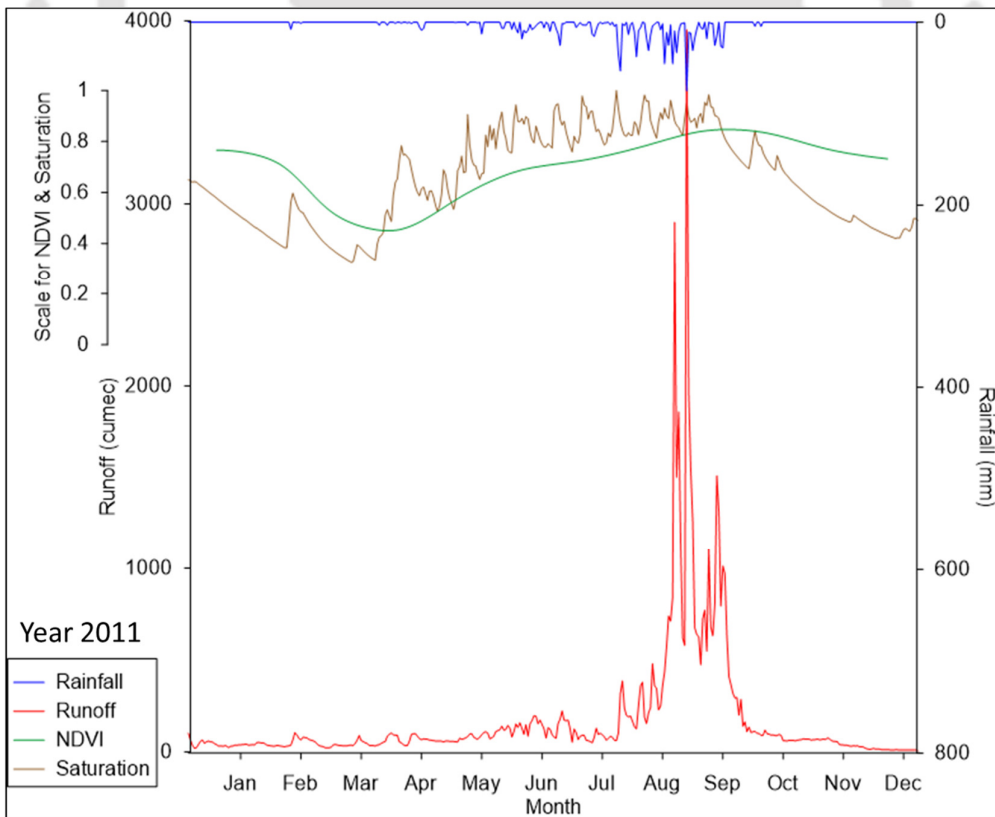
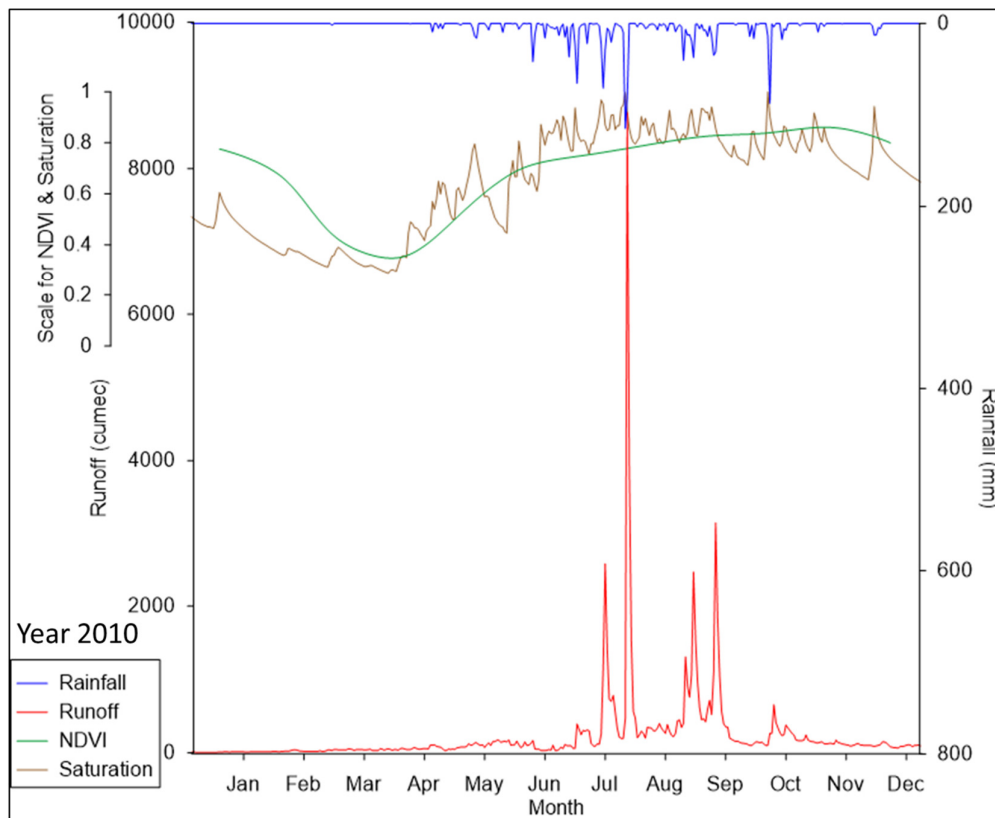




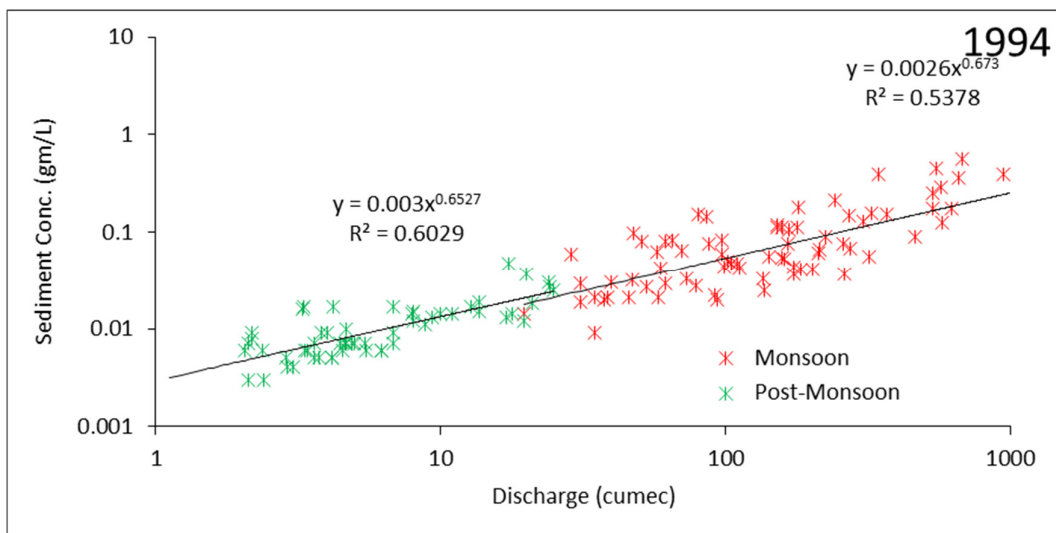
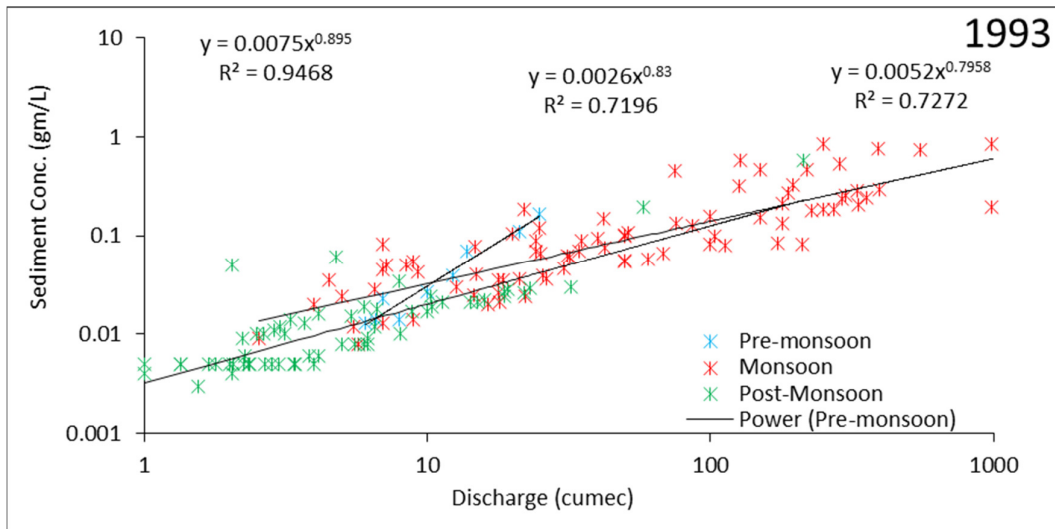
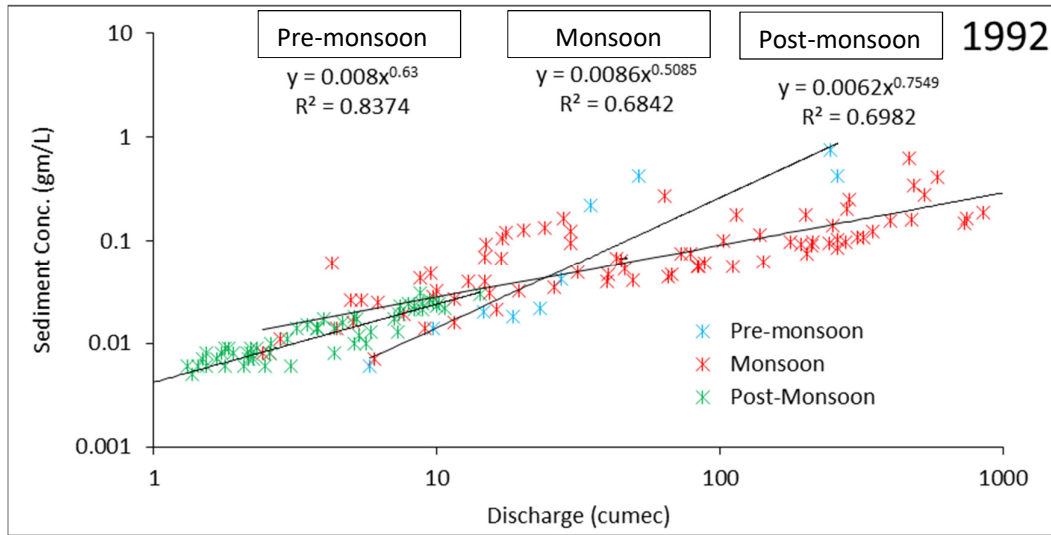


