A MATHEMATICAL MODEL FOR SEDIMENT YIELD IN AGRICULTURAL WATERSHED

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THESIS

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requirement for the degree

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DECLARATION

I hereby declare that this thesis entitled " ***A MATHEMATICAL MODEL FOR SEDIMENT YIELD IN AGRICULTURAL WATERSHED"*** *is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, the diploma, associateship, relationship, followship or other similiar title or any other University or Society.*

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CERTIFICATE

Certified that this thesis, entitled ***"A MATHEMATICAL MODEL FOR SEDIMENT YIELD IN AGRICULTURAL WATERSHED"*** *is a record of research work done independently by* ***Sri. Babu,*** *V. under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to him.*

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SYMBOLS AND ABBREVATIONS USED

ASAE	American Society of Agricultural Engineers
ASCE	Ameican Society of Civil Engineers
cm	Centimetre (s)
CWC	Central Water Commission
CWRDM	Centre for Water Resources Development and Management
Dept.	Department
Div.	Division
Engg.	Engineering
et al	and other people
etc.	et cetara
Fig.	Figure
gm/lit	gram per litre
ICAR	Indian Council of Agricultural Research
i.e.	that is
IS	Indian Standard
ISAE	Indian Society of Agricultural Engineers.

J	Journal
km	Kilometre(s)
km^2	Kilometre(s) Square
km^2 mm.	Kilometre(s) Square Millimetre(s)
m	Metre(s)
m^3/day	cubic metre per day
mm	millimetre
m/s	meter per second
msl	mean sea level
MUSLE	Modified Universal Soil Loss Equation
Res.	Research
S/G	Stream Gauge
sq.Km	Square kilometre
SWC	Soil and Water Conservation
t	Tonne(s)
t/day	tonne(s) per day
t/h	tonne(s) per hour
t/km^2	tonne(s) per kilometre square
TNAU	Tamil Nadu Agricultural University

Trans	Transactions
t/sq.km^2	tonne(s) per square kilometre
USDA	United State Department of Agriculture
WMO	World Meteorological Organisation
0	phi

Introduction

INTRODUCTION

Land, one of nature's greatest gift to man, is covered by a larger of top soil extending from a few centimetres to a few meters. It takes hundreds to thousands of years to develop a 5 cm layer of fertile soil whereas it can be washed away in a single rainstorm event. It is estimated that the world's average yield of sediment and solutes by rivers is equivalent to a lowering of the earth's surface by 3 cm every 1000 years or 42 tonnes/Sq.km/year, and for Asia alone the denudation rate is 600 tonnes/Sq.km/year. Out of the 328 million hectares of geographical area of India 68 million hectares are severly eroded. The average annual loss of soil from various land surface has been estimated to be 5333 million tonnes out of which rivers carry approximately 2050 million tonnes. Of this, nearly 480 million tonnes are deposited in various reservoirs and 1572 million tonnes were washed into sea. In India, soil erosion is taking place at an alarming rate of 16.35 tonnes/Sq.km/year (Dhruvanarayana, 1993) which is not only detrimental to current agricultural production but is a threat to the survival of mankind.

The erosion and sedimentation are the major problems that reduce the productivity of crop land, degrade water quality and carry polluting chemicals. Deposition of sediment in reservoirs reduces its capacity, thereby adversely affecting the water supply for irrigation, domestic and industrial use and for power generation. Sediment deposited in stream channels reduce the flood carrying capacity, resulting in more frequent overflow and greater flood water damages to adjacent properties. The deposition of sediment in irrigation and in drainage canals, in navigational channels and floodways, in harbours, on streets and highways and in buildings not only create nuisance but also inflicts a high public cost in maintanance, removal or any reduced services. The erosion of catchments also changes, ground water regime and results in loss of top fertile agricultural soil, resulting in reduction of agricultural production. The chemical composition of soil in the catchment also changes sometimes.

Due to a series of rainfall induced erosive process, particulate matter eventually reaches a stream course after being transport through a great variety of distances in a drainage basin. The sediment transported in a stream may be accomplished by three generally accepted modes, namely contact, saltation and suspended load. The saltation load in combination with the contact load is generally assumed to comprise the bed load. The sum of the suspended load and the bed load gives the total load. The suspended load contribution to total sediment yield are very high, ie 90-95 %. Therefore, in many areas suspended sediment yields may be considered to reflect the watershed sediment yield process.

The knowledge of temporal-distribution of sediment yield is required in the design and operation of soil and water conservation programmes on watershed basis. At present very little information is available about the sediment yield from catchments in the country. For the project planning purpose, the estimates made are mostly based on experience. Such estimates are very approximate and grossly inadequate for engineering analysis. Therefore there is an urgent need for rational analysis of erosion data from catchments, inorder to obtain relationship for erosion rate.

Most of the existing sediment yield prediction methods have been developed for streams under the assumption that there is a determinate relationship between sediment yield and dominant variables, though the sediment yield process is totally a stochastic process. The procedures consider watershed characteristics, land use and treatment but do not consider individual storm characteristics which are primarily responsible for wash load/sediment load production from a watershed. The sediment yield prediction based on individual storms is found to be more accurate than annual prediction procedures and would enable a better understanding of the watershed runoff-sediment yield process.

The complexity of physical processes between rainfall, runoff and sediment flow, and also the several man-induced activities such as land management and agricultural practices, contribute to make the problem of erosion and sedimentation a very difficult task to deal with. Further, in the hydrology of natural catchments, rainfall runoff-sediment flow ralations are usually non-linear. However, comparative studies have shown that the combined effect of all the non-linearities is usually small.

In view of the nature of hydrological data (large random errors) it becomes problematic whether the attempts to reduce the systematic errors, arising from non-linearities, by the use of non-linear analysis is warranted and so linear models are used frequently. Linear models have practical advantage of case of application and are mathematically much more convenient to handle than non-linear models. The linear theory can be extended for sediment yield models also.

Sediment graph prediction can be achieved by employing systems approach. The spatial variation of sediment discharged into waterways and the detailed transport process can be lumped together into a single system. The mobilized sediment which is the result of rainfall-runoff process, is treated as input to the system and the direct sediment discharge as the system output. The geomorphic characteristics and the hydrologic factors of a watershed are considered as a set of lumped system parameters which transform inputs to outputs through the system.

During the past years, there has been success in applying the linear and time-invariant assumptions to sedimentation engineering and hydrology, making it possible to solve certain non-linear problems. Linearity and time-invariance are the bases for the development of the hydrograph theory. Considerable progress has been made in the last two decades in developing techniques to estimate erosion and sediment yield for individual storms and for various locations over a watershed.

In peninsular India, soil erosion and sedimentation are widely prevelent in the Western Ghats, which forms the boundary of several watersheds of the south. The Bharathapuzha basin is the largest west flowing river basin, rises in the eastern slopes of Anamalai hills of the Western Ghats and flows in the north westerly direction. The Gayathripuzha, the Kalpathipuzha, the Chitturpuzha and the Thuthapuzha (Pulanthode river) are the important tributaries of Bharathapuzha basin. All the four tributaries rise in the western slopes of the different ranges of the Western Ghats. The Thuthupuzha drainage basin is selected for the present study with a total drainage area of 940 sq.km.

The present study deals with the development of a linear discrete time invariant watershed sediment yield model corresponding to the combined approach of translation and attenuation using Muskingum routing equation for Thuthapuzha, sub watershed of Bharathapuzha basin in Western Ghats, based on the input-output concept. The specific objectives of the study are:

(i) Collection of data
(ii) Analysis of the data to develop the mathematical model
(iii) To estimate the model parameters using Langrange multipliers method
(iv) Testing of the model to simulate the field condition
(v) Statistical analysis of the field data using multiple regression co-efficients.

Review of Literature

REVIEW OF LITERATURE

Sedimentation is a vital concern in the conservation, development and utilization of our soil and water resources. It embodies the process of erosion, entrainment, transportation, deposition and the compaction of sediment. The principal external dynamic agents of sedimentation are water, wind, gravity, ice and temperature. Although each may be important locally, only the hyudrospheric forces of rainfall and runoff are the major factors of our locality which have to be considered.

2.1. SEDIMENT TRANSPORT PROCESS

In a river system the total sediment discharge is defined as the average quantity of sediment passing a section of a stream per unit time. Sediment transport by water takes place as sheet flow, rill and gully flow, stream flow and flow through reservoirs. Knowledge on each mode of transport is important to the overall understanding of sediment-erosion-transport- deposition chain of process taking place within a catchment. For instance, without the knowledge of the supply of sediment from the land surface to the stream channel, our ability to predict the sediment transport through the river will become incomplete.

2.2. SUSPSENDED SEDIMENT LOAD (WASH LOAD)

The suspended sediment loads in a stream are the result of processes of erosion and transport within the drainage basin area (Einstein, 1964). The sediment transported in a stream is subdivided into two categories, according to the dominant mode of transport, suspended load and bed load. It was estimated that the bed load contribution to the total sediment is usually small and may in some cases be neglected from total yield calculations and in many instances the washload may comprise 90-95 % of the total sediment.

2.3.HYDROLOGIC INVESTIGATION

Many approaches to the study of hydrologic problems have evolved over the years. These approaches can be divided broadly in to two groups (Amoracho and Hart, 1964); (i)physical approach and (ii) system approach. The former is also refered to as a basic, pure, dynamic or theoretical approach and the latter as an operational, applied, empirical, black box and parametric approach. These are infact most appropriately called basic research and applied research. Aggregations of studies involving the former can be called physical hydrology; those involving latter, system hydrology.

2.3.1. PHYSICAL APPROACH

In the physical approach the primary motivation is the study of physical phenomena and their understanding. If we want to determine sediment yield due to rainfall from agricultural watersheds then we need data on (1) rainfall characteristics (2)physiographic characteristics (3) antecedent soil moisture condition (4) physical laws including laws of conservation of mass and momentum of water, laws of conservation for sediment and runoff and (6) initial boundary conditions.

2.3.2. SYSTEM APPROACH

In this approach we are concerned with the system operation, not the nature of the system itself (its components, their connection with one another and so on) or the physical laws governing its operation. The sytem operation is the link between input and output. If the nature of the system or the physical laws changed, the system operation also changes.

A system representation of watershed sediment yield due to rainfall is obtained by considering the watershed as a system. The system operation involves construction of (1) a rainfall- runoff relationship and (2) runoff-sediment relationship. A universal soil loss equation (Wischmeir and Smith, 1960) and a unit sediment graph (Rendon Herrero, 1978) are two of the examples. In this approach the hydraulics of sediment movement or the dynamic forces that govern sediment discharges in watershed are not concerned. The parameters appearing in this approach are estimated using historical records.

2.4. MODELLING IN HYDROLOGY

The basic purpose of a model is to simulate and predict the operation of the system that is unduály complex and the effect of changes on this operation. The use of hydrologic models for prediction purposes arises largely because of the inadequacy of hydrologic data (Dooge,1972). The increasing effect of hydrologic activity on the elements of hydrologic cycle will tend more and more to render hydrological data of limited use for the direct prediction of corresponding behaviour of future events.

Sediment yield predictions are needed for many specific purposes and the needs are so varied that no single model could meet them without a great loss of efficiency. A number of sediment yield models have been developed during the past three decades yet they are in a stage of infancy. Shen and Li (1976) classified the sediment yield models into four main catagories, namely, (1) statistical regression models (2) system models represented by unit sediment graph approach, (3) parametric models and (4) stochastic models.

The statistical regression models are used to estimate sediment yield by means of either computing gross erosion and sediment delivery ratio or directly determining sediment yield. In system models the system concepts are introduced to the modelling of sediment yield on a sequential time basis. The parametric models are having numerical values called parameters to quantify the factors affecting erosion, transport and deposition. The behaviour of the hydrologic system and the processes which take place in it are considered to vary with sequential time function of the probability of occurence in stochastic models.

System concept to the modelling of sediment yield is the present state of art of modelling in the area of sediment hydrology. As this study is based on systems concept, the review of research work is restricted to the development of sediment yield, determination of system parameters and evaluation of the model.

2.5. SEDIMENT YIELD MODELS.

Rendon-Herrero (1974) advanced the concept of unit sediment graph analogous to the unit graph concept in surface hydrology. His study disclosed that a significant relationship existed between the excess rainfall or runoff and the washload (suspended sediment load) that was mobilized by it over the watershed area during a particular storm event and that a series graph could be used as a method to predict wash-load and its variation with time.

Bruce et al. (1975) described the rate and quantity of runoff, sediment and pesticides transported from watersheds on storm basis.The sediment yield was based on runoff model developed by Snyder (1974). Sediment yield was derived from rill and interill estimates that was routed through the rill system to the watershed outlet.

Renard and Laursen (1975) computed sediment graphs by multiplying the storm hydrograph flow rates by sediment concentrations predicted with a sediment-transport model.

Williams (1975) developed a sediment routing technique to route sediment yield from small watersheds, through streams and valleys to the outlet of large watershed. The technique is based on the MUSLE (Modified Universal Soil Loss Equation) and a first order decay function of travel time and particle size. He also reported the advantages of sediment routing. He found that the procedure performed satisfactory in test routing.

A procedure for predicting sediment graphs was devised by William (1978) by convolving an instantaneous unit sediment graph with source runoff in a manner similar to Bruce et al. (1975). Test with 50 storms from five watersheds showed that the model was applicable to agricultural watersheds in the Texas blacklands. The model was useful in designing reservoirs or in water quality-modelling problems.

