MODELING OF SUSPENDED SEDIMENT DYNAMICS IN TROPICAL RIVER BASINS

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CERTIFICATE

This is to certify that this thesis titled **"Modeling of Suspended Sediment Dynamics in Tropical River Basins"** is an authentic record of the research work carried out by Sri. T. Chandramohan, under my supervision and guidance at the Department of Physical Oceanography, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Ph.D. degree of Cochin University of Science and Technology under the Faculty of Marine Sciences and no part thereof has been presented for the award of any degree in any university.

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PREFACE

Soil erosion in the upstream river basins, its transport, and deposition play a major role in understanding many activities of global significance. The recent activities of man in changing river courses and construction of dams across natural rivers have significantly altered the sediment yield regime. In estuarine and coastal zones, which are major sinks of sediment, alteration of the natural sediment supply can cause considerable changes in ecosystem propagation. Comprehensive studies are required to analyse the spatial and temporal variation in sediment yield by the rivers in any region and to identify the factors responsible for this variation.

It was proposed to analyse the sediment transport characteristics of 16 river basins of Kerala, using the data collected from the Central Water Commission (CWC) and to study the seasonal and spatial distribution of sediment load carried by these rivers. Pamba River was selected as the representative hydrologic regime for detailed studies and modeling of sediment hydrodynamics. Empirical (Sediment Rating Curve, Modified Universal Soil Loss Equation - MUSLE), conceptual (Unit Sediment Graph - USG), and distributed (Water Erosion Prediction Project - WEPP) models were tested using field data by monitoring rainfall, discharge, and suspended sediment concentration for selected micro-watersheds within this river basin.

Analyses of data indicated that the distribution of rainfall and the topographical characteristics are the major factors influencing the variation of sediment flux in rivers of Kerala. Sediment transport from northern rivers is highly influenced by the SW monsoon, whereas both the southwest and northeast monsoons controls the sediment yield of southern rivers. About 90 - 95 % of the sediment load is carried by the monsoon river flows and few particular days in monsoon supplies bulk of the annual sediment load transported by the rivers.

Sediment rating curves were developed for these rivers on annual and seasonal basis and the rating curve parameters indicated that the rivers basins from northern and southern regions of the State consisted of intensively weathered loose materials, which are prone to be eroded and transported rather easily compared to the rivers from the central Kerala. Rating curves were also developed by grouping the data on seasonal and monthly basis, for Pamba and tested for its applicability for simulating sediment load using known discharge data. Statistical tests indicated that the rating curves developed on monthly and seasonal basis gives better results.

Based on annual and seasonal sediment load transported by the rivers, it was found that a broad classification of the state into four zones is possible. These are:

- high sediment yielding northern zones,
- north-central zone with low to medium yield,
- south-central zone with low to medium yield, a sizeable share of which occurs during northeast monsoon season, and
- southern zone with medium yield, where the yield is similar for both the monsoon seasons.

Unit Sediment Graphs (USG) were derived for three micro-watersheds with varying characteristics to represent the sediment dynamics associated with rainfall events. The USG, along with MUSLE and WEPP were applied for different rainfall events and the results were compared with observed sediment rates from the watersheds. ILWIS (Integrated Land and Water Information System) GIS was used to compute the parameters for MUSLE application. It is found that Unit Sediment Graph model fares well with the degree of watershed and channel details available for this study.

The present study gives an insight into the seasonal pattern of the sediment transport through the major west flowing rivers of Kerala. The effects of rainfall, discharge and basin characteristics on this variation were examined. The regional classification of the State into different sediment yielding zones enables the planners and engineers to adopt separate strategies for each of these zones. A suitable model was suggested for the simulation of suspended sediment dynamics from small watersheds.

Chapter I

INTRODUCTION

1.0 INTRODUCTION

Continental erosion and subsequent transfer of the eroded material to ocean play an important role in the understanding of many activities of global ecosystem. Erosion, entrainment, transportation, deposition, and compaction of soil particles are natural and complex processes that have been active throughout the geological ages and shaped the present landscape of our world.

The basic erosion processes that occur on upland areas are soil detachment, transport, and deposition. Detachment occurs when forces exerted by rainfall and flowing water exceeds the soil's resistance to those forces. Detached particles can be transported both by raindrop splash and flow. Deposition occurs when the quantity of detached particles exceeds transport capacity. Interrelationships between the various sources of erosion and their associated delivery system result in conceptualizing the total catchment or basin delivery system. Improved knowledge of all phases of the delivery system provides linkages among the processes.

Development of erosion prediction technology is required for a conservationist at the field level, to examine the impact of various management strategies on soil loss and to plan for optimal use of land (Flanagan et al., 2002). It also allows policy makers to assess the current status of the land resources and the potential need for enhanced or new policies to protect soil and water resources.

The measurement of sediment yield is an integral part of studies designed to assess continental erosion or to manage water resources. There have been a number of advances associated with techniques for measuring sediment yields in recent years (Hadley et al., 1985). Photoelectric turbidity meters, ultrasonic and nuclear sediment gauges, automatic particle size analyzer, etc. are the latest advances.

The soil erosion and sediment yield studies are utilised for a number of purposes including (Bobrovitskaya, 2002):

- estimating the rate of overland scour and ravine erosion
- assessing the impact of soil improvement, road construction, etc.

- computing sediment inflow to reservoirs to assess rate of siltation
- predicting sediment transport in rivers and canals
- documenting sediment inflow to seas and the World Oceans
- quantifying role of sediment runoff as a factor of contaminant transport and deposition

Of the above, temporal and spatial variation of suspended sediment yield from rivers to coastal regions, erosion and suspended sediment yield assessment and associated aspects are dealt in detail in subsequent sections.

1.1 Factors affecting Erosion and Sediment Yield

River sediment fluxes are sensitive to many factors, including construction of dams, land use changes, mining activities, soil and water conservation measures, sediment control programmes, and climate change (Walling and Fang, 2003). The major factors affecting erosion and sediment yield are discussed below.

1.1.1 Climate

Climatic factors affecting erosion are temperature, humidity, solar radiation, wind and precipitation. However, relationship between rainfall, runoff and soil loss are of critical in nature and hence more studies were taken up in that direction (Douglas, 1967; Wilson, 1972; Dendy and Bolton, 1976; Ward and Elliot, 1995; Matinez-Mena et al, 2001). Since runoff is the carrier of sediment particles, its seasonality and peak value affects sporadically high sediment load in rivers.

According to Langbein and Schumm (1958), maximum sediment yield occurs at an annual precipitation of approximately 300 mm. When the precipitation exceeds 300 mm, increased vegetation growth protects the surface. Sikka et al. (2003) studied the role of intensity of rainfall in sediment deatachment and transport.

Syvitski et al. (2003) grouped the global river data into different climatic zones; polar, temperate and tropical, and found that polar region gives lowest sediment yield and tropical rivers are having high sediment yields.

1.1.2 Physiographic Factors

The influence of river basin characteristics such as geology, soil and relief on sediment yield was investigated by Jansson (1982). The Pacific Southwest Inter-Agency Committee (PSIAC, 1965) developed a methodology for arid and semi-arid areas in USA. It involves 9 factors, which represent climate, runoff, land use, geology, soil, vegetation, and erosional development. The influence of geology on erosion is high with respect to channel erosion, but marginal with respect to hill slope erosion (Chakrapani, 2005). Rivers flowing over crystalline terrains erode with difficulty, whereas sedimentary rocks yield greater sediment loads to rivers.

The excessive soil loss on steep slopes was studied by many scientists (Khola and Saroj, 1996; Bhardwaj and Sindhwal, 1998; Fox and Bryan, 2000; Ram and Khola, 2000). Milliman and Syvitski (1992), based on their studies on 280 rivers, showed that mountain rivers (relief > 3000 m) are having greater sediment loads and yield.

Basin area integrates several factors such as gradient, storage capacity, etc., which influences sediment yield. Brune (1948) showed that sediment yield decreases with catchment size and this was supported by several other studies (Maner, 1958; Roehl, 1962; Dendy and Bolton, 1976; Dunne, 1979; Walling, 1983). However, studies conducted for a number of world rivers by Milliman and Syvitski (1992) showed that the sediment yield is increasing with basin area. Similar findings were reported by Meade (1982), Ashmore (1992), Kithiia (1997) and Krishnaswamy et al. (2001). Xu and Yan (2005) studied sediment yield - basin area relationship based on data from the Yellow River basin and found that the sediment yield increases with area, reaches a maximum and then declines.

1.1.3 Land Use

The major effects of vegetation in reducing erosion are:

- protecting soil from rain drop impact and holding soil in place
- reducing surface runoff velocity
- improving soil structure with roots
- plant residue and increased biological activities in the soil
- increasing transpiration rates

The effect of land use on sediment yield is closely linked to climate and physiography, which in turn exert a major control on land use practice. Wherever its effects can be isolated, the influence of land use on sediment yield can be noticed. Wilson (1972) reviewed earlier studies to relate sediment yields to climatological indices and concluded that the most important single control is land use.

Hill and Peart (1998) found from their studies that vegetation is the major control on sediment production. The effect of changes in land use pattern, afforestation /deforestation activities, was studied by many researchers (Sharma et al., 2000; Vinod et al., 2003; Joshi et al., 2004; Piegay et al., 2004; Restrepo et al., 2006).

1.1.4 Human Influence

Erosion and sedimentation processes are closely related to the natural conditions in a basin. However, these processes can be influenced and aggravated by man's activities. Such activities may radically change the natural conditions and cause serious disasters; unless development projects are planned accordingly based on our knowledge of sedimentation processes in different environments.

Together with land use change, deforestation, and soil conservation practices, the natural sedimentary cycle has been greatly altered. A decrease in sediment transport through rivers results in increased coastal erosion and deterioration of coastal marine eco-system. Vorosmarty et al. (1997) estimated that 30 % of the global sediment flux is trapped behind large dams. Nelson and Booth (2002) reported that the urban development caused an increase of nearly 50 % in the annual sediment yield.

1.2 Erosion and Sediment Yield Modeling

Theoretical developments of sediment transport functions are based on assumptions of different degrees of complexities. Some of the simplified assumptions are based on idealized laboratory conditions that may not be true for the more complicated natural river system. Empirical solutions based on observations may be useful only for a particular site where the data were collected. Many of the sophisticated theoretical solution require large number of parameters that are difficult to obtain (Yang, 2002). There should be a balance between theoretical concepts and practical approach for solving such problems, which will help to improve our understanding of the processes. The following paragraphs enumerate broad classification of methodologies available for computation of erosion and sediment yield.

1.2.1 Empirical Prediction Equations

The empirical equations are developed to estimate the mean annual sediment yield from an ungauged basin from knowledge of basin characteristics and hydro-meteorological conditions. These equations differ considerably in their conceptual basis and their degree of sophistication and suffer from inclusion of empirical constants and coefficients. Prediction equations are commonly developed using multiple regression and therefore possess all the statistical limitations inherent in such techniques. The need to describe catchment characteristics such as geology, soil, and vegetation may also present difficulties with this approach.

The important factors used in the empirical equations are quantity and distribution of rainfall, discharge, geology, relief and land use of the catchment. Since the sediment yield is different from season to season, sequence of seasons can also be a factor.

One of the most popular and widely used empirical models is the Universal Soil Loss Equation (USLE) by Wischmeier and Smith (1965). It is designed to predict long-term average soil loss under specified conditions and used to estimate erosion rate for different combinations of crops and management practices. The USLE was subjected to many improvements to suit different geographic and climatic regions.

When discharge and sediment concentration data is available for a wide range of climatic conditions, sediment-rating curves are commonly used for the prediction purpose. The relation between suspended sediment concentration and discharge, rating curve, takes the form of power law; $\mathbf{C_s = a\ Q_w^{\ b}}$ where, C_s is the sediment concentration and Q_w is the discharge. 'a' and 'b' are the rating curve coefficients.

1.2.2 Conceptual Models

They are lumped models where spatial variation of sediment discharge and transport processes can be lumped into a single system. Sediment producing factors such as rainfall and runoff can be treated as inputs to the system and sediment yield becomes output. Geomorphic characteristics and hydrologic factors of the watershed are a set of system parameters, which transforms inputs to outputs through the system. Unit Sediment Graph (USG) is a widely used conceptual model in sediment yield studies.

Information concerning the form of sediment graph (sediment flow rate as a function of time) associated with a runoff hydrograph is essential for sediment yield assessment, for providing input data for prediction models of reservoir sedimentation, and for water quality modeling. A few conceptual models for computing sediment graph have been reported, such as:

- multiplying storm hydrograph ordinates by concentrations predicted with a sediment transport model
- based on erosion and sediment transport capacity
- based on USG
- based on relationship between dimensionless USG and catchment characteristics
- based on Instantaneous Unit Sediment Graphs (IUSG)

1.2.3 Physically Distributed Models

These are largely based on mathematical descriptions of physical processes or based on combining mathematical process description with some empirical relationships. These were largely based on the detachment-transport concepts of Meyer and Wischmeier (1969) or Foster and Meyer (1972) for sediment entrainment by rill and inter-rill erosion and by using various transport equations for sediment movement. The physically based models provide an improved understanding of the fundamental sediment producing processes, having the capability to access the spatial and temporal variations of sediment entrainment, transport and deposition processes.

There have been many attempts to develop improved representations of erosion, transport and deposition in channels (Bennett and Nordin, 1977; Leytham and Johanson, 1979; Lane and Shirley, 1981; Lane, 1982; Kothyari et al., 1994; Fox and Bryan, 2000; Kumar and Das, 2000; Sharma, 2004; Lee and Singh, 2006). Although, much of these work was directed towards individual components of erosion-sediment yield system, understanding of these components paved way for further development of comprehensive physically based prediction models. Based on the principles of sediment detachment and transport and coupling with other hydrologic and meteorological components, many models are presently available in literature.

1.2.4 Statistical and Stochastic Models

Sediment Yield Prediction Equation (SYPE), derived from statistical analysis has been frequently used to estimate sediment yield. These equations usually relate sediment yield to one or more catchment and climatic parameters.

Stochastic modeling is one of the major tools in hydrology for building mathematical models to generate synthetic hydrological records, to forecast hydrological events, and to detect changes (Maidment, 1993). The steps involved in stochastic modeling are; identification and removal of significant trends present in a time series, identification and mathematical description of periodicity, identification and separation of dependent stochastic components, and modeling of residuals for frequency distribution (Gangyan et al., 2002). Lack of long duration records of sediment yield has hampered the application of various stochastic and time series modeling procedures developed for runoff to sediment yields. However, some developments are evident and three aspects merit further comment.

The first is essentially conceptual and relates to the need to consider stochastic processes in developing sediment yield models. Woolhiser and Blinco (1975) proposed several general models in which sediment yield was treated as a stochastic process. Secondly, there have been several attempts to couple sediment yield models with stochastically generated input series to simulate long term sediment yield records. This approach provides a useful method of extending limited data, since a model developed with the available data is then used to synthesis a long-term series. A third area in which developments are evident is the application of transfer function and Auto-Regressive Moving Average (ARMA) models to the records of sediment concentration or load and water discharge from drainage basin. This approach may be viewed as an extension of the simple sediment rating curve.

2.0 REVIEW OF LITERATURE

Observations, measurements and research obviously are the forerunners of mathematical modeling. Erosion and sediment yield studies have incorporated many new advances and developments during recent times. Equations and theories were developed to relate the amount of sediment transport with the hydraulic factors governing the phenomena, such as discharge, shear stress and velocity (McBean and Al-Nassari, 1988). Complex models are also available for predicting individual storm sediment yield and determining the location and amount of deposition on small watersheds. However, these models require various components related to meteorology, hydrology, hydraulics and soil. As a result, the number of input parameters required for these models will be more, and hence practical application of such models are limited to experimental watersheds.

2.1 Erosion and Sediment Yield Modeling

Modeling of sediment transport began long before the days of computers. DuBoys is one of the earlier researchers in sediment transport modeling with his theory of tractive force for bed load transport in 1879. The studies by Kennedy (1895) and Lacy (1930) laid the foundation of basic fluvial hydraulics.

Efforts for mathematically predicting soil erosion started only about seventy years ago. Number of equations are available in literature, by considering rainfall energy, soil properties, slope and land cover as variables (Ellison, 1945; Browning et al., 1947; Smith and Whitt, 1948; Lloyd and Eley, 1952; Van Doren and Bartelli, 1956).

The Universal Soil Loss Equation (USLE) by Wischmeier and Smith (1965) was a major step towards predicting average soil loss from small watersheds. Since 1965, efforts were gone into the improvement of USLE to suit additional types of land use, climatic conditions and management practices (Renard et al., 1974; Blackburn, 1980; Hadda and Sandhu, 2001; Kurothe et al., 2001; Mikos et al., 2006).

Williams (1975) modified USLE as MUSLE using a runoff factor instead of rainfall energy factor, for predicting individual storm sediment yield. Onstad and Foster

(1975) and Onstad and Bowie (1977) modified the USLE to include both rainfall and runoff energy terms. Renard et al. (1991) revised the USLE to RUSLE by computerizing the technology to assist with the calculation.

The development of digital computers enabled the integration of hydrologic and erosion/sediment transport models. Crawford and Donigian (1973) developed Pesticide Transport and Runoff (PTR) model with Stanford Watershed Model as the hydrologic component. Many hydrological models were cited in literature wherein USLE and its variants are used for estimation of erosion rates (Frere et al., 1975; Williams and Hann, 1978; Glidden and Plocher, 1990; Duggal et al., 2000)

Number of mathematical models, based on different variations on rill/inter-rill erosion concept, is available (Bruce et al., 1975; Simons et al., 1977; Wade and Heady, 1978; Rohlf and Meadows, 1980).

There are many physically based and semi-distributed models mentioned in literature. Some of them are:

- ANSWERS (Areal Non-point Source Watershed Environmental Response Simulation) (Beasley et al., 1980)
- CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980)
- AGNPS (Agricultural Non-Point Source Pollution Model) (Young et al., 1987)
- KINEROS (Kinematic Runoff and Erosion Model) (Woolhiser et al., 1990)
- EPIC (Erosion Productivity Impact Calculator) (Sharpley and Williams, 1990)
- WESP (Watershed Erosion Simulation Program) (Lopes and Lane, 1990)
- HEC-6 (Hydrologic Engineering Centre) (HEC, 1993)
- SWAT (Soil and Water Assessment Tool) (Arnold et al., 1995)
- LISEM (LImburg Soil Erosion Model) (DeRoo et al., 1996)
- SHESED (Basin Scale Water Flow and Sediment Transport Modeling System) (Wicks and Bathurst, 1996)

- EUROCEM (European Soil Erosion Model) (Morgan et al., 1998)
- SHETRAN (Distributed River Basin Flow and Transport Modeling System) (Ewen et al., 2000)
- STAND (Sediment-Transport-Associated Nutrient Dynamics) (Zeng and Beck, 2003)
- MEFIDIS (Physically Based Distributed Erosion Model) (Nunes et al., 2005)

Many studies were conducted using WEPP (Water Erosion Prediction Project) (USDA, 1995), a process oriented model, which predicts hydrologic and erosion processes (Elliot et al., 1995; Tysdal et al., 1997; Purandara, 1998; Tyagi, 2002).

Comparison of different models using observed field data are also available in literature. Wu et al. (1993) applied AGNPS, ANSWERS, and CREAMS to three watersheds. They observed that all the models underestimated sediment yield, with ANSWERS giving consistent results. Reyes et al. (1999) tested GLEAMS, RUSLE, EPIC and WEPP with the observed data and found that none of the models predicted sediment yield satisfactorily. Amore et al. (2004) applied WEPP and USLE to three large Sicilian basins in which better results were obtained from WEPP.

Krishnaswamy et al. (2000) used a Bayesian dynamic linear model (DLM) for Yadkin river basin in USA. Picouet et al. (2001) presented the results of two models, one based on a statistical approach using relationships for rising stage and recession period of flood and the second, a lumped conceptual model.

Behera and Rajput (2003) developed a dimensionally homogeneous and statistically optimal model, using principal component analysis, for predicting sediment production rate from the ungauged watersheds. Pyasi and Singh (2004) used a dynamic approach for sediment yield modeling of a watershed.

Curtis et al. (2005) developed a conceptual model illustrating the key processes controlling sediment dynamics. Rompacy et al. (2005) used long-term sedimentation records of Italian reservoirs to calibrate a spatially distributed sediment delivery model. The study by DeVente and Poesen (2005) revealed that soil erosion rates measured at one scale are not representative at another scale level. DeVente et al. (2005) reviewed the performance of nine semi-quantitative models and concluded that semi-quantitative approach can provide accurate and reliable estimates.

Artificial Neural Network (ANN) based models were employed in the field of suspended sediment estimation and forecasting (ASCE, 2000; Cigizoglu, 2004; Raghuwanshi et al., 2006). Such models were found to simulate the complex, non-linear behaviour of sediment dynamics relatively better than conventional models.

2.2 Rating Curve Techniques

The application of physically based equations in sediment transport is difficult because of non-availability of hydraulic and sediment transport characteristics. Hence, empirical approaches, such as suspended sediment rating curve, were commonly used.

Rating curve which relates suspended sediment concentration (C_s) and water discharge (Q_w) is expressed in the form of a power equation $\mathbf{C_s = a\ Q_w^b}$. Sediment load is also widely used, instead of concentration (McBean and Al-Nassri, 1988; ASCE, 1990; Crawford, 1991, Julien, 1998). Sediment rating curves tend to under predict the high, and over predict the low sediment concentration (Walling, 1977; Walling and Webb, 1982; Williams, 1989; Cordova and Gonzalez, 1997). A simple correction factor is proposed by Ferguson (1986) in order to overcome the underestimation of sediment load due to degree of scatter about the rating curve. McBean and Al-Nassari (1988) analyzed the degree of uncertainty associated with the use of sediment concentration and load. Rowe et al. (2002) studied the scatter of data points around rating curves and its effect on sediment concentration estimates.

The relationship between sediment concentration and discharge was further complicated by hysteresis effects (Williams, 1989; Gracia, 1996; Asselman, 1999). This prompted efforts to develop separate relationships for seasons, months and rising and falling stages, with sufficient availability of data (Lopes and Ffolliot, 1993; Moliere et al, 2004; Langlois et al., 2005).

Formulation of power function as a linear model requires a logarithmic transformation and a subsequent correction for transformation bias. Rating curve parameters for both the bias corrected, transformed linear or non-linear models were derived by method of least squares (Crawford, 1991). Lopes and Ffolliot (1993) found that transformation bias is greater when large number of measurements is at low discharges. Jansson (1996) developed sediment rating curves by stratification of data into discharge-based classes, which circumvents the bias introduced by linear regression analysis of log-transformed variables. Jansson (1997) reported that the variance is identical for logged load and logged concentration.

2.2.1 Rating Curve Parameters

Sediment rating curve can be considered a black box type of model and the coefficients 'a' and 'b' has no physical meaning. However, Walling (1974) and Sarma (1986) stated that b-coefficient indicates the extent to which new sediment sources become available when discharge increases. The values of b-coefficient obtained for different rivers were used to discuss differences in transport characteristics. Morgan (1995) defined a-coefficient as an index of erosion severity; high a-values indicate intensively weathered materials, which can be easily transported. The b-coefficient represents the erosive power of the river.

Several workers suggested that the rating curve parameters might be predicted from knowledge of catchment and sediment characteristics (Walling, 1974; Rannie, 1978; Mimikou, 1982; Kazama et al., 2005). Syvitski et al. (2000) stated that the rating coefficient 'a' (the mathematical concentration at Q = 1 cumec) is inversely proportional to mean discharge and is related to the average temperature and relief. The rating exponent 'b' correlates with the average temperature and basin relief.

It was also shown that the a- and b-coefficients of sediment rating curves are inversely correlated (Rannie, 1978; Mimikou, 1982; Thomas, 1988; Asselman, 2000). Hence, it is more appropriate to use the steepness of the rating curve, which is a combination of the a- and b-values, as a measure of soil erodibility and erosivity of the river.

2.3 Unit Sediment Graph (USG)

Sediment flow rate plotted, as a function of time at a given location is known as sediment graph. Jeje et al. (1991) and Gracia (1996) classified sediment graphs according to their position with reference to the hydrograph peak into four principal groups;

- advanced, when sediment graph peak occurs before the flood peak
- in-phase, when sediment and discharge peaks occur at the same time
- delayed, when sediment graph peak occurs after the hydrograph peak
- multiple peaks, when runoff with several peaks resulting in several peaks in the sediment graph.

Although different procedures exist for the generation of hydrographs, there are few guidelines for the generation of sediment graphs. One technique commonly proposed for sediment graph generation is the unit sediment graph (USG). Jeje et al. (1991) gave detailed information about sediment graph theory, where the phenomenon is well described, although no computation criteria are proposed.

Johnson (1943) first proposed the application of unit hydrograph theory to suspended sediment concentration. Rendon-Herrero (1974, 1978) defined the USG as sediment graph for one unit of sediment for a given duration distributed over a watershed and used it as an indicator of the degree of disturbances to the natural regimen of sediment production in small watersheds. Renard and Laursen (1975) computed sediment graphs by multiplying storm hydrograph flow-rates by concentrations predicted with a sediment transport model. Bruce et al. (1975) described a sediment graph model, based on erosion and transport capacity, but several parameters were to be optimized by using gauged data.

Williams (1978) simulated sediment graph by convoluting runoff with an instantaneous unit sediment graph (IUSG). To predict a sediment graph from an ungauged watershed, runoff and sediment yield models are required to compute the IUH and sediment yield for a particular storm. Chen and Kuo (1986) introduced a model based on one-hour sediment graph, which can be generated by convoluting one-hour USG with effective sediment erosion of one-hour duration. They developed a dimensionless USG and related peak sediment discharge, time to peak, and time base with soil erodibility and geomorphic parameters of the basin.

Conceptual models for the formulation of IUSG were also introduced based on; routing mobilized sediment through a series of linear reservoirs (Kumar and Rastogi, 1987, Sharma and Murthy, 1996), the time-area diagram of sediment transport (Das and Agarwal, 1990, Raghuwanshi et al., 1994), the IUH and a dimensionless sediment concentration distribution (Banasik and Walling, 1996) and in conjunction with Kalman filter (Lee and Singh, 1999).

Sadeghi and Singh (2002) developed a model with sediment mobilized as input, which was obtained from a relationship between sediment mobilized and excess runoff. The excess runoff was estimated by using a precipitation-runoff relationship. Kalin et al. (2004) used a modified USG approach for source identification based on hydrograph and sediment graph data from several rainfall events.

2.4 Sediment Characteristics of World and Indian Rivers

A considerable body of information concerning the magnitude of sediment yields and their control by human activity, climate, and catchment characteristics were available (UNESCO, 1982; Peart and Walling, 1986). It is now well established from earlier studies (Holeman, 1968; Meybeck, 1976; Martin and Meybeck, 1979; Milliman and Meade, 1983; Meybeck et al., 2003) that understanding of continental fluvial processes requires detailed studies of medium sized rivers. More than 70 % of the presently estimated global sediment flux of 18×10^9 ton is being contributed by the medium and small size river basins. Therefore, studies on such rivers are also useful in better understanding of the controlling factors of sediment transport.

2.4.1 Sediment Yield Studies for World Rivers

Wilson (1972) analysed sediment yield patterns of United States Rivers with respect to variation in climatic regime across the country. Analysis of sediment yields from 61 Kenyan catchments by Dunne (1979) allowed the refinement of regional relationships between yields and their major controls. The soil erosion in the Baltic

Sea region is found to be dependant on five factors; climate, relief, geology and soils, vegetation, and man's activities (Jansson, 1982; Lajczak and Jansson, 1993).

Annual sediment yields for 47 basins of North Island, New Zealand were analysed by Griffiths (1982). Prediction equations for yield were derived for four arbitrary regions, all of which feature rainfall as the independent variable. From the historical analyses of data for 1963 - 1985, Keown et al. (1986) reported that there exists a 50 % reduction in annual sediment transport from the Mississippi river basin.