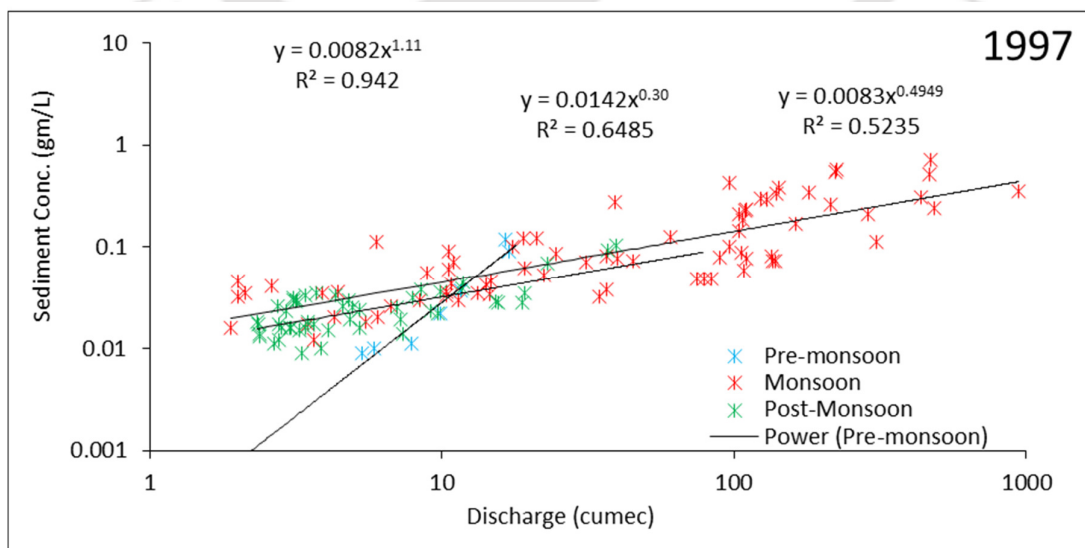
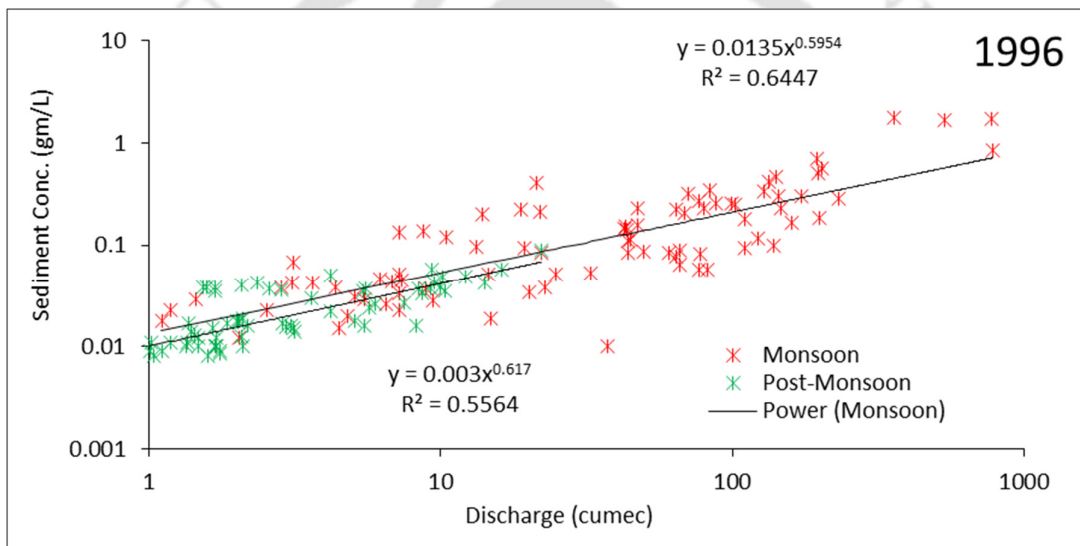
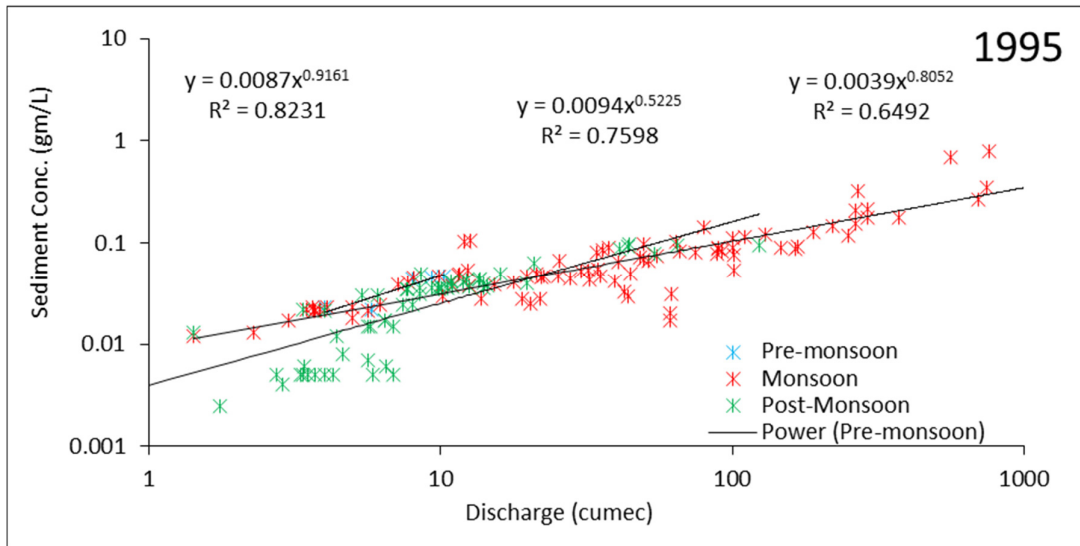
Appendix A5: Rainfall, runoff, NDVI and soil saturation variation at Kesinga Watershed

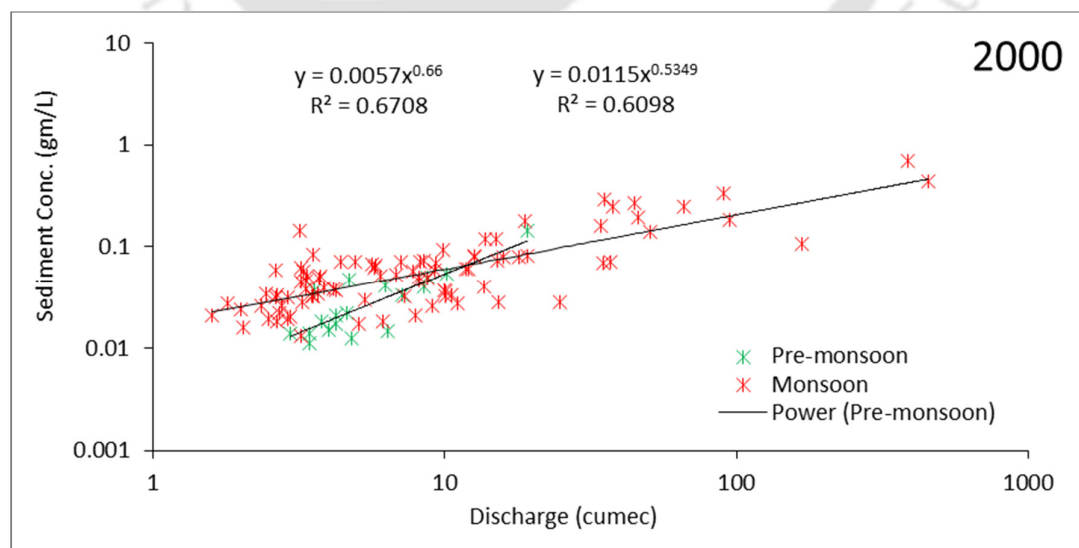
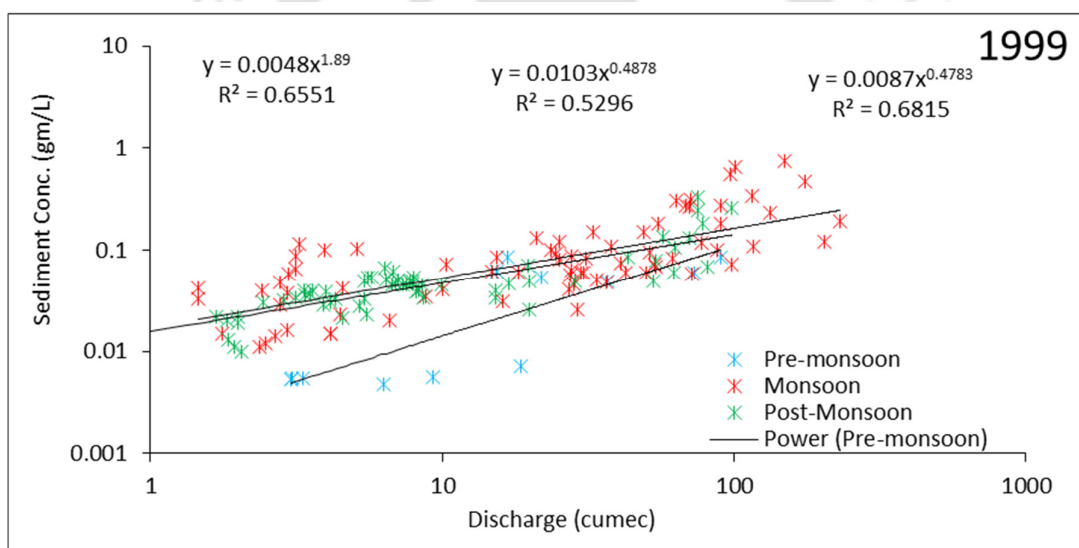
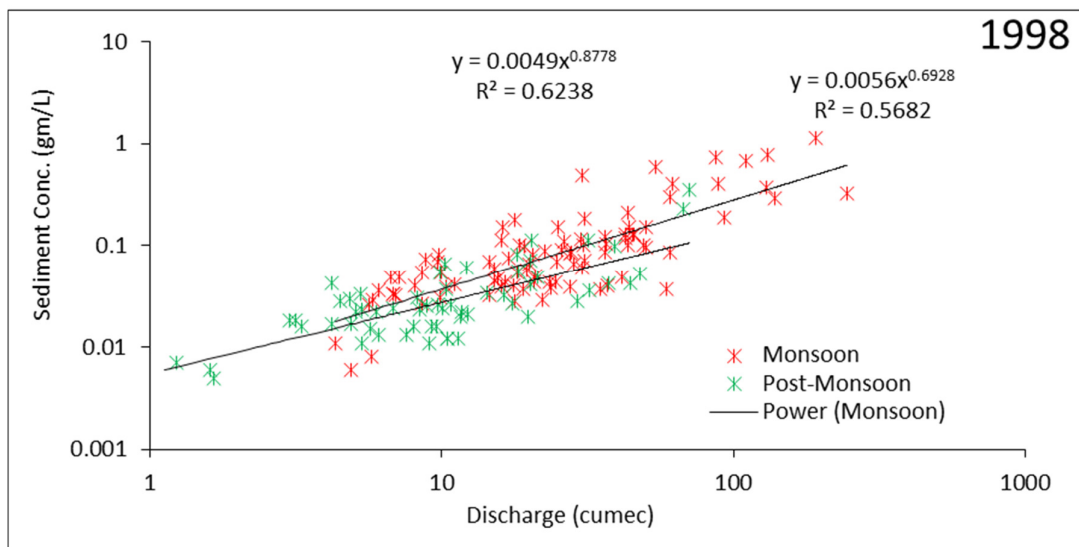




Appendix A6: Rainfall, runoff, NDVI and soil saturation variation at Kesinga Watershed