Rendon-Herrero (1978) suggested a method to find out the individual unit sediment graph ordinates. He found that the unit sediment graph can be used to produce a sediment graph if the hydrograph and hyetograph of a particular storm events are known. The hydrographs and concomitant sediment graphs used are generally parallel in shape and coincide during peak flow.

Sharma and Dickinson (1980) applied input-output system concept to the modelling of daily runoff-sediment yield of the Thames river in Southern Ontario, Canada. It was shown that a linear discrete dynamic model was possible in terms of log - transformed daily runoff and sediment yield sequences and a second order discrete dynamic model with seven parameters was found adequate to model daily sediment yield.

The model developed by Rendon-Herrero (1978) was adopted by Asokan (1981) for developing series graphs of sediment flow of the Ramganga catchment.

A synthetic unit sediment graph model and an instantaneous unit sediment graph model based on the Clarks model (1945) was proposed by Das (1982) for Himalayan catchments of the Ramganga river. Mobilized sediment was used as input to develop design sediment graph.

Prasad (1983) derived a unit sediment graph and dimensionless unit sediment graphs for Bino watershed of the Ramganga reservoir catchment by modifying Snyders method (1938) and William's model (1975). He used synthetic and dimensionless unit sediment graphs to generate sediment flow graphs and showed that the generated graphs were close to the observed sediment flow graphs.

A linear time-invarient dynamic model was developed by Srivastava et al.(1984) for a small watershed of Nainital tarai using system approach. The sediment flow graphs generated by the memoryless sediment yield rate prediction equations were in close agreement with the actual observed sediment flow graphs as compared to sediment flow graphs generated by the unit sediment graphs.

Kumbhare and Rastogi (1985) developed a unit sediment graph for Gagas watershed of the Ramganaga reservoir catchment and found that the sediment flow graphs generated using it were in good agreement with naturally observed ones.

A synthetic procedure to generate unit sediement graphs for ungauged watershed was given by Chen and Kuo (1986). The base time, peak time and peak sediment discharge were correlated with the hydrologic parameters, soil properties and watershed geomorphic characteristics. Results of both spatial and temporal verifications of the developed model showed that the synthetic graphs fairly agreed with actual sediment graphs. The model was based on a one-hour unit sediment graph.

Kattan et al. (1987) developed a simple hydrological model to estimate the surface discharge which allows seperation of different flow components of annual hydrograph and the suspended sediment loads is correlated with the surface discharges. It was found that the main contribution to the rivers suspended sediment transport; originated from slope erosion, which supplied 50-80 % of the total sediment-transport.

Kumar and Rastogi (1987) developed a conceptual model of instantaneous unit sediment graph for Chaukhutia watershed for sediment yield prediction and to determine the effect of soil conservation measures on sediment flow by routing sediment through a series of linear reservoirs. The mobilized sediment during storm was related to rainfall excess.

The series graph method analogous to unit hydrograph procedure of Sherman (1932) was used by Raghuwanshi et al (1988) for prediction of the temporal distribution of sediment washload from the Chaukhutia watershed. The sediment graph generated by the series graph method resulted in close agreement with measured sediment graph.

Vinod Kumar and Rastogi (1989) developed a mathematical model of instantaneous unit graph based on time-area histogram for a small agricultural watershed located at the Crop Reasearch Centre, Pantnagar. The instantaneous unit hydrograph was used for generaation of runoff hydrograph. The predicted runoff hydrograph were found to be in good agreement with the observed runoff hydrograph.

Das and Agarwal (1990) developed a conceptual model of instantaneous unit sediment graph for the prediction of suspended sediment by using the concept of time area histogram. Empirical relationships based on the watershed parameters have been generated to determine sediment storage constant. The developed model has been used to study changes in basin characteristics of the watershed due to various soil conservation measures practiced in it, and to predict sediment graphs with rainfall data as input.

A sediment routing procedure for mountaneous Himalayan Region, India was devised by Das and Chauhan (1990). The sediment yield from subwatersheds determined through a modified USLE was routed to the watershed outlet by using a first order decay function. The procedure performed satisfactorily in test routing and the results compared favourably with measured data.

Kumar et al. (1990) routed mobilized sediment through a series of linear reservoirs for sediment graphs prediction.The storm sediment graphs were generated by convolving instantaneous unit sediment graphs with corresponding values of mobilized sediment of storms. The computed sediment graphs revealed remarkable accuracy to the measured sediment graphs.

Kumar et al. (1990) also developed a dimensionless unit sediment graph model and peak sediment rate formula for the prediction of sediment rate. The ordinates of the dimensionless unit sediment graph was expressed as

$$Q_s/Q_{sp} = (t/t_p)^{-n_s} \exp[-2ns[\{1/\ (t/t_p)\} - 1] \qquad (1)$$

in which Q_s and Q_{sp} are the sediment flow rates in t/h at times t and t_p respectively and n_s is the shape parameter of the sediment graph. The equation for peak sediment flow was:

$$Q_{sp} = 2A_r\, E_s/(t_p + t_{rs}) \qquad (2)$$

where A_r is the watershed area in Km^2, E_s is the mobilized sediemnt in t/km^2, t_p is the time to peak in hours and t_{rs} is the time of recession for triangular sediment graph in hours. The predicted sediment graph resulted in over estimation of sediment volume but the peak sediment rate compared favourably well.

Jha and Rastogi (1990) developed a sediment graph model based on instantaneous unit sediment graph for a Himalayan sub catchment of the Ramganga river by routing the mobilized sediment volume through series of linear reservoirs and series of linear channels.

An Impulse response function model was developed by Kumar and Rastogi (1991) for Gagas watershed of the Ramganga reservoir catchment to predict sediment graph considering the watershed as lumped linear time-in varient system. The impulse response function was expressed in terms of watershed area A_r as:

$$S_{w2} = 2C_{s1} A_r + C_{s2} S_{w1} \qquad (3)$$

in which S_w is the sediment output, C_{s1} and C_{s2} are the sediment routing coefficients and the subscripts 1 and 2 refer to begining and end of time intervals. The results showed that the single linear reservoir model can adequately be used for prediction of sediment graph.

Patel (1991) derived a unit sediment graph model from the impulse response function based on Muskingum model for predicting temporal distribution of suspended sediment yield on storm basis for Chaukhutia watershed. For the same watershed, a discrete linear two reservoir cascade sediment yield model was developed by Agarwal (1991) using transfer function approach to generate distinct sediment flow graphs on storm basis.The sediment flow graphs generated by the model conformed reasonably well with measured sediment flow graphs.

Dicrete linear transfer function models proposed by Wang et al .(1991) for estimating runoff and sediment discharge hydrograph from the Loess plateau of China showed good agreement between the observed and predicted runoff and sediment.

Raghuwamshi et al. (1993) developed a conceptual model of the instantaneous unit sediment graph based on routing of time area histograms to generate the temporal distribution of washload on storm basis and applied the model on Chaukhutia watershed. The instantaneous unit sediment graph converted into unit sediment graph with the mobilized sediment for generation of sediment graphs. The generated sediment graphs showed fairly good agreement with their observed counterparts.

2.6. DETERMINATION OF SYSTEM PARAMETERS

Many models require calibration to obtain parameter values. Several optimization techniques have been developed that determine values of system parameters which maximize or minimise some dependent function of those parameters and such techniques are completely objective (Dawdly and O Donnel, 1965). In the present context of review, optimization means minimizing the errors betweeen a synthesized sediment flow and an observed record.

Sharma and Dickinson (1980) used linear least square method for estimation of parameters. The final estimates of the parameters were determined based on structure of the noise component.

Jha et al. (1983) used Roseubrock's optimization technique to determine optimized parameter set for the conceptual model. The objective function used in optimization was minimization of the sum of squares of the difference between observed and estimated runoff, as

$$\text{Min } F = \sum_{i=1}^{n} (Qobsi - Qesti)^2 \qquad (4)$$

where Qobsi and Qesti are the observed and estimated runoff at i^{th} time respectively.

The model parameters were estimated by Wang et al. (1991) from observed runoff and sediment discharge data using ordinary least squares. The objective function, F for estimating parameters was expressed as:

$$F = \sum_{t=1}^{m} e^2(t) = \sum_{t=1}^{m} [Sd(t) - \sum_{i=1}^{p} Ci\ Sd\ (t-i) - \sum_{j=1}^{p} Wj\ Q(t-j)]^2 \qquad (5)$$

where e(t) is the difference between the observed and estimated sediment discharge, Sd(t) is the observed sediment discharge, Q(t) is the observed runoff discharge and C and W are parameters of the model.

2.7. MODEL VALIDATION

A model is scientifically valid if its assumptions conform to basic scientific principles. Without proof of validity, a model, however elegant may be nothing but a tentative excercise in abstract logic. The problem of how to validate a model remains, however the most critical, difficult and elusive of all problems associated with computer simulation (Hillel, 1977).

Ramuson and Fluchler (1990) opined that model validation in its rigorous and narrow sense required a model to be run with completely independently determined system parameters, a prerequisite which was rarely met in field case studies.

2.8. MODEL EVALUATION CRITERIA

There is a need to evaluate the usefulness of watershed models and to evolve standards or criteria to compare the performance of the models. For conceptual models; (1) Percentage Absolute Error in peak sediment flow rates (PAE), (2) Absolute Prediction Error (APE), (3) Integral Square Error (ISE), (4) Correlation coefficient (R) and (5) Coefficient of Efficiency (CE) have been recommended as basis for evaluation criteria.

Materials and Methods

MATERIALS AND METHODS

The proposed-study deals with the development of a conceptual sediment yield model corresponding to Muskingum routing equation for Thuthapuzha drainage basin. Linearity and time invariance are considered as the basis for the development of this model. The model is based on the spatially lumped form of the continuity equation and the storage discharge relationship. These provides useful results, efficiently and economically for some hydrological problems. It contains parameters, some of which may have direct physical significance and can therefore be estimated by using concurrent observations on input and output. As the modelling involves number of computational steps, the model is written in FORTRAN language.

3.1. MATERIALS

From the inventory point of view, the 486 computer and programme written in FORTRAN 77 are the major computational support materials. A real subwatershed viz., Thuthapuzha and the observations made in the watershed are the major calibration support materials.

3.2. DESCRIPTION OF THE STUDY AREA

The Bharathapuzha basin is the largest west flowing river basin that drains into the Arabian sea of Kerala State. This basin is bounded in the east by Cauvery basin, in the west by the Arabian sea and in the south by Keecheri, Puzhakkal, Karuvannur and Chalakudy basins. The basin lies approximately between 10° 26' and 11° 13' North latitude and 75° 53' to 77° 13' East longitude. The basin is elongated in shape and finds its outlet into the Arabian sea. The total drainage area of the basin is 6186 sq.km., out of which nearly 71 percent lies in the Kerala state. The statewise distribution of drainage area is given in table 1.

TABLE 1 STATEWISE DISTRIBUTION OF BHARATHAPUZHA BASIN

Name of State	Drainage area	% of total
Tamilnadu	1786	29
Kerala	4400	71
Total	6186	100

The Bharathapuzha or Ponnani river, as it is called in the lower reaches rises in the eastern slopes of Anamalai hills of the Western Ghats at an elevation of 2250 m above msl and flows in the north westerly direction in the Pollachi taluk of the Coimbatore district in Tamilnadu. Fig.1 shows the location map of Bharathapuzha basin with respect to Kerala.

The Gayathripuzha, the Chitturpuzha (Kannadi or Amaravathi), the Kalpathipuzha and the Thuthapuzha are the four main tributaries of Bharathapuzha basin (fig. 2). Of which the Thuthapuzha drainage basin is selected for the present study.