From the study on sedimentation pattern and denudation rate of Ganges and Brahmaputra in Bangladesh, Islam et al. (1999) reported that the average denudation rates for both the basins together was about 0.37 mm/year. Petkovic et al. (1999) reviewed the sediment yield over Serbian territory and found that extensive erosion control measures reduced the erosion intensity. Wass and Leeks (1999) established sediment monitoring network within main tributaries of the River Rhine and estimated that the sediment yield from the river is very low (15 ton/km^2/year).

Rondeau et al. (2000) established a mass balance budget of suspended sediment in the St. Lawrence River, Canada, to identify sediment sources. Krishnaswamy et al. (2001) studied the spatial pattern of suspended sediment in 29 basins of Costa Rica.

Klaghofer et al. (2002) studied the trends in sediment yield in the Danube basin and noted an average increase of 32 % during 40-year period (from 1950 to 1990). Long-term data on sediment concentration were utilized by Yang et al. (2002) to study the variation in sediment supply by Yangtze River. During 1950-1960, sediment discharge increased by 12 % and thereafter, it showed a reduction by 38 %.

Asselman et al. (2003) estimated the effects of changes in climate and land use on the mobilization of fine sediment and its net transport to the lower Rhine delta. Xu (2003) studied temporal variation of sedimentation rate in Lower Yellow River over the past 2300 years in relation to climate change and the impact of human activities. Cornwell et al. (2003) reported that the denudation rates of three river basins of Nanga Parbat Himalaya, Pakistan, vary from 0.2 mm/year to 6 mm/year.

Simon et al. (2004) analysed flow and sediment data from across 2900 sites across United States to estimate flow and suspended sediment transport conditions. Restrepo et al. (2006) studied the sediment yield and its response to control variables, hydrologic, morphometric, and climatic, in the Magdalena River basin in Columbia, based on sediment load data from 32 tributary catchments.

2.4.2 Sediment Yield Studies for Indian Rivers

While considering the sediment transport characteristics of Indian rivers, a distinct divide between the Himalayan and non-Himalayan rivers can be observed. Data compiled by Holeman (1968), and Meybeck (1976) indicated that the bulk amount of sediment from the South Asian regions is transported by the Ganges and Brahmaputra. The Himalayan rocks are sedimentary of recent origin and are soft and friable, which causes heavy erosion (Sundd, 1991). Godavari, Mahanadi, and Krishna basins lie in the Deccan trap of the country, whereas Cauvery, Narmada, and Tapti basins lie in hard rocks. They carry lesser quantity of sediment, owing to the stable geologic settings towards weathering.

Average erosion rate of India is 0.21 mm/year (Subramanian, 1978), which is high compared to 0.046, 0.015, and 0.040 mm/year for the Amazon, Congo, and Mississippi (Gibbs, 1967). It was estimated that the sediment transport of the entire Indian sub-continent is 1.21×10^9 ton/year (Subramanian, 1983). These estimates indicated that average Indian sediment yield rate, 327 ton/km^2/year, is about twice the global sediment yield, 150 ton/ km^2/year. Morris (1995) reported that 27 of the major 116 reservoirs might loose half of their original capacity by 2020.

Garde and Kothyari (1987) prepared iso-erosion factor map of India and relationships were developed to estimate average sediment yield from climatological and topographical factors. Tiwari and Lal (2002) used data from 274 stations in Madhya Pradesh and Chattisgarh to prepare iso-erodent map.

The total sediment transport and erosion rate of the Krishna River basin is estimated to be 4.11×10^6 ton and 16 ton/km^2/year (Subramanian, 1982; Ramesh and Subramanian, 1988). This rate is much lower as compared to any other Indian (except for Cauvery) and world rivers (Ramesh and Subramanian, 1986). Based on the sampling of the Ganges basin, chemical and sediment load transported was computed by Abbas and Subramanian (1984).

Biksham and Subramanian (1988) reported that in terms of sediment transport and the rate of physical erosion (555 ton/ km^2/year), the position of the Godavari River is ninth and fifth respectively in the world. Vaithiyanathan et al. (1988, 1992) found that the sediment load carried by the Cauvery is low compared with other rivers and monsoon accounts for 85 % of the annual sediment transport. Jha et al. (1988) studied the sediment characteristics of river Yamuna, and found that the majority of suspended load is carried during the monsoon season.

The Brahmaputra River is characterised by high seasonal variability in flow, sediment transport, and channel configuration (Goswami, 1985). Singh (2006) studied the causes of spatial variability in erosion in this basin and impacts of high erosion rates on the sediment flow into Bay of Bengal.

Annual, seasonal, monthly, and daily variation of the sediment discharge in the Mahanadi River was studied by Chakrapani and Subramanian (1990). More than 95 % of the sediment discharge took place in the monsoon. Rao et al (1997) examined sedimentation in the Chenab basin using the data provided by Central Water Commission (CWC). Singh et al. (2003) assessed sediment concentration, load, and yield for Dokriani Glacier basin located in the Garhwal Himalayas.

2.5 Application of GIS in Sediment Yield Studies

Geographical Information System (GIS), a technology designed to store, manipulate and display spatial and non spatial data, has become an important tool in the spatial analysis of topography, soil, land use, etc. It provides a digital representation of the catchment, which can be used in hydrologic modeling. In GIS, the details regarding soil, land use, rainfall distribution, slope, etc., can be stored in grid squares and can be used for modeling spatial pattern hydrologic processes taking place.

Spanner (1982) and Spanner et al., (1983) combined Landsat Multi Spectral Scanner (MSS) data and a digital elevation model (DEM), which enabled the quantification of three of the six coefficients of USLE. Tim et al. (1992) coupled two models, Soil loss (SLOSS) model and the Phosphorous yield model (PHOSPH), with a GIS to delineate critical areas of non-point source pollution at catchment level.

DeRoo (1993) linked ANSWERS model to a GIS to incorporate the variable contributing area concept for simulation of saturated overland flow. Engel et al. (1993) integrated AGNPS with a raster-based tool GRASS (Geographical Resource Analysis Support System). He et al. (1993) integrated GIS and an erosion model to evaluate the impacts of agricultural runoff on water quality. Heidtke and Auer (1993) applied GIS based methodologies for non-point source loading.

Tim and Jolly (1994) evaluated agricultural non-point source pollution using ARC/INFO GIS and AGNPS model. Savabi et al. (1996) used GRASS GIS together with WEPP. Integrated Land and Water Information System (ILWIS) GIS was used by Jain (1997) to compute soil erosion in individual homogeneous grids, generation of sediment delivery map and to route the eroded material to the outlet. Jain (1998) used ILWIS and USLE to estimate sediment yield from Lower Sutlej Basin.

Integration of remote sensing, GIS and sediment yield models were also reported by many researchers (Mitasova et al., 1996; Kothyari and Jain, 1997; Marshrigni and Cruise, 1997; Jain and Kothyari, 2000; Jain and Dolezal, 2000; Baban and Yusof, 2001; Finlayson and Montgomery, 2003; Jain et al., 2005; Singh and Phadke, 2006).

Jain (2000) integrated ILWIS GIS and ERDAS image processing software with ANSWERS model to estimate soil erosion and sediment yield. Sharma et al. (2001) used remote sensing and GIS to categorize 25 watersheds based on Sediment Yield Index (SYI). Jain and Goel (2002) used the Watershed Erosion Response Model (WERM) and ERDAS imaging software for sediment yield modeling. Kothyari et al. (2002) introduced a GIS based methodology to estimate temporal variation of sediment yield (USG) by translation of sediment yield from the grid cells and routing through a linear reservoir.

Svorin (2003) tested the applicability of three erosion models incorporated in the SEAGIS (Soil Erosion Assessment using GIS) and reported that the results are dependent on the method of estimating the input parameters. Chakraborty et al. (2004) applied remote sensing data along with USLE and ARC/INFO GIS to predict the soil erosion status of a small watershed. Pandey et al. (2005) tested the Soil and Water Assessment Tool (SWAT2000) model for the development of management scenarios. The attributes of sub-watersheds were generated through Arc View GIS.

2.6 Studies on Rivers of Kerala

The major problems related to water resources and environmental sector, which the State face are:

- rivers flow only during monsoon season, and dry during non-monsoon season, which causes salt water intrusion
- illegal deforestation of the dense forests on Ghat and plantation activities results in concentrated overland runoff and erosion
- sand mining, results in deepening of groundwater table, unstable river banks, damage to hydraulic structures, and faster flow to the sea
- decrease in sediment supply to coast, due to reservoirs and sand mining, which affects coastal eco-system and causes coastal erosion
- industrial pollution, bad management of inland waterways, filling up of natural ponds, and other water-bodies
- filling out of paddy fields, which act as sponges to retain rainwater, over extraction of groundwater

For a region like Kerala, where environmental issues exist, sediment load carried by the rivers is one of the important components in environmental impact assessment. The 41 west flowing rivers discharge large amount of sediment load to the coastal region, which consists of complex interlinking of backwaters, estuaries, and the Arabian Sea. Hence it is necessary to study the water related environmental problem in greater detail with a view to point out the necessity for judicious use of water resources and its scientific management (James, 1998).

Even though many studies are available in literature about the hydrological and environmental aspects of rivers of Kerala, only few studies could be located on erosion and sediment yield research. The Central Water Commission (CWC) is regularly monitoring the suspended sediment concentration in 16 west flowing rivers for last 15-20 years.

Alexander and Thomas (1982) discussed about various soil conservation strategies for forest plantations. Chandrasekhara (1991) studied the sedimentation rates of reservoirs in Western Ghat of Kerala. James et al. (1992) calculated the sediment yield from using USLE and found that the sediment yield from dense forest is only one-sixth of that from fully exploited catchments.

Thomas et al. (1997) reported that sediment yield from exploited basins are about 4 times higher than that of protected basins, whereas plantation induce erosion. Similar conclusions were given by CWRDM (1998, 2000a) from their studies. Studies of erosion and sediment yield were reported by Babu Mathew (1998), Gopakumar and James (1999) and Anitha et al. (2000).

In another study by CWRDM (2000b), the sediment data collected from Central Water Commission (CWC) were analysed to derive rating curves for the rivers. CESS (2003) studied the sustainable level of sand mining from rivers of Kerala and estimated the optimum amount of sand that can be mined at various locations (called Kadavu). They listed out the general impacts of river sand mining on various components of the river eco-systems.

Sikka et al. (2003) prepared erosion map of Kerala State by calculating soil loss from 338 points distributed over entire State, using USLE. The result showed that major portion of the State (52 %) fell in 0–5 ton/ha/year soil loss category. Nandakumar et al. (2004) attempted sediment yield modeling of 48 micro-watersheds of Kerala by performing multiple regression analysis of sediment yield with geomorphic, physiographic and soil characteristics. TERI (2004) assessed the impact of watershed treatment measures on Pulinkatta watershed of Idukki district and found that the measures undertaken resulted in a reduction of soil erosion.

Prasad and Ramanathan (2005) studied the hydro-geochemical processes taking place in the Achankovil basin and found that the material transport is low compared to other Indian rivers. Anderson et al. (2005) reported low sediment concentration from the rivers of Kerala, which is unexpected for tropical monsoon fed rivers. They reasoned that this is due to the lack of fracturing by tectonic activities over southern Western Ghat region. The sediment yield rates were estimated to 90 ton/km^2/year.

Sreeba and Padmalal (2006) analysed the present status of sand mining from different physiographic regions of 7 rivers. The impact of mining on the river stability and ecology was conducted. Various mining scenarios were considered and recommendations were proposed for minimizing the ill effects of sand mining.

2.7 Scope of the Present Study

A detailed review of the studies/research activities conducted on global and Indian basis, on various aspects of erosion and sediment yield, has been done in the preceding sections. From the above discussions, it is felt that the following points need to be studied further for the State of Kerala.

- CWC is monitoring sediment load from 16 rivers of Kerala; however, no attempt has been made so far to study the spatial and seasonal variation of the sediment load and its major controlling factors
- Simulation of temporal distribution of sediment concentration on a rainfall-runoff event basis has not been attempted for Western Ghat region
- Different models are available in literature for estimating erosion and sediment yield. However, selection of a suitable model appropriate for the tropical Western Ghat region, has not been done

The above factors were considered while listing out the objectives for this research work and efforts were made to fill the gaps in understanding the suspended sediment dynamics of the rivers of Kerala, originating from intense rainfall regions of western ghats, flowing through steep terrains and debouching into a large system of backwaters, estuaries and coastal region.

3.0 OBJECTIVES OF THE THESIS

It is proposed to study the suspended sediment transport characteristics of river basins of Kerala and to model suspended sediment discharge mechanism for typical micro-watersheds. The Pamba river basin is selected as a representative hydrologic regime for detailed studies of suspended sediment characteristics and its seasonal variation. The applicability of various erosion models would be tested by comparing with the observed event data (by continuous monitoring of rainfall, discharge, and suspended sediment concentration for lower order streams). Empirical, conceptual and physically distributed models were used for making the comparison of performance of the models.

The main objectives of the study are as follows:

- to analyse discharge and suspended sediment data of rivers of Kerala in order to understand its seasonal and spatial variation of river sediment transport and to identify the controlling factors
- to study the suspended sediment yield characteristics of a representative river basin and to test the applicability of rating curves
- to develop of Unit Sediment Graphs (USG) for micro-watersheds with varying characteristics
- to compare the performance of three sediment yield models with the observed data of micro-watersheds
- to evolve a conceptual approach in river basin planning/management for the State by considering variation in sediment yield pattern in relation to hydro-meteorological and river basin characteristics

4.0 CONTENTS OF THE THESIS

The thesis is divided into four chapters.

Chapter I gives general introduction about the erosion and sediment yield, the factors affecting, and methods of estimation. It is followed by a detailed literature review regarding erosion and sediment yield research, erosion and sediment yield estimation methods and modeling, rating curve techniques, unit sediment graph, sediment characteristics of Indian and World rivers, a short literature review of rivers of Kerala and objectives of the study.

Chapter II on materials and methods gives a description of the hydrology of Kerala, characteristics of the rivers, description on Pamba river basin and about the three watersheds selected for sediment yield modeling. The chapter also gives the methodology used in the analyses of sediment yield characteristics of the west flowing rivers using the discharge-sediment data collected from CWC and the basin characteristics estimated using various maps. It describes the field works conducted in Pamba basin and for the micro-watersheds and the methodology for the development of USG and rating curves. The three sediment yield models used for the comparison are also explained in detail.

Chapter III describes the results from the data analysis and model application and interpretation of the results. It compares the sediment yield characteristics of different rivers flowing through different regions of the State and the major controlling factors were identified. The results from the detailed studies made on Pamba river were discussed with respect to applicability of rating curves, contributions of different river reaches and hysteresis effects. Accuracy of three selected models was explained with observed data from three micro-watersheds, wherein these models were applied.

Chapter IV gives the major findings from the study and specific conclusions.

A listing of the references, which are cited within the text, follows this.

Chapter II

MATERIALS AND METHODS

1.0 STUDY AREA

1.1 Introduction

The amount of soil eroded from a particular location is affected by rainfall erosivity, soil erodibility, topography, land use and conservation measures. With an average rainfall ranging from 1550 to 4000 mm, according to the zonation of the Western Ghats (Sikka and Singh, 2000), major part of Kerala is in "very high rainfall and lower altitude" zone. Large area is covered by dense vegetation in the form of forests and plantation. The land slope ranges from 2 % to over 40 %. Paddy is the main crop and rubber, coconut, coffee and cashew are the main plantation. Mango, jackfruit and banana are some of the fruit trees cultivated. Spices like pepper and cardamom are also extensively grown. Field bunding and terracing are the commonly adopted soil conservation practices.

State of Kerala lies between 8° 18' and 12° 48' N and 74° 52' and 77° 22' E and covers an area of 38864 km^2. It is a narrow strip of land with width varying from about 30 km in the north and south to 130 km in the central portion. The location of the State is shown in Figure 1. Though the area of the State is small, variation in physical features is very wide. It covers altitudes ranging from below sea level, in Kuttanad to about 2700 m above sea level, along Western Ghat.

Wayanad plateau, Nelliampathy plateau, Periyar plateau and Agasthys mala are parts of the Western Ghat range at different elevations; the highest peak is Anamudi (2695 m). Palghat Gap is a major break in the Western Ghats, which has got a significant role in determining climate of the State. The northeast monsoon winds enter the State through this gap. The steep sloped mountain ranges and high intensity rainfall give birth to a number of rivers and results in varied landforms.

1.1.1 Topography

Based on the topography, the State can be divided into three well-defined natural regions.

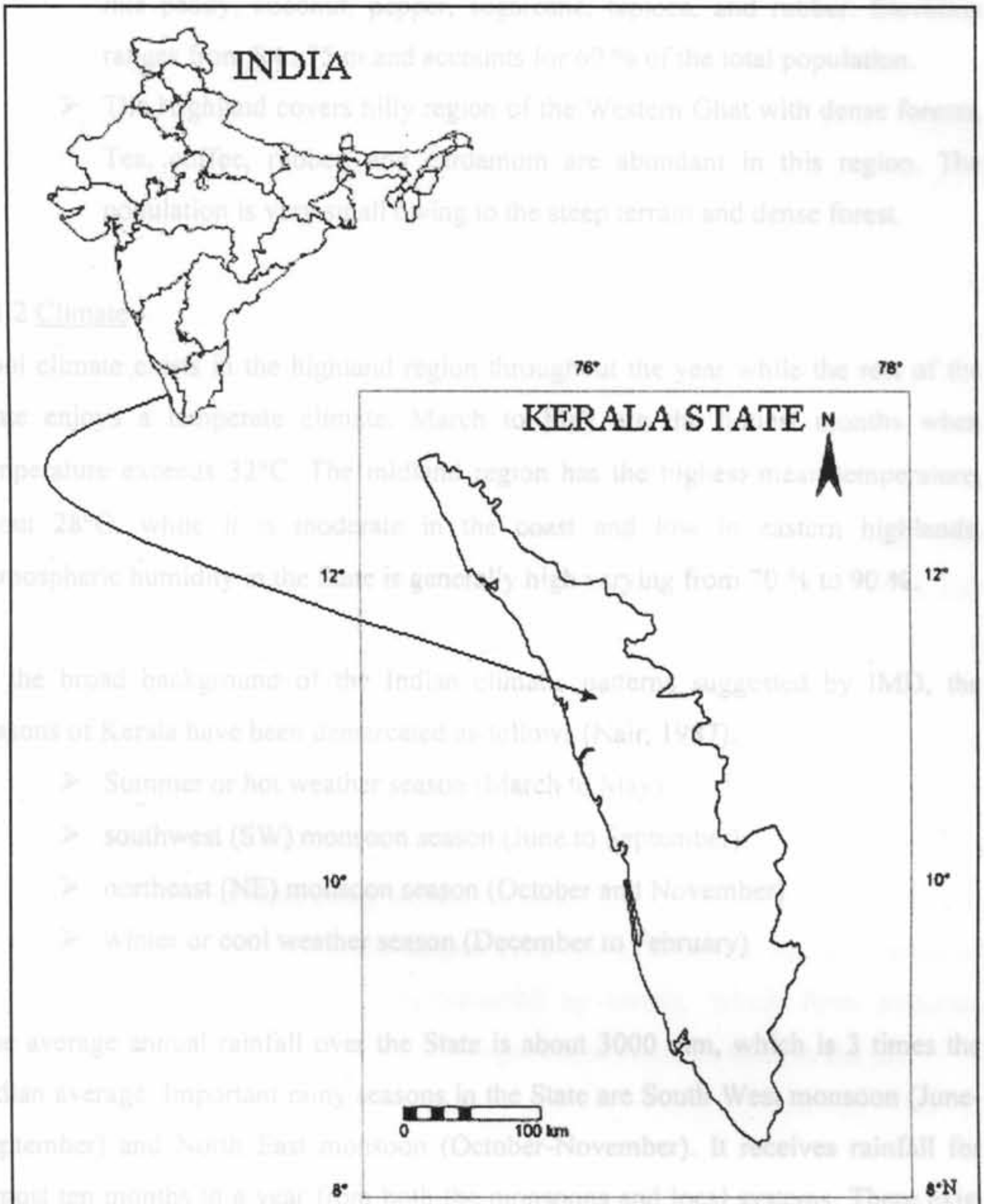


Figure 1. Location of the Kerala State

- The Lowland consists of coastal belt with backwaters and paddy fields. It has an elevation upto 8 meters and 25 % of the population lives here.
- The Midland covers central portion of the Sate with a diversity of crops like paddy, coconut, pepper, sugarcane, tapioca, and rubber. Elevation ranges from 8 to 75 m and accounts for 60 % of the total population.
- The Highland covers hilly region of the Western Ghat with dense forests. Tea, coffee, rubber, and cardamom are abundant in this region. The population is very small owing to the steep terrain and dense forest.

1.1.2 Climate

Cool climate exists in the highland region throughout the year while the rest of the State enjoys a temperate climate. March to May are the hottest months when temperature exceeds 32°C. The midland region has the highest mean temperature, about 28°C, while it is moderate in the coast and low in eastern highlands. Atmospheric humidity in the State is generally high varying from 70 % to 90 %.

In the broad background of the Indian climatic patterns suggested by IMD, the seasons of Kerala have been demarcated as follows (Nair, 1987):

- Summer or hot weather season (March to May)
- southwest (SW) monsoon season (June to September)
- northeast (NE) monsoon season (October and November)
- winter or cool weather season (December to February)

The average annual rainfall over the State is about 3000 mm, which is 3 times the Indian average. Important rainy seasons in the State are South West monsoon (June-September) and North East monsoon (October-November). It receives rainfall for almost ten months in a year from both the monsoons and local systems. There exist two pockets of heavy rainfall, around Pirumed (491 cm) and Kanjirappally (410 cm) in the south and around Vythiri (437 cm) and Kuttiyadi (435 cm) in the north (Nair, 1987). About 65 % of the annual rainfall is received during the SW monsoon and 20 - 25 % during the NE monsoon. However, the percentage of the NE monsoon is comparatively more for central and southern portion of the State.

The annual rainfall; for the low land region ranges from 900 mm to 3500 mm, from 1400 mm to 4000 mm for the midland region and from 2500 mm to 5000 mm in the high land region; from south to north.

1.1.3 Water Resources of Kerala

The State is situated in the humid tropics with unique geomorphology, geology, meteorology, land use and cropping pattern. These factors considerably influence the water resources and its management. There are 44 rivers flowing in the State (with minimum length of 15 km), out of which 41 originates from the Western Ghats and flow towards west (CWRDM, 1995). The other three originates from the Western Ghats and join Bay of Bengal (Kabbini, Bhavani, Pambar). Most of these rivers are ephermal, with input from rainfall, mainly during the monsoons.

As per the national norm (Basak, 1998), rivers with drainage area more than 20000 and 2000 km^2 are called major and medium rivers respectively and less than 2000 km^2 are termed as minor rivers. Therefore, Kerala has only 4 medium rivers, Periyar, Bharathapuzha, Pamba, and Chaliyar. These rivers drain about 35 % of the total area of the State. The annual discharge from all the rivers is estimated to be 77900 MCM.

State (mainland) has a total coast length of 580 km. There exists a continuous chain of lagoons and backwaters along the coastal line, with 34 estuaries. The Vembanad estuary in the central part is the largest (135 km^2), followed by the Ashtamudi Kayal. These backwaters are interconnected by canals, which form important navigation system, and having small openings, which connects them to the sea.

1.1.4 Land Use

The land use types are distinctively governed by physiography and climate of the State. There are five main types of vegetation in the State (Nair, 1987):

- tropical wet evergreen forests,
- tropical semi-evergreen forests,
- tropical moist deciduous forests,
- subtropical broad-leaved hill forests, and
- montane wet temperate forests.

The arable land forms a continuous stretch along the entire State spanning from the coast to the inland up to 100 m above sea level, and further east along the river valleys. The next important group is the forestland, western limit of which can be marked by the 300 m contour. Several plantations are developed within the forests, such as tea, coffee, cardamom and rubber. Grasslands are observed in isolated patches. Extensive wastelands, formed of hard crust laterite, which are unsuitable for cultivation, are found mostly in the northern part of the State.

1.1.5 Geology

Geologically the major formations of the State are:

- crystalline rocks of Archaenage,
- sedimentary rocks of Tertiary age,
- laterites capping the crystalline and sedimentary rocks, and
- recent to sub-recent sediments in low-lying areas and river valleys.

The State is mainly comprised of crystalline rocks such as charnokites, khondalites, gneisses, and Dharwar schists of pre-cambrian age. Late tertiary sedimentary formation forms linear coastal outcrops north of Cannanore and from Kottayam to Trivandrum in south. Laterites cover wide areas in Kerala and along the midland region, it forms as a residual deposit due to weathering of crystalline rocks.

1.1.6 Soil Types

Lateritic, forest loams and coastal loams cover the major soil types of the State. Based on the physio-chemical properties and morphological features, they are classified into ten broad groups (NBSS, 1996):

- Coastal alluvium, along the coastline
- Riverine alluvium, in river valleys
- Red loam, occurs in isolated patches in foothills
- Lateritic soil, distributed throughout the State
- Greyish onattukara, acidic and deficient in major plant nutrients
- Acidic saline, found in Kuttanad region

- Brown hydromorphic soil, found in wetlands
- Hydromorphic saline soil, observed along the coastal strip
- Black soils, found in northeastern parts of Palghat
- Forest Loam, occurs in the eastern part within forest area

1.1.7 Characteristics of Rivers Selected for the Study

CWC is maintaining discharge and sediment monitoring stations on 16 west flowing rivers of Kerala for a period ranging from 15 to 20 years. These rivers are considered for the present study. They extend from Payaswini in Kasaragod district of north Kerala to Vamanapuram in Thiruvananthapuram, the southernmost district. Location of the rivers is shown in Figure 2 and the salient features of the rivers basins are given in table 1.