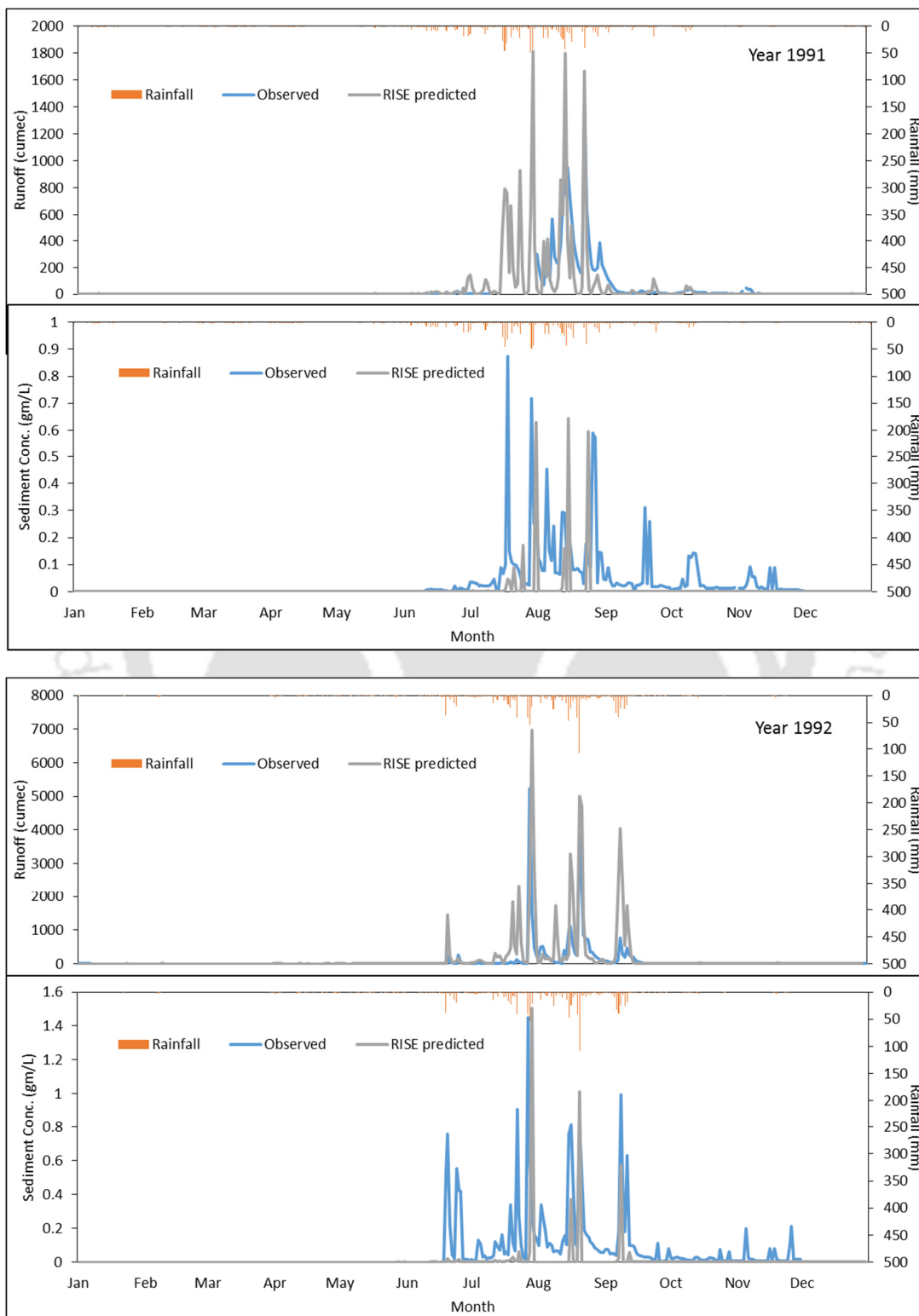


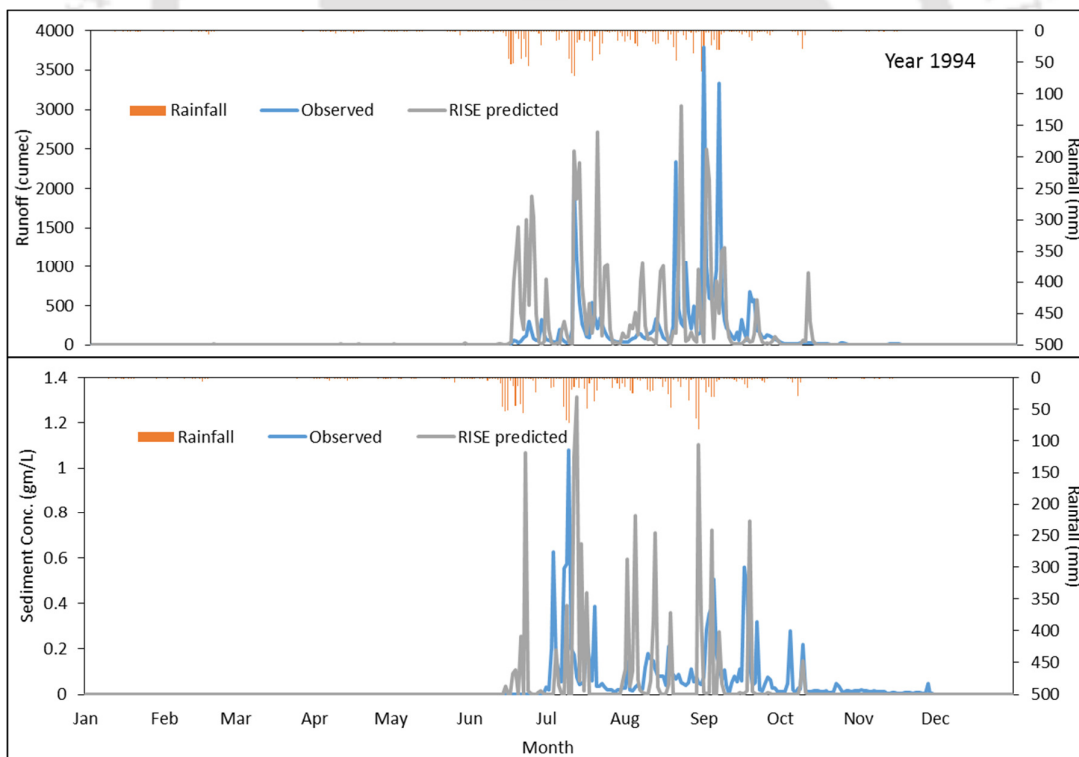
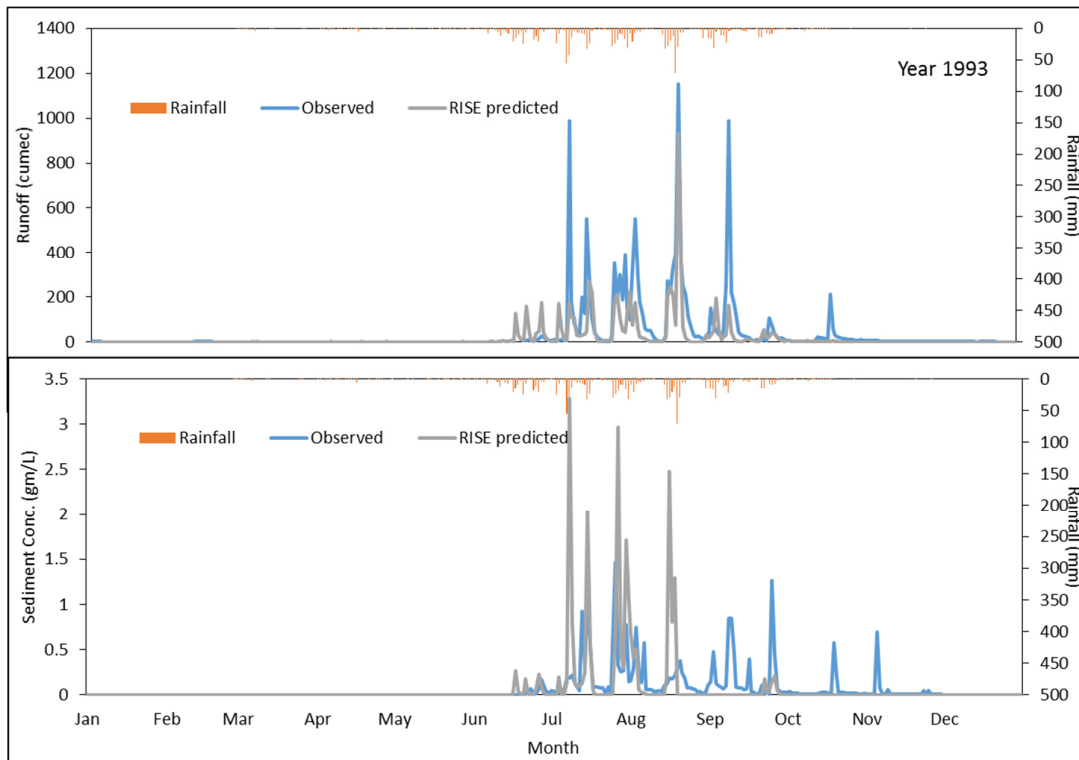