The Thuthapuzha drainage basin (fig. 3) in the Ottapalam taluk of Palaghat district is one of the four major tributaries of Bharathapuzha basin comprising an area of 940 sq.km. (catchment area up to site) lying in 76° 11' 50" longitude and 10° 53' 50" latitude of geographical coordinates. The Thuthapuzha originates from the Silent Valley hills and after a circuitors course, joins the main river about 2km, from Pallipuram railway station. The

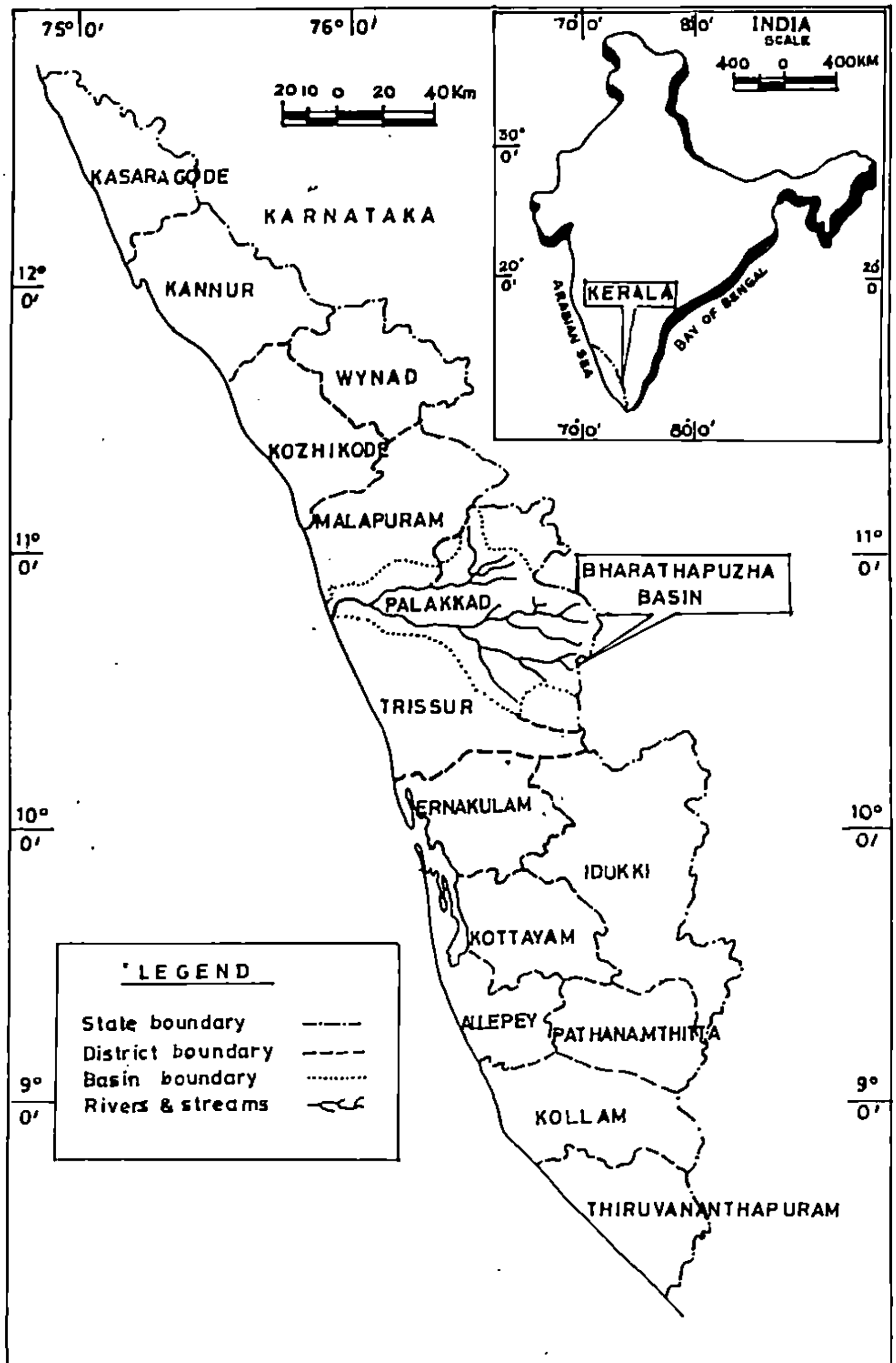


FIG1 LOCATION MAP OF BHARATHAPUZH BASIN WITH RESPECT TO KERALA STATE

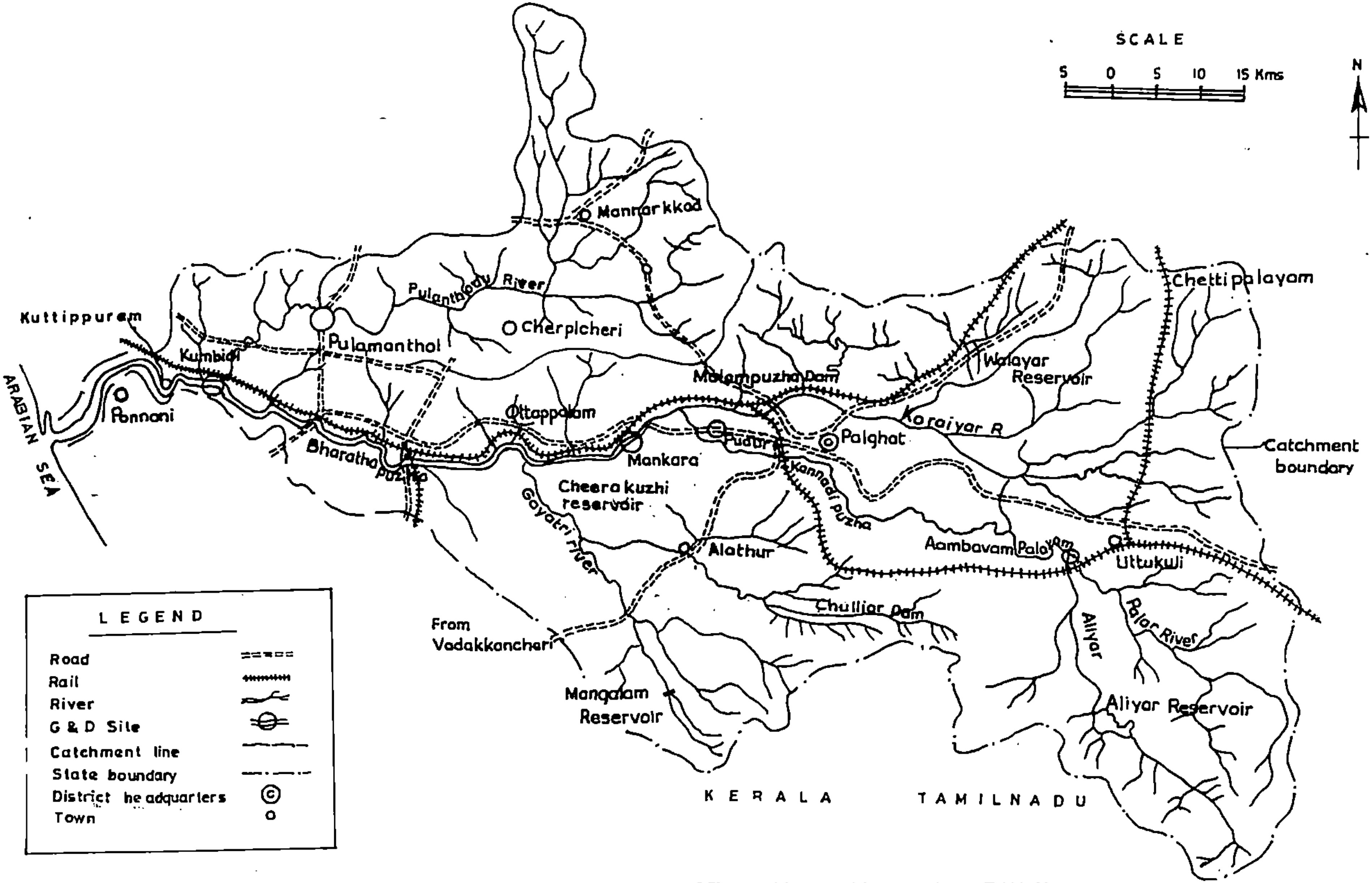


FIG. 2 BASIN MAP OF BHARATHAPUZHA RIVER

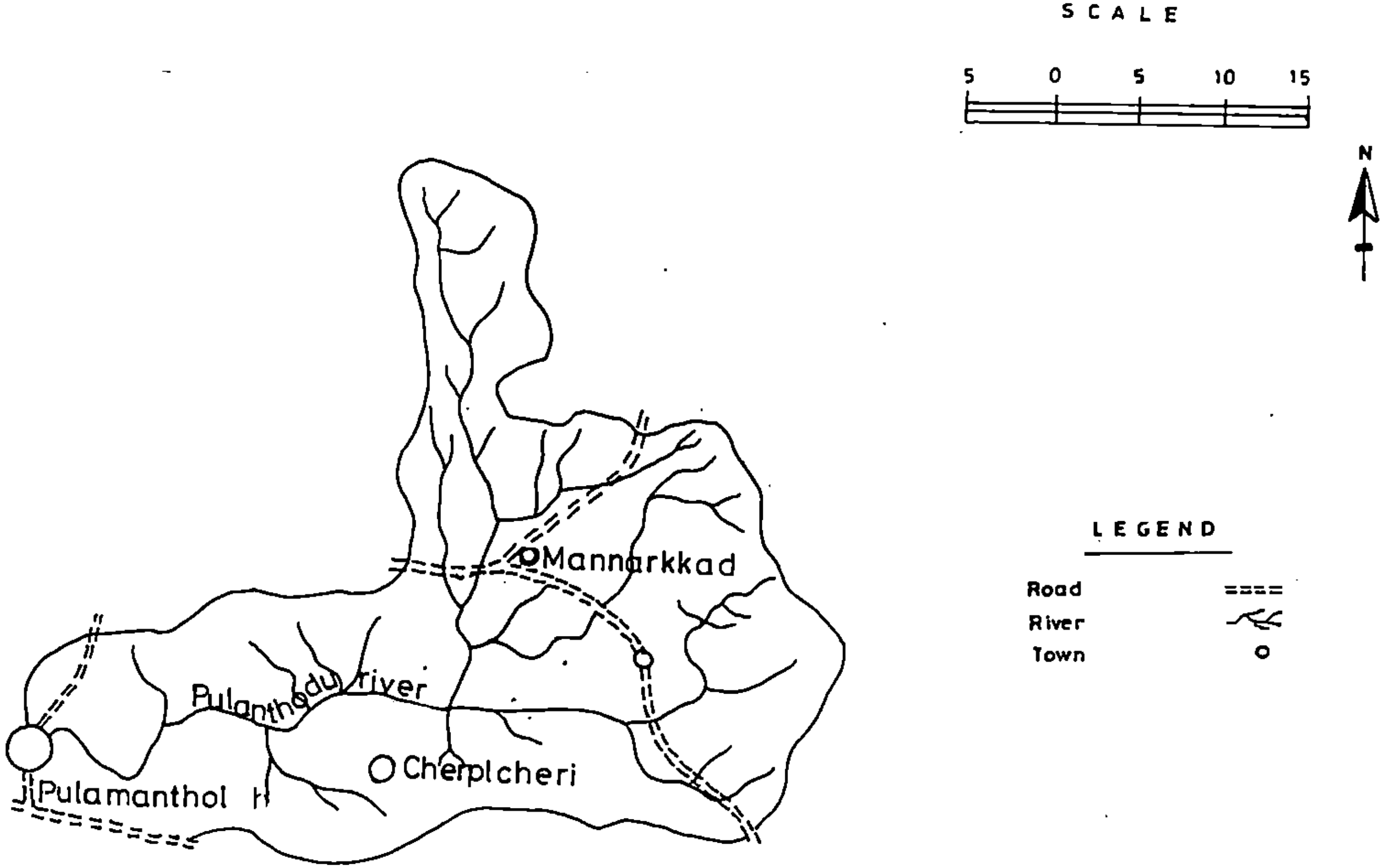


FIG 3 BASIN MAP OF THUTHAPUZHA DRAINAGE BASIN

important streams which feed Thuthapiuzha are the Kunthipuzha, the Ambankadavu and the Thuppanadpuzha. The Kanjiramukku thodu is also included in this basin.

Since the basin is located in tropical region, the temperature varies with season. The basin experiences two distinct monsoons namely, the South West (June-Aug) and North East (Sept-Nov). Ninety percent of the annual rainfall is obtained during these two monsoons. The basin receives copious rainfall during the South West monsoon as it lies in the rainshed regions of Wesern Ghats and accounts for about 60 percent of the annual rainfall. The rainfall varies from 2000 mm to 2800 mm in the midland to 3000 mm in the highland region.

3.2.1. TOPOGRAPHIC CHARACTERISTICS

The Thuthapuzha drainage basin is leaf shaped, having a drainage area of 940 sq.km up to the site and sloping from north to south in high land and east to west in mid land. The slope varies from 0.5 % to 18%. The elevation of the basin varies from 1800 m near the northern ridge to 50m at the gauging station above mean sea level.

3.2.2. PHYSIOGRAPHIC CHARACTERISTICS

Physiographically the Thuthapuzha drainage basin can be divided into two natural zones, the mid land and high land. These zones form parallel belts running across the width of the basin. The undulating midland with lateritic formation is characterized by a number of elas or small cultivated watersheds which are peculiar to the Kerala region. A number of low laterite hills in this region are interspersed with paddy fields, coconut and areacanut groves. Most of the reserve forests of the basin are situated in the high land region. The Silent Valley forest area is situated in this region.

3.2.3. GEOLOGICAL FEATURES

Geologically, the major rock formations of the Thuthapuza drainage basin may be classified into four groups: (i) crystalline rocks of Archaean age, (ii) sedimentary rocks of Tertiary age, (iii) laterite capping over crystallines and sedimentary rocks and (iv) recent and sub recent sediments forming the low-lying areas and river valleys.

3.2.4. SOIL AND LAND UTILIZATION

The mid land is characterised by laterite interspersed with patches of brown hydromorphic soils and the forest loams occur in the high lands. The major land utilization of the basin includes forest land, grass land, cultivated land and barren land. The forests of the basin may broadly be classified into wet evergreen, semi evergreen, moist decidious and temporate shola.

3.3.HYDROLOGIC INSTRUMENTS, MEASUREMENT AND DATA COLLECTION

The Central Water Commission named the Thuthapuzha as Pulanthode river and coded as KRAOOG 4. The CWC started to collect sedimentation data at Pulamanthole (gauging station of Pulanthode river) from 1986 onwards. Hydrological equipments such as current meter, fish weight head phone assembly, wading rod, sounding rod, suspension cable, automatic revolution counter and FRP boat with accessories were installed to monitor the sediment flow more accurately. The details of the silt monitoring station at Pulamanthole is given in Table 2.

TABLE 2 DETAILS OF SILT MONITORING STATION AT PULAMANTHOLE.