Table 1: Characteristics of the River Basins Selected

Name of the River (North to South)	Average Annual Rainfall (mm)	Length of River (km)	Catchment Area (km^2)	Average Slope (m/m)	Average Yearly Discharge (MCM)	Average Annual Sediment Load (ton)
Payaswini	4000	105	957	0.012	2384	239934
Valapatanam	3600	101	1070	0.013	3543	252144
Chaliyar	3800	169	1876	0.012	4175	401614
Kadalundi	3400	86	750	0.013	1303	85171
Bharathapuzha	2300	209	5755	0.009	4326	369186
Pulamthode	2600	78	940	0.013	1756	101771
Chalakudy	3600	120	1342	0.010	1798	50234
Periyar	3200	244	4234	0.007	6895	320029
Muvattupuzha	3100	92	1208	0.011	5068	157001
Kaliyar	3000	71	405	0.014	1194	44667
Meenachil	3000	61	615	0.017	1756	36566
Manimala	3300	90	731	0.012	1795	70486
Pamba	3600	176	1654	0.009	4016	156851
Achankovil	2600	138	810	0.005	1247	77130
Kallada	2800	92	1210	0.016	1636	104447
Vamanapuram	2200	88	540	0.020	701	68619

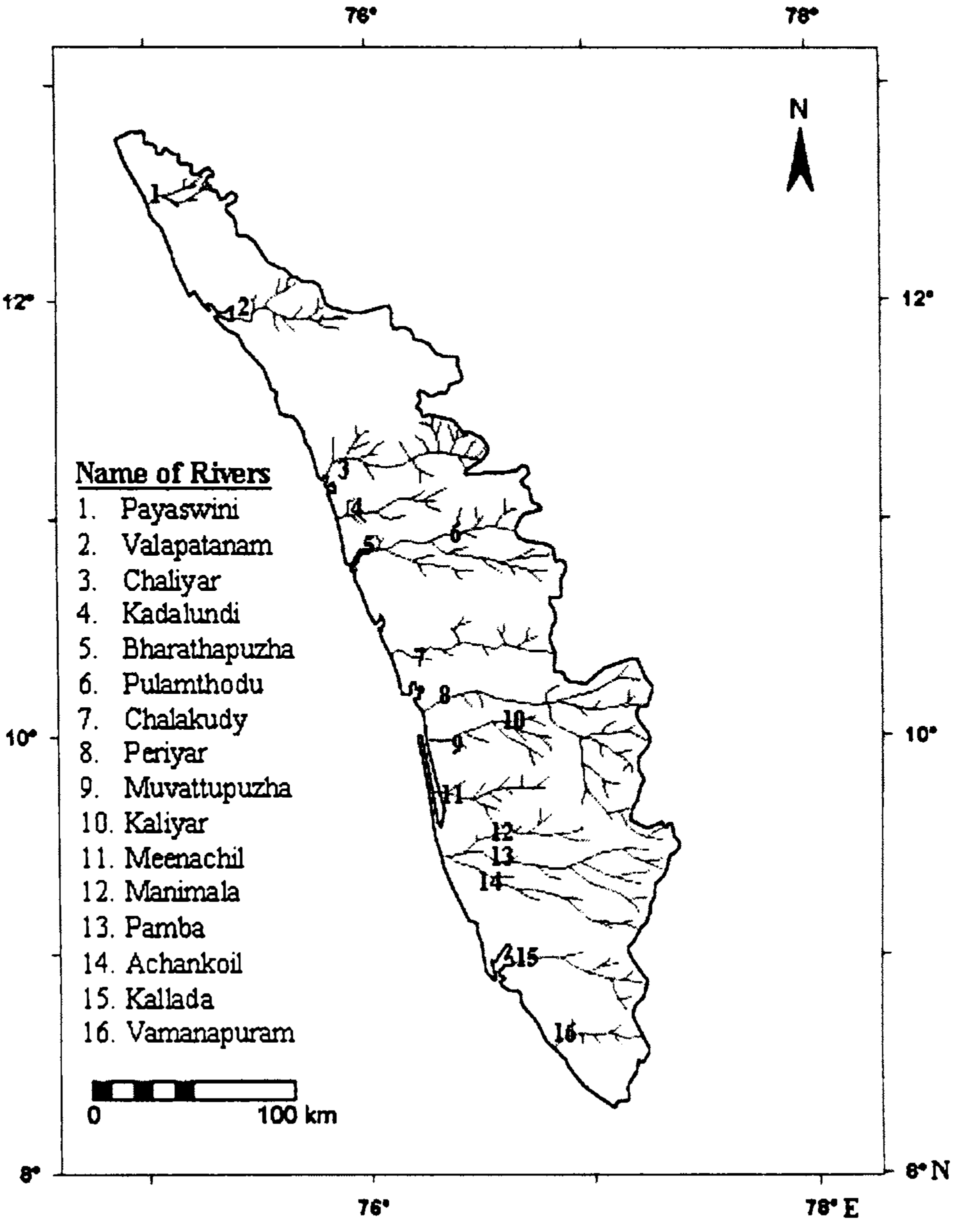


Figure 2: Location of Selected West Flowing Rivers

1.2 Pamba River Basin

The Pamba river, 176 km in length, is the third longest river in Kerala and is formed by the confluence of the Pamba Ar, Azhutha Ar, Kakkad Ar, and Kall Ar. The total catchment area of the river basin is 2235 km^2, upto the confluence with the estuary. The basin lies entirely in Kerala State (Pathanamthitta, Idukki, and Alleppy districts). The basin experiences good rainfall, moderate temperature and humid atmosphere. The SW and NE monsoon have great influence over the climatic conditions. As per IMD, normal daily temperature varies from 22.6° C and 32.7° C. Average annual rainfall varies from 2276 mm to 4275 mm. Average monthly rainfall amount for different physiographic zones within the study area are given in Table 2.

Table 2: Average Monthly Rainfall (mm) in Pamba River Basin

Physiographic zones/Months	High land	Mid land	Low land
January	36.6	37.3	5.4
February	39.4	71.4	20.7
March	136.4	151.8	62.6
April	161.7	210.5	191.3
May	229.2	241.5	295.1
June	711.5	565.4	633.9
July	740.1	448.4	556.6
August	557.7	432.9	463.3
September	416.8	392.2	338.9
October	388.0	338.3	446.1
November	276.2	266.4	210.1
December	68.4	68.9	74.3
Total (yearly)	3761.8	3225.0	3298.0

Pamba river upto the CWC gauging site at Malakkara is selected for the present study. It falls between 9° 10' and 9° 37' 10" N and 76° 39' 10" and 77° 17' 30" E and covers an area of 1654 km^2. The basin map with its drainage network is shown in Figure 3. The discharge observation at Malakkara (by CWC) started from 1985 and the sediment data from 1986. Maximum water level recorded is 7.82 m on 03/08/94 with a corresponding discharge of 1988 cumec. Average annual water and sediment flow recorded is given in Table 3.

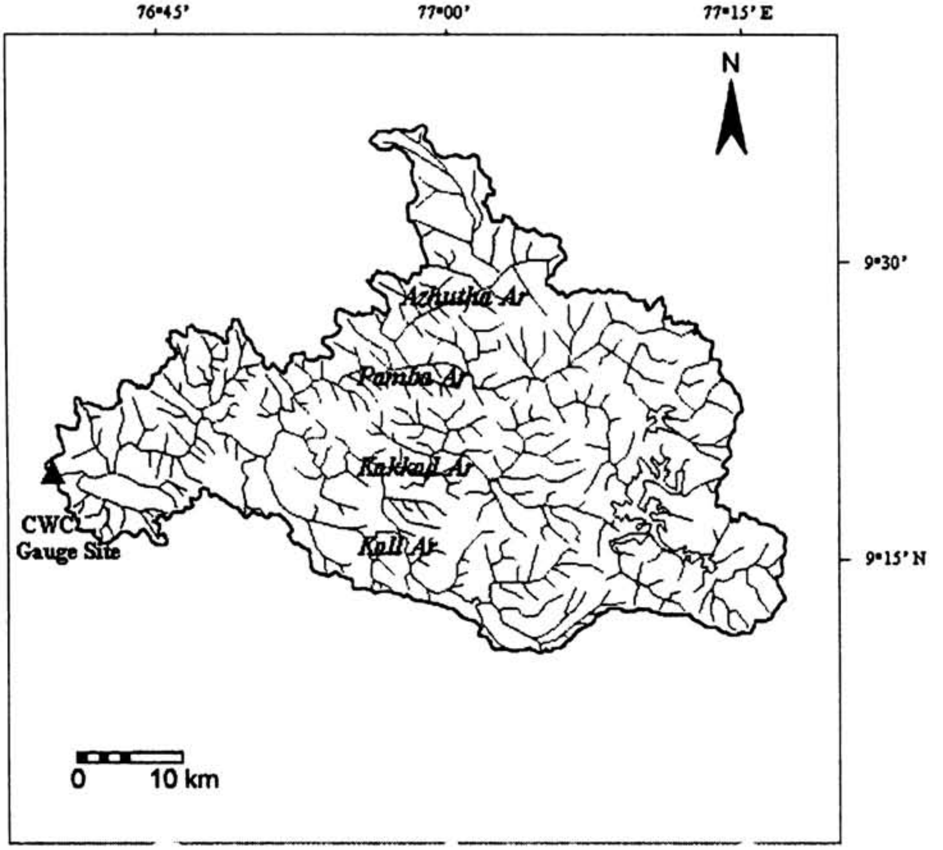


Figure 3: Drainage Map of Pamba River Basin

Four different types of soils are predominant in the basin. They are greyish onattukara, lateritic soil, forest loam and riverine alluvium along the river course. The land use of the basin is dominated by forest. About 52.4 % is covered by forest, 25.4 % by plantations (rubber, coconut, teak, tea, etc), 16.3 % by agriculture, and the rest (5.9 %) fallow lands.

Table 3: Annual Flow and Sediment Load at Malakkara CWC Gauge Site

Year	Flow (MCM)	Sediment Load (ton)
1986-87	3112	106291
1987-88	3163	143116
1988-89	3649	144923
1989-90	4355	173227
1990-91	3289	65770
1991-92	4064	104768
1992-93	5397	501562
1993-94	4300	117457
1994-95	4721	201516
1995-96	4247	131380
1996-97	3786	98562
1997-98	3666	95468
1998-99	5296	290250
1999-00	3728	90005
2000-01	3458	88468

1.3 Micro-Watersheds Considered for Sediment Yield Modeling

Objectives of the present study include simulating the temporal distribution of sediment yield by deriving unit sediment graph (USG) for micro-watersheds and to test performance of erosion and sediment yield models. In order to achieve this objective, it was necessary to monitor the sediment flux carried by small streams. Therefore, three micro-watersheds are selected for continuous (event-based) monitoring of rainfall, runoff, and suspended sediment concentration within the Pamba basin. They are selected on the basis of diversity in altitudinal zones, slopes, and land use classes. The location of these watersheds is shown in Figure 4. The characteristics of the watersheds are described below.

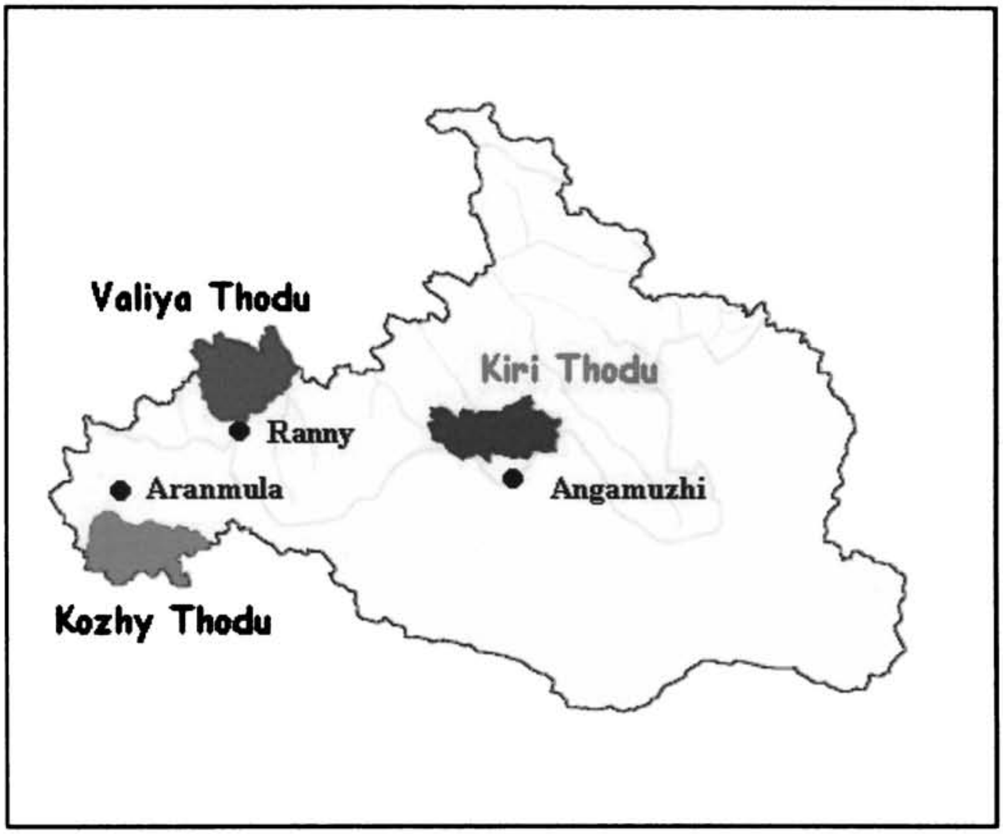


Figure 4: Location of the Micro-Watersheds

1.3.1 Kozhy Thodu Watershed

This watershed lies in the mid land region of the State and characterised with plain to gentle sloping topography with a small part of the upstream region falling within medium sloped topography. The watershed lies between 9° 15' 50" and 9° 19' 15" N and 76° 40' 40" and 76° 46' 20" E and is having a geographical area of 37.49 km^2. This stream joins Pamba near Aranmula. Figure 5 shows the watershed with its stream network. The major features of the watershed are listed in table 4.

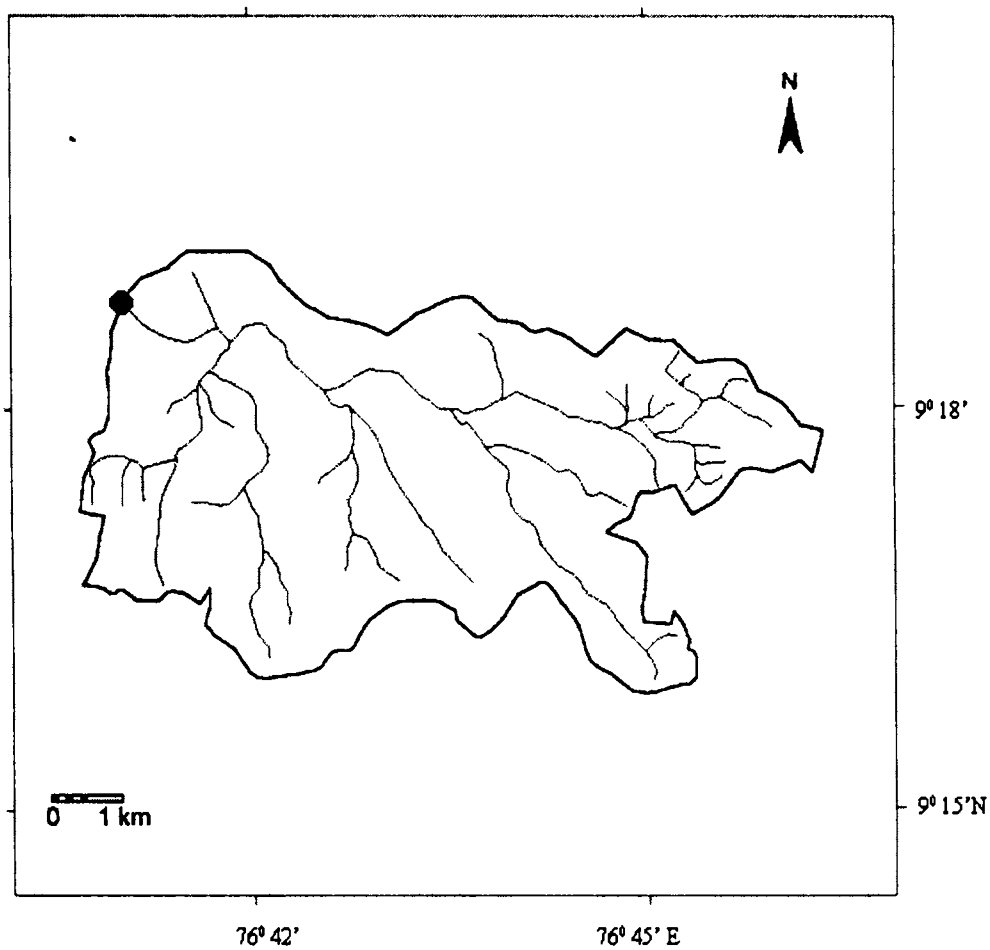


Figure 5: Kozhy Thodu Watershed with Stream Network

Owing to the plain topography, the watershed is having a sparse stream network. The main channel is a 4^{th} order stream. Length of the main channel from the origin is about 10 km. The gauge site is located at 3 km from Aranmula on Aranmula - Kidangoor road. The altitude ranges from 20 m to 120 m, with majority of the watershed falling in the altitude range 20 - 50 m. 50% of the topography falls under the slope class 0 - 2 % and the upstream portions have a slope of about 10 - 50 %. Agriculture is the major land use class followed by plantations. Sandy loam soils are predominant and loam and silty loam soils covers the remaining watershed area.

Table 4: Characteristics of Kozhy Thodu Watershed

Stream Order	No. of Streams	Total Length (km)
1 2 3 4	32 18 9 2	29.91 10.17 8.35 1.79
		Drainage density 1.340 km^{-1}
Altitudinal Zone (m above msl)	Area (km^2)	% Area
20 – 30 30 – 50 50 – 100 > 100	21.64 8.07 6.84 0.94	57.7 21.5 18.3 2.5
Slope Class (%)	Area (km^2)	% Area
0 – 1 1 – 2 2 – 5 5 – 10 10 – 25 25 – 50 > 50	13.78 3.90 2.48 3.36 8.17 4.90 0.90	36.7 10.4 6.6 9.0 21.8 13.1 2.4
Land Use Type	Area (km^2)	% Area
Agriculture Fallow Plantation	23.75 3.79 9.95	63.4 10.1 26.5
Soil Type	Area (km^2)	% Area
Loam Sandy Loam SandyLoam (Plantation) Silty Loam	11.87 7.30 9.48 8.84	31.7 19.5 25.3 23.5

1.3.2 Valiya Thodu Watershed

Located within the transitional zone between midland and high land, the watershed represents a combination of altitude, slope, and land use of both the regions. It lies between 9° 23' and 9° 27' 15" N and 76° 45' 30" and 76° 50'15" E and covers a geographical area of 41.15 km^2. The watershed with its drainage system is shown in Figure 6. The salient features of the watershed are given in table 5.

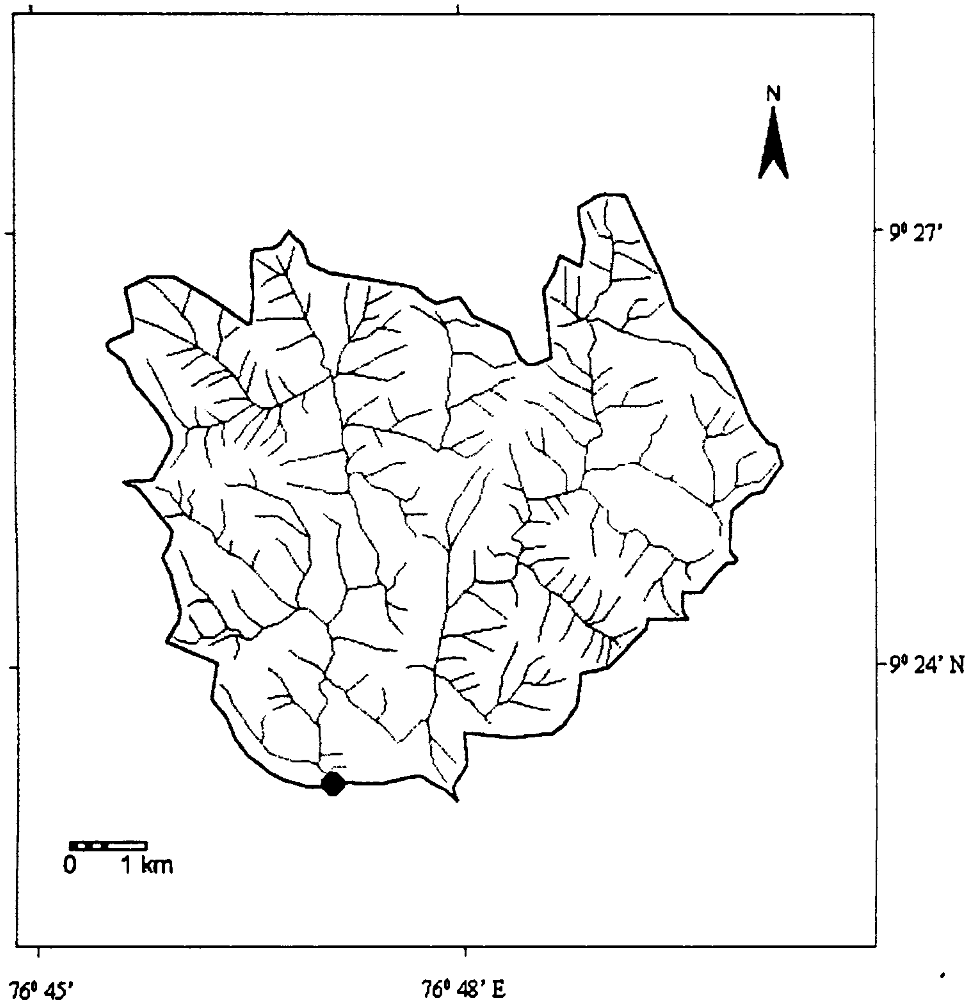


Figure 6: Valiya Thodu Watershed with Stream Network

The altitude varies between 20 m to 278 m with upstream portions having steep sloped topography. This topography gives rise to a dense drainage network, with a drainage density of 3.23 km^{-1}. The gauge site is located about 4 km from Ranny along Ranny – Thiruvalla road. The stream at the gauging point is a 5^{th} order stream, with the main channel is about 7.5 km in length, and joins Pamba at Ranny. The watershed is equally distributed into the three altitudinal zones 20 - 50, 50 - 100 and 100 – 200 m. 10 - 25 % slope class covers major portion followed by 25 - 100 % class. Loam and sandy loam soils cover about 70 % of the watershed. Plantation covers almost 50 % of the watershed with forest and agriculture follows closely.

Table 5: Characteristics of Valiya Thodu Watershed

Stream Order	No. of Streams	Total Length (km)
1	174	84.61
2	85	23.25
3	44	12.45
4	32	10.80
5	6	1.63
		Drainage density 3.226 km^{-1}
Altitudinal Zone (m above msl)	Area (km^2)	% Area
20 – 50	12.42	30.2
50 – 100	13.81	33.5
100 – 200	12.93	31.4
> 200	1.99	4.9
Slope Classes (%)	Area (km^2)	% Area
0 – 1	3.26	8.0
1 – 2	1.99	4.8
2 – 5	3.70	9.0
5 – 10	4.40	10.9
10 – 25	15.69	38.4
25 – 100	11.74	28.7
> 100	0.10	0.2
Land Use Type	Area (km^2)	% Area
Agriculture	7.60	18.5
Fallow	1.38	3.4
Forest	11.55	28.0
Plantation	20.62	50.1
Soil Type	Area (km^2)	% Area
Loam	9.34	22.7
Loam (Forest)	5.66	13.8
Sandy Clay Loam	5.91	14.4
Sandy Loam	5.30	12.9
Sandy Loam (Forest)	9.10	21.9
Silty Loam	5.84	14.3

1.3.3 Kiri Thodu Watershed

Kiri thodu watershed falls in the high land region of the State with altitude ranges from 100 to 700 m above msl. The watershed lies between 9° 21' 10" and 9° 24' 15" N and 76° 55' 55" and 77° 01' 55" E and has a geographical area of 36.55 km^2. Table 6 explains the major characteristics of the watershed.

Table 6: Characteristics of Kiri Thodu Watershed

Stream Order	No. of Streams	Total Length (km)
1	157	77.63
2	79	23.31
3	25	7.93
4	37	9.69
5	4	12.22
		Drainage density 3.578 km^{-1}
Altitudinal Zone (m above msl)	Area (km^2)	% Area
100 – 200	5.94	16.3
200 – 350	13.30	36.4
350 – 500	13.05	35.7
> 500	4.26	11.6
Slope Classes (%)	Area (km^2)	% Area
0 – 1	0.54	1.5
1 – 5	1.21	3.3
5 – 10	0.42	1.2
10 – 25	12.13	33.2
25 – 100	21.30	58.2
> 100	0.95	2.6
Land Use Type	Area (km^2)	% Area
Agriculture	4.27	11.7
Fallow	1.08	3.0
Forest	28.51	78.0
Plantation	2.69	7.3
Soil Type	Area (km^2)	% Area
Loam (Forest)	13.69	37.5
Sandy Loam	5.25	14.4
Sandy Loam (Forest)	17.61	48.1

The watershed is characterised with steep slopes (> 25 %) as major portion of the watershed comes between 200 - 500 m altitudinal zone. This encourages high stream density. The main stream is a 5^{th} order stream and joins Pamba at Angamuzhy just downstream of the gauge site. The main channel length is 4.6 km. Figure 7 shows the Kiri Thodu watershed with its drainage network. The major slope class for the watershed is 25 - 100 % followed by 10 - 25 %. Forest area covers about 80 % of the watershed. Sandy loam soils are predominant in the watershed.

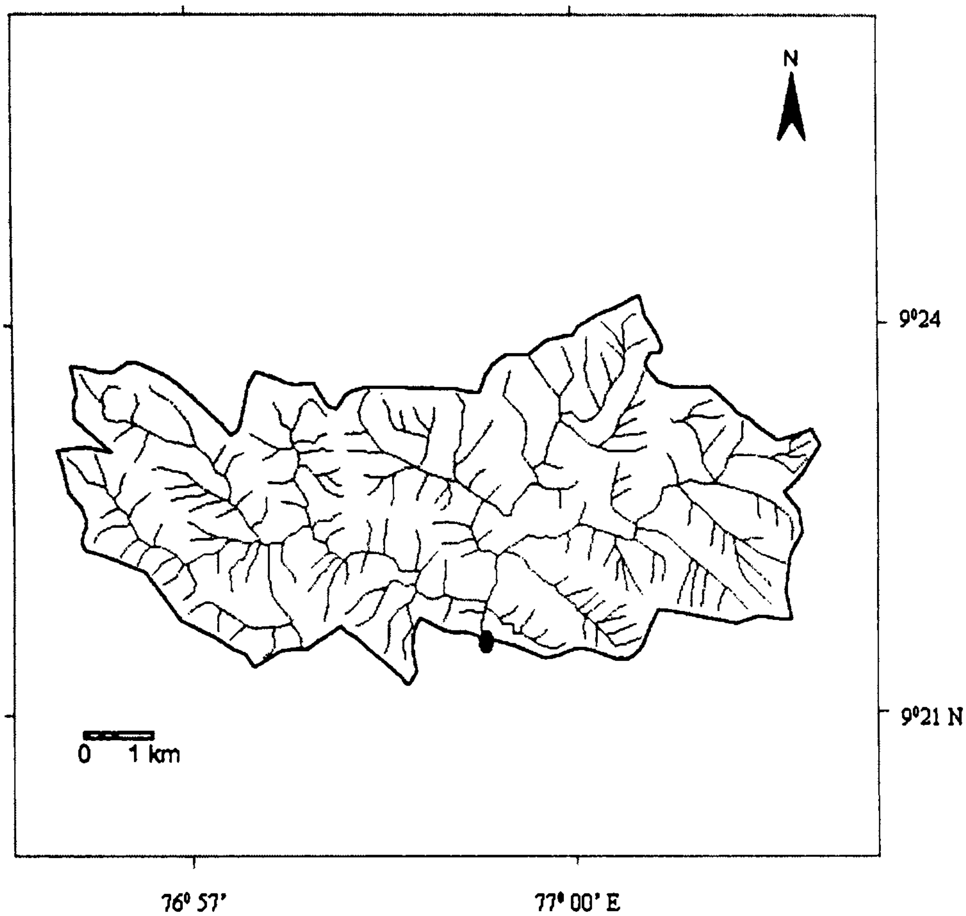


Figure 7: Kiri Thodu Watershed with Stream Network

2.0 METHODOLOGY

2.1 Variation of Sediment Load in the Rivers of Kerala

Discharge data in cumec and suspended sediment data in g/l, pertaining to 16 west flowing rivers are collected from the Central Water Commission (CWC), for 15 years (1986-87 to 2000-01). The sediment concentrations are converted into load by multiplying with the corresponding discharge and by applying (unit) conversion factor. This sediment load data is used to calculate monthly, seasonal and yearly carrying capacities of individual rivers.

There is a marked difference in rainfall pattern, slope, and geology between northern, central and southern Kerala. The effect of these factors on sediment load can be studied by analyzing its temporal variation. To enable this, monthly and seasonal sediment loads are converted into percentages of annual loads.

However, for comparing carrying capacities of individual rivers, sediment load data alone is inadequate. Therefore, the sediment load values are converted into;

- sediment yield, sediment load per unit area (ton/km^2/year)
- average concentration, which is sediment load per unit discharge

These two parameters clearly differentiate the carrying capacities of each of the 16 rivers studied. When these factors are compared on seasonal and annual basis, a definite demarcation of different sediment yielding zones is noticed for the rivers from north to south. Rating curves are drawn for each of these zones, using daily sediment loads and corresponding discharge values.

2.2 Studies Conducted on Pamba River Basin

Daily data for 15 years is used to study the temporal variation of sediment load carried by the river. Usually rating curves prepared on annual basis are not able to predict the sediment loads to desirable accuracy level. Hence the data is bifurcated into monthly and seasonal basis. Data for 8 years are used for the computation of rating curve and the remaining data is used for the verification. Statistical, goodness of fit, analyses are done to test the suitability of rating curves computed on monthly and seasonal basis. The hysteresis effect in the sediment data is also studied.

The percentage of different sediment fractions, namely coarse (diameter > 0.2 mm), medium (0.2 > diameter > 0.075 mm) and fine (diameter < 0.075 mm) are analysed to study the characteristics of the suspended sediment carried by the river.