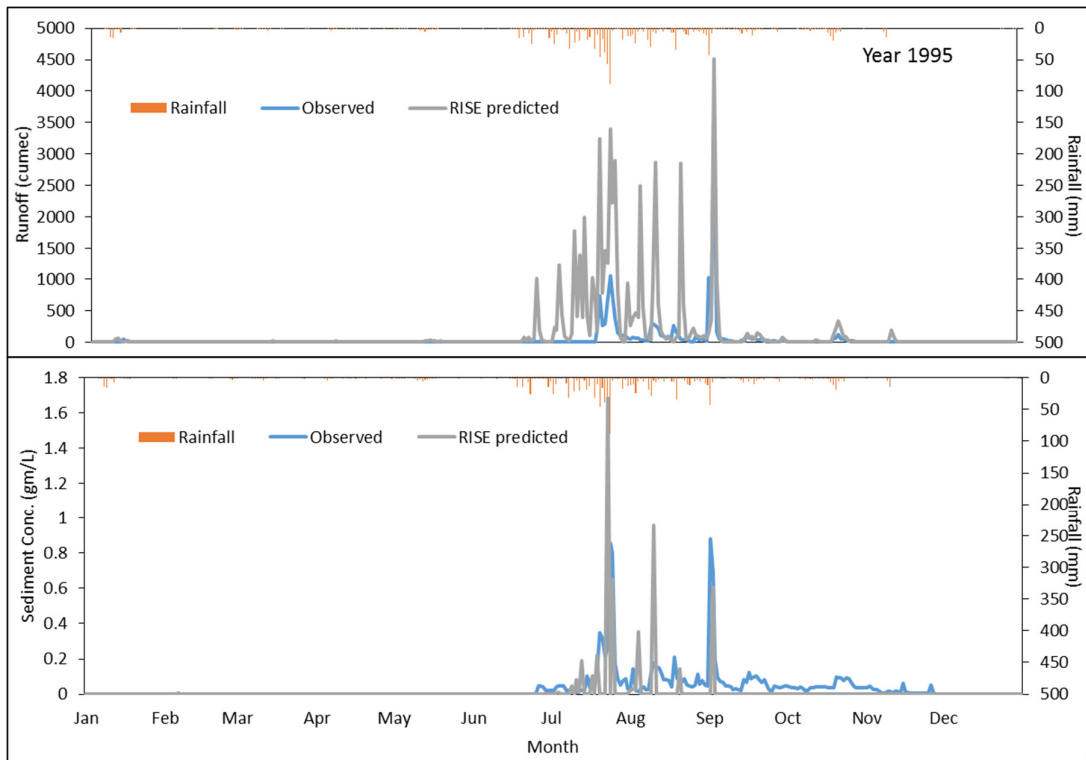


Appendix – B: Chapter Five

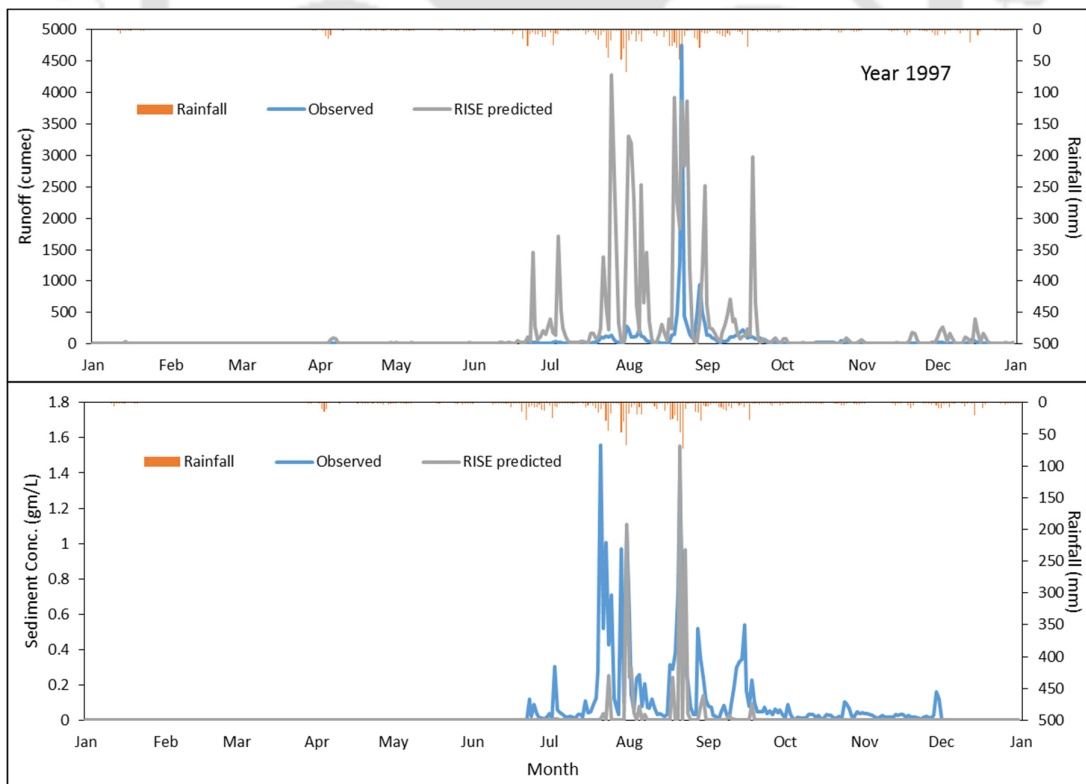
Appendix B1: Observed vs RISE simulated runoff and sediment concentration at Baronda watershed during calibration period (1990-1995)

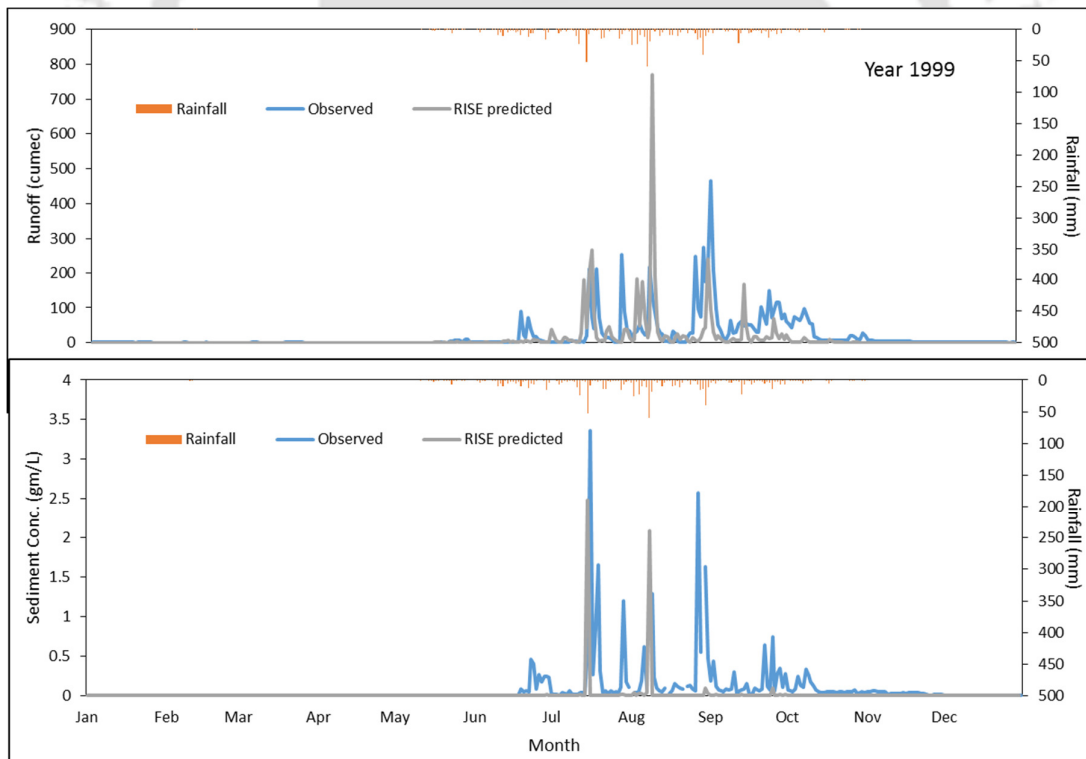
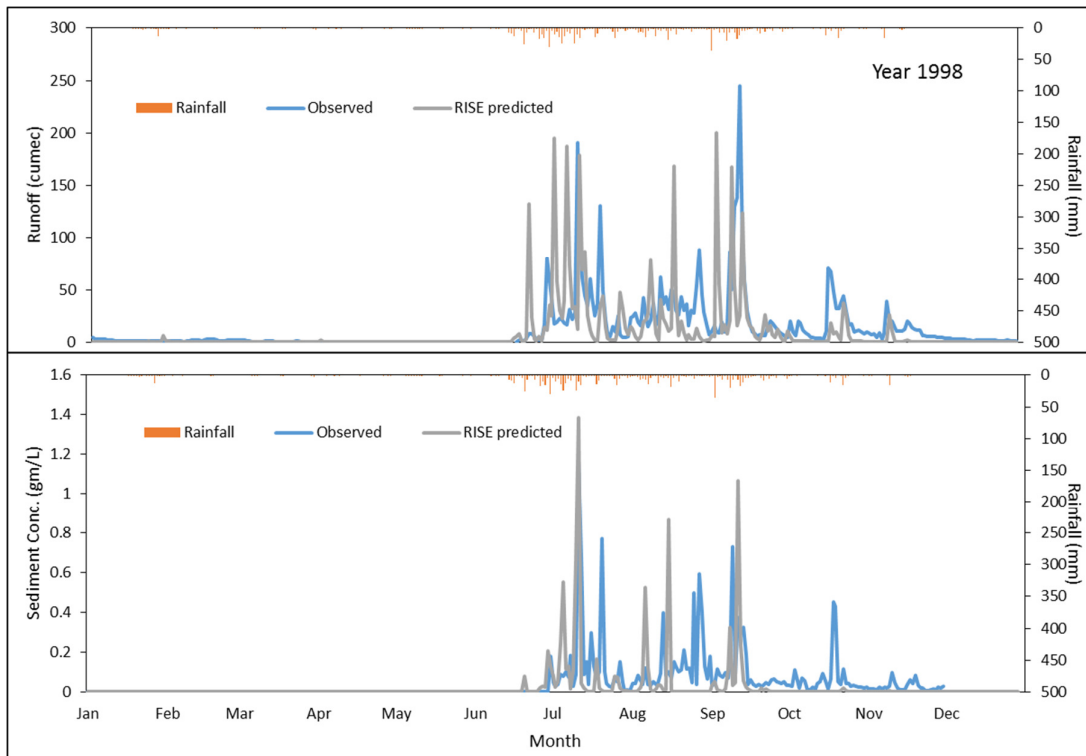


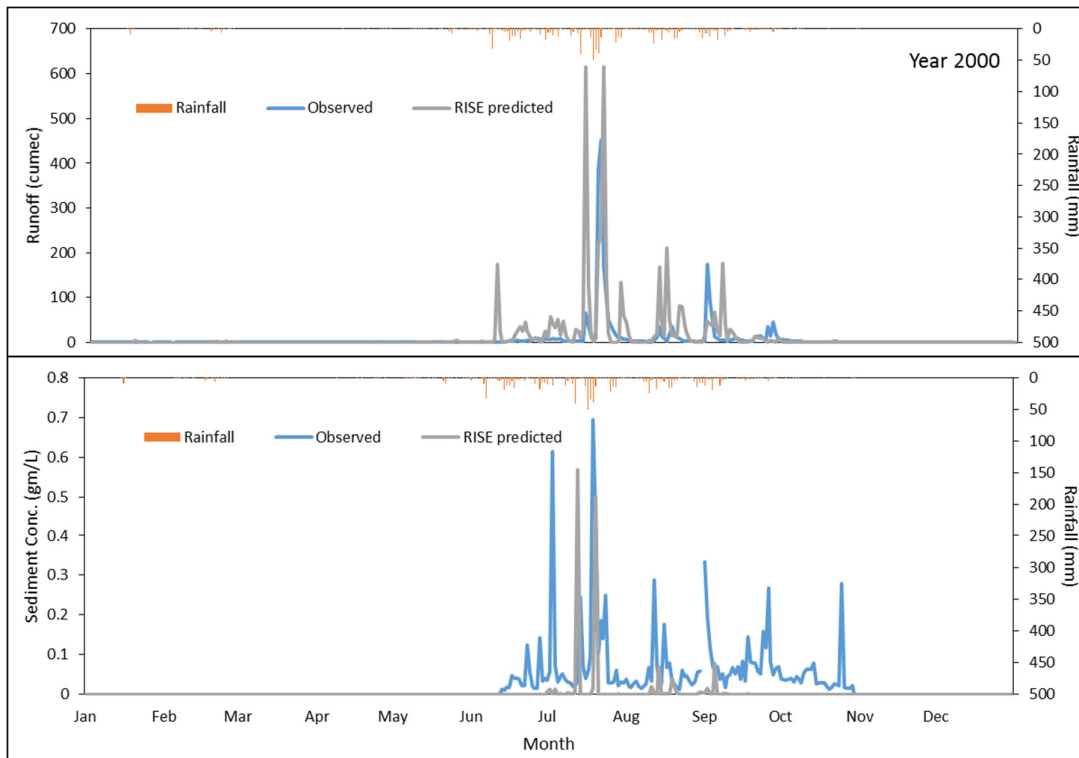




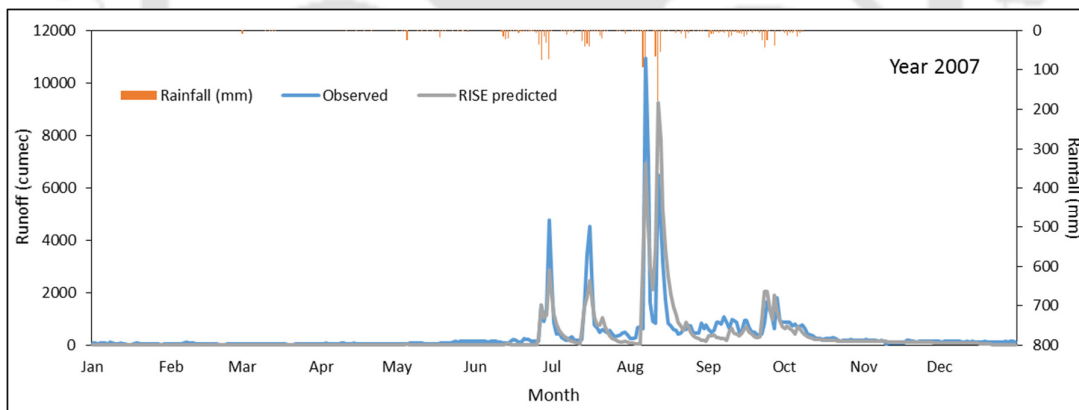
Appendix B2: Observed vs RISE simulated runoff and sediment concentration at Baronda watershed during validation period (1996-2000)