Sl No.	Particulars	
1.	Name of stream / river	Pulamanthode (Thuthapuzha)
2.	Name of basin	Bharathapuzha
3.	Name of sub-basin	Pulanthode
4.	Location of site	
	Village	Vilayur
	Taluk	Ottapalam
	District	Palghat
	State	Kerala
5.	Geographical co-ordinates	
	Longitude	76^{o} 11’ 50"
	Latitude	10^{o} 53’ 50"
6.	Catchment area upto site	940 km^2
7.	Length of stream upto site	
	from start	65 km
8.	Average height of bank	
	Right	8 m
	Left	6 m
9.	Nature of river bed	Sandy
10.	Nature of banks	Steep.

3.3.1. MEASUREMENT OF HYDROLOGICAL DATA

3.3.1.1. RAINFALL MEASUREMENT

The daily rainfall data of the basin was collected from the Office of the Superintending Engineer, Field Studies Circle Office, Hydrology Sub Division Thrissur. The name and location of rain gauge stations considered are shown in Fig.4. Rainfall measurement was done by non-recording raingauges.

3.3.1.2. RUNOFF MEASUREMENT

The runoff was measured by multiplying the cross sectional area of the flow with mean velocity of flow. The area of cross section of flow has been determined by sounding and plotting the profile. The velocity of flow may be recorded by using cup type current meter as per IS:3918 - 1966 by boat with cable way or without board engine at higher stages and by wading at lower stages. Further, when the velocity observation by current meter are not possible, float observations are carried out.

On the days when the runoff observations are not conducted due to holidays or any other reasons, runoff have been estimated from the established stage discharge relation of the current year against 0800 hours stage. Fig 5 shows the cross section at stream gauge line pre - monsoon 1989.

3.3.1.3. MEASUREMENT OF SUSPENDED SEDIMENT

Suspended sediment observations are simultaneously made along with the discharge observations daily. Sampling is done from boat or by wading. The Punjab type bottle sampler is used for collecting the sediment sample. The collection is done at 0.6m depth

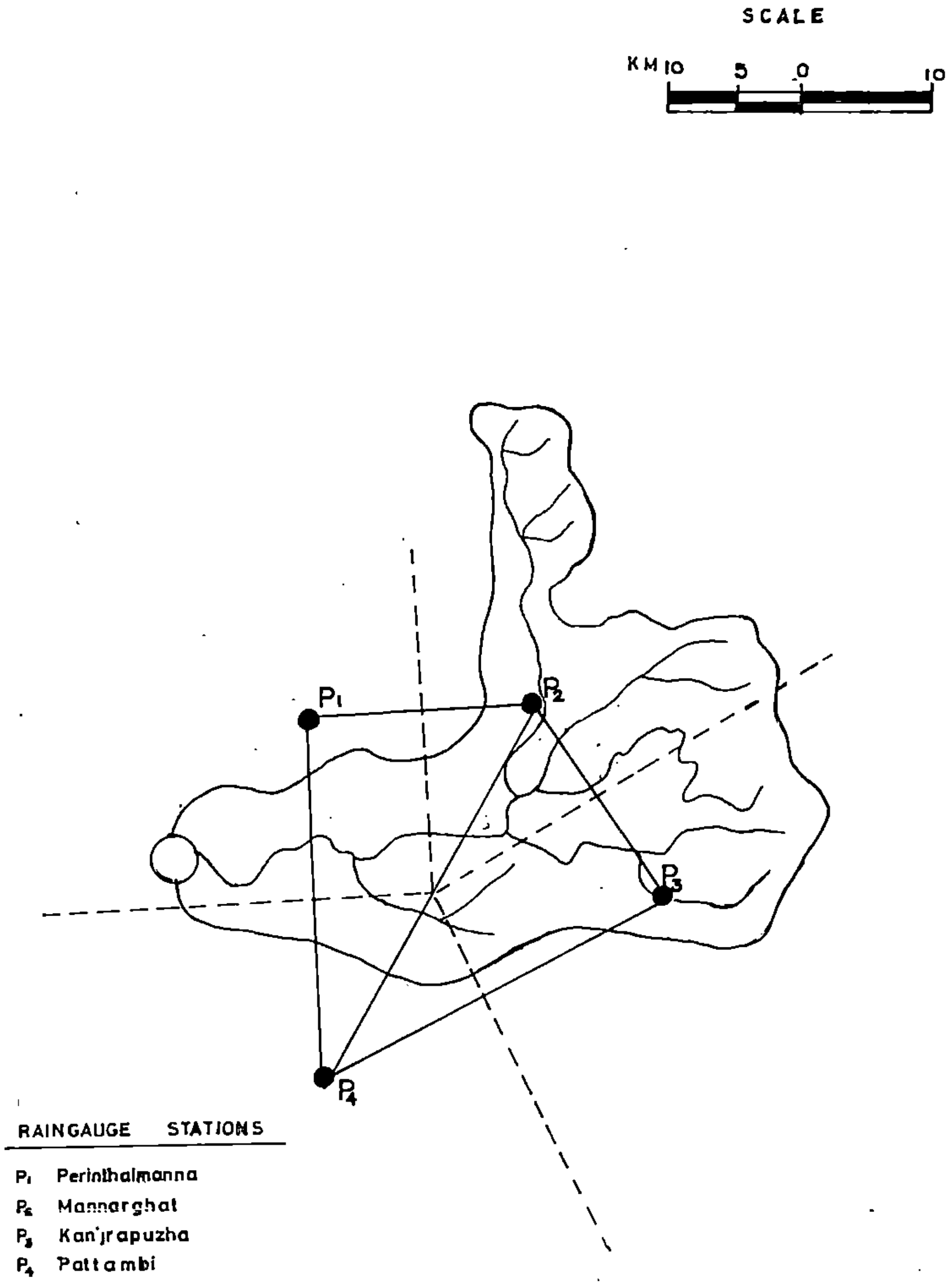


FIG 4 THUTHAPUZHA DRAINAGE BASIN SHOWING THEISSEN POLYGONS

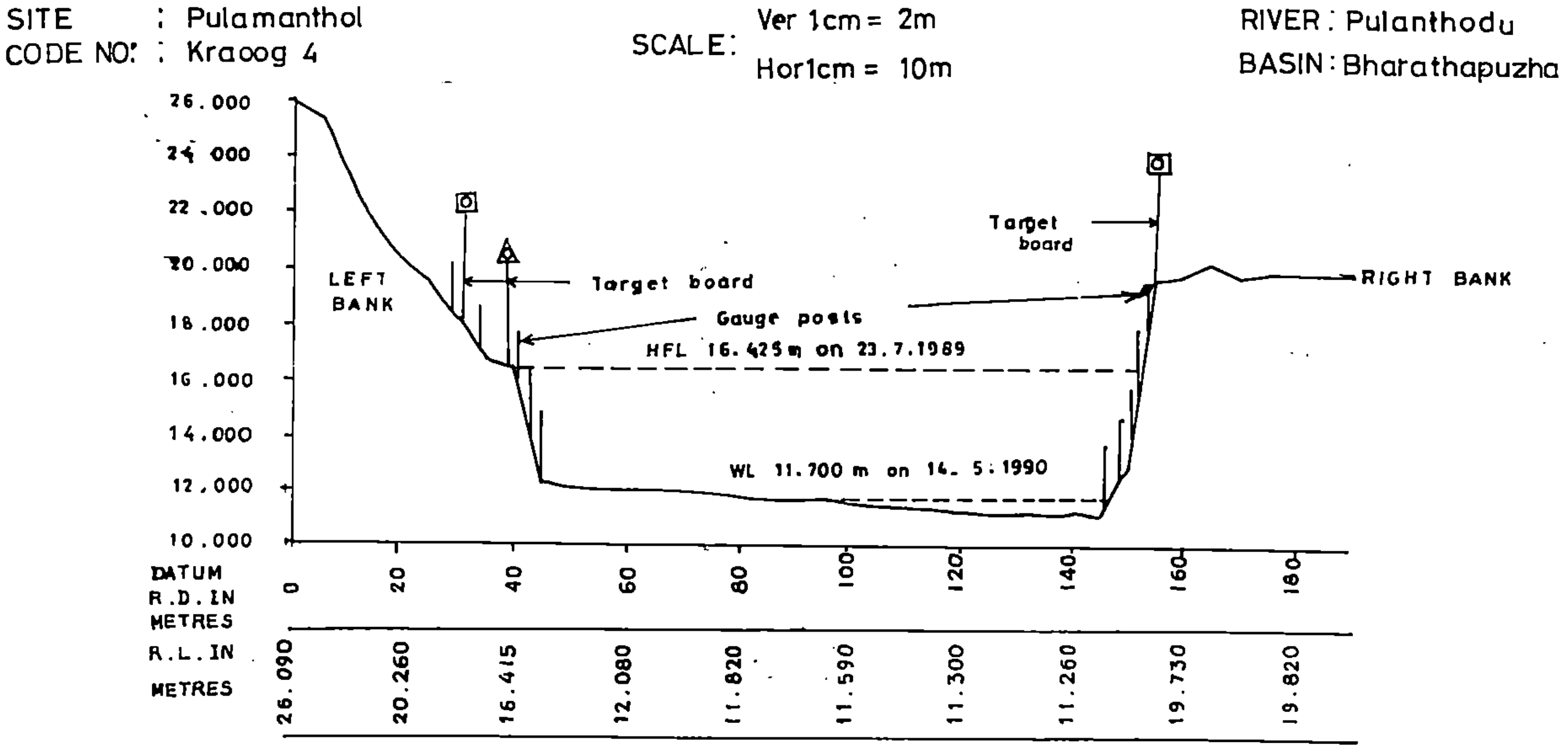


FIG 5 CROSS SECTION AT S/G LINE PRE MONSOON 1989

from various verticals along the cross sections of the river. The verticals are grouped into three or more composite sections for the purpose of analysis of sediment. For analysis of fine grade the sediment samples are combined in to a single group and analysed.

The sediment samples thus collected from flowing channels are analysed for the three grades of sediment viz, coarse, medium and fine grades. Coarse and medium grades are separated by the sieving process and fine grade sediment by filtration. Gradewise concentration is determined by the gravimetric method.

3.3.2. COLLECTION OF HYDROLOGIC DATA

The data on general description of Thuthapuzha drainage basin ie, location and climatic characteristic, topographic features, soils, land use pattern and crops were collected from Centre for Water Resources Development and Management (CWRDM), Kozhikode. The hydrologic data related to rainfall was obtained from the office of the Superintending Engineer, Field Studies Circle Office, Hydrology sub Division, Thrissur and runoff and sediment concentration were obtained from the Central Water Commission (CWC), Cochin for hydrologic analysis. The storm events for the year 1986 - 1993 were considered for the present study.

3.4. ANALYSIS OF HYDROLOGIC DATA

The successful field testing of most techniques for predicting sediment yield depends entirely upon availability of a reliable watershed data base of effective rainfall, direct runoff and sediment flow. To obtain the effective rainfall, runoff and sediment hydrographs for the development of the mathematical models, the rainfall, runoff and suspended sediment data of selected storm events of Thuthapuzha drainage basin were analysed.

3.4.1. ANALYSIS OF RUNOFF DATA

3.4.1.1. SELECTION OF STORM EVENTS

Thirty seven storm events for Thuthapuzha watershed satisfied the following criteria were selected for development of total runoff hydrographs.

(i) the storms which were relatively isolated
(ii) the storms which exhibited approximate uniform areal distributions over the entire watershed
(iii) the storage hydrographs which had a well defined rising limb culminating in a single peak followed by sustained recession
(iv) all stage hydrographs for the same watershed showing approximately the same period of rise.

3.4.1.2. TOTAL RUNOFF HYDROGRAPHS

The water constitutes a stream flow may reach the stream channel, through any of the several paths from the point where it first reaches the earth as precipitation. Some water flows over the soil surface as surface runoff and reaches the stream soon after the occurence as runoff. Some water infiltrates through the soil surface and contributes to sustained flow of the stream during periods of dry weather.

In many situations the stream flows response with time at a point in a stream, during a storm occurence is known as a hydrograph. In addition, the ordinates of the hydrograph will be proportional to the volume of overland flow produced as an integral expression of the physiographic and climatic characteristics that govern the relations between rainfall and runoff of a particular watershed.

The discharge (rate of flow) passing the gauging station was determined by multiplying the cross-sectional area of the flow section at right angles to the direction of flow by the average velocity of water (flow) given as

Discharge = Area x Velocity

$$Q = a \times v \qquad (6)$$

in which

Q= discharge rate, m^3/s

a= area of cross section of the flow, m^2 and

v= velocity of flow, m/s.

The following formula was used to determine the total runoff in m^3/day

$$Q_t = 86400\,Q \qquad (7)$$

where

Q_t = total runoff in m^3/day

The total runoff hydrographs for the storm events of Nov 4-11 ,86 and July 18-25, 91 for Thuthapuzha drainage basin are shown in Fig.6 and 7 and Tables 3 and 4.

3.4.1.3. DETERMINATION OF BASEFLOW

The total runoff may be divided into two parts; direct runoff and baseflow and both parts may contain certain amount of the surface runoff. The direct runoff hydrograph was obtained by separating the baseflow from the total runoff hydrograph. A number of empirical and conventional methods were used for baseflow separation. For practical hydrograph analysis, the baseflow separation is made usually in an arbitrary manner and it is not significant even to consider the exact amount to be included or excluded from the base flow.