Pamba river is having three major tributaries, Pamba Ar, Kakkad Ar and Kall Ar. Each of these tributaries has drainage areas with different characteristics and hence *the sediment flux to the main river from each of these will also be different. In order to quantify the sediment flow through these tributaries, monitoring stations are* established. Monitoring is done on regular intervals for three years during 2002-2004. The Pamba river with its major tributaries and monitoring stations is shown schematically in Figure 8.

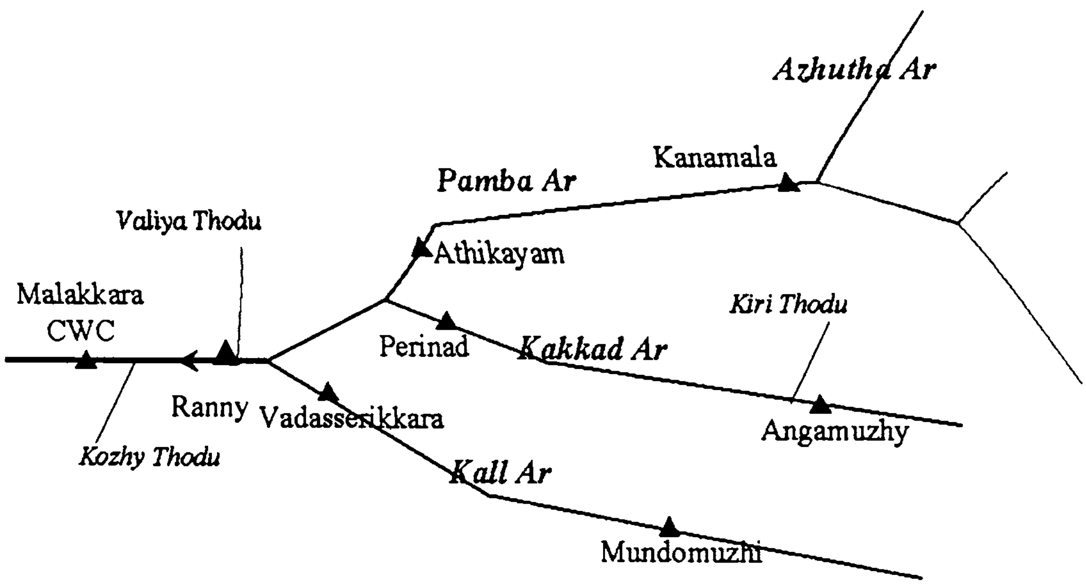


Figure 8: Pamba River System with the Monitoring Stations (▲)

2.3 Integrated Land and Water Information System (ILWIS)

Geographic Information System (GIS) is a computer-based system for collecting, storing, retrieving, analysing, and displaying spatial data. The increasing volume of available environmental information have led to the development in the application of computers to data handling and the creation of subsequent information system, which is capable of transforming these data into usable information.

The data to be entered in a GIS are of two types, spatial and associated non-spatial attribute data. The spatial data represent the geographic location of features, which are input using points, lines, and areas. Non-spatial (attributes) data supplies respective values or descriptions associated with spatial data. Spatial data can be of vector or raster formats. Besides the other applications of GIS, it can be used in Hydrology for (Valenznela, 1990),

- land use planning and management
- natural resources mapping and management
- land information systems
- urban and regional planning

The GIS used in this study is ILWIS (Integrated Land and Water Information System), developed at International Institute of Aerospace Survey and Earth Sciences, Enschede, The Netherlands (ITC, 1997). ILWIS functionality for vectors includes:

- digitizing with mouse/digitizer
- interpolation from iso-lines or points
- calculation of segment or point density
- pattern analysis

ILWIS functionality for raster includes:

- creation of a Digital Elevation Model (DEM)
- calculation of slope/aspect
- deriving attribute maps
- classifying and crossing maps
- manipulating maps with iff-statements

For satellite imagery:

- creation of histograms
- colour composites
- sampling and classification
- filtering
- multi-band statistics

A conversion program imports remote sensing data, tabular data, raster maps, and vector files in other formats. Analog data can be transferred into vector format by means of digitizing program. Complex modeling of features can be executed by the map calculation. It integrates tabular and spatial databases. Tabular and spatial databases can be used independently and on an integrated basis.

GIS is used in this study to automate the estimation of soil loss from the micro-watersheds using the Modified Universal Soil Loss Equation (MUSLE).

2.4 Erosion Modeling for the Micro-Watersheds

Three erosion and sediment yield models are used with varying theoretical background, methodology, data availability, and type of output.

Modified Universal Soil Loss Equation (MUSLE) is an empirical model, which gives average soil loss produced by a rainfall event. The information about runoff energy, soil erodibility, slope length and steepness, and vegetative cover and management practices are expressed as factors. Average soil loss will be obtained by multiplying these factors. In this study, the model is used in a GIS environment.

Unit Sediment Graph (USG) is a conceptual model, which can be used to develop a sediment graph representing temporal variation of sediment concentration. For the derivation of USG, observed data is required on hourly basis for number of rainfall events. Once an average USG is developed, sediment graph can be computed for any rainfall events by a rainfall-discharge-suspended sediment load relationship.

WEPP (Water Erosion Prediction Project) is a physically distributed model, in which the watershed is broken into many hill slopes and channels and the soil movement from hill slopes to channels and through channels to the outlet of the watershed is being simulated.

2.4.1 Modified Universal Soil Loss Equation (MUSLE)

Universal Soil Loss Equation (USLE) is designed to predict the long-term average field soil loss under specified conditions. This model enables the planners to estimate the average rate of soil erosion for each feasible alternative combination of crop system and management practices. The USLE model groups numerous physical and management parameters that influence erosion under six factors, which can be expressed numerically. Interrelation between the variables involved in erosion processes is represented in the flowchart shown in Figure 9.

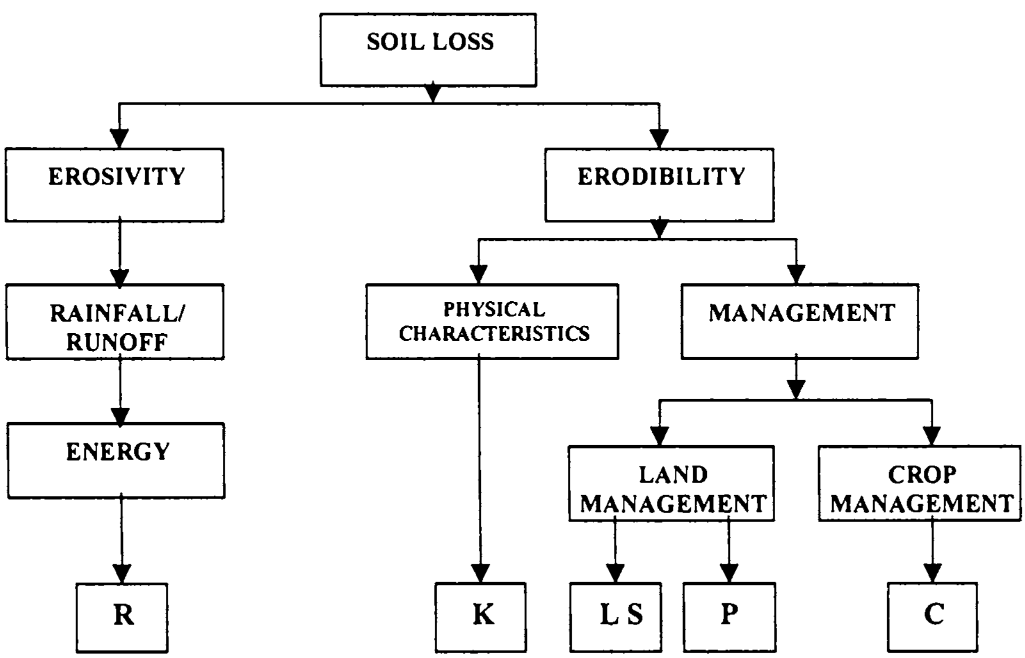


Figure 9: Schematic Representation of USLE Components

The Universal Soil Loss Equation is given by,
Average annual soil loss in tons/ha/ year, A = R*K*L*S*C*P

Rainfall erosivity factor (R): Erosivity factor is determined by both rainfall and the energy imparted to the land surface by the rain drop impact.

Soil erodibility factor (K): K is expressed as soil loss per unit of area for unit plot. USDA (1978) suggested a nomograph for determining soil erodibility, using particle size, organic matter, and permeability class.

Slope length (L) and Steepness (S) factor: Slope length factor is the ratio of soil loss from field slope length to that from 22.13 m length plot under identical conditions. The slope steepness factor is the ratio of soil loss from the field slope gradient to that from 9 % slope under otherwise identical conditions.

Cover and management factor (C): The crop management factor is the expected ratio of soil loss from land cropped under specified conditions to soil loss from clean, tilled fallow or identical soil and slope and under the same rainfall.

Support practice factor (P): The P factor is expressed as a ratio, which compares the soil loss from investigated plot cultivated up and down the slope. P ranges from 1.0 for up and down cultivation to 0.25 for contour strip cropping of gentle slope.

Modified USLE (MUSLE) is an improvement upon USLE (Williams, 1975) whereby the soil loss from an isolated rainfall event can be estimated. In MUSLE the rainfall energy term is replaced by a runoff energy factor. Sediment yield for a rainfall event is given by:

$$T = a\,(VQ_p)^{0.56}\,KLSCP$$

where, T = Sediment yield for a storm event (ton)

a = a constant, 11.8 for SI units

V = Volume of runoff (m^3)

Q_p = Peak runoff rate (cumec)

K, L, S, C, P factors remain the same as that for USLE.

2.4.2 Unit Sediment Graph (USG)

The use of instantaneous sediment measurements is not adequate for modeling of sediment and pollutant dynamics during a storm. A sediment graph associated with a runoff hydrograph provides temporal variation of sediment flow, which can be used for studying suspended sediment dynamics resulting from a rainfall event. Sediment graph is a time history of sediment transport during a storm at a given location.

USG represents one unit of effective sediment yield from a watershed resulting from a rainfall event of unit duration generated uniformly over the basin. The ordinates of a USG are obtained by dividing the corresponding direct sediment graphs ordinates by the total sediment yield under the sediment graph. Once a one-hour USG has been established, the direct sediment graph due to a number of one-hour effective sediment erosion intensities for a watershed can be obtained by applying linear and time-invariant principles.

The methodology proposed by Chen and Kuo (1986) is used here to develop, test and apply USG model to the micro-watersheds. In this methodology, ER is the volume of the direct or effective runoff; ES, the direct or effective sediment yield; ERR, the effective runoff rate; and ESR, the effective sediment yield rate. Then for a specific watershed, there exists a log-transformed linear relationship between ES and ER, $ES = a\ ER^b$, which was found and tested by many researchers. Similar relationship also can be developed between ESR and ERR, $ESR = c\ ERR^d$. The development of USG is illustrated schematically as shown in Figure 10.

ERR corresponds to a variation of the effective rainfall intensity ERI, while ESR responds to the variation of the effective sediment erosion intensity ESEI. In other words, the effective rainfall produces direct runoff and in turn direct runoff produces direct sediment yield. Therefore, it can be postulated conceptually that the effective rainfall intensity generates its counterpart the effective sediment erosion intensity, which through the unit sediment graph, results in sediment graph. ERI and ESEI are the causes, which produce ERR and ESR.

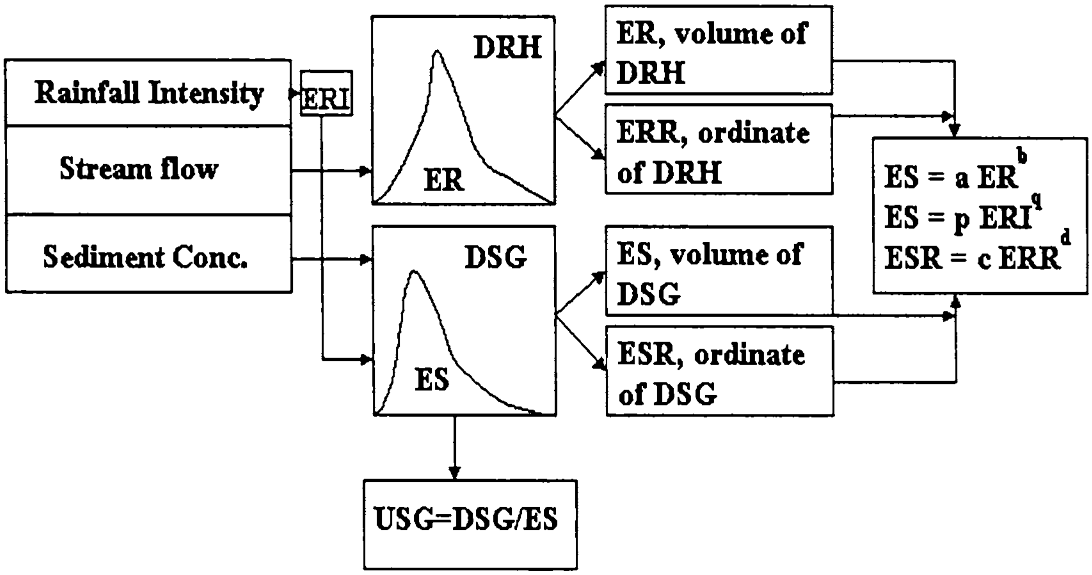


Figure 10: Schematic Representation of Computation of Unit Sediment Graph

ESEI values are not recorded in the field and hence the correlation coefficients between them cannot be evaluated through regression analysis. Therefore, ESEI and ERI can be related using the same coefficients used in ESR-ERR relationship. However, when one-hour USGs are considered, ES values can be used instead of ESEI, since for a rainfall event of one-hour duration, ESEI equals ES. The average one-hour USG and the relationship between ESEI and ERI can be used to obtain the direct sediment graph resulting from a number of one-hour ESEI for a watershed.

2.4.3 Water Erosion Prediction Project (WEPP)

The USDA WEPP model (USDA, 1995) is a distributed, continuous, small watershed erosion model, which simulates the spatial and temporal variability of the erosion processes. In addition to the erosion component, it also includes a weather generation component, hydrology component, daily water balance component, plant growth and residue decomposition component and an irrigation component.

A watershed is defined in WEPP as one or more hill slopes draining into one or more channels and/or impoundment. The smallest possible watershed includes one hill slope and one channel. The schematic representation of a hill slope and watershed for WEPP application is shown in Figure 11.

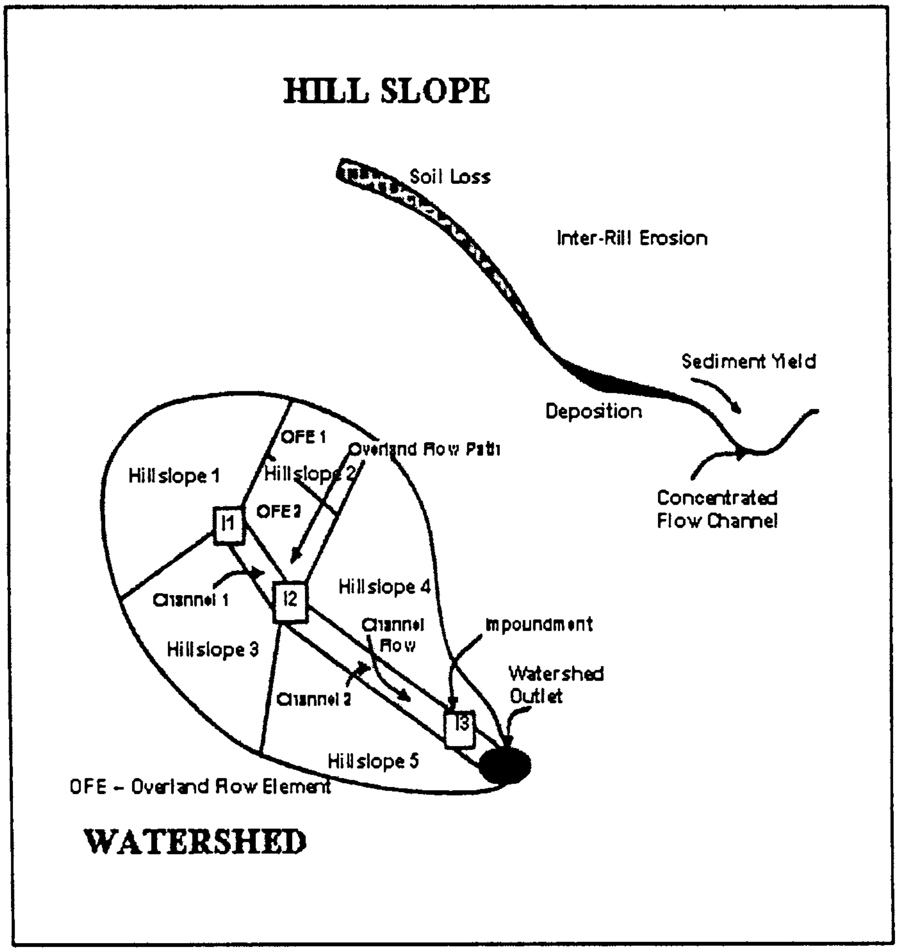


Figure 11: Representation of Hill Slopes and Watershed in WEPP

The model is made up of three major modules; hill slope, channel, and impoundment. The controlling variables, which affect hill slope erosion, are rainfall intensity, rainfall duration, peak flow rate, and flow shear stress. The primary purpose of the hill slope module is to supply the erosion calculations with peak discharge, duration of runoff, and flow shear stress. In watershed applications, the model allows linkage of hill slope profiles to channels and impoundment. The channel erosion and deposition calculations are similar to those of the hill slope. The impoundment module computes deposition and sediment yield from terrace and reservoir impoundment.

The WEPP erosion component uses the steady state spatially varied sediment continuity equation, to describe the movement of sediment in a rill. Based on large number of experiments, prediction equations for hydrologic and erosion parameters of WEPP have been developed and evaluated (Haan et al., 1994). The basic governing equation is,

$$dq_s/dx = D_i + D_r$$

where, D_i and D_r are inter-rill and rill erosion rates (kg/sec.m^2), q_s is sediment load (kg/sec.m^2), and x is the distance downslope (m).

Inter-rill erosion is conceptualised on a process of sediment delivery to rill and considered proportional to the product of rainfall intensity and inter-rill runoff rate. Net soil detachment is related to detachment potential and transport capacity by,

$$D_r = D_{rc}(1 - q_s/T_c)$$

where, D_{rc} is detachment potential (kg/sec.m) and T_c is transport capacity (Kg/sec.m).

Detachment potential is defined by shear excess as,

$$D_{rc} = K_r(\tau - \tau_c)$$

where, K_r is the rill erodibility, τ is the stress acting on the soil particles (pascal) and τ_c is critical tractive force (pascal). When $\tau < \tau_c$, detachment is zero.

Net deposition is given by,

$$D_r = \beta_T \frac{V_s}{q}(q_s - T_c)$$

where, β_T is a parameter defining the impact of turbulence on settling (taken as 0.5 for WEPP). This formulation is the laminar form of overflow rate, but the relationship approaches that of a turbulent form because the slope is discretized into segments.

Concentrated flow erosion tends to develop channels with vertical walls and with an equilibrium width (W_e) that is proportional to flow rate. In WEPP, rectangular shape is assumed with user defined/calculated width. Flow depth is calculated using the Darcy-Weisbach friction factor, rill width, and average slope. With the calculated depth and width, hydraulic radius is determined and shear stress on the soil is calculated from,

$$\tau_e = \gamma S_a R(f_s / f_t)$$

where, τ_e is the shear stress on the soil at the end of an average uniform slope (pascal), γ is the density of water (N/m^3), S_a is the average channel slope, R is the hydraulic radius, f_s is the friction factor for soil, and f_t is total friction factor.

Sediment transport is calculated by,

$$T_c = k_t \tau^{1.5}$$

where, T_c is transport capacity, τ is shear stress on the soil surface, and k_t is a calibration coefficient (Finkner et al, 1989).

Chapter III

RESULTS AND DISCUSSION

1.0 GENERAL SEDIMENT YIELD PATTERN FOR RIVERS OF KERALA

Daily data on suspended sediment concentration (g/l) and corresponding discharge (cumec) for 16 west flowing rivers of Kerala, were collected from Central Water Commission, for fifteen years, from 1986-87 to 2000-01. Average rainfall (mm) for each of these catchments was calculated from the daily data of rain gauge stations located within the river catchments. Length of the main streams, average slope and catchment area were extracted from Survey of India toposheets.

Suspended sediment concentration data, C (g/l) was converted into sediment load, S (ton). Daily discharge (Q) and sediment values were used to calculate the monthly, seasonal and yearly discharge and sediment load values. Table 7 gives the discharge and sediment characteristics of the rivers selected for the study.

Table 7: Discharge and Sediment Characteristics of the Rivers

Name of the River	Average annual rainfall (mm)	River Basin area (km^2)	Average yearly discharge (MCM)	Average annual sediment load (ton)	Sediment yield, (ton/km^2)	Max observed sediment conc. (mg/l)
Payaswini	4000	957	2384	239934	251	1090
Valapatanam	3600	1070	3543	252144	236	613
Chaliyar	3800	1876	4175	401614	214	1024
Kadalundi	3400	750	1303	85171	113	345
Bharathpuzha	2300	5755	4326	369186	64	1163
Pulanthode	2600	940	1756	101771	108	791
Chalakudy	3600	1342	1798	50234	38	167
Periyar	3200	4234	6895	320029	76	739
Muvattupuzha	3100	1208	5068	157001	130	595
Kaliyar	3000	405	1194	44667	110	557
Meenachil	3000	615	1756	36566	60	1091
Manimala	3300	731	1795	70486	96	559
Pamba	3600	1654	4016	156851	92	896
Achankovil	2600	810	1247	77130	95	904
Kallada	2800	1210	1636	104447	86	802
Vamanapuram	2200	540	701	68619	127	2944

1.1 Seasonal and Spatial Variation of Discharge and Sediment Load

Based on the 15 years of available data, it was observed that Periyar River yielded maximum yearly discharge of 9968 MCM (during 1991-92) while Vamanapuram contributed the minimum discharge of 288 MCM (during 1986-87). Chaliyar supplied the maximum sediment load in 1992-93 (0.82 x 10^6 ton) and Meenachil transported the minimum (0.015 x 10^6 tons) in 1990-91.

Seasonal (*) distribution of discharge and sediment load is shown in Table 8. The discharge during monsoon season was in the range of 92-98 %, except for Periyar, Muvattupuzha, Pamba, Kallada and Vamanapram. In the case of sediment load, about 92-99 % of the annual load was transported during monsoon season. Similar observations were made for other Indian rivers (Goswami, 1985; Biksham and Subramanian, 1988; Ramesh and Subramanian, 1988; Vaithiyanathan et al., 1992).

Table 8: Seasonal Variation of % Q and % S for the Rivers

Name of the River	% Discharge (Q)				% Sediment Load (S)			
	Monsoon			Non-monsoon	Monsoon			Non-monsoon
	SW	NE	Total		SW	NE	Total	
Payaswini	83.5	13.5	97.0	3.0	90.0	9.5	99.5	0.5
Valapatanam	86.2	11.3	97.5	2.5	94.0	5.3	99.3	0.7
Chaliyar	79.6	15.8	95.4	4.6	87.0	11.9	98.9	1.1
Kadalundi	77.3	20.0	97.3	2.7	79.0	19.6	98.6	1.4
Bharthapuza	74.5	19.7	94.2	5.8	79.9	18.1	98.0	2.0
Pulamthode	72.6	21.8	94.4	5.6	73.8	24.3	98.1	1.9
Chalakudy	75.7	16.8	92.5	7.5	84.2	14.1	98.3	1.7
Periyar	67.9	18.2	86.1	13.9	89.8	8.3	98.1	1.9
Muvattupuzha	56.9	19.2	76.1	23.9	65.9	25.4	91.3	8.7
Kaliyar	77.1	18.9	96.0	4.0	75.7	22.6	98.3	1.7
Meenachil	69.7	22.8	92.5	7.5	71.8	23.7	95.5	4.5
Manimala	69.4	23.6	93.0	7.0	68.1	27.4	95.5	4.5
Pamba	65.5	23.3	88.8	11.2	54.9	40.3	95.2	4.8
Achankovil	62.3	29.7	92.0	8.0	53.9	41.7	95.6	4.4
Kallada	50.7	32.4	83.1	16.9	39.8	53.8	93.6	6.4
Vamnapuram	50.3	35.2	85.5	14.5	41.4	51.4	92.8	7.2

* Seasons as per the Indian Meteorological Department (IMD) norms
M - Monsoon (June to Nov.) NE - Northeast Monsoon (Oct. and Nov.)
NM- Non-Monsoon (Dec. to May) W - Winter (Dec. to Feb.)
SW - Southwest Monsoon (June to Sept.) S - Summer (March to May)

Southwest (SW) monsoon was the major source of discharge for northern rivers, about 84 % in the north and it decreased to 50 % in the south. On the other hand, northeast (NE) monsoon yielded about 13 % for northern rivers and 35 % for southern rivers. During non-monsoon (NM) season, central and southern rivers carried 17 % of discharge. Muvattupuzha yields 24 % discharge in non-monsoon, which includes diverted water from Idukki hydel project in the Periyar river.

Sediment load in SW monsoon ranged from 74-94 % for northern rivers and was about 41-75 % for southern rivers. During NE monsoon season, northern rivers yielded 5-24 % of the annual sediment load whereas the southern rivers transported 22-54 %. Sediment load during non-monsoon season was nominal for northern rivers. It was noted that variation in seasonal distribution of discharge and sediment load follows a definite regional pattern, while considering the rivers from north to south. This grouping is shown in table 8 and discussed in the following paragraphs.

The seasonal variation of discharge and sediment load can be represented graphically as shown in Figure 12. A definite grouping of data, into four regions, can be observed from the graph. This grouping is clearly noticeable for SW and NE monsoon seasons. Figure 12 clearly shows the demarcation of State into four distinct sediment yielding zones, viz., north zone (NZ), north central zone (NCZ), south central zone (SCZ) and south zone (SZ).

1.1.1 Sediment Yield (S_Y)

Average sediment yield values (ton/km^2) are given in table 7. Northern rivers are having comparatively large values (210-250), followed by southern rivers (90-130). Rivers in Central Kerala show unstable erosion rates (40 to 130). Many of the major rivers of the State drain central region and the region is tectonically stable (Anderson et al., 2005). Similar conclusion was drawn on tropical Kenyan catchments by Dunne (1979). River diversion works and control structures in some of these rivers also result in low sediment yield. The upstream reaches of these rivers are covered by fairly thick forest, which may be another reason for the low sediment yield.