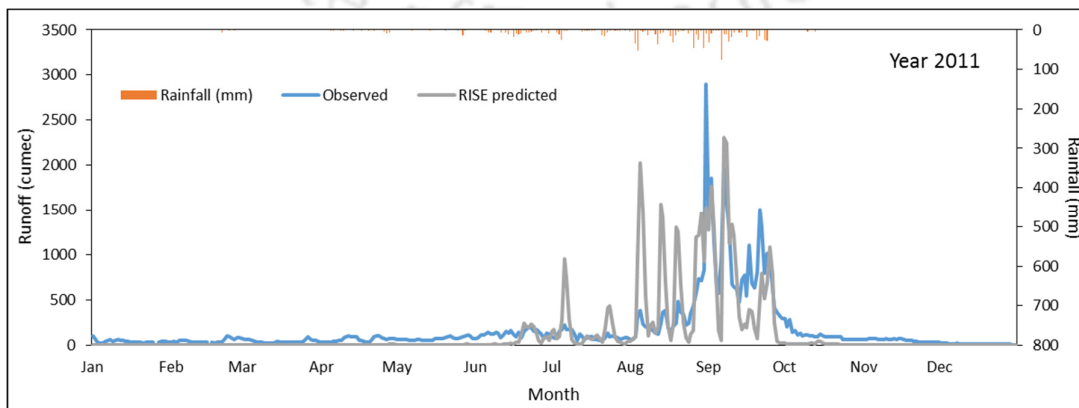
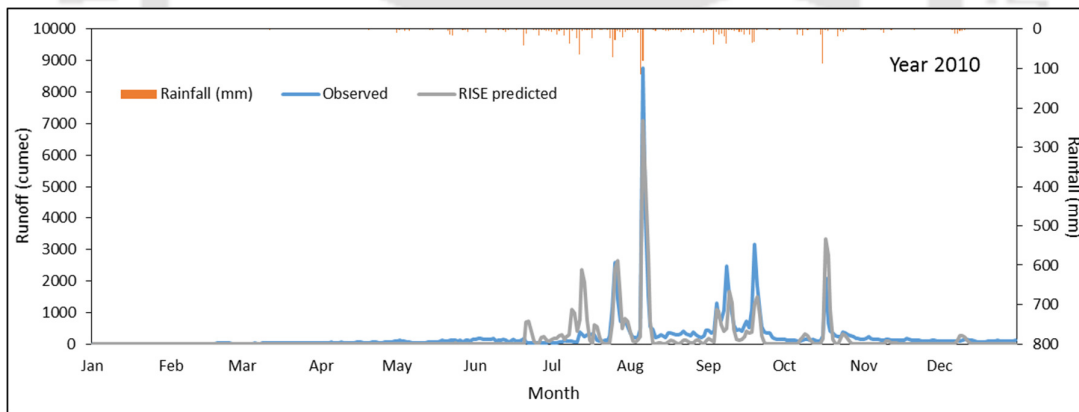
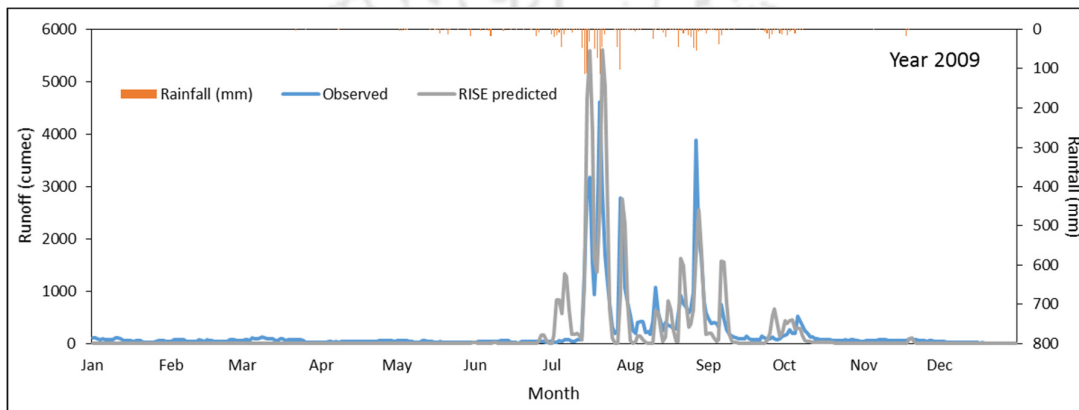
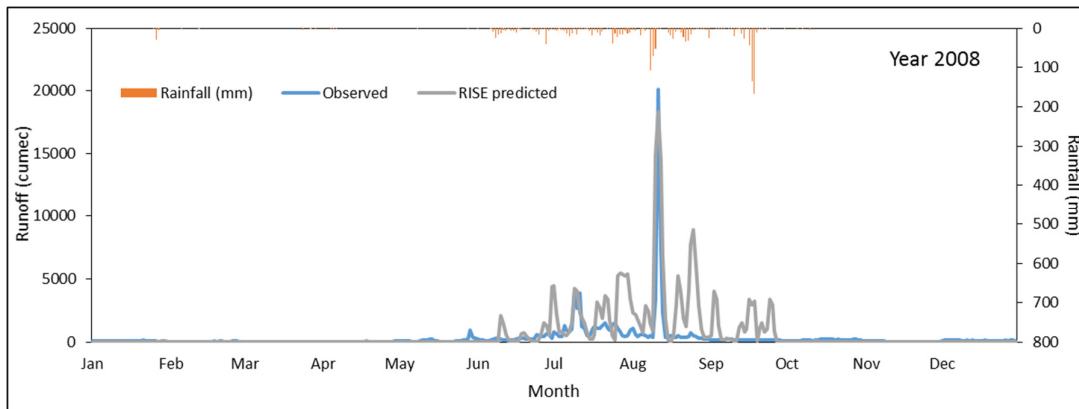






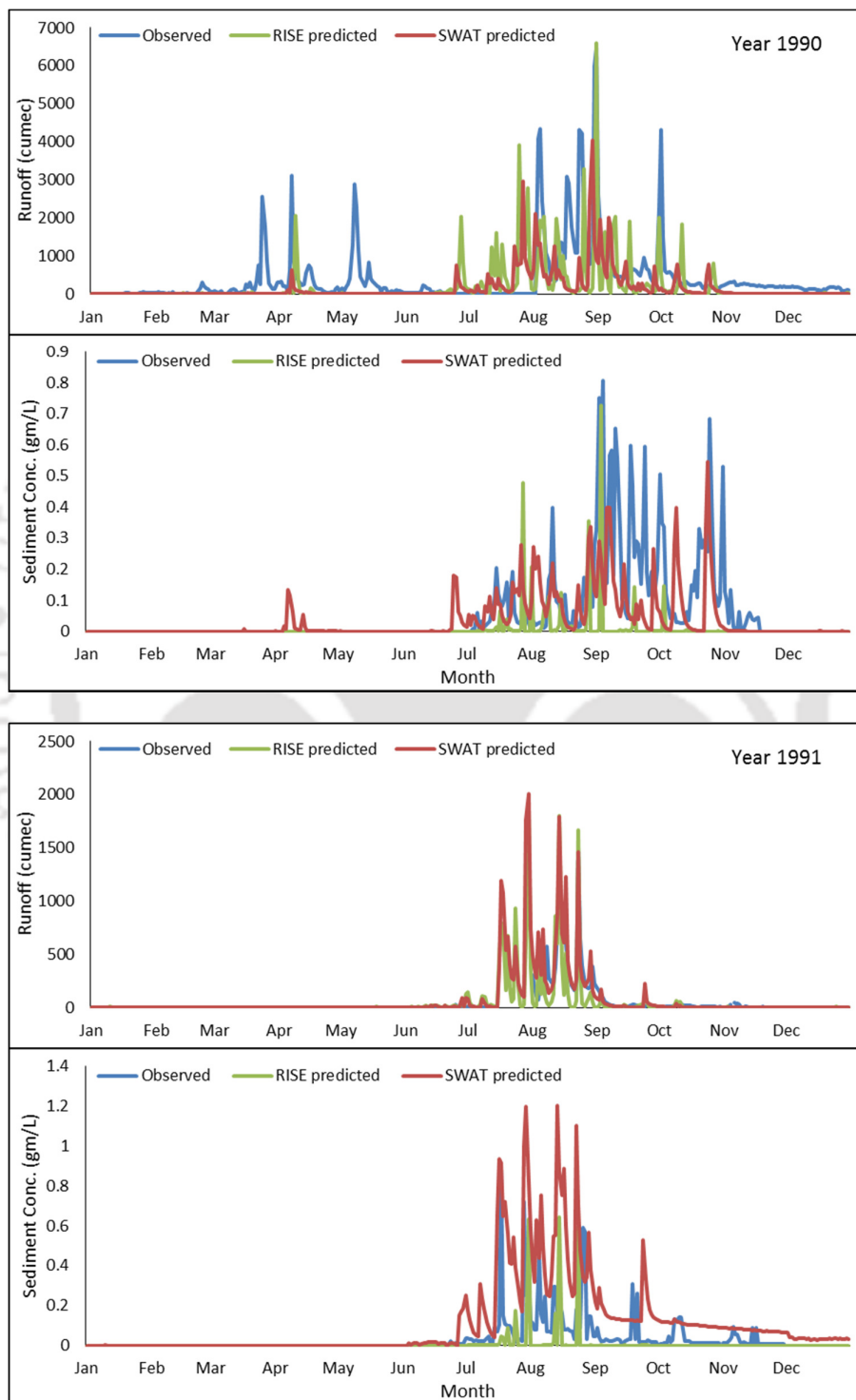
Appendix B3: Observed vs RISE simulated sediment concentration at Kesinga watershed during validation period (2006-2011)