Base flow separation method suggested by Chow (1964), was used for separating the base flow from the total runoff hydrograph. The base flow was separated by the extension of the previous ground water recession curve from the *rising* point A of the hydrograph, to a point B which was arbitrarily taken (about 1/10 of the base of the hydrograph) beyond the time of peak flow. Fig.6 and 7 illustrate this method of base flow separation used in the study. The curve AB was inclined towards the right at a slowly decreasing rate. The ground water recession curve of the hydrograph was extended back from point D towards peak and point C was marked on the extension line in the middle of the line joining points B and D. Between points B and C a smooth curve with a convex curvature upward was intoduced. The curve ABCD represents the entire baseflow of the hydrograph.The Fig. 6 & 7 shows the separation of the base flow for the storm events Nov 4 - 11, 1986 and July 18-25, 1991

3.4.1.4. DIRECT RUNOFF HYDROGRAPHS

For a given storm event, the volume of direct runoff was detemined after separating the baseflow from the total runoff. The ordinates of direct runoff hydrograph were determined by deducting the baseflow from total runoff hydrograph using the following relationship.

$$Qdi = Qti - Qbi \qquad (8)$$

where

Qdi = direct runoff in m^3/day

Qti = total runoff in m^3/day

Qbi = baseflow in m^3/day

i - refers to the time at which runoff values were measured.

The total direct runoff due to storm was determined by

$$Qv = (D/24) \sum_{i=1}^{n} 1/2\,(Qdi + Qd(i+1)) \qquad (9)$$

where

Qv = runoff volume or total direct runoff due to storm in m^3

D = The time differene between ith and (i+1)th ordinates, in hours.

The runoff depth is determined by

$$RD = Qv/A \qquad (10)$$

where

RD = runoff depth in mm

A = area of catchment in km^2

The direct runoff hydrographs for the storm events of Nov.4- 11, 1986 and July 8-25, 1991 are shown in Figs. 8 and 9 and the corresponding values of these direct runoff hydrographs are given in Tables 3 and 4.

Table 3

COMPUTATION OF DIRECT RUNOFF HYDROGRAPH AND DIRECT SEDIMENT GRAPH FOR THE STORM EVENT OF NOV 4-11,1986

Date	Total Runoff (m^3/day)	Base Flow (m^3/day)	Direct Runoff Flow (m^3/day)	Total Sediment Flow (t/day)	Base Sediment Flow (t/day)	Direct Sediment Flow (t/day)
4	58.92	58.92	0.00	18.88	18.88	0.0
5	65.92	58.92	7.00	43.51	18.88	24.63
6	135.56	58.92	76.64	191.14	18.88	172.26
7	207.19	58.92	148.27	366.73	18.88	347.85
8	152.93	61.84	91.09	235.51	22.50	213.01
9	84.33	61.84	22.49	46.38	30.66	15.72
10	65.16	61.84	3.39	32.55	30.66	1.89
11	61.84	61.84	0.0	30.66	30.66	0.0

Table 4

COMPUTATION OF DIRECT RUNOFF HYDROGRAPH AND DIRECT SEDIMENT GRAPH FOR THE STORM EVENT OF July18-25, 1991

Date	Total Runoff (m^3/day)	Base Flow (m^3/day)	Direct Runoff Flow (m^3/day)	Total Sediment Flow (t/day)	Base Sediment Flow (t/day)	Direct Sediment Flow (t/day)
18	44.65	44.65	0.0	9.38	9.38	0.0
19	66.33	44.65	21.68	15.89	9.38	6.51
20	167.36	44.65	122.71	257.73	9.38	248.35
21	302.23	44.65	257.58	411.03	9.38	401.65
22	230.95	50.30	180.65	258.66	15.20	243.46
23	100.39	57.49	42.90	106.41	27.59	78.82
24	60.89	57.49	3.40	50.72	27.59	23.13
25	57.49	57.49	0.0	27.59	27.59	0.0

3.4.2. ESTIMATION OF EFFECTIVE RAINFALL

3.4.2.1. EFFECTIVE RAINFALL HYETOGRAPHS

As the catching area of a raingauge is very samll compared to the areal extent of a storm, to get a representative picture of a storm over a catchment there should be sufficient number of raingauges in the catchment area. On the otherhand, economic considerations to a larger extent and other consideratins such as topography, accessibility etc. to some extent restrict the number of gauges to be maintained. As the selected watershed having an area of 940 km^2, the rainfall data were collected from four stations in and around the watershed. To convert the point rainfall values at various stations into an average value over the catchment, the Thiessen-Polygon method was used. These average values of rainfall was considered for computing the hyetographs. For the watershed, thirty seven storm events which resulted in single peaked runoff hydrographs were selected for analysis.

3.4.2.1.1. THIESSEN-POLYGON METHOD

If some gauges are considered more representative of the area in question than others, then relative weights may be assigned to the gauges in computing the areal average. The Thiessen method assumes that at any point in the watershed the rainfall is the same as that at the nearest gauge. Hence the depth recorded at a given gauge is applied to a distance halfway to the next station in any direction. The relative weights for each gauge are determined from the corresponding areas of application in a Thiessen polygon network, the boundaries of the polygon being formed by the perpendicular bisectors of the line joining adjacent gauges, if there are J gauges, and the area within the watershed assigned to each is Aj , and Pj is the rainfall recorded at the jth gauge, the areal average precipitation for the watershed is

$$P = 1/A \sum_{j=1}^{J} Aj\ Pj \qquad (11)$$

where the watershed area

$$A = \sum_{j=1}^{J} Aj \qquad (12)$$

The Thiesen Polygons for the Thuthapuzha drainage basin is shown in Fig. 4.

In hydrograph analysis involving storms of highly non uniform rainfall distribution, it may be necessary to separate the effective rainfall from abstractions on a hyetograph in a way similar to the baseflow separation on a hydrograph. The rainfall excess and the duration of the rainfall excess were obtained from the rainfall hyetograph by subtraction of the absolute loss to the system ie. portion of rainfall which never emerges as runoff at the outlet point. The duration of the effective rainfall is the time elapsed between the beginning and end of the effective rainfall. Here, a simple Ø index (infiltration index) method was utilized for determining the rainfall excess.

3.4.2.2. ESTIMATION OF Ø INDICES

This method is based on the assumption that, for a specified storm with given initial conditions, the rate of basin recharge remains constant throughout the storm period. The Ø index is an average rate of infiltration derived from a time intensity graph of rainfall, in such a manner that the volume of rainfall excess will be equal to the volume of storm runoff. The Ø index is the simplest of the infiltration indices and represents the combined effect of interception and depression storage, as well as infiltration.

$$\phi \text{ index} = \frac{\text{Basin Recharge}}{\text{Duration of Rainfall}} \qquad (13)$$

Effective rainfall or excess rainfall was determined by the following calculations

$$I = TR - RD \qquad (14)$$

$$\phi \text{ Index} = I/te \qquad (15)$$

$$ER = TR - \phi \times te \qquad (16)$$

where

I = Infiltration in mm

TR = total rainfall in mm

te = duration of rainfall excess in days

ER = Effective rainfall or excess runoff in mm

RD = runoff depth in mm

The hyetograph and ϕ indices for the storm events of Nov.4-11, 1986 and July 18-25, 1991 are shown in Figs. 6 and 7.

3.4.3. SEDIMENT DATA ANALYSIS

In many instances the wash load (suspended load) comprised 90 to 95 % of the total sediment yield. Hence this study is limited solely to measured suspended load produced in the watershed. For the development of the mathematical models for predicting sediment yield, daily data of suspended sediment yield at the gauging station is required. The temporal data of sediment concentration in gm/litre of the selected storm events was converted into tonnes/day by the following equation.

$$Sti = Sc \times Qti \times 10^{-3} \qquad (17)$$

where

Sti = Sediment discharge in t/day

Sc = Sediment concentration in gm/litre

Qti = Total runoff in m^3/day

3.4.3.1. TOTAL SEDIMENT GRAPHS

The total sediment graphs were developed on the assumption that the time to peak for total sediment graphs and runoff hydrographs are equal. The daily values of total suspended sediment flow rates for the storm events of Nov, 4-11, 1986 and July 18-25, 1991 are given in Tables 3 and 4 and the total sediment graphs for these storm events are shown in Figs. 6 and 7.

3.4.3.2. DETERMINATION OF BASE SEDIMENT FLOW

The baseflow for the sediment graph was assumed to be the sediment flow prior to the beginning of the rise of sediment graph for a particular storm event. The baseflow separation techniques for sediment graph is same as that of the runoff hydrograph base flow separation. The base sediment flow separation for the storm events of Nov,4-11, 1986 and July 18-25, 1991 are shown in Figs. 6 and 7. The temporal base sediment flow values for these storm events are given in Tables 3 and 4.