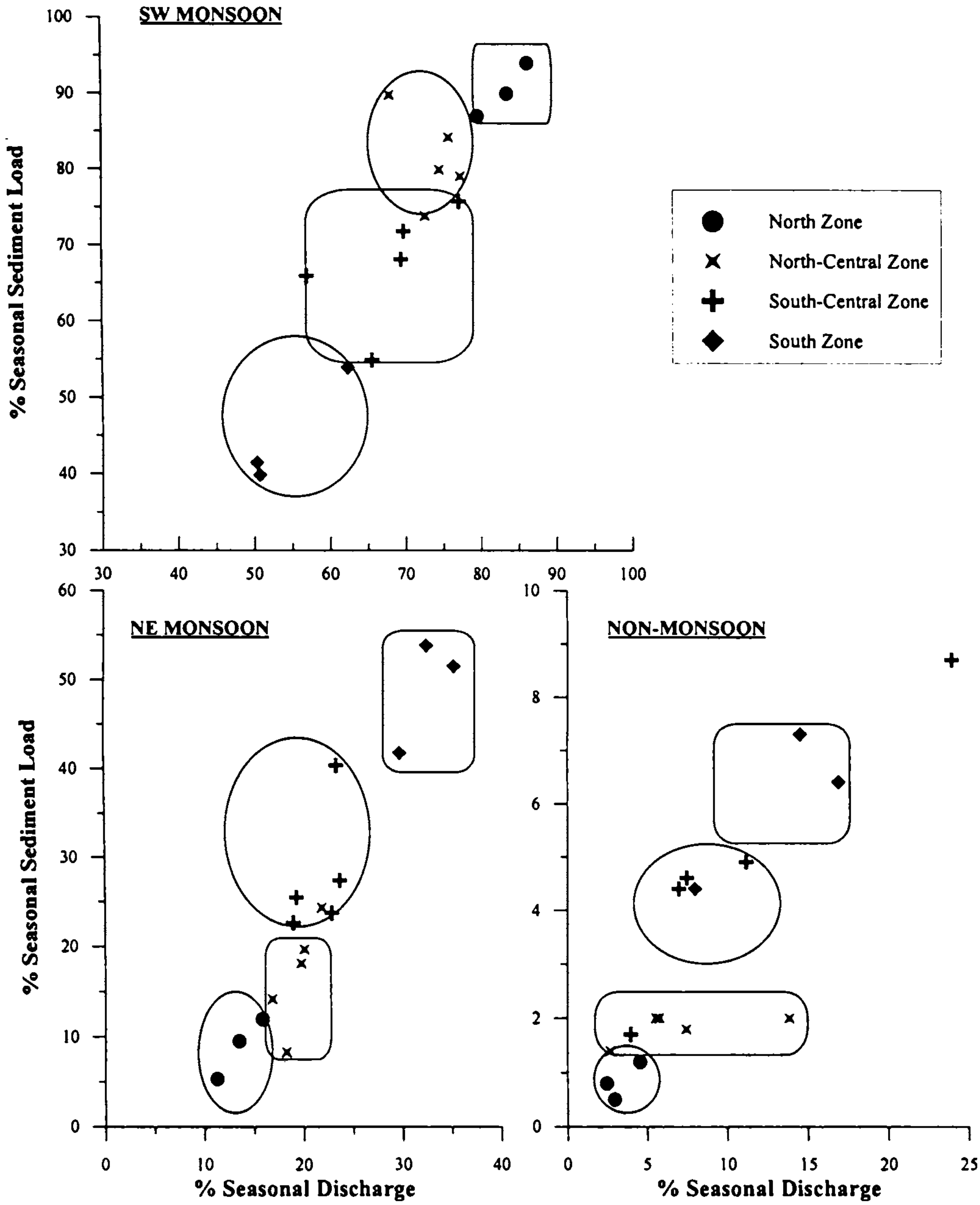


Figure 12: Seasonal % Q Vs % S Relationship Showing the Demarcation of Different Zones

1.1.2 Annual Variation in Sediment Load

Chaliyar River transported the highest average annual sediment load of 0.40 x 10^6 ton, whereas Meenachil River supplied the lowest, 0.04 x 10^6 ton. For most of the rivers from central and southern regions, sediment load showed a decreasing trend with corresponding increase in discharge. Reason for this may be the presence of numerous dams and diversion structures within these rivers. Only northern rivers Valapatanam, Chaliyar, Bharathapuzha and Chalakudy showed increasing trend in sediment load.

Annual variation of sediment load in a river depends on the rainfall and discharge, as other factors such as catchment characteristics remain the same. The minimum and maximum values of discharge and sediment load observed during the 15 years of study period is given in table 9. Maximum variation in the load was observed for Kallada River basin and variation was minimum for Muvattupuzha and its tributary Kaliyar. The variation in discharge was almost constant for all the rivers except for the southernmost rivers Kallada and Vamanapuram. This shows the extreme inter-annular variability in sediment transport prevailing in these river basins.

Table 9: Variation of Discharge, Q (MCM) and Sediment Load, S (ton)

Name of the River	Max Q	Min Q	Max/Min	Max S	Min S	Max/Min
Payaswini	3301	1543	2.2	404286	119574	3.4
Valapatanam	4742	1904	2.5	470511	67935	6.9
Chaliyar	6060	2158	2.8	814941	156087	5.2
Kadalundi	1950	806	2.4	152549	44032	3.5
Bharathapuzha	6785	2645	2.6	769037	154816	5.0
Pulanthode	2470	1046	2.4	194727	42833	4.6
Chalakudy	2765	1115	2.5	130120	15408	8.5
Periyar	9968	4867	2.1	646802	87188	7.4
Muvattupuzha	6703	3894	1.7	230057	88270	2.6
Kaliyar	1578	945	1.7	72632	29260	2.5
Meenachil	2311	1334	1.7	61756	14041	4.4
Manimala	2398	1282	1.9	108041	34442	3.2
Pamba	5397	3117	1.7	501562	65770	7.6
Achankovil	1912	747	2.6	182022	17724	10.3
Kallada	2839	902	3.2	564145	39037	14.5
Vamanapuram	1134	288	3.9	278977	21606	12.9

1.1.3 Monthly Variation in Sediment Load

Analyses of data of individual rivers indicated that the monsoon months (July, August, October, and November) are responsible for most of the annual sediment transported. Due to the spatial variation in monsoon rainfall, monthly distribution of sediment load varies between north and south regions. For northern rivers, July contributed about 40-50 % of sediment load. Southern rivers showed two peaks with July accounted for 20-30 % sediment load whereas October/November month contributed 20-40 % of annual load. Monthly variation of rainfall, discharge, and sediment load for rivers from different regions of the State is shown in Figure 13. It can be seen that the discharge and sediment flow pattern closely follow the monthly rainfall distribution. Northen rivers showed a uni-mode distribution whereas south-central and southern rivers developed a bi-mode distribution. The dominance of NE monsoon rainfall on sediment transport over the southern region can be seen from the high percentage sediment load for these rivers.

1.1.4 Daily Variation in Sediment Load

Analysis of sediment data for individual rivers indicated that a very few days during the monsoon season accounted for the bulk of sediment load. The highest sediment concentration recorded on a day was 2944 mg/l, on 14th November 1992, for the river Vamanapuram, which accounted for 64 % of annual sediment load. Chalakudy registered the lowest maximum daily sediment concentration of 167 mg/l on 10th July 1989.

- Valapatanam River supplied 48 % of annual sediment load on 23rd July 1989
- For Pamba, two days in October 1992, accounted for 43 % of its annual load.
- Four days in July 1989 accounted for 51 % of annual load in Periyar.
- Meenachil River transported 49 % of annual load in three days of July 1991.
- Four days in July 1989 accounted for 43 % of annual load in Chaliyar.
- Vamanapuram supplied 39 % of its annual load on 8th August 1986.
- Achankoil supplied 43 % of its annual load during 4 days in August 1986.
- On November 15th, 1992, Kallada transported 30 % of its annual load.

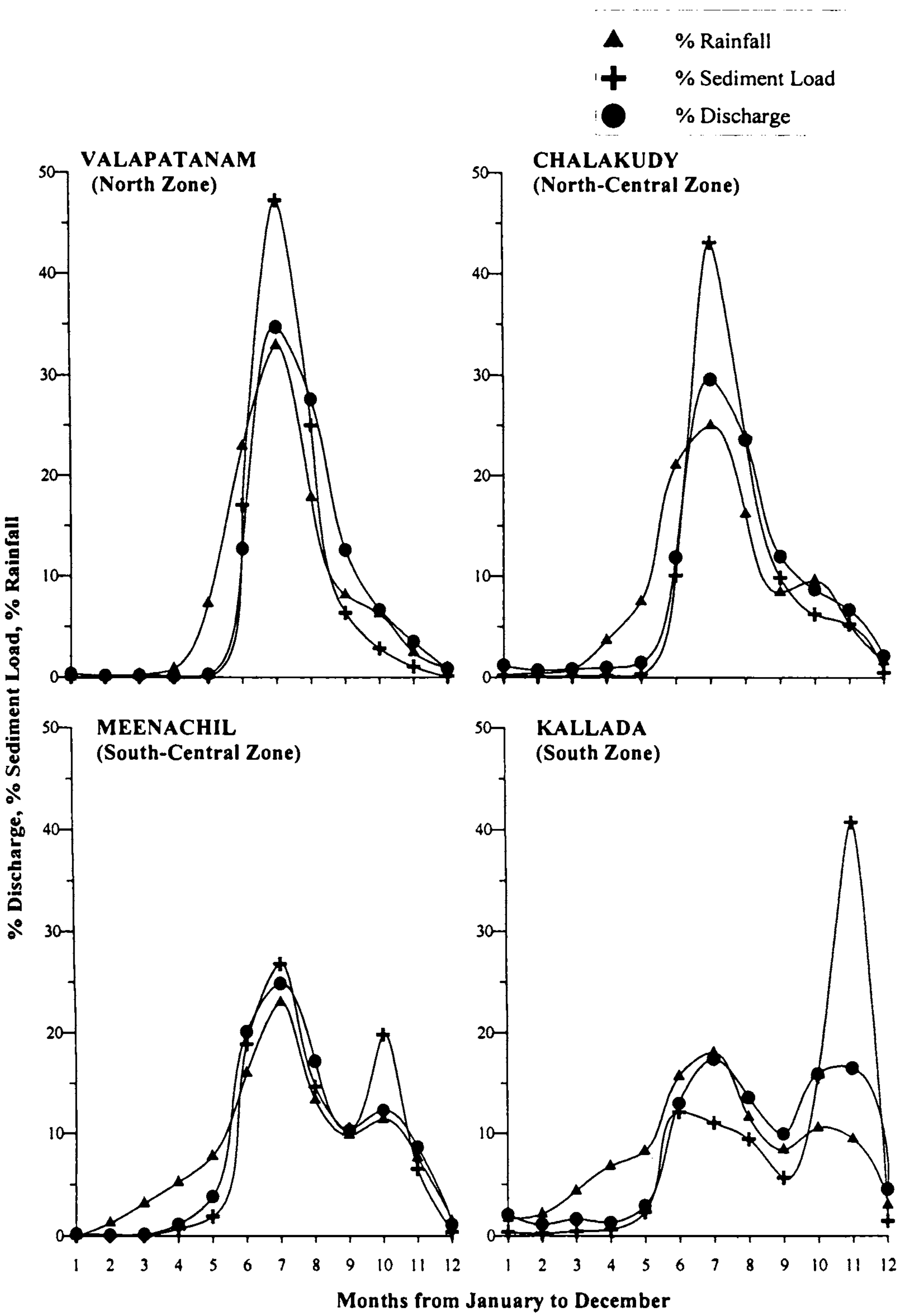


Figure 13: Monthly Distribution of (%) Rainfall, Discharge and Sediment Load for River Basins from Different Zones

1.1.5 Particle Size

Suspended sediment particles are divided into three size groups by CWC, coarse (diameter > 0.2 mm), medium (diameter, between 0.2 mm and 0.075 mm) and fine (diameter < 0.075 mm). For all the rivers, sediment particle size varied seasonally, annually as well as from river to river. Due to the gentle slope and decreased flow velocity at the downstream reaches, there was total dominance of finer particles at the gauging stations. Fine particle fraction was of the range 65 – 79 % for northern rivers, 78 – 93 % for central rivers and about 88 % for southern rivers. The northern rivers, Payaswini, Valapatanam, and Chaliyar, transported large fraction of coarse particles during SW monsoon season.

1.2 Comparison of Sediment Yield Characteristics of the Rivers

Analysis of seasonal and annual sediment load may not yield any inference on the comparative yield characteristics of the rivers. The sediment load in a river depends mainly on the size of catchment from where it originates and on the discharge, which carries it. Hence, two factors were utilized here to compare the sediment yield pattern among individual rivers. Those factors were, ratio of sediment load to discharge (S/Q), which is a measure of the concentration; and ratio of sediment load to catchment area (S/A), which is known as sediment yield or erosion rate.

While analyzing seasonal sediment data for the rivers, it is noticed that there is a marked change in the pattern (seasonal as well as annual) in their carrying capacities from north to south, as already discussed. This differentiation was once again verified with the above indices. Studies to delineate broad regions with similar erosional patterns were carried out earlier by Griffiths (1982) for North Island basins, New Zealand and Lajczak and Jansson (1993) for Baltic drainage basins.

1.2.1 Sediment Load - Discharge Ratio (S/Q)

The annual and seasonal ratios (S in ton and Q in cumec) for the individual rivers are given in Table 10. The ratio is large for the northern rivers, showed a declining trend towards central rivers and again increased towards south. This denotes high erodibility of the northern and southern zones and indicates the availability of material for transport rather than the stream conditions. Slope of the terrain also is a factor, which is more for northern and southern Kerala where the land width becomes narrow. The specific sediment yielding regions, as shown in Figure 12 and 13, is applicable here also.

When season-wise yield was considered, the trend was similar for monsoon season. The ratio during SW monsoon is more for northern rivers while it is higher during NE monsoon for southern rivers. The ratio is almost equal during both the seasons for the central zone. During non-monsoon season, the ratio is almost constant except for the southern most rivers, where the summer rains are of appreciable quantity.

Table 10: Variation of the S/Q and S/A Ratios for the Rivers

Name of the River	Sediment Load/ Discharge (S/Q)					Sediment Load/ Catchment Area (S/A)				
	Year	M	NM	SW	NE	Year	M	NM	SW	NE
Payaswini	8.7	8.9	1.3	9.4	6.2	250.7	249.6	1.2	225.7	23.9
Valapatanam	6.2	6.3	1.9	6.7	2.9	235.7	233.8	1.8	221.4	12.4
Chaliyar	8.3	8.6	2.1	9.1	6.3	214.1	211.6	2.5	186.2	25.4
Kadalundi	5.7	5.7	3.0	5.8	5.5	113.6	112.0	1.6	89.7	22.3
Bharatapuzha	7.4	7.7	2.5	7.9	6.8	64.2	62.9	1.3	51.3	11.6
Pulanthode	5.0	5.2	1.7	5.1	5.6	108.3	106.2	2.1	79.9	26.3
Chalakudy	2.4	2.6	0.6	2.7	2.0	37.4	36.8	0.7	31.5	5.3
Periyar	4.0	4.6	0.6	5.3	1.8	75.6	74.1	1.5	67.9	6.2
Muvattupuzha	2.7	3.2	1.0	3.1	3.6	130.0	118.6	11.4	85.7	33.0
Kaliyar	3.2	3.3	1.4	3.2	3.9	110.3	108.4	1.9	83.5	25.0
Meenachil	1.8	1.9	1.1	1.9	1.9	59.5	56.8	2.7	42.7	14.1
Manimala	3.4	3.5	2.2	3.3	4.0	96.4	92.1	4.3	65.7	26.5
Pamba	3.4	3.6	1.5	2.8	5.8	91.6	87.1	4.5	50.3	36.9
Achankovil	5.4	5.6	3.0	4.6	7.5	95.2	91.0	4.2	51.3	39.7
Kallada	5.5	6.2	2.1	4.3	9.2	86.3	80.8	5.6	34.4	46.4
Vamnapuram	8.5	9.2	4.2	7.0	12.4	127.1	117.9	9.2	52.6	65.3

1.2.2 Sediment Load – Catchment Area Ratio (S/A)

From Table 10, it can be seen that the sediment yield is maximum for northern rivers. The rivers in the central and southern zones showed highly unstable values, with a reducing trend towards central parts of the State and increasing towards southern zone. This factor also denotes the high erosion rates for the northern rivers, low rates for southern rivers and least for the central rivers. The effect of seasonal rainfall on the sediment yield can also be seen from the table.

The differentiation between the four sediment-yielding zones is noticeable in this case also. However, demarcation between south-central and north-central zones is not well defined as in the other cases. The reason for these unstable values might be:

- comparatively larger rivers drain this region
- inter-basin water transfer exists between Periyar and Muvattupuzha
- extreme discharge and sediment load events noticed for these rivers from the data set, which affected the (S/A) ratio

1.2.3 Regional Classification

Based on the analysis of annual and seasonal water and sediment flow as explained above, the Kerala State can be divided into four zones with similar sediment transport characteristics; north zone, north-central zone, south-central zone, and south zone. This difference in transport characteristics among the zones was mainly attributed to the spatial variation of rainfall, slope along the course of rivers, and physiography of the river basins.

The demarcation of the four sediment yielding zones is shown in Figure 14. The average (%) seasonal discharge, (%) sediment load and sediment yield (S_y), for these four zones, are shown in Figure 15. The sediment yield for the northern rivers goes up to 230 ton/km^2, whereas for the rest of the state this ranges from 80 to 100 ton/km^2. However, the differentiation in the distribution of sediment load and to some extent the discharge, from the northern to southern region, during the two monsoon seasons is obvious as can be noticed from Figure 15 (i) and (ii).

1.3 Factors Influencing the Variability in Sediment Load

1.3.1 Rainfall

It can be seen from the above discussion that the rainfall is the major factor controlling the sediment load patterns of the rivers studied. The major reason for the differences in sediment yielding pattern across the State results from the seasonal and regional distribution of rainfall. The discharge and sediment load peaked during July/August for northern rivers, and with 2 peaks during July/August and October/November for south-central and southern rivers, as shown in Figure 13.

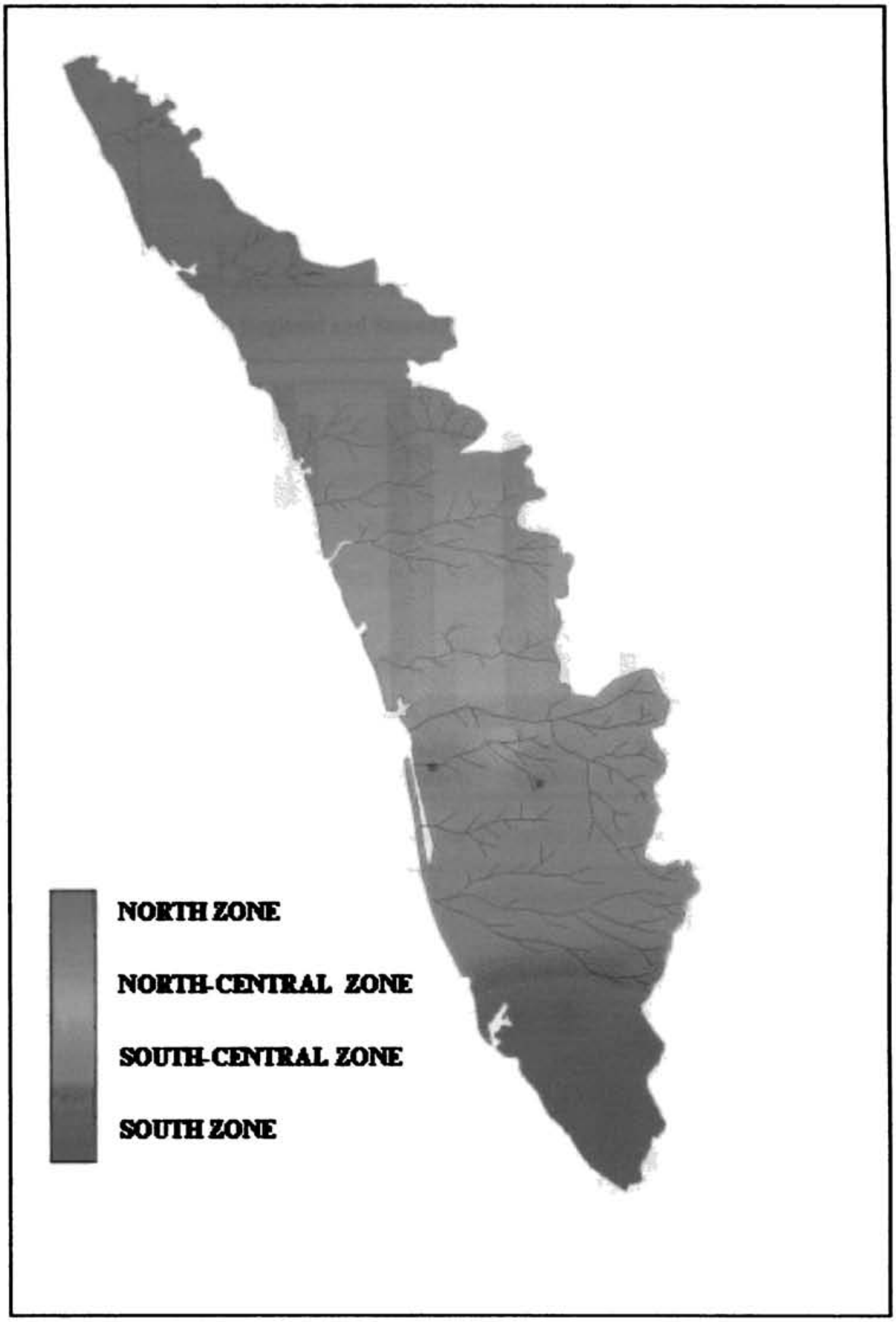
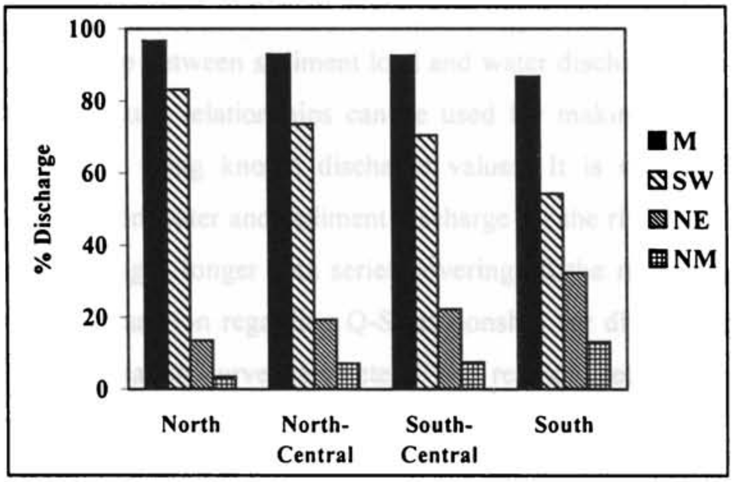
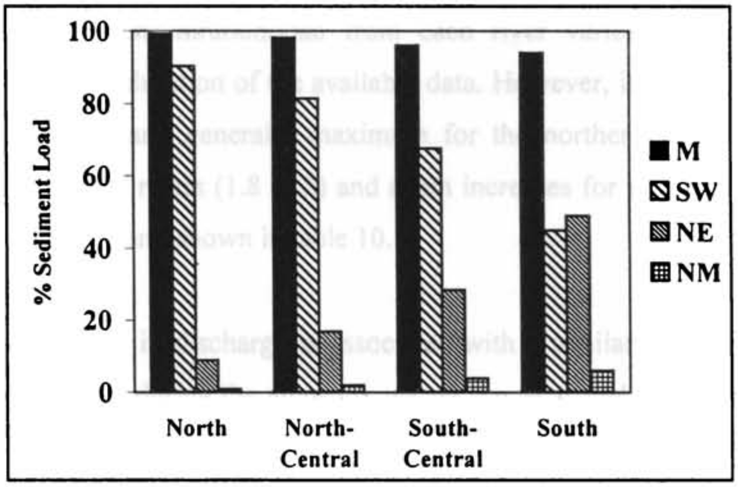


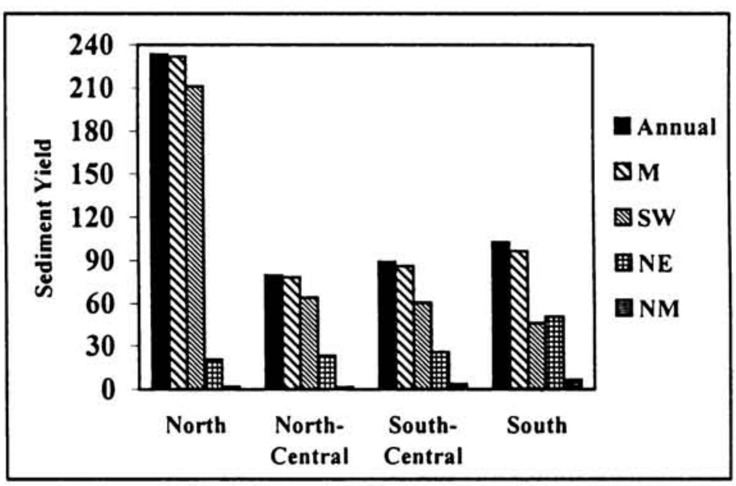
Figure 14: Sediment Yielding Zones of Kerala



(i) Regional and Seasonal Variation in Discharge



(ii) Regional and Seasonal Variation in Sediment Load



(iii) Regional and Seasonal Variation in Sediment Yield (S_y)

Figure 15: Regional and Seasonal Distribution of % Q, % S and S_y from North to South

1.3.2 Discharge

Establishing a relationship between sediment load and water discharge in a river basin is always desirable, since such relationships can be used for making an initial estimates about the sediment flux using known discharge values. It is observed that a good correlation existed between water and sediment discharge for the rivers. This relationship improved by incorporating a longer data series covering all the ranges of hydrological conditions. Detailed explanation regarding Q-S relationship for different rivers is given in the discussion about rating curve parameters. The relation between average annual sediment load and discharge by considering all the rivers is;

$$\text{Sediment Load, } S = 7.05\, Q^{0.96} \qquad (R^2 = 0.62)$$

The annual sediment concentration/load from each river varies with corresponding discharge over the entire duration of the available data. However, it is found that the S/Q fraction is not constant and generally maximum for the northern rivers (5.7 to 8.7), decreases towards central rivers (1.8 to 5) and again increases for southern rivers (3.4 to 8.5) as already discussed and shown in table 10.

The inter-annular change in discharge is associated with a similar increase in sediment load. When monthly data during the monsoon period was analysed, generally an increase in discharge by a factor 4 or 5 resulted in an increase in sediment load by a factor 5 to 50. This indicated that sediment load is not entirely dependent on the discharge but also on the availability of material to transport.

1.3.3 Geology

The geology is one of the important factors, which control the amount and texture of sediment transported by a river. However, in the present case, geological distribution, from upstream to downstream, for most of the rivers is similar. The upstream reaches of these rivers are covered by crystalline rocks, with low sediment yield, and the midlands are by sedimentary rocks, with high erodibility. Hence, geology may not be a major factor for the variability in sediment load from individual rivers. However, the central Kerala region is considered to be tectonically stable (Anderson, 2005), and therefore the sediment yields are low from this region. Detailed monitoring of smaller tributaries is required to estimate the contribution of each of these geological formations.

1.3.4 Soil and Land Use

Lateritic, sandy/silty loams and forest loams cover the major soil types for the river basins upstream of the monitoring stations. Forest loams and loamy soils under rubber plantations are less prone to erosion due to roots, litter and undergrowths.

Slopes of the Western Ghats in the central Kerala is covered by fairly dense forest (Periyar reserve forest). This region resists soil erosion and this causes low sediment yield rates. However, encroachment along the river banks and agricultural activities encourages erosion and subsequent sediment transport.

In forested regions, landslide and soil creep appears to be the significant mechanism that contributes sediment to stream channels. This encourages high sediment flow during heavy rainfall days and is noticed in the case of the rivers studied. Other factors are road construction and plantation and deforestation activities.

1.3.5 Physiography

Kerala State is having maximum width at the center (130 km) and narrows towards northern and southern regions (about 30 km). Northern and southern regions are characterized by steep slopes, with northern slopes extends almost upto the coast. These features are also attributed to the high sedimentation rate for these two zones.

Using the data of 16 rivers, sediment yield, annual average sediment load and discharge were correlated to catchment area as shown below:

$$\text{Sediment Yield, } S_y = 304.3\, A^{-0.15} \qquad (R^2 = 0.044)$$

$$\text{Sediment Load, } S = 304.3\, A^{0.85} \qquad (R^2 = 0.59)$$

$$\text{Discharge, } Q = 167.1\, A^{0.72} \qquad (R^2 = 0.63)$$

This demonstrated that catchment area is having an important control on discharge and sediment transport. Several of the small river basins are being eroded more intensively than the bigger catchments. These eroded materials will be deposited when it reaches the larger order streams and on flood plains.

1.4 Rating Curve Parameters

Using monthly values of sediment load and discharge, rating curves were developed for SW monsoon, NE monsoon, Summer, and Winter. The rating coefficients are as shown in the table 11. The coefficient 'a' denotes the erosion severity and 'b' the erosion power of the river. The steepness of rating curve is a measure of erodibility. Steep rating curve is characterized with low 'a' value and high 'b' value, and results from low sediment transport. On the other hand, flat curves represent a river, which carries enough sediment material at all discharges.