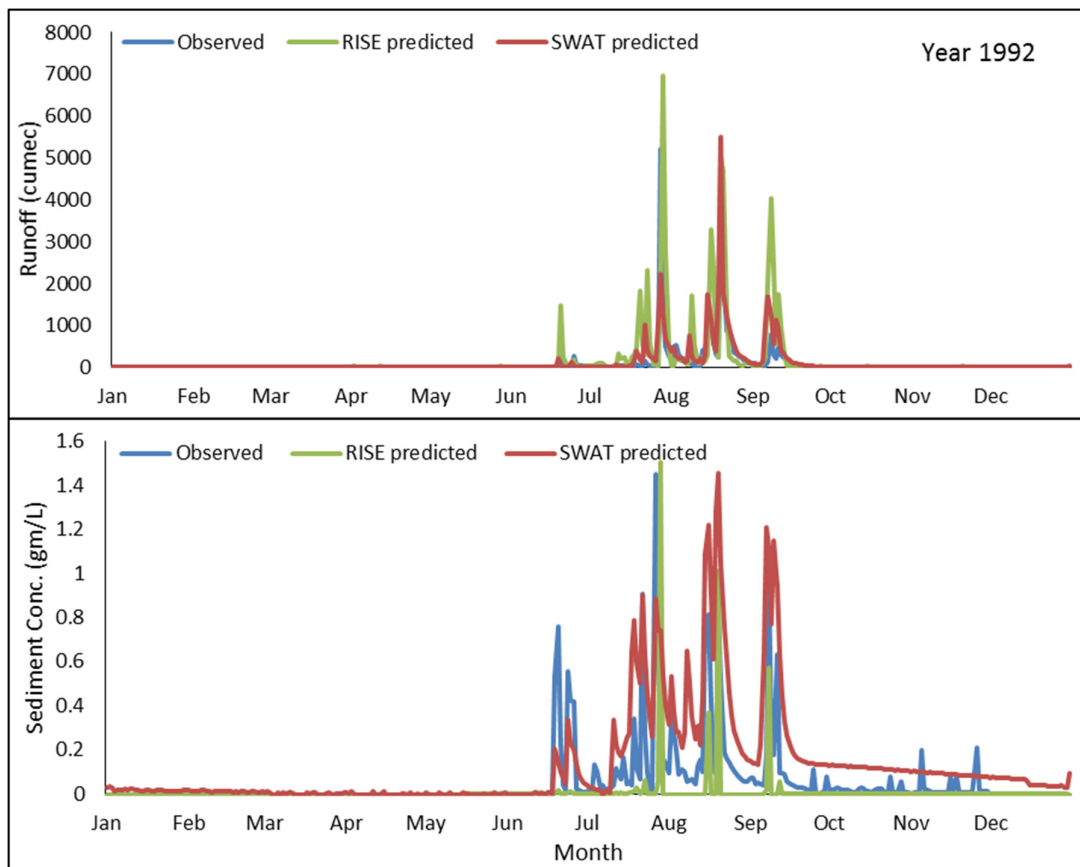


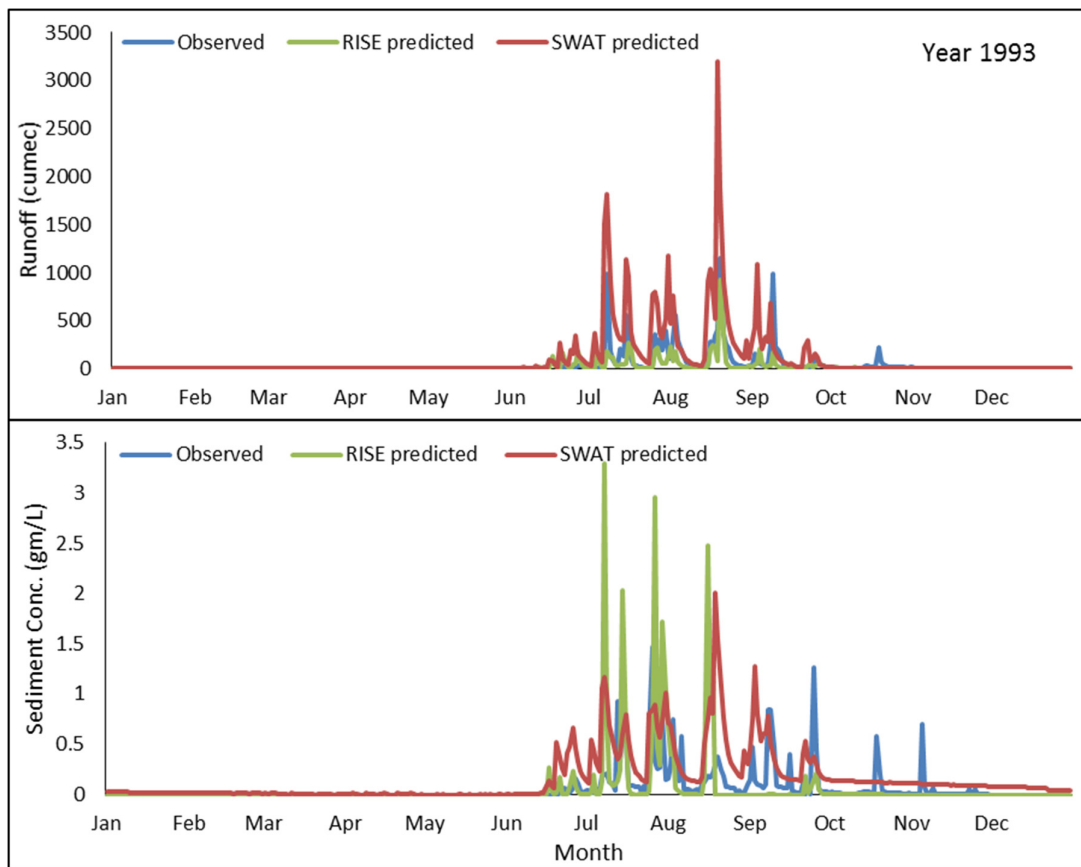


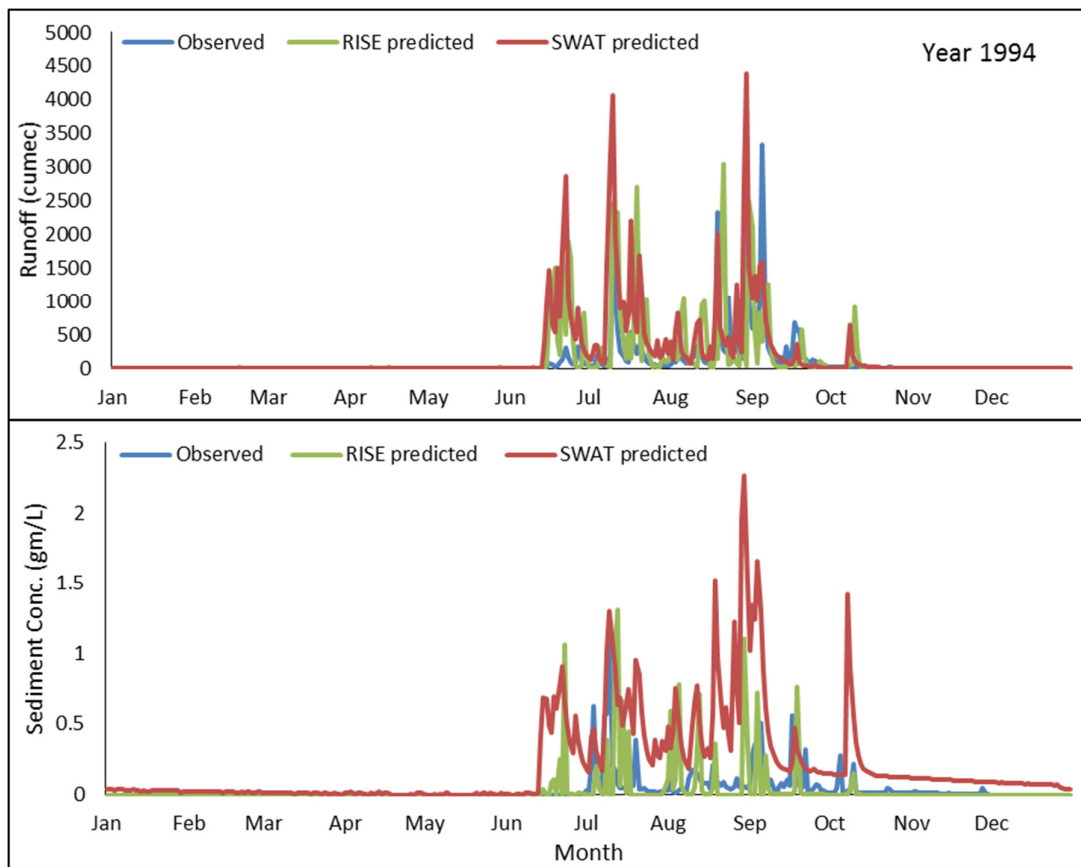
Appendix – C: Chapter Six

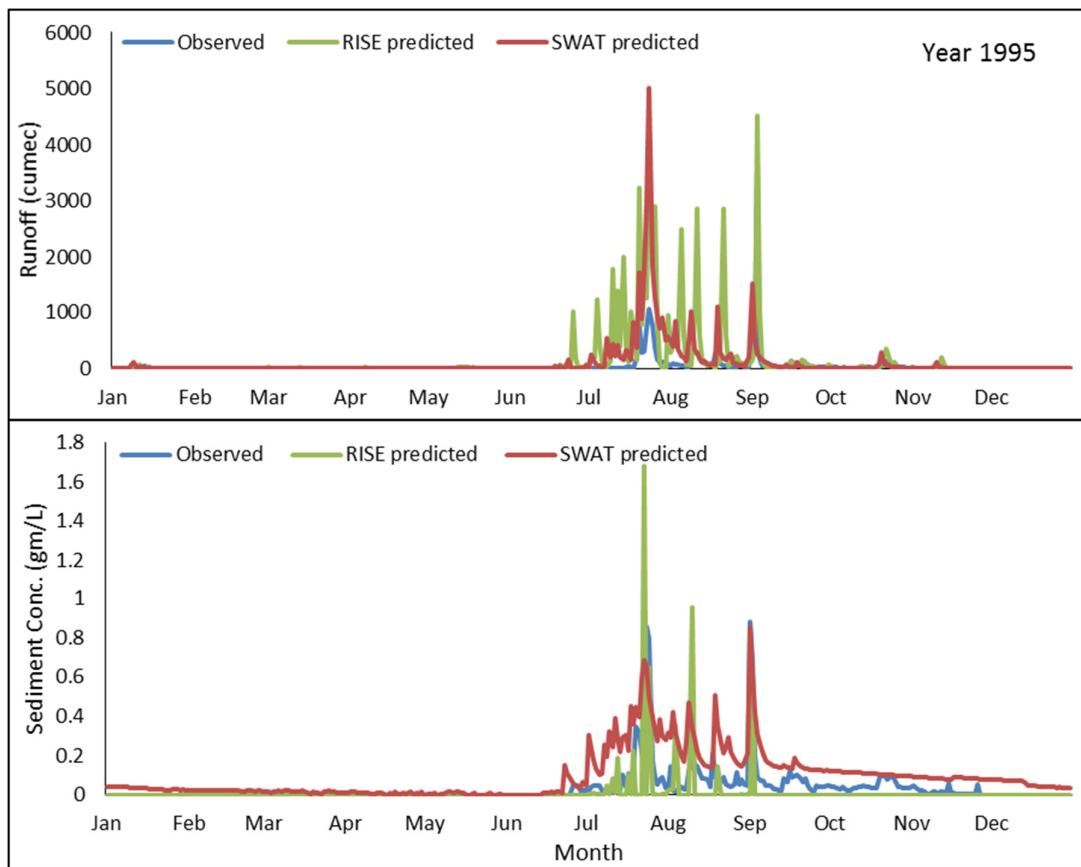
Appendix C1: Comparison between RISE and SWAT model outputs for Baronda Watershed