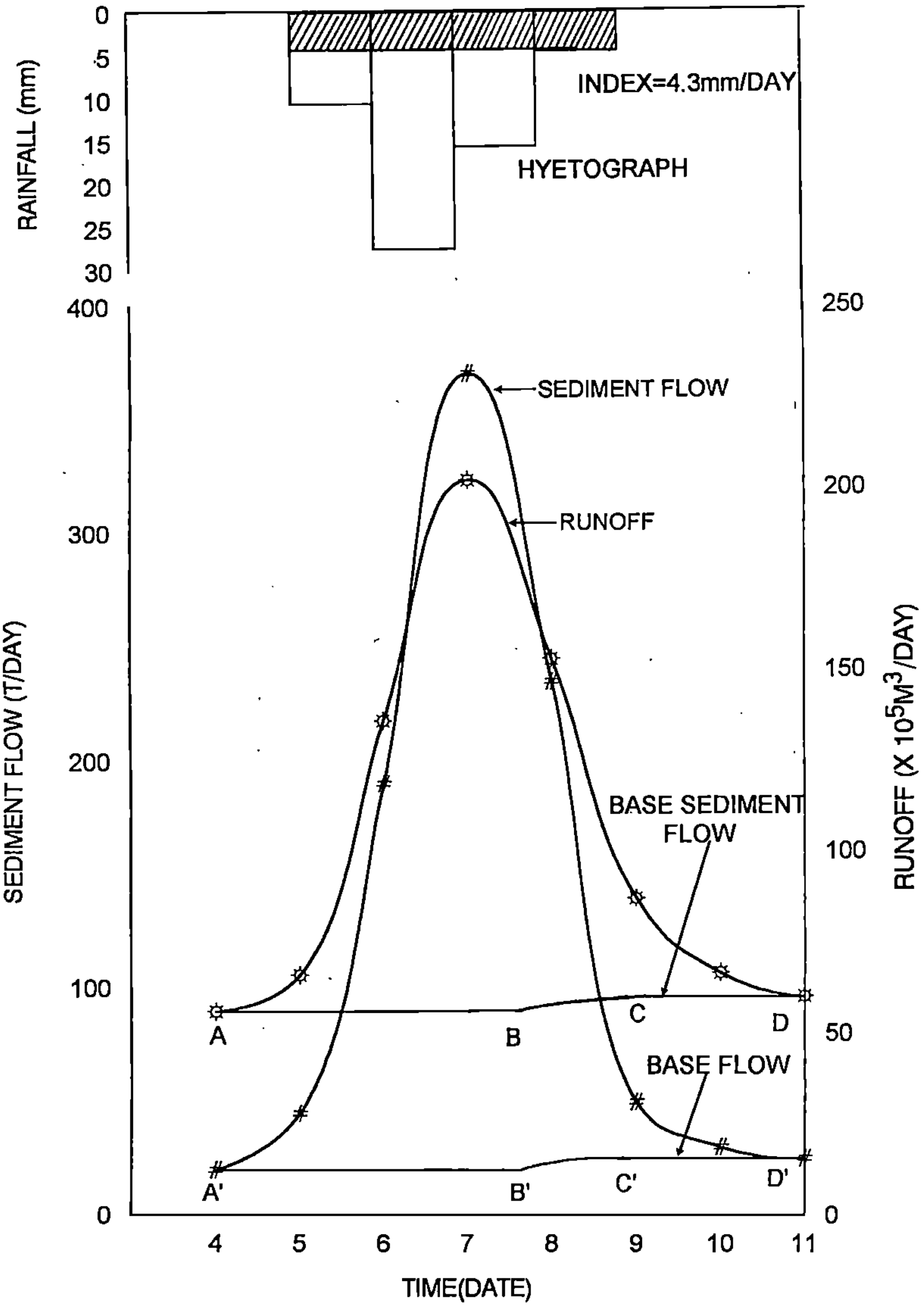


FIG 6. HYETOGRAPH, RUNOFF HYDROGRAPH AND SEDIMENT GRAPH FOR THE STORM EVENT OF NOVEMBER 4 -11, 1986

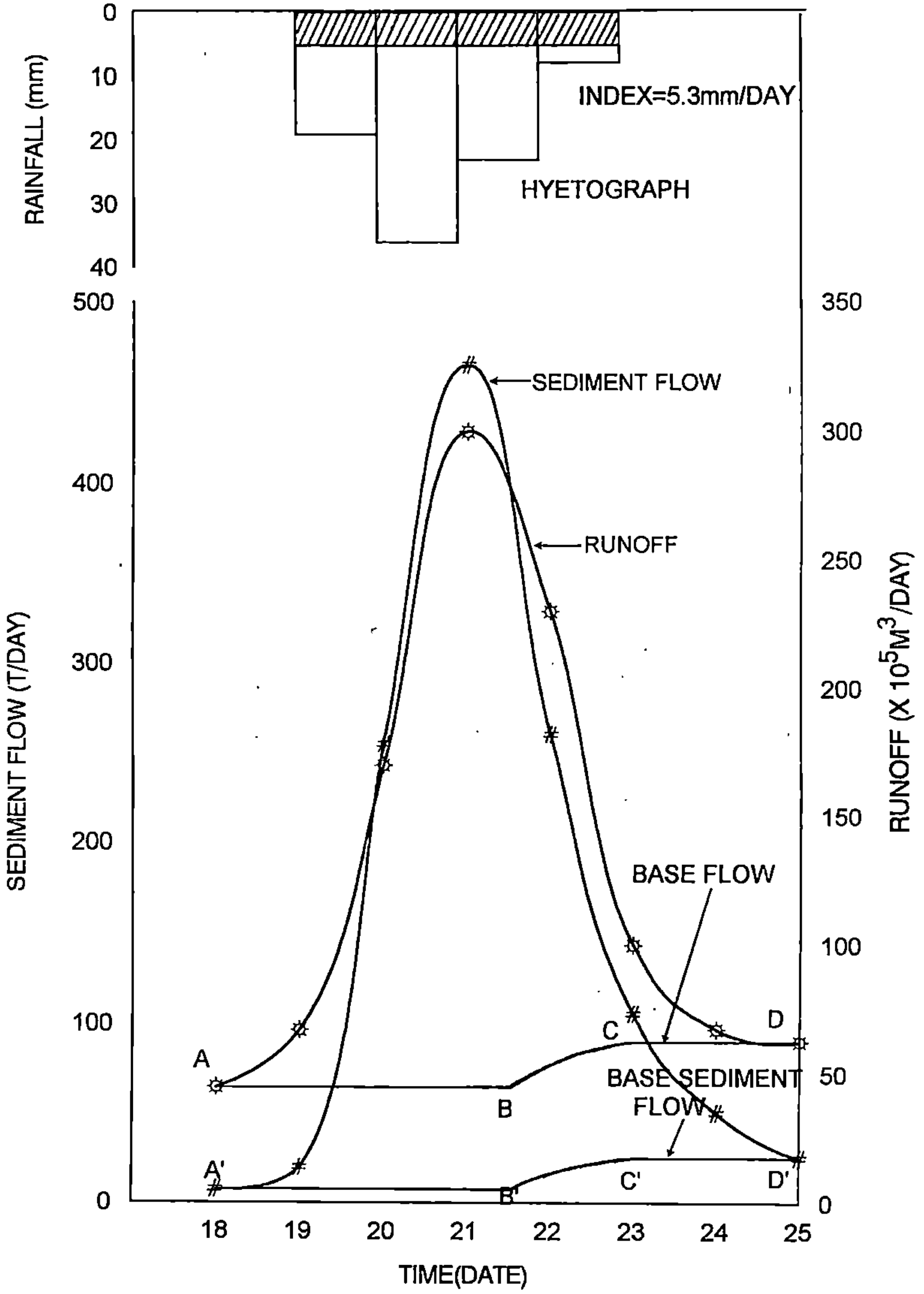


FIG 7. HYETOGRAPH, RUNOFF HYDROGRAPH AND SEDIMENT GRAPH FOR THE STORM EVENT OF JULY 18-25, 1991

3.4.3. DIRECT SEDIMENT GRAPHS

The direct sediment flow rates at daily intervals for the storm events considered were calculated by subtracting the base sediment flow ordinates from the corresponding ordinates of the total sediment graph using the following relationship.

$$Sdi = Sti - Sbi \tag{18}$$

where

Sdi = direct sediment discharge in t/day

Sti = total sediment discharge in t/day

Sbi = base sediment discharge in t/day

i = refers to the time at which sediment discharge values are measured.

The direct sediment graph for the storm events of Nov, 4-11, 1986 and 18-25, July, 1991 are shown in Figs. 8 and 9 and the values of direct sediment flow for these storm events are given in Table 3 and 4 respectively.

Once the observed total sediment graphs were graphically converted to direct sediment graphs by deducting the base sediment flow, the following calculations were performed.

$$SPR = D/24 \sum_{i=1}^{n} [1/2\,(Sdi + Sd\,(i+1))] \tag{19}$$

$$HV = ER \times Am \tag{20}$$

where

D = Time in hours

ER = Effective rainfall in mm

SPR = Total volume of sediment produced in tonnes

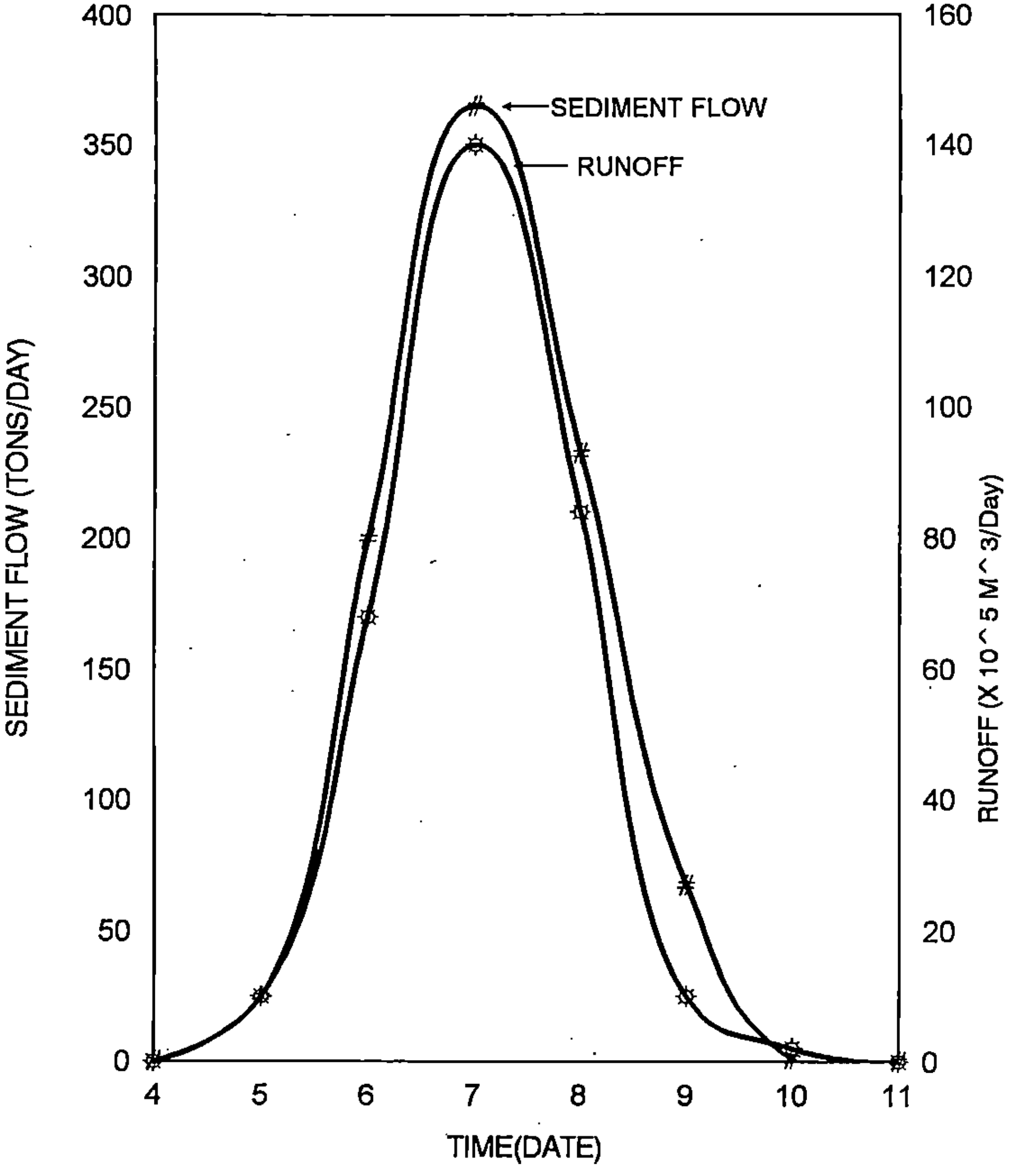


Fig 8 **DIRECT RUNOFF HYDROGRAPH AND DIRECT SEDIMENT GRAPH FOR THE STORM EVENT OF NOVEMBER 4-11, 1986**

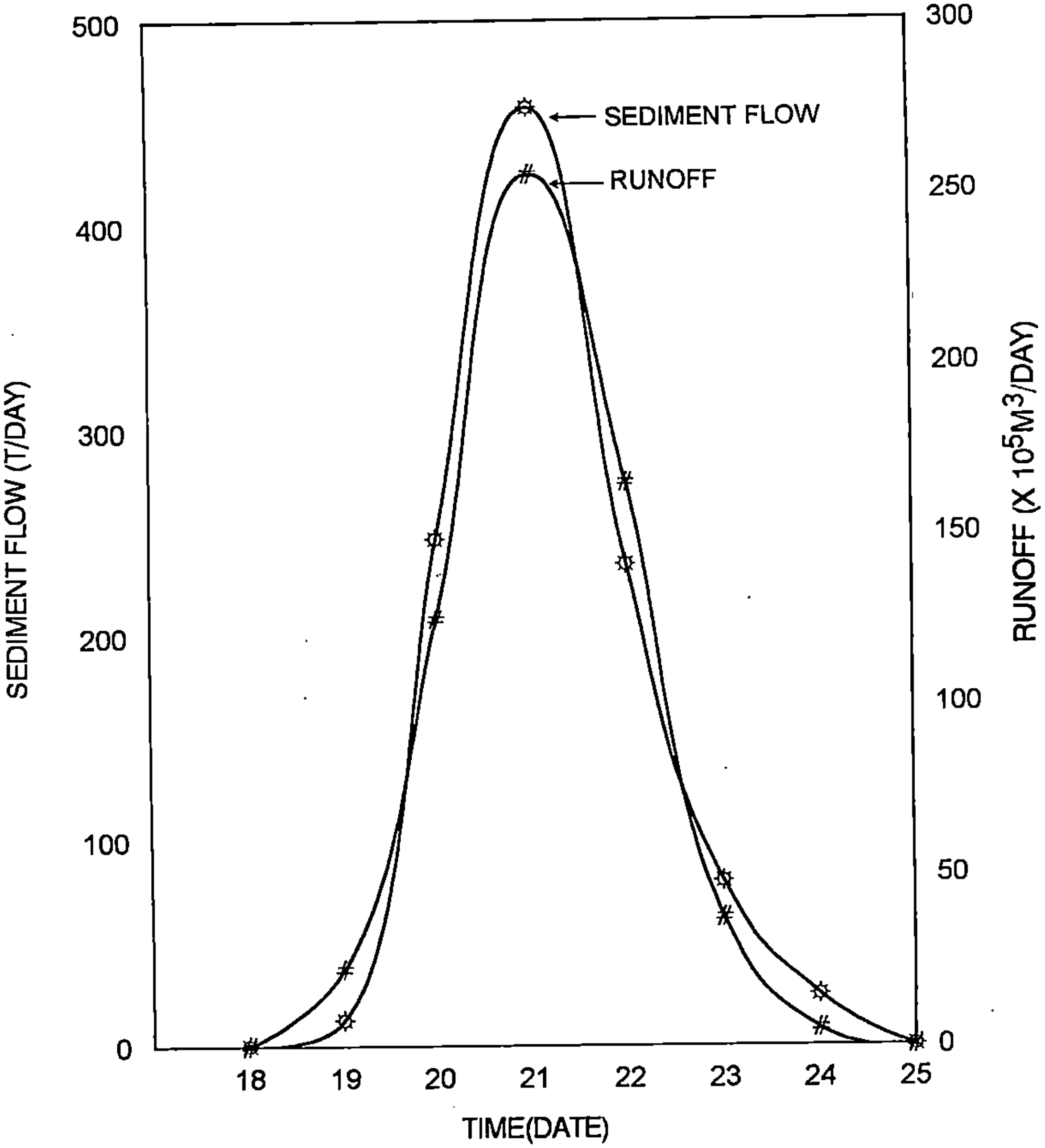


FIG 9. DIRECT RUNOFF HYDROGRAPH AND DIRECT SEDIMENT GRAPH FOR THE STORM EVENT OF JULY 18-25, 1991

HV = Volume of hyetograph in km^2 mm.

Am = Area which mobilize the sediment in km^2

By equating the total volume of hyetograph with sediment production rate, the area which mobilizes the sediment could be calculated which was used to compute the mobilized sediment (t/km^2).

3.5. DEVELOPMENT OF THE MODEL

Sediment graph prediction can be achieved by employing a system approach. The spatial variation of sediment discharged into waterways and the detailed transport process can be lumped together into a single system. The sediment producing factors such as rainfall and runoff can be treated as inputs to the system and the sediment yield becomes the system output.

In hydrology, a system is referred to as linear if it satisfies the properties of proportionality and superposition. A system is said to be time invariant when its parameters do not change with time. In otherwords, the form of output depends only on the form of the input and not on the time at which the input is applied.

The shape of the hydrograph from a drainage basin is dependent on runoff travel time through the basin and on the shape and storage characteristics of the basin. The same concepts also holds true for the sediment graph of the sediment flowing out in suspension with the runoff. Thus similar to the development of hydrographs in the development of sediment graphs, it is assumed that watershed storage of sediment also applies two functions to the sediment mobilized (equivalent to rainfall excess) in the watershed. The first is the translation of the sediment mobilized through the watershed and the second is its attenuation.