Table 11: Rating Curve Parameters 'a' and 'b' Using Monthly Data

Name of the River	a				b			
	Annual	SW	NE	NM	Annual	SW	NE	NM
Payaswini	0.39	0.055	$4.0*10^{-4}$	1.18	1.33	1.58	2.26	1.01
Valapatanam	0.39	0.008	0.06	1.32	1.26	1.73	1.46	0.94
Chaliyar	0.29	0.08	0.057	1.21	1.36	1.51	1.57	1.05
Kadalundi	0.62	0.18	0.064	4.24	1.26	1.42	1.61	0.91
Bharatpuza	0.19	0.29	0.009	0.32	1.38	1.35	1.76	1.26
Pulanthode	0.085	0.14	$5.5*10^{-4}$	0.11	1.49	1.43	2.18	1.32
Chalakudy	0.02	0.014	0.02	0.16	1.59	1.61	1.59	1.29
Periyar	$1*10^{-3}$	$1.6*10^{-4}$	0.032	1.87	1.84	2.07	1.45	1.01
Muvattupuzha	$9*10^{-4}$	0.017	$8*10^{-5}$	0.11	1.91	1.57	2.22	1.34
Kaliyar	0.18	0.065	0.04	0.41	1.37	1.50	1.63	1.16
Meenachil	0.015	$1.9*10^{-4}$	0.011	0.04	1.58	2.09	1.69	1.46
Manimala	0.14	0.002	0.009	0.39	1.37	1.87	1.77	1.08
Pamba	0.015	0.005	$9.6*10^{-5}$	0.10	1.59	1.71	2.24	1.41
Achankovil	0.22	0.077	0.11	0.24	1.40	1.51	1.55	1.39
Kallada	0.19	0.27	0.006	0.31	1.39	1.34	1.86	1.26
Vamanapuram	0.28	0.016	0.022	1.25	1.41	1.82	1.80	1.09

From table 11, it can be seen that coefficient 'a' values for north zone and south zone rivers are higher than that of central rivers, which is a measure of erosion severity. Coefficient 'b' is slightly larger for the central rivers. Therefore, the central rivers produce steeper rating curves, which indicate that these rivers transports little sediment at low discharges. For the northern and southern rivers, a high 'a' values and low 'b' values results in a flat rating curve, which indicates that the river reaches are with intensively weathered material or loose sedimentary deposits, which can be easily transported at almost all discharges.

Composite rating curves were developed for each of the four zones, which are represented by the following power functions and shown in Figure 16.

For North Zone	$S = 0.35\ Q^{1.31}$	$R^2 = 0.96$
For North-Central Zone	$S = 0.16\ Q^{1.34}$	$R^2 = 0.89$
For South-Central Zone	$S = 0.08\ Q^{1.39}$	$R^2 = 0.91$
For South Zone	$S = 0.25\ Q^{1.38}$	$R^2 = 0.90$

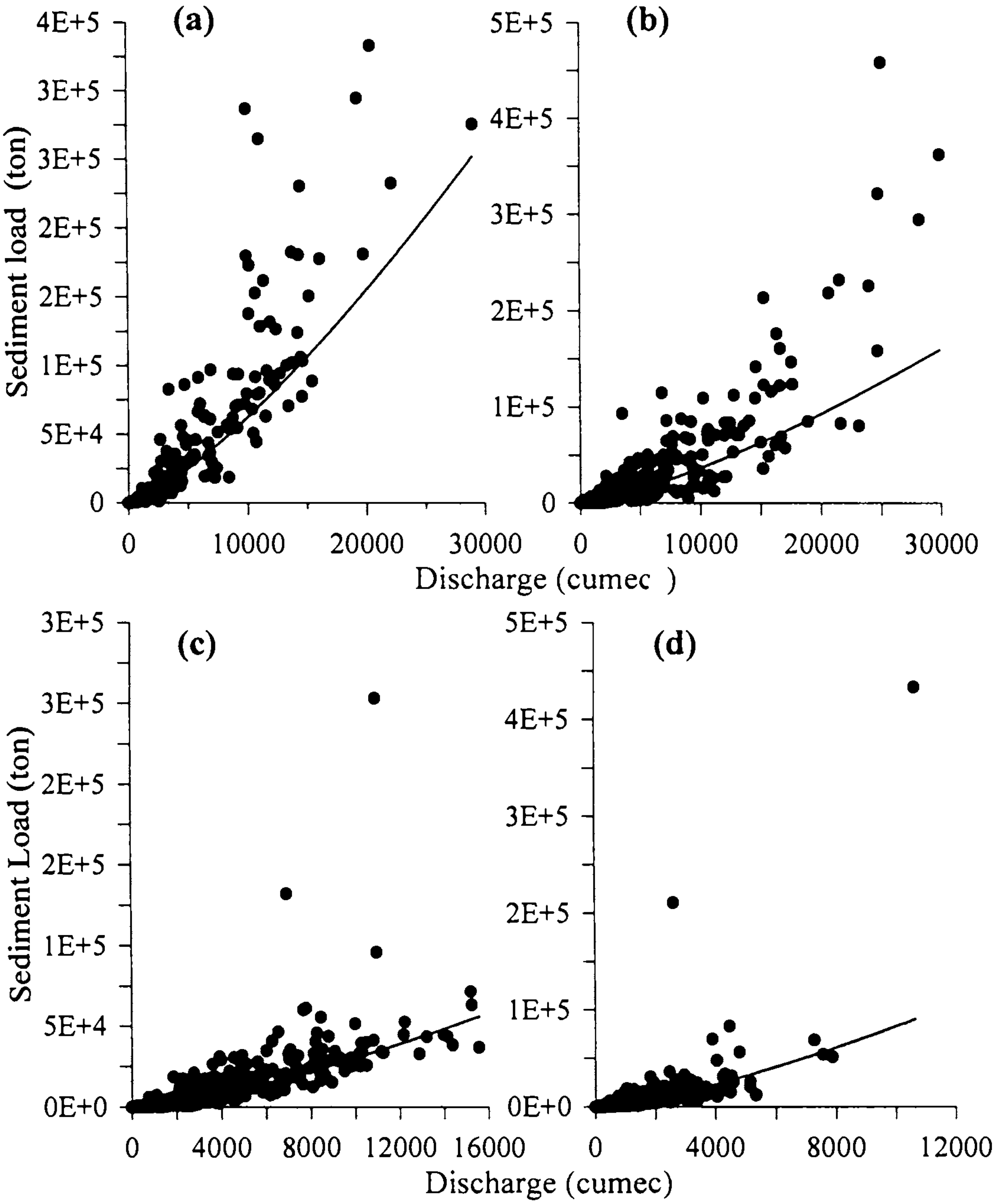


Figure 16: Rating Curves for Different Zones of Kerala State
(a) North Zone (b) North-Central Zone (c) South-Central Zone (d) South Zone

2.0 SEDIMENT CHARACTERISTICS OF PAMBA RIVER BASIN

Pamba River was selected as the representative basin for detailed studies since northern and southern rivers are highly skewed in its sediment load distribution due to the influence of SW and NE monsoons. Proximity, convenience and availability of facilities for extensive field monitoring were also some of the deciding factors.

Daily data for fifteen years were used for studying the characteristics of Pamba River basin. Rating curves were developed on annual, seasonal and monthly basis and tested their applicability. Monitoring stations were maintained on each of the three major tributaries of the river and periodical measurements were done at these stations. Three micro-watersheds were selected and monitored for rainfall, runoff and sediment concentration, and three models were applied for testing the accuracy.

2.1 Sediment Yield and Discharge Characteristics

Analyses of daily discharge and sediment data showed that there is a large variation in these values from year to year. During the study period, Pamba discharged a minimum flow of 3116 MCM in 1986-87 to a maximum of 5397 MCM in 1992-93. Minimum sediment load transported by the river is 65770 tons in 1990-91 and maximum load of 501562 tons 1992-93. Yearly variation in Q and S is shown in Figure 17.

About 92 % of the average annual discharge was transported during June-December. In the case of sediment transport, the river discharged 95 % of it average annual sediment load within a period of 6 months, from June to November.

Average monthly variation is as shown in Figure 18. July supplied the maximum discharge whereas October transported the maximum sediment load. The highest discharge and sediment load were transported in the year 1992-93. On 10th October 1992, the river transported maximum suspended sediment discharge, 896 mg/l, which accounted for about 35 % of annual load.

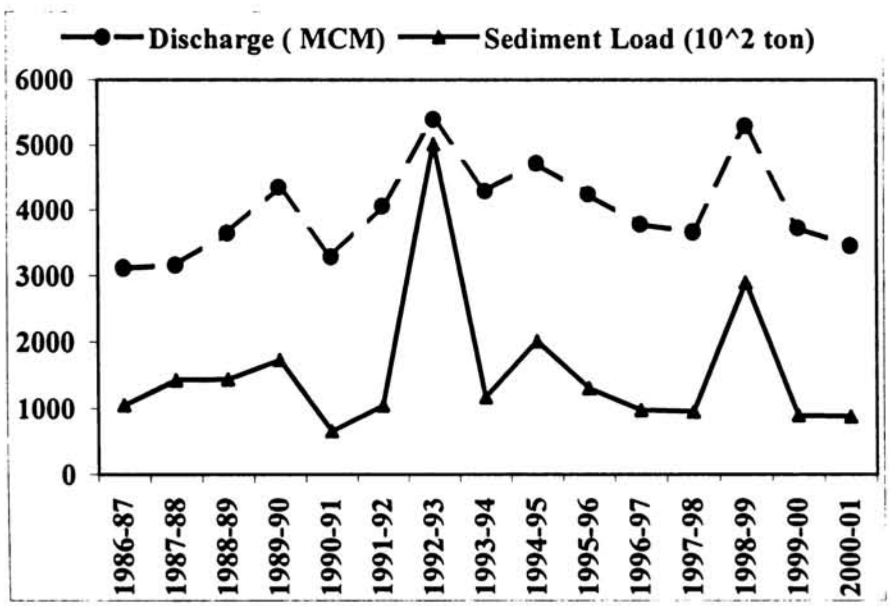


Figure 17: Annual Variation in Discharge and Sediment Load for Pamba

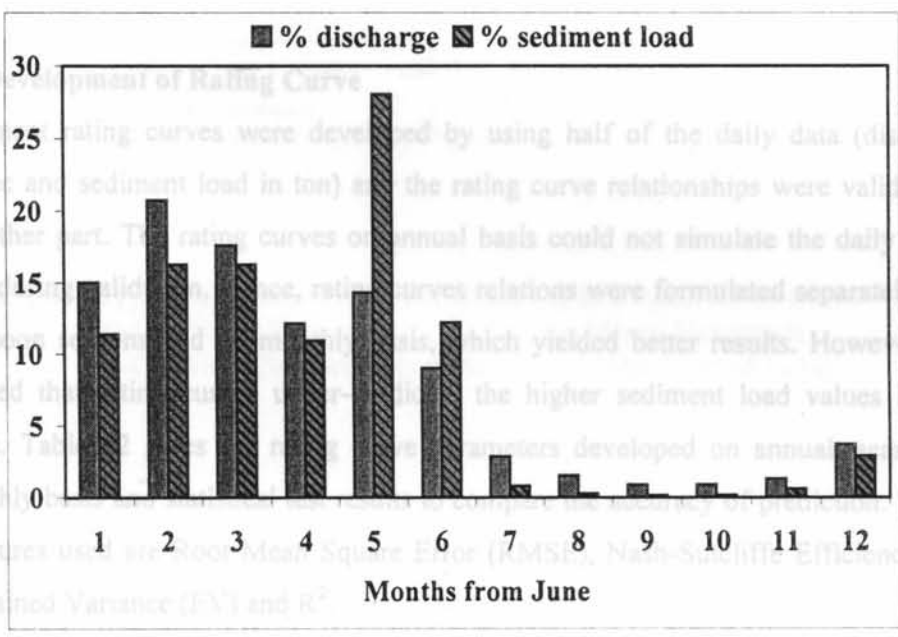


Figure 18: Monthly Variation of % Discharge and % Sediment Load for Pamba

Relationship between daily and event based suspended sediment concentration (C) and discharge (Q) was studied qualitatively. Rating curves only give average and long term relationship. However, depending on the availability of sediment transport at different points of time, different types of hysteresis can be seen in this relationship. Five types of hysteresis are mentioned in literature, namely, single valued (straight or curved), clockwise, counter-clockwise, single valued plus loop, and figure eight (Asselman, 1999). These result from C/Q relations at different time, time of occurrence of peaks, spread and skewness of temporal distribution graphs.

When the Pamba data was analysed for hysteresis effect, the majority of rainfall events produce clockwise loop, which is the most common type. This occurs when sediment peak arrives at stream cross section before discharge peak. It is due to the depletion of the sediment source in the channel system. Depending on the spread and skewness of temporal graphs, different forms of clockwise loops were formed. However, during the months of July and August, counter-clockwise hysteresis also were noticed, wherein the discharge peaks before sediment concentration. This may be due to the delayed sediment supply from a distant source/tributary or due to bank erosion. Typical hysteresis patterns for the basin are shown in Figure 19.

2.2 Development of Rating Curve

Sediment rating curves were developed by using half of the daily data (discharge in cumec and sediment load in ton) and the rating curve relationships were validated with the other part. The rating curves on annual basis could not simulate the daily sediment load during validation. Hence, rating curves relations were formulated separately for two monsoon seasons and on monthly basis, which yielded better results. However, it was noticed that rating curves under-predicted the higher sediment load values in all the cases. Table 12 gives the rating curve parameters developed on annual, seasonal and monthly basis and statistical test results to compare the accuracy of prediction. Statistical measures used are Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), Explained Variance (EV) and R^2.

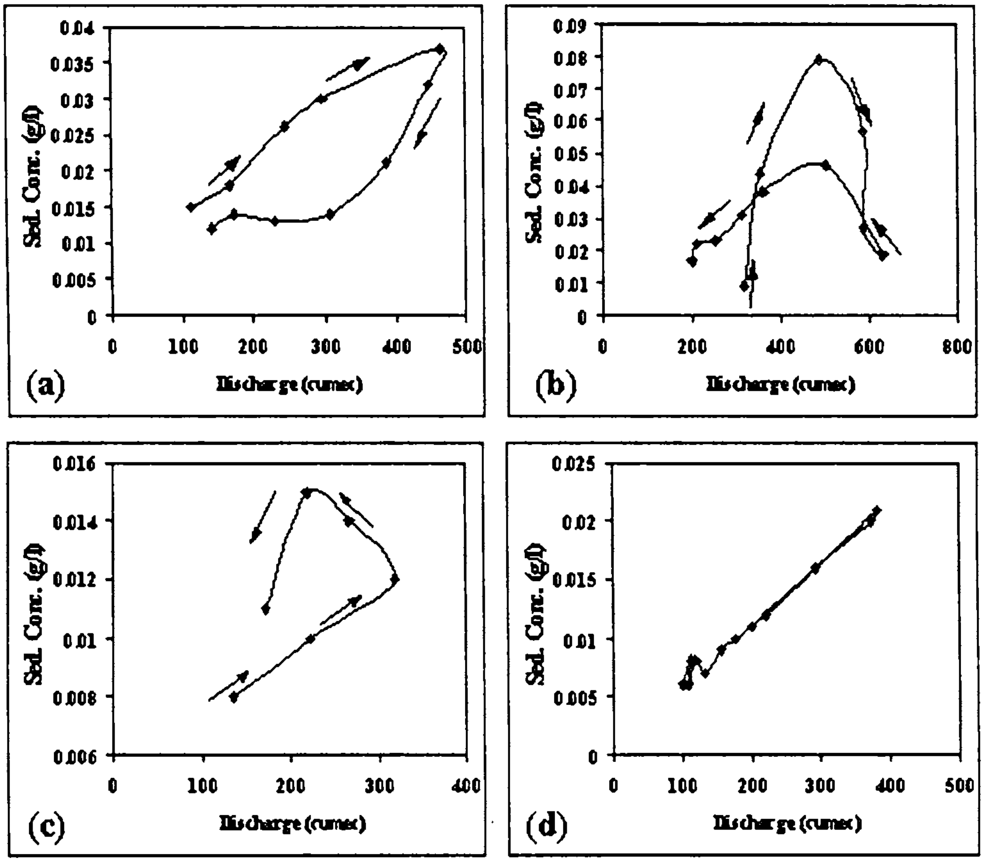


Figure 19: Typical Hysteresis Patterns Observed in Pamba River Basin
(a) Clockwise Hysteresis (b) Mixed Hysteresis
(c) Counter-Clockwise Hysteresis (d) Single Valued Loop

Table 12: Rating Curve Parameters and Goodness of Fit Test Results

	a	b	Statistical Parameters of Fitting			
			RMSE	NSE	EV	R^2
Annual	0.038	1.737	4868	0.24	0.24	0.48
SW Monsoon	0.039	1.690	1499	0.62	0.62	0.78
NE Monsoon	0.016	1.971	3643	0.38	0.39	0.62
June	0.460	1.271	794	0.70	0.71	0.66
July	0.058	1.598	833	0.57	0.61	0.76
August	0.330	1.703	2405	0.61	0.62	0.68
September	0.013	1.943	553	0.56	0.59	0.67
October	0.008	2.118	8023	0.59	0.59	0.58
November	0.044	1.742	4802	0.23	0.25	0.47

Goodness of fit analyses showed that the agreement between predicted and observed values is very less for rating curves developed on annual basis. SW monsoon data showed better results compared to NE monsoon data. The poor fitting in NE monsoon season is due to the presence very high values of sediment load during NE monsoon. The same is applicable for the months October and November. SW monsoon, June, July and September showed the best agreement between observed and predicted. This analysis showed that the rating curve methodology could be applied with better accuracy by grouping the data on a monthly or seasonal basis.

2.3 Contributions from Different River Reaches

The Pamba river is having three major tributaries, Pamba Ar, Kakkad Ar and Kall Ar. Pamba Ar drains about 50 % of the total catchment area and flows through varying topographical and land use regions. The upstream of this tributary consists of two reservoirs, Pamba and Sabarigiri. The Kakkad Ar flows through the central part of the basin and the catchment area mainly consists of plantations. There is a control structure at Maniyar, which is near to the confluence point with other two tributaries. Kall Ar, except for its downstream portion flows through forests.

Two monitoring stations were established at each of the three tributaries to understand the sediment transport characteristics from different regions of the catchment as shown in the schematic diagram in Figure 8. Rating curves were developed for these six stations as given in table 13. Kakkad Ar shows steep rating curves (low 'a' and high 'b') which denotes low sediment transport for low discharges, compared to other two tributaries.

Table 13: Rating Curves for Tributaries of Pamba

Pamba Ar	**Kakkad Ar**	**Kall Ar**
Kanamala $S = 6.35\ Q^{0.78}$ $R^2 = 0.94$	Angamuzhy $S = 3.76\ Q^{0.84}$ $R^2 = 0.98$	Mundomuzhi $S = 5.39\ Q^{0.68}$ $R^2 = 0.93$
Athikayam $S = 2.75\ Q^{0.80}$ $R^2 = 0.97$	Perinad $S = 0.74\ Q^{1.03}$ $R^2 = 0.98$	Vadasserikkara $S = 4.22\ Q^{0.78}$ $R^2 = 0.95$

Periodic measurements were taken at all three tributaries, just before their confluence and at a point after the confluence, on the main river. The stations were Athikayam on Pamba Ar, Perinad on Kakkad Ar, Vadasserikkara on Kall Ar and Ranny on the main river. The sediment load was estimated and compared as shown in table 14. It was observed that the Pamba Ar tributary is the main contributor of sediment for the whole river system and most of the sediments carried by the Kakkad Ar is trapped at the control structure at Maniyar.

Table 14: % Contribution of sediment Load from Major Tributaries

Date	Station	Q cumecs	C mg/l	S ton/day	% contribution
28th June, 2003	Athikayam	115.75	101	1010.1	50.38
	Perinad	52.55	42	190.7	9.52
	Vadasserikkara	72.16	129	804.27	40.10
	Ranny	185.00	112	1790.2	
27th July, 2003	Athikayam	171.20	185	2736.5	62.63
	Perinad	102.28	77	680.5	15.58
	Vadasserikkara	88.87	124	952.1	21.79
	Ranny	278.00	174	4179.4	
17th August 2003	Athikayam	194.65	190	3195.4	39.25
	Perinad	126.42	110	1201.5	14.76
	Vadasserikkara	175.46	247	3744.5	45.99
	Ranny	365.00	247	7789.4	
30th July, 2004	Athikayam	136.17	144	1694.2	33.20
	Perinad	128.00	118	1305.0	25.58
	Vadasserikkara	136.01	179	2103.5	41.22
	Ranny	259.00	201	4497.9	
20th August, 2004	Athikayam	211.85	198	3624.2	53.00
	Perinad	143.44	119	1474.8	21.57
	Vadasserikkara	129.89	155	1739.5	25.43
	Ranny	329.00	201	5713.6	

3.0 DEVELOPMENT OF UNIT SEDIMENT GRAPH (USG)

For the computation of USG, three watersheds were selected within the Pamba river basin with varying slope, land use and falling in different physiographical regions of the State. They were;

- Kozhy Thodu watershed having an area of 37.49 km^2 mainly covered with plantation and agriculture,
- Valiya Thodu watershed having 41.15 km^2, with plantation and forest as the major land use types, and
- Kiri Thodu watershed, 36.55 km^2 in area and mostly covered with forest area.

Hourly rainfall data for storm events for the selected watersheds were measured using rainfall collectors having standard area of opening and with standard measuring jar. Both hourly stream flow and sediment concentration data were also required for the study. Cross sectional details of the river monitoring station, current meter records and depth of water were used for estimation of discharge. Water samples were collected in one-litre cans and using standard laboratory filtering methods, suspended sediment concentration was estimated.

Much effort was put into data collection during the course of this study and many rainfall events were monitored for the watershed during monsoon season of 2002-2005. Since this study was intended to derive 1 hr USG, only the rainfall events with effective duration of 1 hr were selected. The characteristics of rainfall, runoff and sediment yield for selected rainfall events are given in the tables 15, 16 & 17. The events were separated into events for derivation of USG and events for testing.

For each event, a direct stream flow hydrograph and direct sediment graph were generated. The corresponding ordinates of the direct stream flow and sediment graphs were expressed as ERR and ESR. Integrating the area under discharge and sediment hydrographs, the effective runoff ER and effective sediment yield ES were obtained. Relationships were established between ERR - ESR and ER - ES. Relationship was also established between the effective rainfall and the sediment yield (ERI – ES). The coefficients of the power relationship are shown in table 18.

Table 15: Storm Events Identified for Kozhy Thodu Watershed

Event No.	Date	Rainfall (mm)	Runoff (mm)	Sediment Yield (ton/km^2)	Hydro-graph Base Duration (hr)	Peak Discharge	
						Water (cumec)	Sediment (ton/day)
Events used for the development of average USG							
1	07-07-02	33.0	24.00	5.93	22	35.0	1986.77
2	09-07-02	17.0	12.68	2.08	20	17.0	663.90
3	29-06-03	48.0	33.71	9.61	24	46.0	2782.08
4	12-07-03	41.0	29.19	7.56	22	40.0	2225.67
6	04-10-03	27.0	19.30	5.31	20	32.0	1545.52
8	13-08-04	24.0	17.48	4.53	20	28.0	1424.91
Events used for verification							
5	02-10-03	30.0	21.89	6.82	20	34.0	1836.00
7	10-08-04	37.0	26.22	6.55	22	36.0	1869.35
9	19-08-04	44.0	30.63	9.04	24	42.0	2460.33
10	06-09-04	35.0	24.20	6.34	22	33.0	1776.30

Table 16: Storm Events Identified for Valiya Thodu Watershed

Event No.	Date	Rainfall (mm)	Runoff (mm)	Sediment Yield (ton/km^2)	Hydro-graph Base Duration (hr)	Peak Discharge	
						Water (cumec)	Sediment (ton/day)
Events used for the development of average USG							
3	06-07-02	35.0	21.35	2.81	15	45.0	820.37
4	27-08-02	43.0	23.53	3.07	13	49.0	884.82
5	14-09-02	26.0	14.09	1.72	14	30.0	442.71
7	26-07-03	29.0	17.94	2.51	15	39.0	673.92
8	28-07-03	38.0	21.78	4.35	14	45.0	1166.40
9	16-08-03	23.0	15.75	2.15	15	30.0	520.99
10	08-09-04	28.0	17.15	2.60	15	33.0	824.00
12	05-06-04	20.0	11.02	1.08	14	21.0	341.11
Events used for verification							
1	15-06-02	33.0	19.25	2.47	14	38.0	660.96
2	16-06-02	19.0	9.93	1.14	14	20.0	292.29
6	05-10-02	25.0	16.36	2.10	15	33.0	579.57
11	12-09-03	40.0	21.26	4.10	14	44.0	1186.10

Table 17: Storm Events Identified for Kiri Thodu Watershed

Event No.	Date	Rainfall (mm)	Runoff (mm)	Sediment Yield (ton/km^2)	Hydro-graph Base Duration (hr)	Peak Discharge	
						Water (cumec)	Sediment (ton/day)
Events used for the development of average USG							
1	21-08-04	49.0	24.43	2.36	18	33.0	504.66
3	26-08-02	30.0	17.04	1.57	17	24.0	319.33
5	27-06-03	21.0	12.51	0.95	16	17.0	174.79
6	19-08-03	19.6	10.64	0.77	16	13.0	156.04
8	07-06-04	33.0	20.00	1.95	18	27.0	319.33
9	19-06-04	45.0	24.13	3.15	16	35.0	677.38
11	02-07-04	35.0	19.11	1.93	16	28.0	374.98
Events used for verification							
2	24-08-02	37.0	20.09	2.27	16	29.0	443.49
4	15-09-02	25.0	15.17	1.26	18	20.0	240.19
7	07-10-02	42.0	24.72	2.53	18	39.0	572.83
10	30-06-04	39.0	19.90	2.02	16	30.0	435.46

Table 18: Relationship Between Effective Sediment Load, Runoff and Rainfall

Micro-watershed	ESR = c ERR^d			ES = a ER^b			ES = p ERI^q		
	c	d	R^2	a	b	R^2	p	q	R^2
Kozhy Thodu	0.013	2.33	0.94	2.48	1.43	0.94	1.95	1.36	0.95
Valiya Thodu	0.019	2.03	0.96	1.73	1.41	0.83	0.92	1.38	0.74
Kiri Thodu	0.015	2.09	0.96	0.72	1.55	0.97	0.52	1.38	0.93

USGs were developed for each of the rainfall events given in tables 15, 16 & 17 as per the methodology explained in the previous chapter. These USGs were used for estimating average USG for each of the three micro-watersheds. The ordinates of the average USGs for the watersheds are given table 19 and shown in Figure 20. The steep and narrow USG for Kozhi Thodu watershed denotes heavy and quick sediment flow rate from the watershed.

Four events were kept aside for each watershed for testing the average USGs. ES values were estimated with the relationship between ES-ER and ES-ERI, with known ER and ERI for these events. These ES values along with the average USG for corresponding watersheds were used for estimating the sediment graphs resulting from each rainfall event. The simulated sediment graphs were compared with the observed sediment graphs. Comparison of sediment graph for all the four rainfall events are shown in Figures 21, 22 & 23. The observed rainfall, discharge and sediment rate are marked on each figure. S(Q-S) and S(P-S) in figures represent the sediment rate calculated using the relationship ER-ES and ERI-ES respectively.

The simulated sediment graphs compare well with the observed, except for few cases of Valiyathodu watershed, where the peaks are not coinciding. It can be seen from the figures that the average USG for each watershed can be effectively used to predict the slope and peak characteristics of the sediment graph.