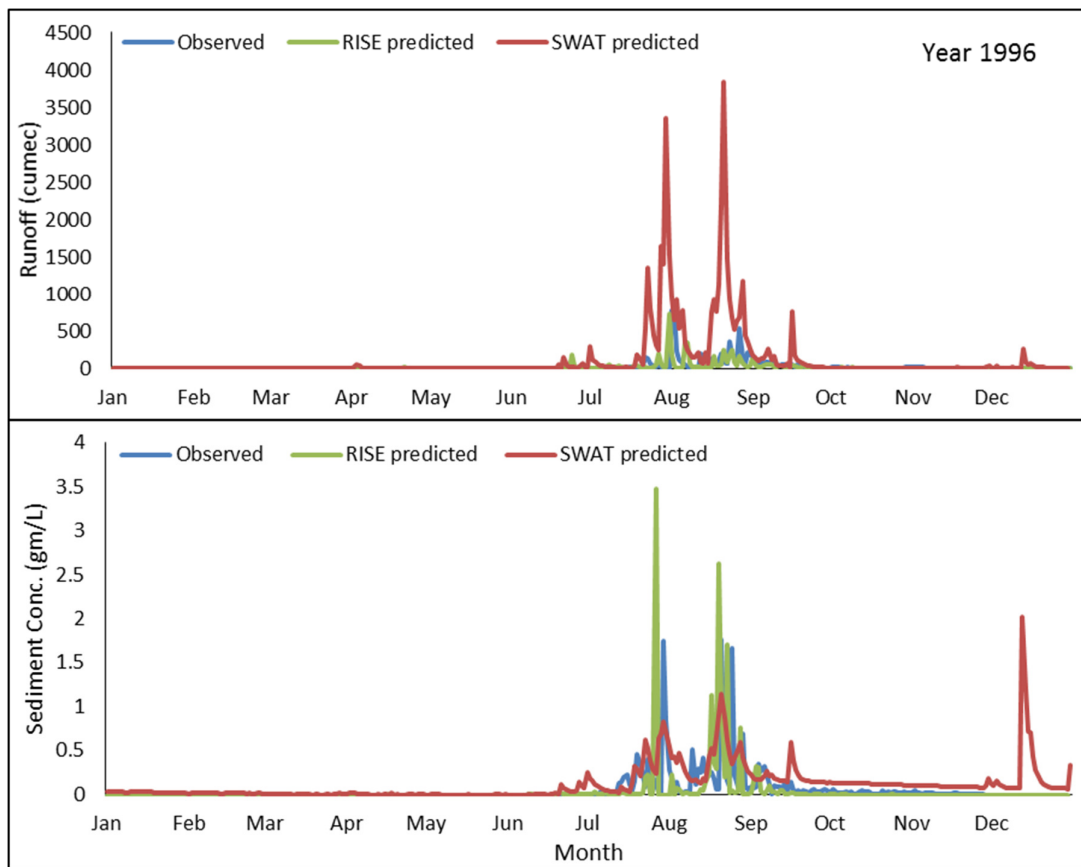


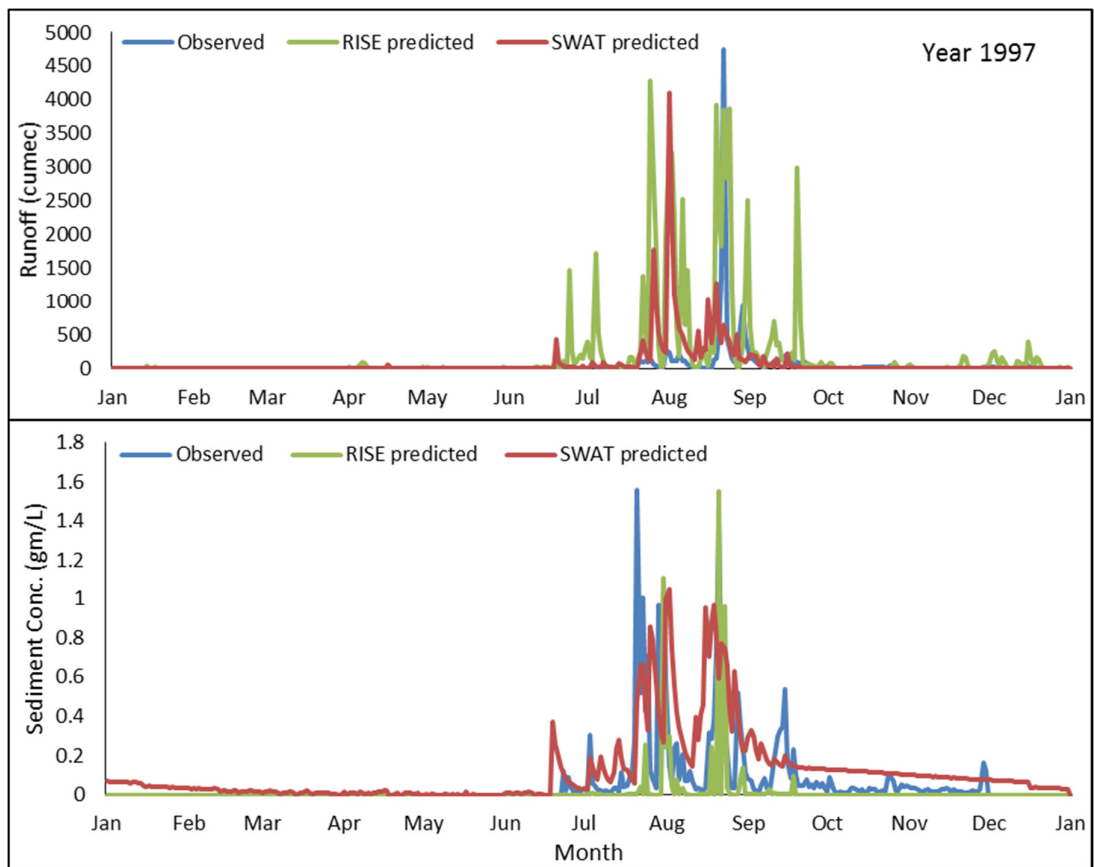


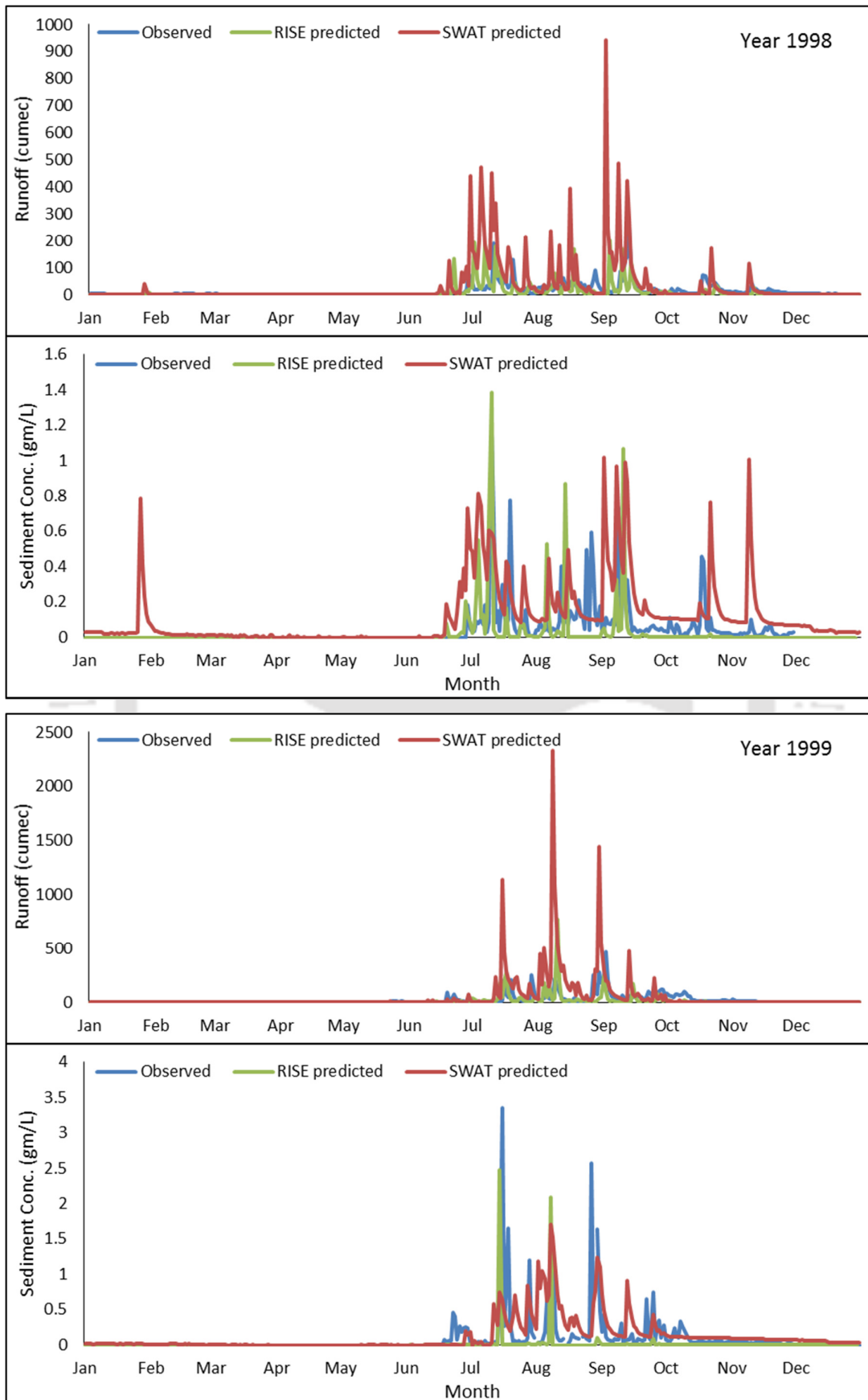


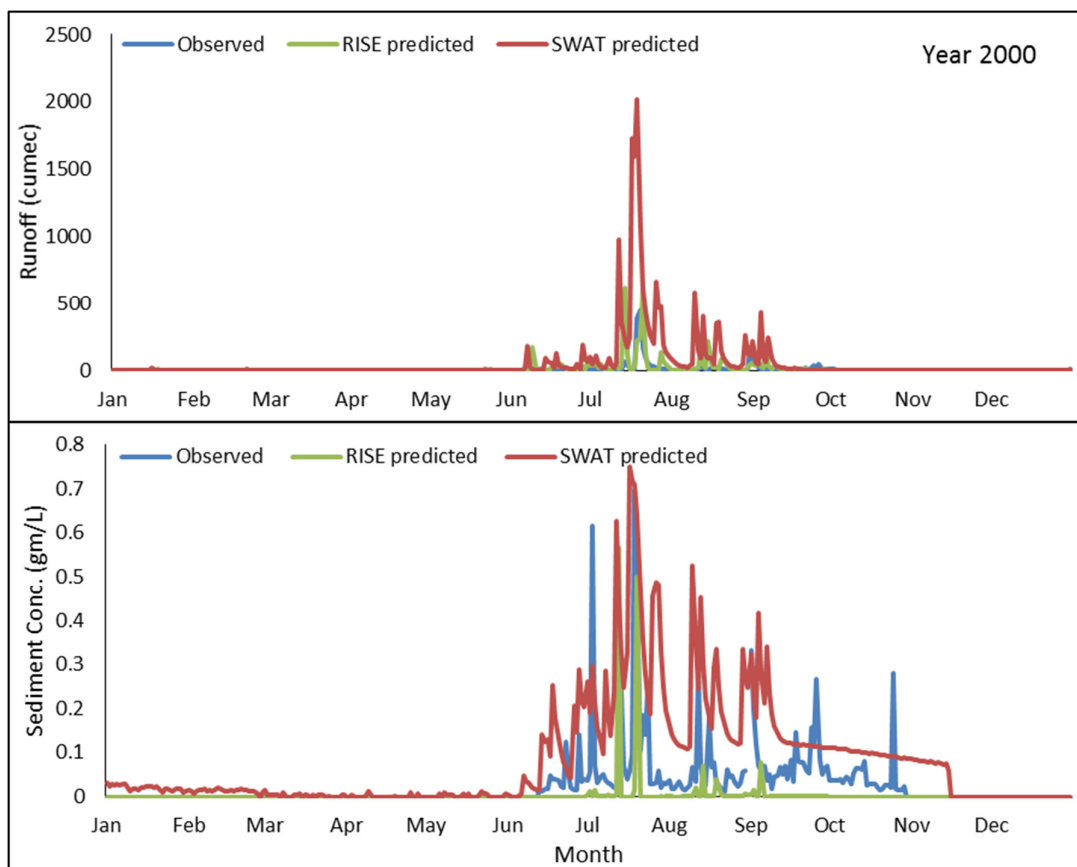




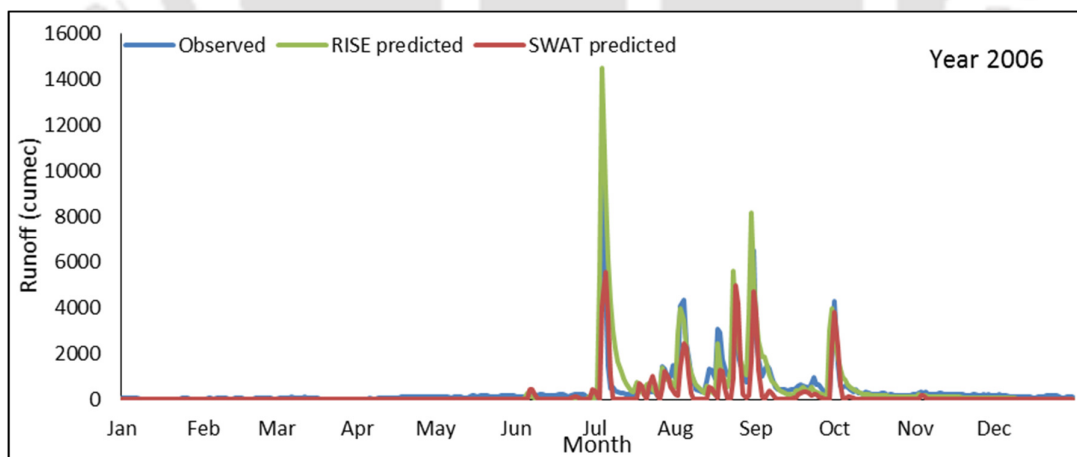


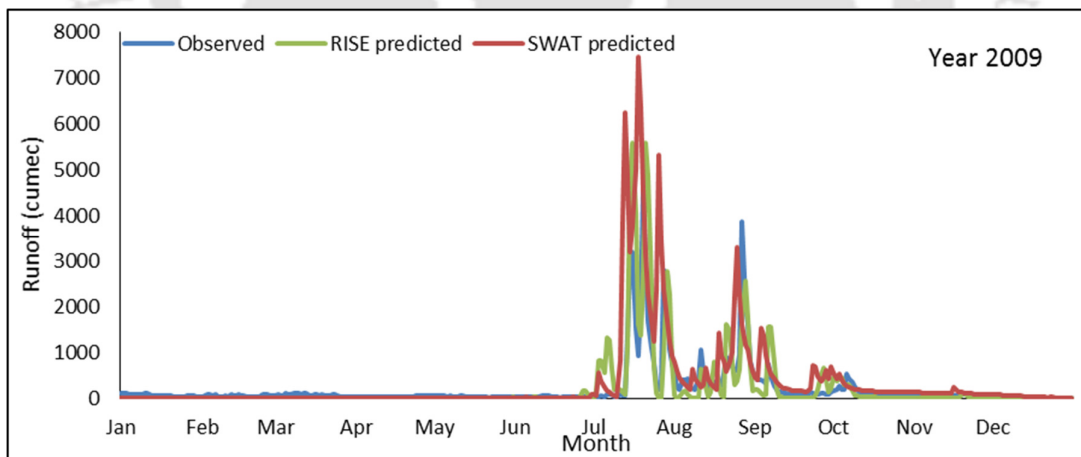
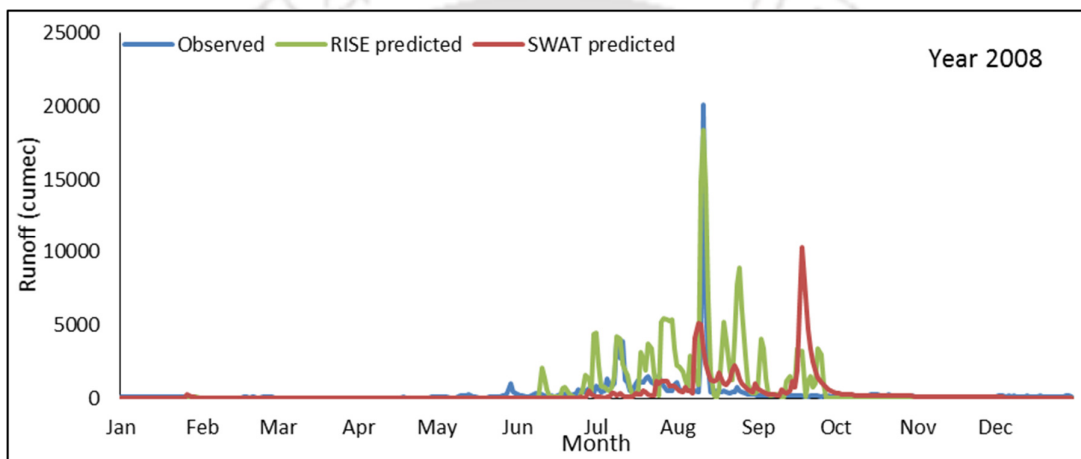
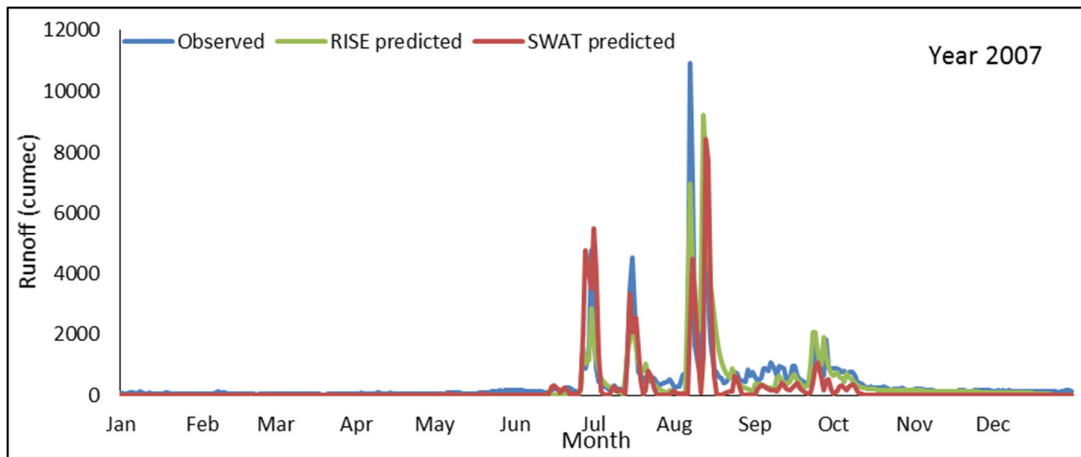


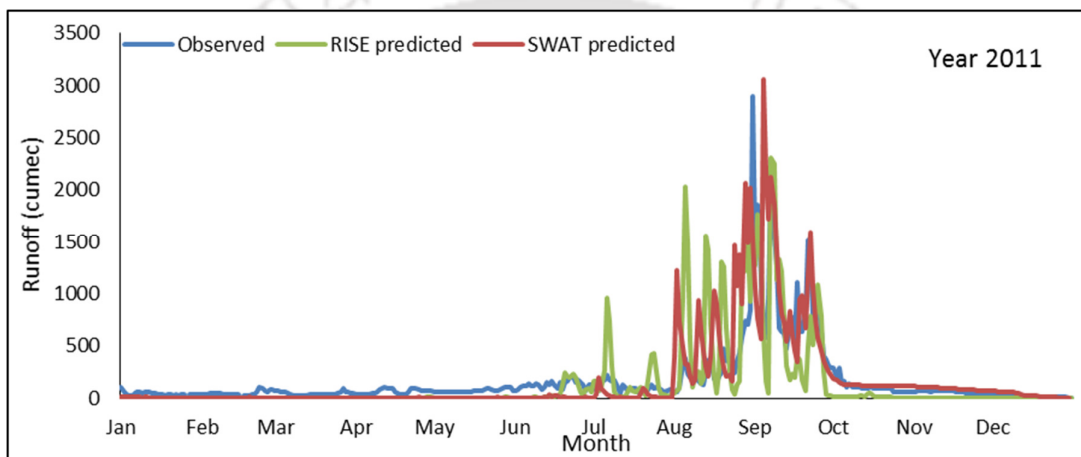
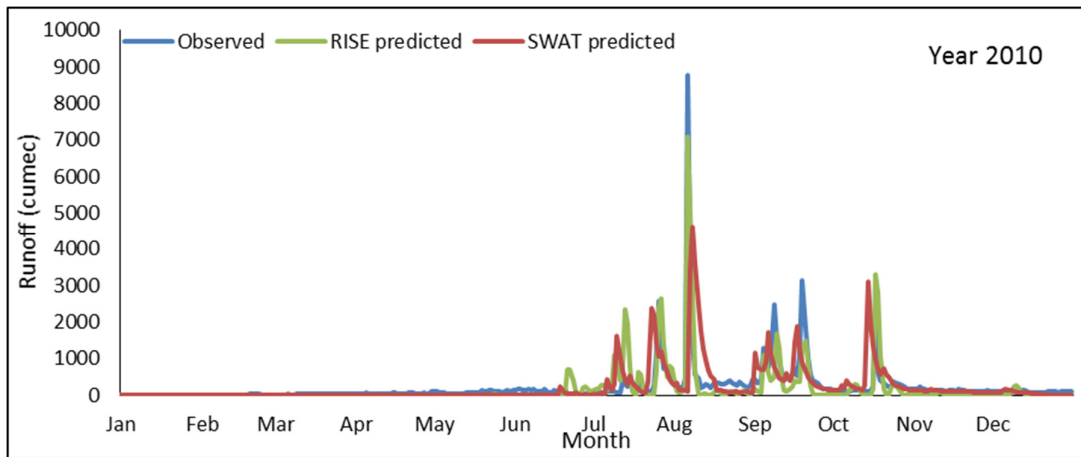




Appendix C1: Comparison between RISE and SWAT model outputs for Kesinga Watershed







Biographical Sketch

Arpit Chouksey was born in 1987 and grew up in Jabalpur, Madhya Pradesh, India. After he completed high school at Kendriya Vidyalaya, he joined Jawaharlal Nehru Krishi Vishwavidyalaya Jabalpur in 2004 to study for a Bachelor of Technology in Agricultural Engineering. During his four year stay at the university, he became interested in fulfilling his career goals in Hydrology. After finishing his B. Tech., he joined Indian Institute of Technology Guwahati in 2008 to obtain a Master of Technology in Civil Engineering with a specialization in Water Resources Engineering. His M. Tech. research involved an assessment of the non-point source pollution of small streams at different altitudes which led him to work even more on hydrology and he then joined Ph.D. program in 2010 at the Department of Civil Engineering, Indian Institute of Technology Guwahati. He received a scientist position in 2013 at Water Resources Department, Indian Institute of Remote Sensing, Dehradun under Indian Space Research Organization. Since then, he is continuing his passion towards hydrology and water resources.