Translation represents the volume of sediment mobilized which will be carried out of the watershed and arrived at the outlet. The sediment graph thus obtained does not provide for the storage properties of the watershed. To overcome this deficiency it is assumed that a linear reservoir is hypothetically available at the watershed outlet to provide the requisite attenuation.

Thus a method of estimating sediment graph ordinates based on a combined approach of translation and attenuation has been developed using Muskingum routing equation. The mobilized sediment can be routed through on elementary storage and the outlet commensurate with the volume of channel storage in the reach.

The Muskingum method is a two parameter lumped linear model which consists of a spatially lumped form of continuity equation.

$$d(Ss)/dt = Sm - Sd \qquad (21)$$

and a linear storage discharge relationship, given by

$$Ss = K\,[xSm + (1-x)\,Sd]$$

where

Ss = storage in t

K = storage constant for the sediment in day

Sm = mobilized sediment in t/km^2

Sd = sediment flow rate in t/day

Mobilized sediment and sediment flow rates are analogous to Muskingum's inflow and outflow respectively.

For convenience, it is commonly assumed that the average of flows at the beginning and the end of a short time period Δt (routing period or discretization time interval) equals the average flow during the period. Expressing equation (21) in finite difference form and then substituting in equation (22) we get.

$$[(Sm(t-1) + Sm(t))/2]\,\Delta t - [(Sd(t-1) + Sd(t))/2]\,\Delta t$$

$$= K[x((Sm(t) - Sm(t-1)) + (1-x)(Sd(t) - Sd(t-1))] \qquad (23)$$

Rearranging and solving for Sd (t)

$$Sd(t) = b_1\,Sm(t) + b_2\,Sm(t-1) + b_3\,Sd(t-1) \qquad (24)$$

where

$$b_1 = (-kx + 0.5\,\Delta t)/(k-kx + 0.5\,\Delta t) \qquad (25)$$

$$b_2 = (kx + 0.5\,\Delta t)/(k-kx + 0.5\,\Delta t) \qquad (26)$$

$$b_3 = (k-kx - 0.5\,\Delta t)/(k-kx + 0.5\,\Delta t) \qquad (27)$$

The coefficients b_1, b_2 and b_3 are such that

$$b_1 + b_2 + b_3 = 1 \qquad (28)$$

The equation (24) represents the linear Muskingum model of sediment flow.

3.6. PARAMETER ESTIMATION

The model can generally be represented in the following form

$$Sdi\,(t) = b_1\,Smi\,(t) + b_2\,Smi\,(t\text{-}1) + b_3\,Sdi\,(t\text{-}1) \qquad (29)$$

for i = 1,2,....n

Let e be the error between the observed and calculated sediment yield, then

$$e = Sdi(t) - [b_1\,Smi(t) + b_2\,Smi(t\text{-}1) + b_3\,Sdi(t\text{-}1)] \qquad (30)$$

for i= 1,2,....n

Let Z be the sum of the squarred error, then

$$Z = \sum_{i=1}^{n} [Sdi(t) - ((b_1\,Smi(t) + b_2\,Smi(t\text{-}1) + b_3 Sdi(t\text{-}1))]^2 \qquad (31)$$

To minimize Z,the objective function is

$$\text{Minimize } Z = \sum_{j=1}^{n} [Sdi(t)\text{-}(b_1\,Smi(t)\text{+}b_2\,Smi(t\text{-}1)\text{+}b_3\,Sdi(t\text{-}1))]^2 \qquad (32)$$

$$\text{Subject to } b_1 + b_2 + b_3 = 1 \qquad (33)$$

Equations (32) and (33) form a non linear optimization problem subject to one equality constraint. The mathematical technique of Lagrange Multipliers method convert this constraint optimization problem into unconstrained optimization problem.

3.6.1. LAGRANGE MULTIPLIERS METHOD

If the non linear programming problem composed of some differentiable objective function and equality side constraints, the optimization may be achieved by the use of Lagrange Multipliers. The method of Lagrange Multipliers is a systematic way of getting the necessary conditions for a stationary point.

$$\text{Minimize } Z = \sum_{i=1}^{n} [sdi(t) - (b_1\, Smi(t) + b_2\, Smi(t\text{-}1) + b_3\ sdi(t\text{-}1))]^2 \qquad (34)$$

subject to the constraint

$$b_1 + b_2 + b_3 = 1 \qquad (35)$$

To find the necessory and sufficient conditions for a minimum value of Z, a new function is formed by introducing a Lagrange Multiplier λ as

$$L(b_1,b_2,b_3,\lambda) = \sum_{i=1}^{n} [Sdi(t)\text{-}b_1 Smi(t)+b_2 Smi(t\text{-}1)+b_3 Sdi(t\text{-}1)]^2$$

$$- \lambda (b_1+b_2+b_3\text{-}1) \qquad (36)$$

The unconstrained function $L\,(b_1,b_2,b_3,\lambda)$ is called the Lagrange function and λ is an unknown constant called the Lagrange Multiplier.

The necessary and sufficient conditions for a minimum value of Z subject to $b_1+b_2+b_3\text{-}1 = 0$ are given by

$$\frac{\partial L\ (b_1,b_2,b_3,\lambda)}{\partial b_1} = 0$$

$$\frac{\partial L\ (b_1,b_2,b_3,\lambda)}{\partial b_2} = 0$$

$$\frac{\partial L\ (b_1,b_2,b_3,\lambda)}{\partial b_3} = 0 \qquad (37)$$

$$\frac{\partial L\ (b_1,b_2,b_3,\lambda)}{\partial \lambda} = 0$$

Eliminating λ from these equations, we get three equations in three u solving these three equations by Guass Jordan Elimination method we will out the approximate solutions of b_1,b_2,b_3. The schematic diagram of model shown in Fig.10.

3.7. COMPUTATION OF MOBILIZED SEDIMENT

The total amount of mobilized sediment during the storm event estimated, inorder to generate a sediment graph for a particular storm e the mobilized sediment during the storm event, a relationship between r and excess rainfall was developed. Thirty seven hydrographs and sedime at the gauging station on a storm basis were considered to develop the regression equation.

$$Sm = a\ (ER)^b$$

where

Sm = mobilized sediment in t/km^2

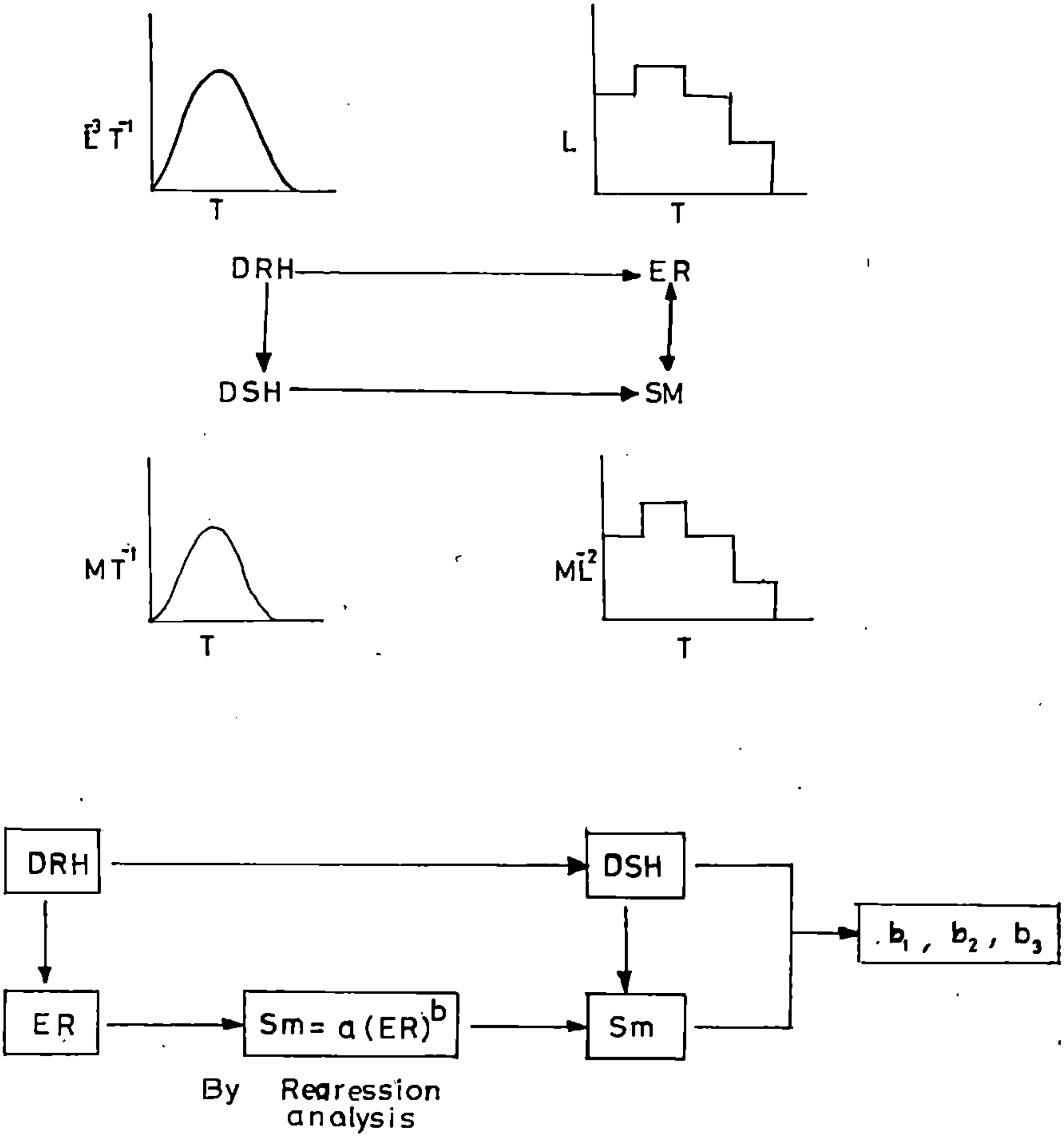


FIG 10 SCHEMATIC DIAGRAM OF MODEL DEVELOPMENT

ER = total excess rainfall during the storm in mm

a, b = constants

This approach entails the estimation of total mobilized sediment on the basis of known or predicted excess rainfall as an initial step, followed by the selection, based on duration, of an appropriate *sediment graph*.

3.8 DISCHARGE - SEDIMENT RATING CURVE

A rating curve for the discharge and sediment production rate (sediment concentration x runoff) was developed. From the rating curve we can find out the sediment production rate for a given discharge if the sediment concentration were not known or taken. Discharge and sediment concentration measured at the gauging station from the year 1986 to 1993 were considered for the development of the following form of regression equation.

$$y = a\,x^{b} \qquad (39)$$

where

y = Sediment production rate in ton/ day

x = discharge in M m^3/ day

a, b = constants

Results and Discussion

RESULTS AND DISCUSSION

In this chapter, the direct sediment flow graphs for various storm events will be regenerated by the mathematical model and will be compared with the observed sediment flow graphs, both qualitatively and quantitatively. The Muskingum sediment yield model will be verified by predicting some storm events which are not used in the development of the model. The relationships of mobilized sediment with effective rainfall, estimated sediment flow rates with observed sediment flow rates and estimated and observed sediment flow rates with effective rainfall and mobilized sediment on storm basis will also be described.

Forty storm events from 1986 to 1993 were selected to assess the accuracy of Muskingum sediment yield model for simulating direct sediment graphs. The data was divided into two sets; a calibration set and a prediction set. The data in the calibration set consisted of thirty seven events from the year 1986 to 1992 and was used for parameter estimation. The data in the prediction set consisted of events in the year 1993 which was used for model verification.