Table 19: Ordinates of Average USGs for the Three Micro-Watersheds

Time (hr)	Kozhy Thodu USG (km^2/hr)	Valiya Thodu USG (km^2/hr)	Kiri Thodu USG (km^2/hr)
0	0.000	0.000	0.000
1	0.013	0.160	0.039
2	0.078	1.286	0.365
3	0.430	4.653	1.769
4	1.333	10.571	4.865
5	3.833	9.471	7.518
6	11.349	6.370	6.679
7	8.342	4.018	4.958
8	5.097	2.216	3.451
9	2.874	1.214	2.486
10	1.592	0.646	1.819
11	0.986	0.348	1.267
12	0.597	0.152	0.704
13	0.370	0.037	0.369
14	0.223	0.007	0.173
15	0.147	0.000	0.067
16	0.100		0.018
17	0.059		0.003
18	0.039		0.000
19	0.018		
20	0.008		
21	0.003		
22	0.001		
23	0.000		

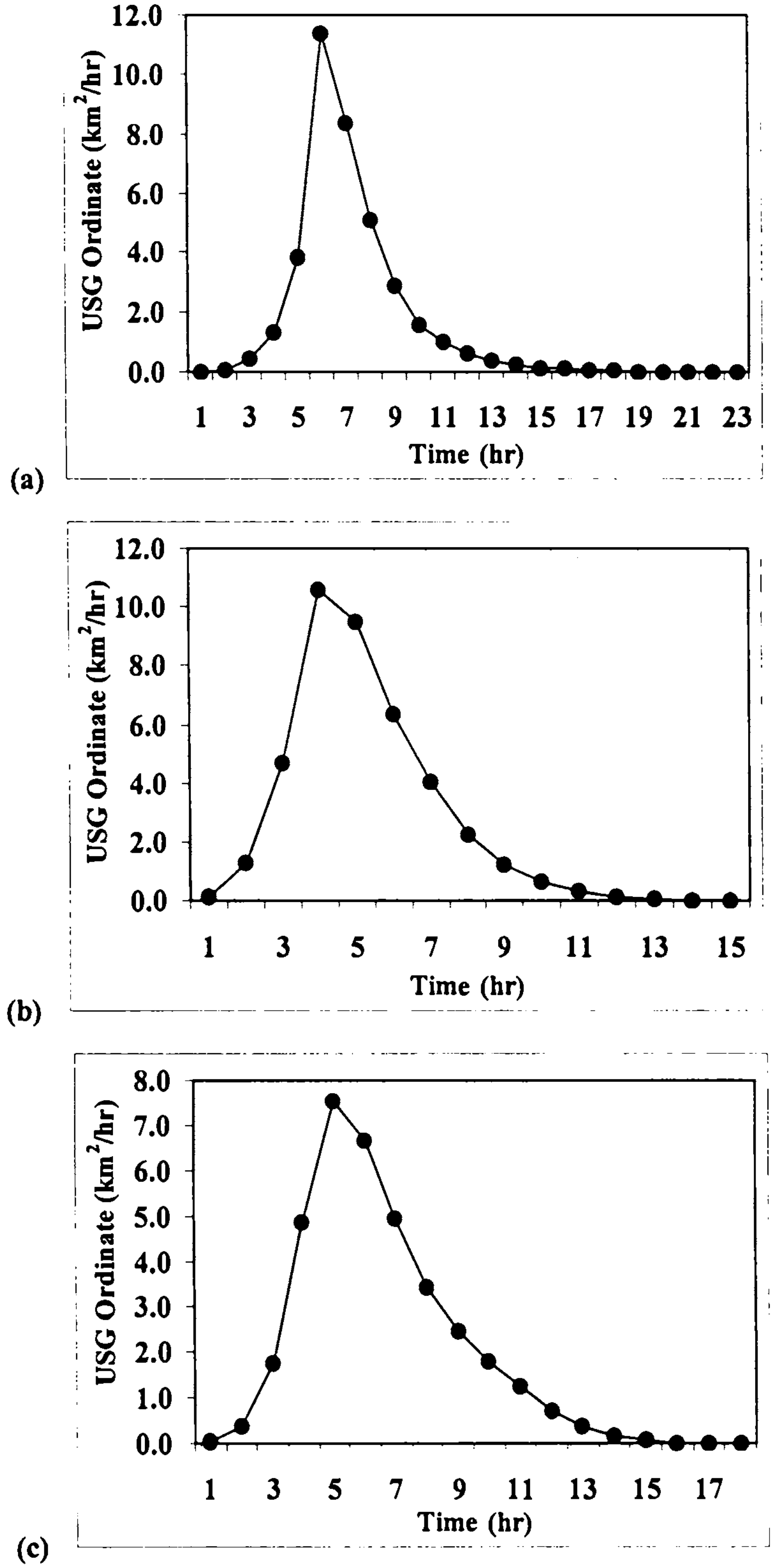


Figure 20: Average USGs for the Micro-Watersheds (a) Kozhy Thodu (b) Valiya Thodu (c) Kiri Thodu

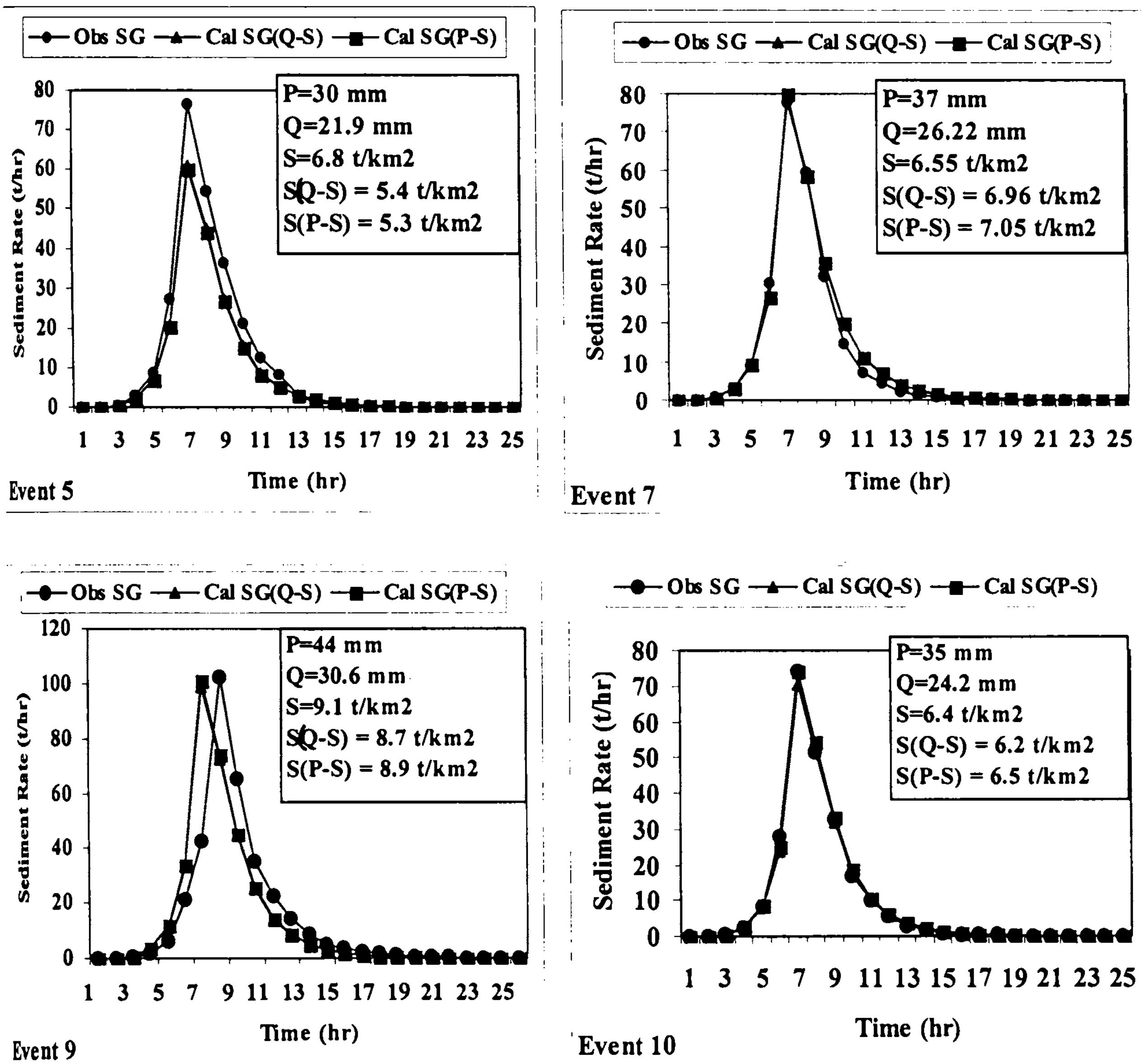


Figure 21: Observed and Computed Sediment Graphs – Kozy Thodu Watershed

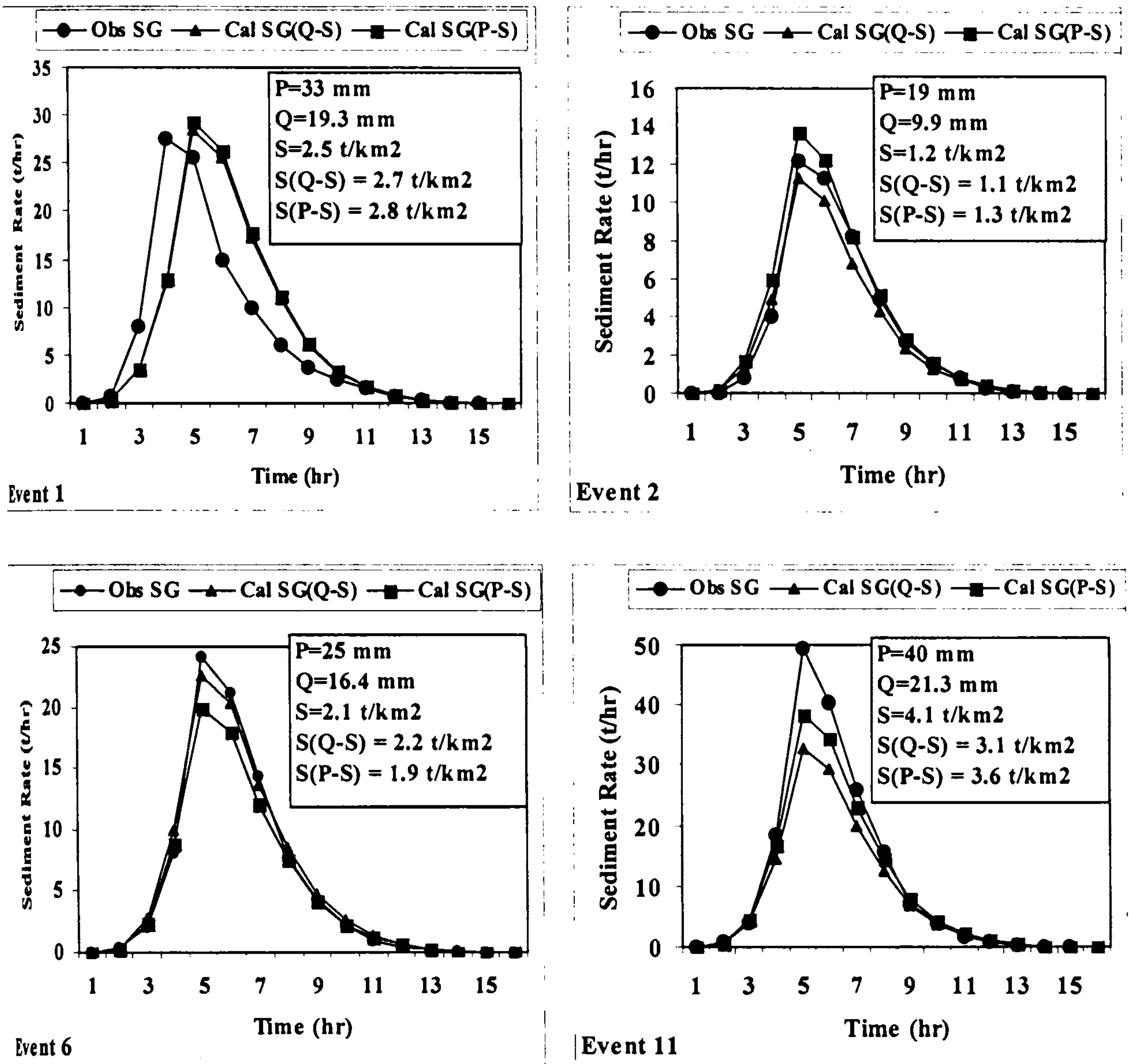


Figure 22: Observed and Computed Sediment Graphs – Valiya Thodu Watershed

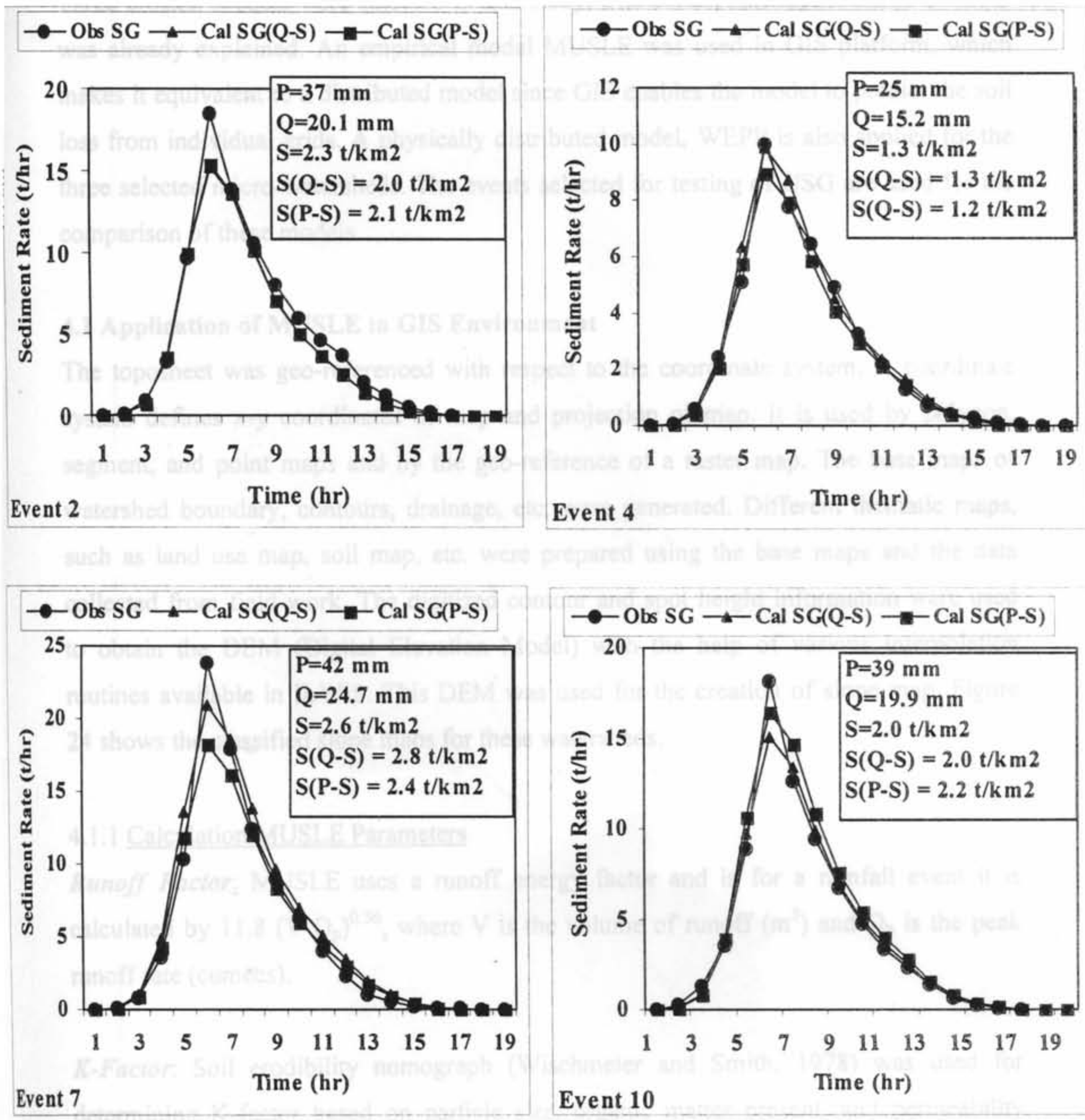


Figure 23: Observed and Computed Sediment Graphs –
Kiri Thodu Watershed

4.0 EROSION AND SEDIMENT YIELD MODELING

Three erosion models were selected in this study. The conceptual model based on USG was already explained. An empirical model MUSLE was used in GIS platform, which makes it equivalent to a distributed model since GIS enables the model to predict the soil loss from individual grids. A physically distributed model, WEPP is also applied for the three selected micro-watersheds. The events selected for testing of USG are used for the comparison of these models.

4.1 Application of MUSLE in GIS Environment

The toposheet was geo-referenced with respect to the coordinate system. A coordinate system defines x-y coordinates of map and projection of map. It is used by polygon, segment, and point maps and by the geo-reference of a raster map. The base maps of watershed boundary, contours, drainage, etc. were generated. Different thematic maps, such as land use map, soil map, etc. were prepared using the base maps and the data collected from field work. The digitized contour and spot height information were used to obtain the DEM (Digital Elevation Model) with the help of various interpolation routines available in ILWIS. This DEM was used for the creation of slope map. Figure 24 shows the classified slope maps for these watersheds.

4.1.1 Calculation MUSLE Parameters

Runoff Factor: MUSLE uses a runoff energy factor and is for a rainfall event it is calculated by $11.8\ (V\ Q_p)^{0.56}$, where V is the volume of runoff (m^3) and Q_p is the peak runoff rate (cumecs).

K-Factor: Soil erodibility nomograph (Wischmeier and Smith, 1978) was used for determining K-factor based on particle size, organic matter present, and permeability class. An attribute table was prepared using these values for different soil types. Soil erodibilty map was calculated using the soil map and K-factor table. The K-factors used for the calculation are given in table 20.

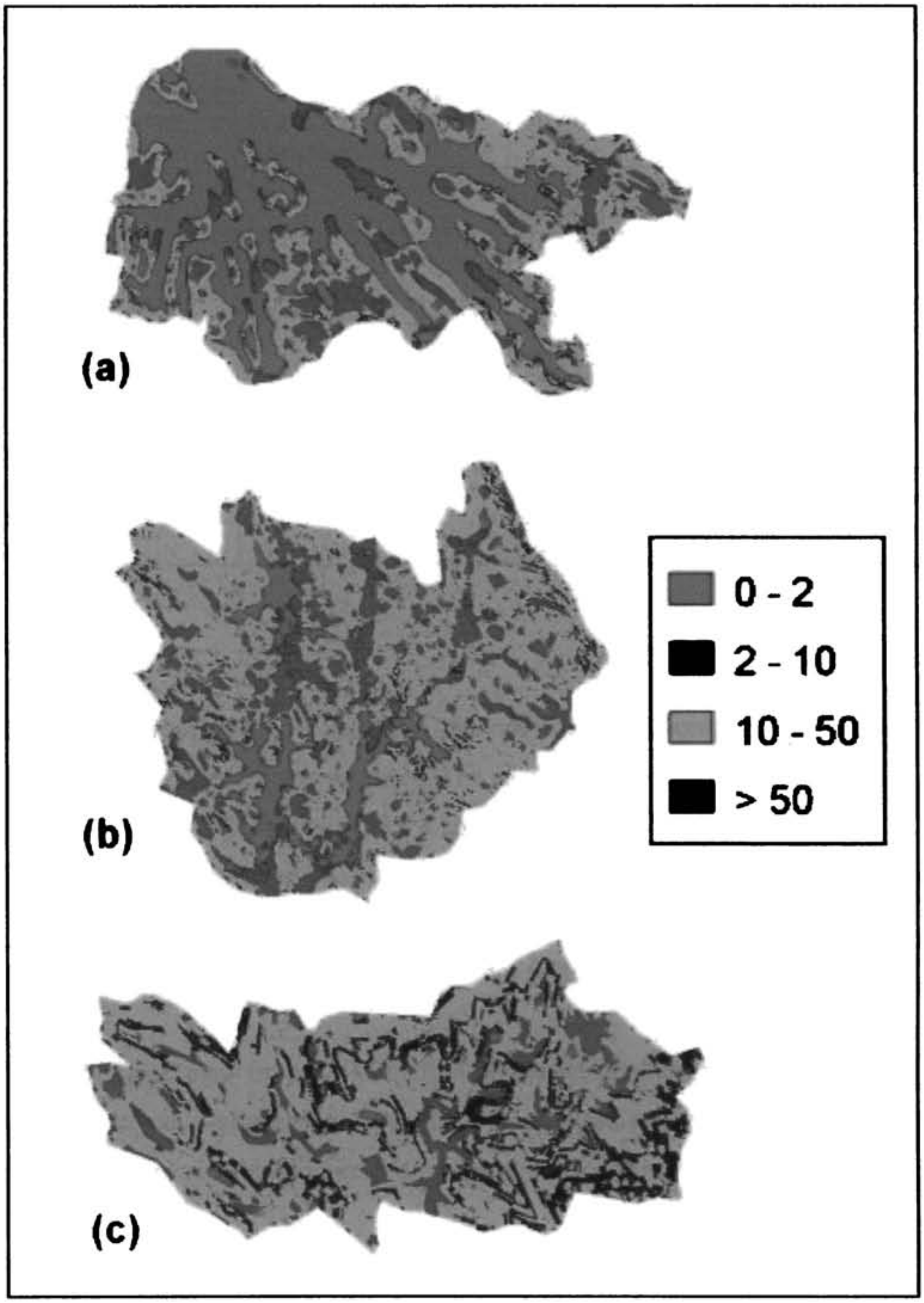


Figure 24: Classified Slope (%) Maps for the Micro-Watersheds (a) Kozhy Thodu (b) Valiya Thodu (c) Kiri Thodu

Table 20: K-Factor for Different Soils of the Micro-Watersheds

Soil Type	Soil Texture		Organic Matter (%)	Soil Structure	Rate of Permeability	K factor
	Sand	Silt + very fine sand				
Loam	42	46	1.0	Medium grained	Moderate	0.37
Sandy clay loam	56	25	2.0	Medium grained	Slow to moderate	0.23
Sandy loam	50	43	2.0	Coarse grained	Rapid	0.19
Silty loam	37	53	2.0	Medium grained	Moderate	0.33
Loam (forest)	46	40	3.5	Fine grained	Moderate to rapid	0.16
Sandy loam (forest)	54	32	3.5	Fine grained	Rapid	0.10

LS-Factor: For slope steepness upto 21%, the original USLE formula for estimating the slope length and slope steepness was used. The equation used was;

$$SL= (L/72.6) * (65.41 * \sin (S) + 4.56 * \sin (S) + 0.065)$$

where, L is the slope length and S is the steepness.

For slope steepness of 21 % and more

$$SL = (L/22.1)^{0.7} * (6.432 * \sin (S^{0.79}) * \cos (S))$$

To calculate slope map from DEM in ILWIS, digital gradient filters df-dx and df-dy were used to create x-gradient and y-gradient map. These two gradient maps were used to derive differences in elevation in all directions in the construction of a slope map

The relationship between the slope steepness in percentage (S) and slope length in metres (L) for the study area was estimated as; L = 0.4*S + 40. From the slope map, using the above equation in map calculation function, slope length map was created. By combining the slope steepness and slope length map, LS- factor map was created.

CP-Factor: The calculation of CP factor for each cover unit was made on the basis of management practices, physical conditions and characteristics of cover units. CP factor for various cropping and management practices for the study area are given in table 21. CP factor map was created by linking the attribute table for the CP factor with the land use map.

Table 21: CP-Factor for Different Land Use Classes for the Micro-Watersheds

Land Use Type	Farming Method	Tillage Practice	P factor	C factor
Agriculture Land	Strip cropping with terracing	Tillage along the contour	0.60	0.18
Plantation	Terracing	No tillage	0.70	0.003
Forests	-	-	1.00	0.002
Fallow	-	-	1.00	0.04

4.1.2 Expected Soil Loss (A) Calculation

Using the map calculation function in ILWIS, the K, LS, and CP maps were multiplied to get the KLSCP map, which denotes the erodibity of the watershed surface. The actual soil loss for each watershed was estimated by multiplying the map KLSCP with the runoff energy factor for each of the selected storms. The results are tabulated as table 22.

The predicted values are showing wide variations from watershed to watershed. The model estimates are over predicted for Kozy Thodu and Valiya Thodu watersheds and under predicted for Kiri Thodu watersheds. Large disturbances (deforestation and plantations) within the forest area may be the reason for the under prediction in Kiri Thodu Watersheds, which consists of 78 % forest cover.

Figures 25, 26 and 27 show the classified soil loss map for each of the watersheds for selected rainfall events. It can be seen that majority of the Kiri Thodu watershed yields low sediment rates (0 – 0.5 t/km^2)

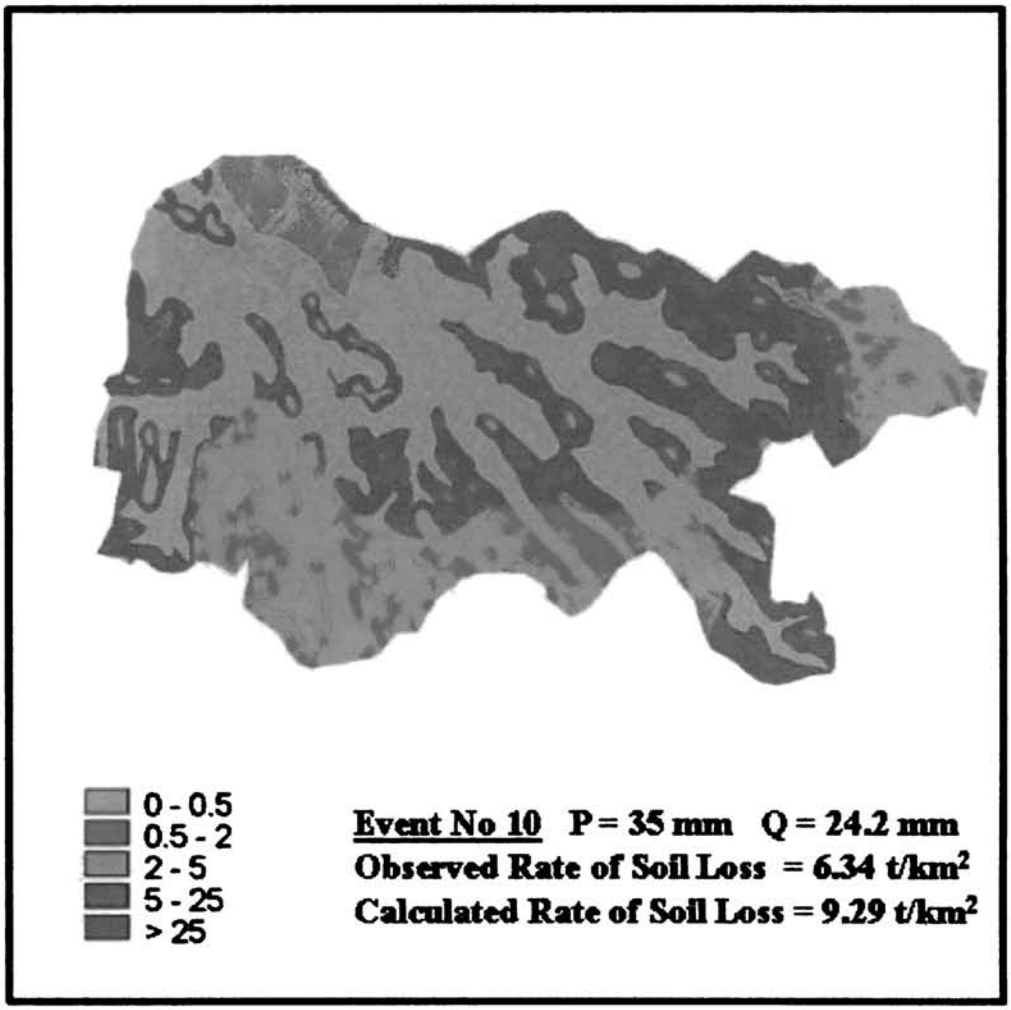


Figure 25: Classified Soil Loss (ton/km^2) Map – Kozhy Thodu Watershed

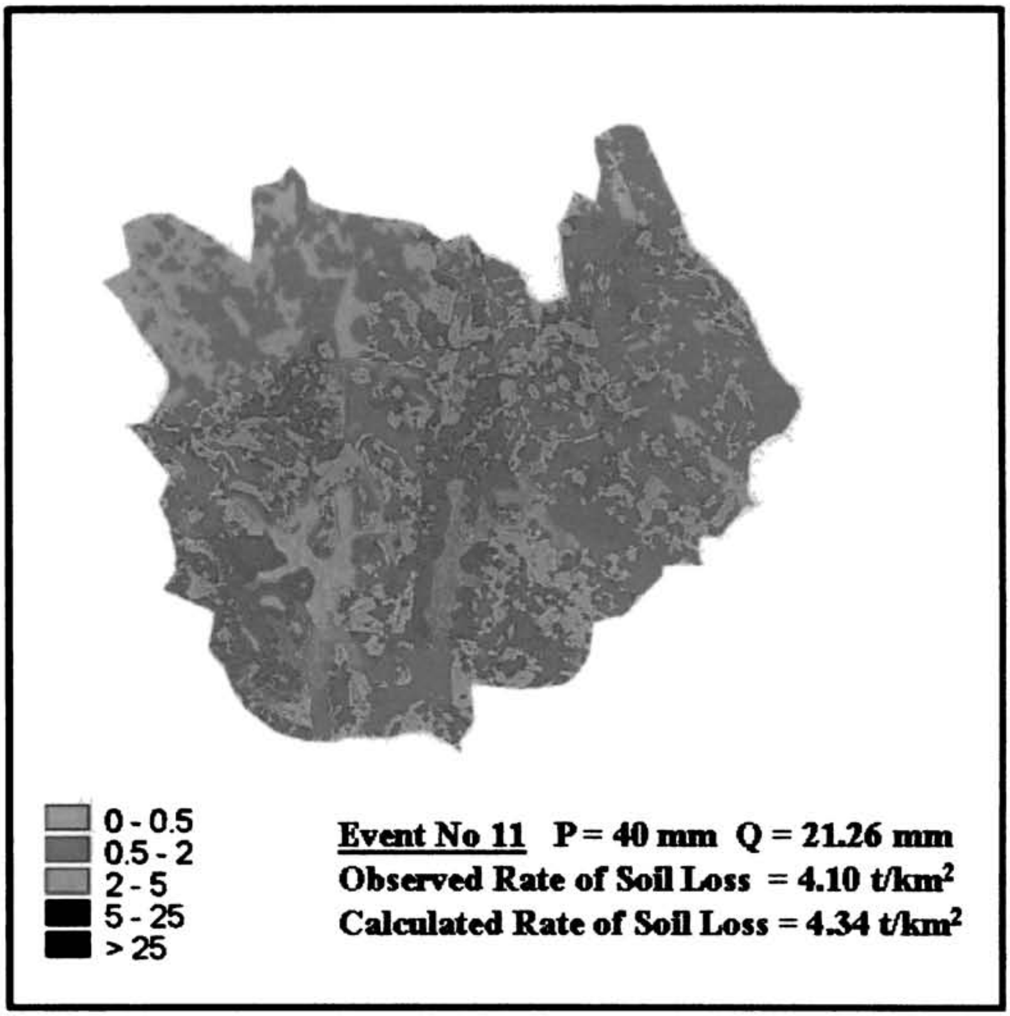


Figure 26: Classified Soil Loss (ton/km^2) Map – Valiya Thodu Watershed

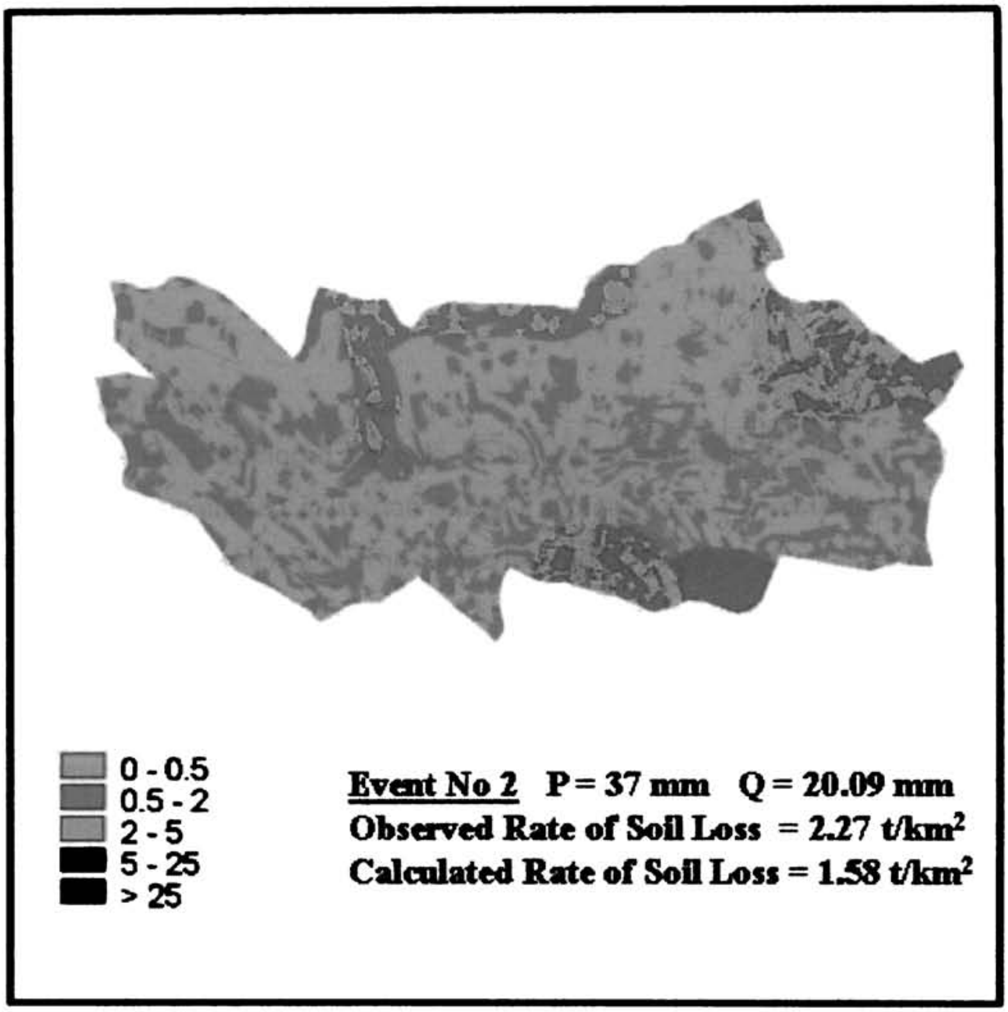


Figure 27: Classified Soil Loss (ton/km^2) Map – Kiri Thodu Watershed

Table 22: Comparison of Observed and Predicted (MUSLE) Soil Loss (ton/km^2)

Watershed and events		Observed Soil loss	MUSLE-ILWIS estimate
Kozhy Thodu	5	6.82	8.93
	7	6.55	10.2
	9	9.04	12.13
	10	6.34	9.29
Valiya Thodu	1	2.47	3.78
	2	1.14	1.82
	6	2.11	3.19
	11	4.10	4.34
Kiri Thodu	2	2.27	1.58
	4	1.26	1.09
	7	2.54	2.09
	10	2.02	1.60

4.2 Application of USG

Average USGs were developed for each of the watershed using the data of observed rainfall events as explained in section 3.0 and applied using the remaining 4 rainfall events for each of the watersheds. The comparison of the results is given in table 23. The sediment loss rate predicted using USG and ES-ER relationship gives better results.

Table 23: Results from Application of USG

Watershed	Event	Predicted (ES-ER) (ton/km^2)	Predicted (ES-ERI) (ton/km^2)	Observed (ton/km^2)
Kozhy Thodu	5	5.38	5.30	6.82
	7	6.96	7.05	6.55
	9	8.69	8.92	9.04
	10	6.21	6.53	6.34
Valiya Thodu	1	2.70	2.78	2.47
	2	1.06	1.30	1.14
	6	2.15	1.89	2.11
	11	3.10	3.62	4.10
Kiri Thodu	2	2.03	2.04	2.27
	4	1.31	1.19	1.26
	7	2.79	2.42	2.54
	10	2.00	2.19	2.02

4.3 Application of WEPP Model

Preparation of input files form the major task in WEPP model. Number of input files required for WEPP, depend on the application for which it is being applied. However, the major input requirement for any WEPP model application are characteristics of climate, cropping/management, soil, slope and channel.

In climatic input file, simulation of single storm event was selected. The new WEPP model is window supported and the data files can be entered directly or the existing input files can be edited. The slope file can be created by graphically previewing the slope shape. The management file builder contains a large number of built-in cropping pattern and management practices, which can be easily brought into the data file and can be edited to suit the prevailing conditions on each hill slope.

First step in the application of WEPP is the process of dividing the study area into a number of hill slopes and channels and shown in Figure 27.

Table 24: Number of Hill Slopes and Channels for each Micro-Watershed

Watershed	No. of hill slopes	No. of channels
Kozy Thodu	39	16
Valiya Thodu	80	32
Kiri Thodu	88	37

The input files were prepared for each hill slopes and channels. Soil characteristics for each hill slope, including type of soil, hydraulic conductivity, soil albedo, initial saturation, number of soil layers, thickness, bulk density, sand, clay, and organic matter percentage, etc. were provided in Soil input file. Slope details (slope profile) were given in Slope input file. Cropping pattern/management types were described in the Management input file. Channel properties such as width and depth of channels, hydraulic properties, channel bank management details, and soil characteristics were given as input data. Wherever such details were not available, WEPP does internal calculations using the provided information. The climate input data include the characteristics (rainfall depth, intensity, pattern, etc.) of each of the rainfall events, earmarked for validation of the models.

The model run was performed for individual hill slope to calculate the sediment yield at the foot of each hill slope. These were routed through channels and the quantities were calculated at the outlet of the watershed. The WEPP program produces different kinds of output, in various quantities. For the present study, the output consisted of runoff and erosion summary information, on a storm-by-storm basis. The results were verified using the observed sediment load data. The results are given in table 25. It can be seen that the model under-predicted the soil loss. Also, the comparison is not encouraging, possibly because of the large requirement of data regarding soil, channels and management factors, which are not easily obtainable from field.

Table 25: Results from WEPP Model Application

Watershed	Event No.	Soil Loss (ton/km^2)		Runoff (mm)	
		Predicted	Observed	Predicted	Observed
Kozy Thodu	5	5.08	6.82	18.56	21.89
	7	5.25	6.55	20.37	26.22
	9	8.02	9.04	23.82	30.63
	10	5.67	6.34	20.08	24.20
Valiya Thodu	1	2.01	2.47	13.54	19.25
	2	0.98	1.14	5.49	9.93
	6	1.53	2.11	10.83	16.36
	11	3.42	4.10	15.13	21.26
Kiri Thodu	2	1.88	2.27	14.98	20.09
	4	0.98	1.26	11.01	15.17
	7	1.87	2.54	17.88	24.72
	10	1.49	2.02	14.21	19.90

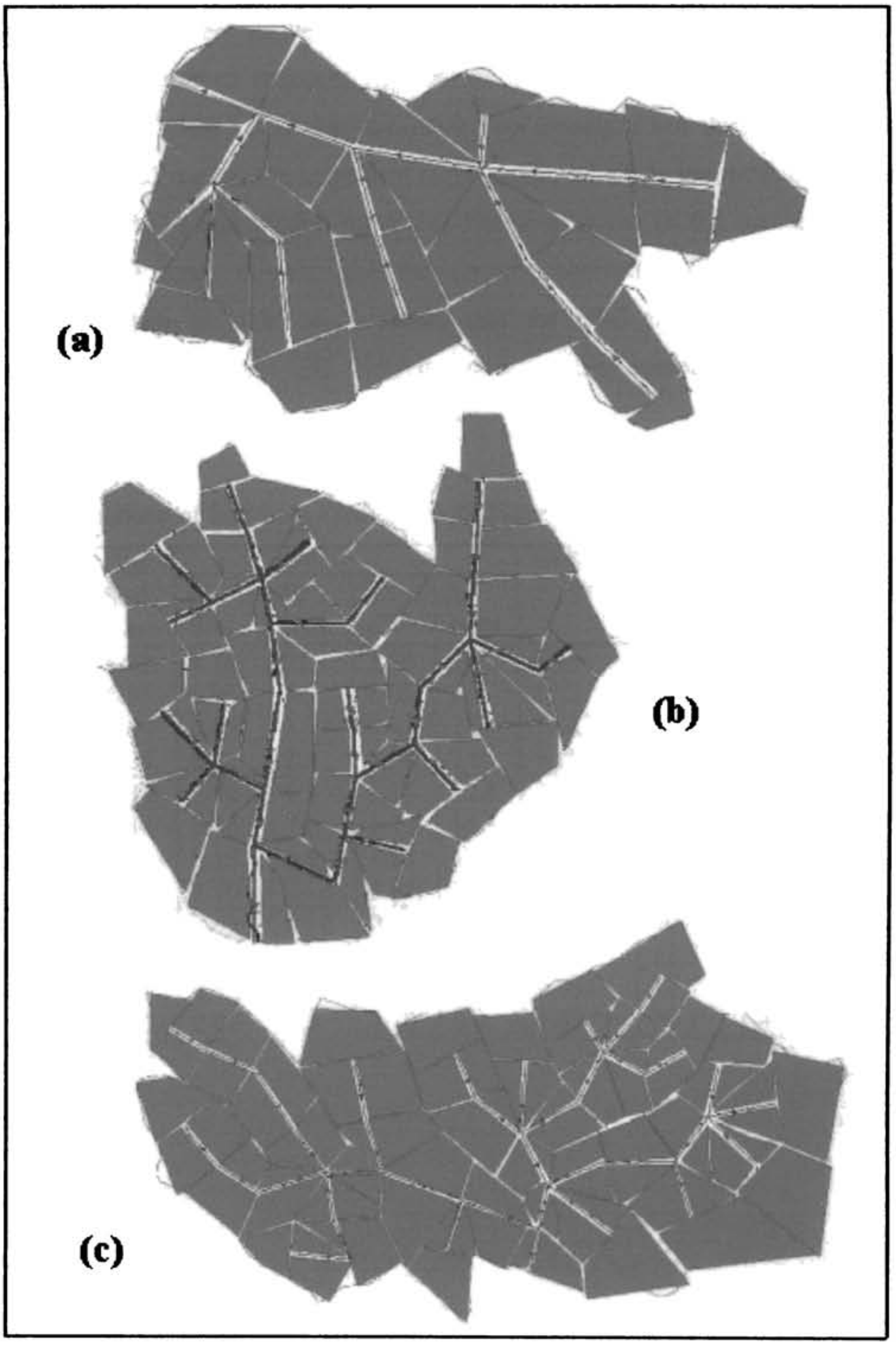


Figure 28: WEPP Application – Hill Slopes and Channels for Micro-Watersheds (a) Kozhy Thodu (b) Valiya Thodu (c) Kiri Thodu

4.4 Comparison of the Models

Three erosion models were applied for the same rainfall events and the results were compared with the observed sediment yield values. It was seen that the USG predicted the rate of sediment yield better than the other two models. Even though WEPP is a physically distributed model, the large data requirement, which is impractical in studies of this scale, affected its prediction accuracy. The comparison of the results from the application of the three models and the error, (observed-predicted)/observed, in prediction are shown in table 26. It shows that the USG methodology using the relationship between ES and ER yielded better results compared to that using relationship between ES and ERI.

Table 26: Comparison of Soil Loss Predicted with Three Models (ton/km^2)

Watershed and events		Obs. Soil loss	USG				MUSLE -ILWIS	% error	WEPP	% error
			ES - ER	% error	ES - ERI	% error				
Kozhy Thodu	5	6.82	5.38	21.1	5.30	22.3	8.93	31.0	5.08	25.5
	7	6.55	6.96	6.3	7.05	7.6	10.2	55.7	5.25	19.9
	9	9.04	8.69	3.9	8.92	1.3	12.13	34.2	8.02	11.3
	10	6.34	6.21	2.1	6.53	3.0	9.29	46.5	5.67	10.6
Valiya Thodu	1	2.47	2.70	9.3	2.78	12.6	3.78	53.1	2.01	18.6
	2	1.14	1.06	7.0	1.30	14.1	1.82	59.7	0.98	14.1
	6	2.11	2.15	1.9	1.89	10.4	3.19	51.2	1.53	27.5
	11	4.10	3.10	24.4	3.62	11.7	4.34	5.9	3.42	16.6
Kiri Thodu	2	2.27	2.03	10.6	2.04	10.1	1.58	30.4	1.88	17.2
	4	1.26	1.31	4.0	1.19	5.6	1.09	13.5	0.98	22.2
	7	2.54	2.79	9.9	2.42	4.7	2.09	17.7	1.87	26.4
	10	2.02	2.00	1.0	2.19	8.4	1.60	20.8	1.49	26.3

Chapter IV
CONCLUSION

CONCLUSION

The fluvial system, consisting of upland erosion zone, transportation zone and downstream sedimentation zone, is an open system that is susceptible to modification by climate change and human activities. Changes in erosion pattern and transportation processes in the first two zones, influence the sedimentation rate within the third zone. If a relationship between the response of a fluvial system to changes in climate and human activities can be established based on recent past data, then the future scenarios can be predicted in response to global climate changes and urban expansion. The present study has been formulated to understand the temporal and spatial variation in suspended sediment input by the tropical rivers of Kerala State, India, to the coastal eco-system and to identify the factors influencing these variations, in line with the above thoughts.

The water and sediment yield data of 15 years (from 1986-87 to 2000-01) for 16 west flowing rivers of Kerala, have been collected and analyzed to study the discharge and sediment carrying characteristics of individual rivers on monthly, seasonal and annual basis. Based on the spatial and temporal distribution of rainfall, topography, geology, and basin characteristics, the variation in the sediment yielding capacities of each river has been analyzed. Further, Pamba river has been selected for detailed studies and for testing the applicability of rating curve methodology. Contributions from its major tributaries have been estimated. Three micro-watersheds have been selected within the Pamba river basin to compare the suitability of three sediment yield models.

Large variations in the discharge and sediment quantities were noticed during a particular year between the river basins investigated and for an individual river basin during the years for which the data was available. In general, the sediment yield pattern follows the seasonal distribution of rainfall, discharge and physiography of the land. This confirms with similar studies made for other Indian rivers.

The analyses of data reveal that the variations of water and sediment yield manifest the following:

- northern and southern Ghat regions are more prone to erosion than the central region
- distribution of rainfall and topographical features are the major factors influencing the sediment yield
- monsoon supplies major share of sediment load; SW monsoon is the driving factor for northern region, whereas both SW and NE monsoons control the sediment flow pattern for southern regions
- sediment yield during non-monsoon season is very low for northern rivers, whereas its contribution is considerable for southern rivers
- within central Kerala, erosion processes have become more stabilized than northern and southern regions, which results in lower sediment yields

To pin point, major findings from the analyses of sediment data for the 16 rivers are:

- Periyar river yields maximum average yearly discharge of 6,895 MCM while Vamanapuram contributes the minimum of 701 MCM
- Chaliyar contributes the maximum average yearly sediment load of 0.40×10^6 ton and Meenachil transports the minimum of 0.04×10^6 ton
- Northern rivers are having comparatively large values of sediment yield (235 ton/km^2), followed by southern rivers (90 - 130 ton/km^2) and central Kerala rivers, which yield unstable erosion rates (40 - 130 ton/km^2)
- Except Valapatanam, Chaliyar, Bharathapuzha, Chalakudy and Pamba (5 rivers), all other rivers show a decreasing trend in sediment load transport from 1986-87 to 2000-01, even though the discharge show increasing trends
- Monsoon months (July to November) are responsible for transporting about 95% of the sediment
- Few days in monsoon accounts for bulk of the sediment load
- Northern rivers exhibits a uni-mode distribution of % monthly sediment load, whereas the distribution is bi-modal for the southern rivers

- Rating curve analyses show that northern and southern rivers produce flat rating curves, which is indicative of river reaches with intensively weathered material that can be transported easily
- Since the gauging sites are within the downstream reach of the rivers, the suspended sediment load is dominated by finer particles (< 0.075 mm)

Pamba river basin was considered for detailed studies for understanding seasonal distribution of sediment dynamics in tropics. Data collected on a daily basis were used to study the seasonal variation in sediment transport and hysteresis effects. Rating curves were developed and tested with the observed data. Contributions from different tributaries were monitored to identify the major source of sediment flow. The following conclusions are drawn with respect to Pamba river basin:

- discharge in the river was minimum at 3,116 MCM during 1986-87 and maximum at 5,397 MCM during 1992-93
- river transported a minimum sediment load of 65,770 ton in 1990-91 and a maximum sediment load of 5,01,562 ton in 1992-93
- SW and NE monsoon accounted for 95 % of the sediment load
- maximum discharge occurred during the month of July, whereas it was during the month of October, that the sediment load attained the maximum value
- maximum sediment concentration recorded was 896 mg/l on 10^{th} October 1992, which accounted for 35 % of annual load
- it is found that clockwise hysteresis appears common for this river basin; however, anti-clockwise loops are also noted during the months of July and August
- Pamba Ar (tributary) accounted for about 50% of the sediment load to the main river system
- sediment rating curves computed on daily data failed to predict sediment load values accurately
- rating curves developed based on seasonal and monthly data gives a better result as per the statistical goodness of fit analyses; however, still rating curves were inadequate to simulate large sediment load values

In order to model the sediment dynamics, three micro-watersheds were selected with varying characteristics, vis-à-vis, topography, drainage density and land use. Average one-hour Unit Sediment Graphs (USG) was computed for each of these watersheds. It is seen that the sediment graphs, simulated using the average USGs were comparable with the observed sediment graphs in its shape and peak.

Next, more advanced tools were utilized for the estimation of average erosion rates in the above watersheds - an empirical model, Modified Universal Soil Loss Equation (MUSLE) in GIS environment, another - conceptual model based on USG, and thirdly, a physically distributed model, Water Erosion Prediction Project (WEPP), and the results were compared with the observed data. It was found that the USG based model predicted the sediment yield rates better than the other two models.

Conceptually, it was observed from this study, that the quantity of sediment transported downstream shows a decreasing trend over the years corresponding to increase in discharge. For sound and sustainable management of coastal zones, it is important to understand the balance between erosion and retention and to quantify the exact amount of the sediments reaching this eco-system. This, of course, necessitates a good length of time series data and more focused research on the behaviour of each river system, both present and past. In this realm of river inputs to ocean system, each of the 41 rivers of Kerala may have dominant yet diversified roles to influence the coastal ecosystem as reflected from this study on the major fraction of transport, namely the suspended sediments.

Additionally, based on the analyses of seasonal variation of discharge and sediment load/yield, a marked feature of variation is noticed from north to south. When this aspect was studied in detail with respect to the distribution of sediment, discharge and rainfall, it was found that the State of Kerala could be divided into four zones as shown in figure 14:

- North zone, with very large sediment yield, majority of which are being transported during SW monsoon
- North-central zone, where the sediment yield characteristics are comparatively lesser than all the other three zones, with small contributions during NE and non-monsoon seasons
- South-central zone, is noted for major sediment yield in SW monsoon; during NE monsoon and non-monsoon seasons, yield is appreciable compared to north-central zone
- South zone, with large sediment yield, where sediment contribution from both the monsoon seasons are almost equal

The table on next page provides the characteristics of the four specifically defined sediment yielding zones.

It is observed from the table below, that river discharge in NCZ is appreciably lower compared to SCZ though the amount of rainfall is nearly equal. This feature relates mainly to the inter basin transfer of water from Periyar river in NCZ to the Muvattupuzha river in SCZ, which directly results in lowering of the runoff coefficient for the NCZ and conversely, a higher value for SCZ.

The NCZ produces the maximum quantum of sediment load followed by NZ. This is due to the fact that two major rivers in terms of catchment area and discharge (Bharathapuzha and Periyar) are located within this zone. However, in the case of NZ, higher erodibility as represented by sediment yield (235 ton/km^2) results in heavy suspended sediment transport. The role of high rainfall intensity in this zone may also be a contributing factor. Added to the above, the physiography of this region does not account for retention in the absence of a defined midland. Denudation rate of 0.168 mm/year in NZ denotes a process linked to the flattening of the Ghats of this zone at a faster pace which is comparable with high sediment yielding Himalayan rivers.

Parameter	North Zone (NZ)	North-Central Zone (NCZ)	South-Central Zone (SCZ)	South Zone (SZ)	Remarks
Rainfall (P mm)	3800	3100	3200	2600	Gradation from north to south direction
% P (SW) % P (NE)	80 10	78 15	62 19	54 24	Seasonal variation in north – south direction
Discharge (Q mm)	2588	1235	2997	1400	The contrast between NCZ and SCZ is due to inter basin transfer
Runoff Coefficient (P/Q)	0.68	0.41	0.94	0.55	
% Q (SW) % Q (NE)	83 14	74 20	68 22	55 33	Similar to the % P variations
Sediment Load (S ton)	8,93,692	9,26,391	4,65,571	2,50,196	Values related to size of the catchment for NCZ and high erodibility for NZ
% S (SW) % S (NE)	90 9	82 17	68 28	45 49	Similar to the % P and % Q variations
Sediment Yield(ton/km^2)	235	75	90	110	Maximum erodibility in NZ
Average S/Q	7.8	4.9	2.9	6.5	SCZ is geologically more stabilized
Slope	0.013	0.011	0.012	0.014	Refers to river longitudinal slope
Fine particles (%)	65 - 75	80 - 95	75 - 85	85 - 90	NZ texture reflects on comparatively coarser particles
Rating Para-meters 'a' 'b'	0.35 1.31	0.16 1.34	0.08 1.39	0.25 1.38	Large '**a**' denotes erodibility; large '**b**' refers to erosive power of river
Denudation Rate (mm/year)	0.168	0.054	0.065	0.079	High value in NZ reflects active terrain processes

Another feature relates to the higher input of sediment load during NE monsoon for the southern rivers, which conflict with the contribution of rainfall and subsequent runoff. The above fact is related to the occurrence of peak sediment load during the month of October (falling within NE monsoon) contrary to the peak discharge recorded during the month of July (falling within SW monsoon). This may be due to the availability of sediment material from distant source(s) or from flood plains or possibilities associated with soil creep.

The central (both NCZ and SCZ) zones feature broad land cross sections, more stable topography and geology, regulated rivers having a long course with flood plains and larger extent of forest cover in the catchment areas. Therefore the yields are less or moderate for these zones compared to the two extreme segments of the State.

Most of the rivers from north and south zones are showing a reducing trend in sediment transport for corresponding increase in discharge over the study period. These rivers are non-regulated compared to the major rivers in the central zones. This trend has to be treated as a matter of concern (for the coastal zone) and strict measures have to be considered to regulate sand mining, which may be a major reason for the above trend. The decreasing yields may reflect a gradual slowing process in fluvial dynamics or does this qualify as part of geo-morphological ageing process? Often, the fluvial system may try to balance this condition by fulfilling its carrying capacity by bank or bed erosion, which could be again detrimental to the ongoing surface process.

It is observed that year-to-year variation in discharge is marginal whereas the corresponding change in sediment load is substantial. Smaller rivers draining north zone and south zone transport at a high rate due to reasons explained in the above sections; this has also been reflected while analyzing the rating curve parameters. Slight changes in any of the influencing parameters will bring about drastic changes in the sediment transport regime of these regions. This signifies the importance of studies in sediment dynamics for the tropical rivers.

Unit sediment graphs, representing a particular watershed, can be computed at certain intervals of time (as illustrated herein) or at instances when changes in sediment transport regime are expected. These changes, due to the alterations in the natural equilibrium of the watershed, can be identified by the modification in peak and spread of the subsequent USGs developed. This approach will then serve as a tool for studies in catchment area management.

It is imperative that taking cognizance of the knowledge of new trends which have been studied and reported herein, more and more rivers be brought under monitoring programs and gauged for both river water and particulate load estimates as these have proved beyond doubt in enhancing our understanding of the vital links pertaining to the land – water surface processes, which impact the eco-system.

The state of Kerala is not only blessed with rains and plenty of runoff but also adequate, purposeful quantum of sediments, which in other quantifiable terms measures to sizable quantities of nutrient load; these, when transported downstream, favour sustainable coastal ecosystems which are complex but highly diversified for this part of the globe. Any active surface process will lead to upset the balance and needs continuous monitoring and corrections, in case of deviations; such an approach is warranted under these circumstances when disparities are abound within the short stretch of this State.

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