4.1. DEVELOPMENT OF THE MODEL

The Muskingum sediment yield model was developed based on the combined approach of translation and routing for simulating sediment graph for Thuthapuzha drainage basin. For this, mobilized sediment and sediment flow rate were taken as input and output parameters respectively. These were taken from the observed runoff hydrograph, hyetograph and direct sediment graph respectively. The parameters of the model was determined by using Lagrange multipliers method. The stormwise values of the model parameters are given in Table 5. On substitution of the average values of the model parameters in the Muskingum sediment yield model, the model is obtained as

$$Sd(t)=41.0975\ Sm(t) - 41.0851\ Sm(t-1)+0.9876\ Sd(t-1) \qquad (39)$$

Table 5 STORMWISE ESTIMATED VALUES OF MODEL PARAMETERS

Sl No.	Date of storm event	Estimated parameter value		
		b_1	b_2	b_3
1	Sep 15-22, 1986	42.8429	-42.8311	0.9882
2	Oct 11-17, 1986	42.1080	-42.1428	1.0346
3	Nov 4-11, 1986	41.8565	-41.8362	0.9797
4	July 13-18, 1987	41.3393	-41.3811	1.0418
5	Aug 22-30, 1987	41.5071	-41.5089	1.0018
6	Sep 3-8, 1987	39.9952	-39.9604	0.9652
7	Sep 21-27,1987	42.6960	-42.6871	0.9910
8	Oct 7-13, 1987	41.2077	-41.1480	0.9403
9	Oct 17-23, 1987	41.2260	-41.2408	1.0148
10	Nov 6-12, 1987	41.3362	-41.3327	0.9965
11	June 4-10, 1988	40.4784	-40.4888	1.0104
12	July 3-11, 1988	40.0522	-40.0496	0.9975
13	Aug 11-18, 1988	42.6608	-42.6604	0.9994
14	Sep 8-13, 1988	39.1246	-39.0879	0.9632
15	Oct 21-27, 1988	42.2618	-42.2430	0.9812
16	June 19-26, 1989	39.5922	-39.5382	0.9461

17	July 18-25, 1989	39.4913	-39.4670	0.9757
18	Aug 14-21, 1989	41.6841	-41.6874	1.0033
19	Sep 17-24, 1989	42.0956	-42.0983	1.0027
20	Oct 3-9, 1989	39.6915	-39.6590	0.9675
21	Nov 8-15, 1989	40.9126	-40.9295	1.0140
22	June 11-15, 1990	42.3724	-42.2383	0.8659
23	July 1-7, 1990	40.2675	-40.2510	0.9836
24	Aug 9-15, 1990	40.9949	-40.9594	0.9645
25	Sep 4-10, 1990	42.5228	-42.5583	1.0355
26	Oct 13-19, 1990	39.4631	-39.4355	0.9724
27	Nov 3-11, 1990	41.1733	-41.1811	1.0078
28	June 6-13, 1991	41.6165	-41.6229	1.0065
29	July 18-25, 1991	40.3022	-40.2952	0.9930
30	Aug 12-19, 1991	41.7319	-41.7538	1.0219
31	Oct 5-12, 1991	42.9764	-42.9562	0.9798
32	Nov 13-19, 1991	40.4802	-40.4585	0.9783
33	June 15-22, 1992	40.6756	-40.6677	0.9921
34	July 13-19, 1992	40.6602	-40.6513	0.9910
35	Aug 16-22, 1992	41.2075	-41.2238	1.0163
36	Sep 17-22,1992	39.7473	-39.6454	0.8981
37	Nov 5-11, 1992	40.2534	-40.2756	1.0222
	Mean	41.0975	-41.0851	0.9876

4.2. QUALITATIVE COMPARISON OF PERFORMANCE OF THE MODEL

4.2.1. REGENERATION PERFORMANCE OF THE MODEL

It is possible to obtain a reasonably good reproduction of the sediment graph for a particular storm event with most models, if the model parameters are estimated for the event to be reproduced. However for a better test model accuuracy, it is to generate a range of sediment graphs using the same parameter values for all events and to note the deviation between generated and observed sediment graphs.

The model was tested by regenerating the direct sediment graphs for the storm events which were used to estimate the model parameters and comparing these graphs with the observed direct sediment graphs. The regenerated and observed direct sediment graphs for the storm events of November 6-12, 1987, September 4- 10, 1990 and August 16-22, 1992 as shown in Fig.11 through 13 were selected for comparison and the corresponding values of the observed and predicted direct sediment graph ordinates were given in Table 6 through 8. The observed and predicted direct sediment graph ordinates of rest of the storm events were given in Appendix II.It is observed that the base length, the time to peak, the rising, crest and recession segments of the direct sediment graphs regenerated by the model are in close agreement with those of the observed direct sediment graphs. As seen from Figs.11,12 and 13, there are little deviations between the generated sediment graphs and observed sediment graphs. If the hydrologic process is truely linear, then the parameter value of the model should be constant for all storms on a given watershed. However, when the parameters were computed from the observed data, they were found to vary from storm to storm. This lack of uniqueness is normally attributed either by the presence of noise in the data or by the inadequacy of the assumption of linearity, which causes the slight variations between the observed sediment graphs and regenerated sediment graphs by the model.

Table 6

OBSERVED AND REGENERATED DIRECT SEDIMENT FLOW ORDINATES FOR THE STORM EVENT OF NOVEMBER 6-12, 1987

Date	Observed sediment flow ordinates (t/day)	Regenerated sediment flow ordinates (t/day)
6	0	0
7	14.07	9.38
8	99.49	101.43
9	243.73	242.81
10	49.24	47.94
11	12.06	6.55
12	0	0

Table 7

OBSERVED AND REGENERATED DIRECT SEDIMENT FLOW ORDINATES FOR THE STORM EVENT OF SEPTEMBER 4-10, 1990

Date	Observed direct sediment flow ordinates (t/day)	Regenerated direct sediment flow ordinates (t/day)
4	0	0
5	6.51	8.13
6	50.39	58.63
7	110.75	107.23
8	43.02	40.18
9	9.38	3.93
10	0	0

Table 8

OBSERVED AND REGENERATED DIRECT SEDIMENT FLOW ORDINATES FOR THE STORM EVENT OF AUGUST 16-22, 1992

Date	Observed direct sediment flow ordinates (t/day)	Regenerated direct sediment flow ordinates (t/day)
16	0	0
17	21.76	18.28
18	188.36	164.51
19	350.17	331.01
20	197.41	172.89
21	59.73	46.47
22	0	0

4.2.2. PREDICTION PERFORMANCE OF THE MODEL

To verify the prediction accuracy of the model, the direct sediment graph ordinates of three storm events of the year 1993 which were not used to develop the model parameters were calculated using their mobilized sediment data and the average values of parameters of calibration events. The ordinates of the direct sediment graphs predicted by the model along with the ordinates of the observed sediment graphs for the storm events of July 19-26, 1993, August 11-17, 1993 and October 5-12, 1993 for the drainage basin are given in Table 9 through 11. The observed and predicted sediment graphs for these storm events as shown in figure 14 to 16 were compared quantitatively based on visual observation, peak repro-

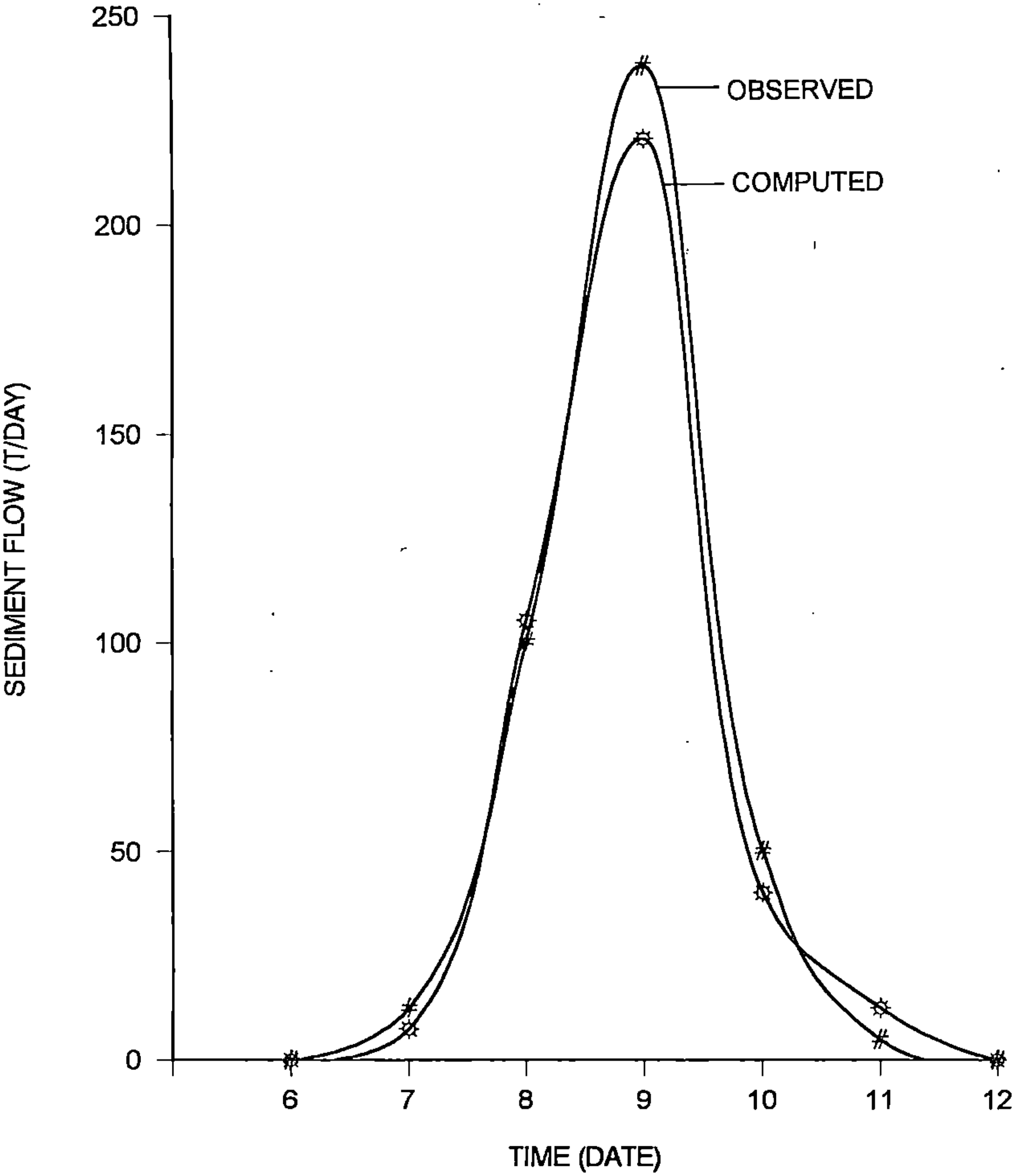


FIG 11. COMPARISON OF OBSERVED AND REGENERATED DIRECT SEDIMENT GRAPHS FOR THE STORM EVENT OF NOVEMBER 6-12, 1987

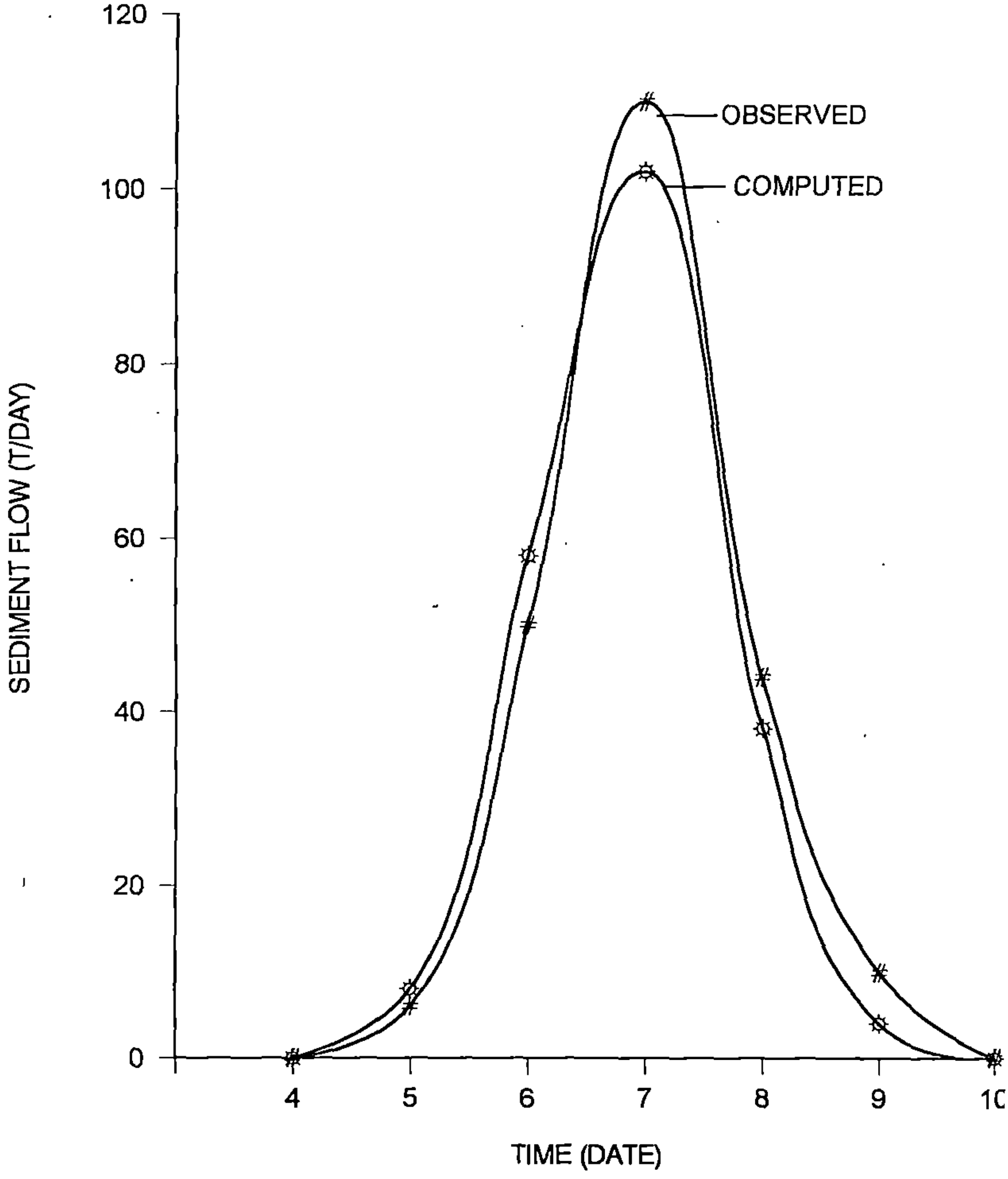


FIG 12. **COMPARISON OF OBSERVED AND REGENERATED DIRECT SEDIMENT GRAPHS FOR THE STORM EVENT OF SEPTEMBER 4-10, 1990**

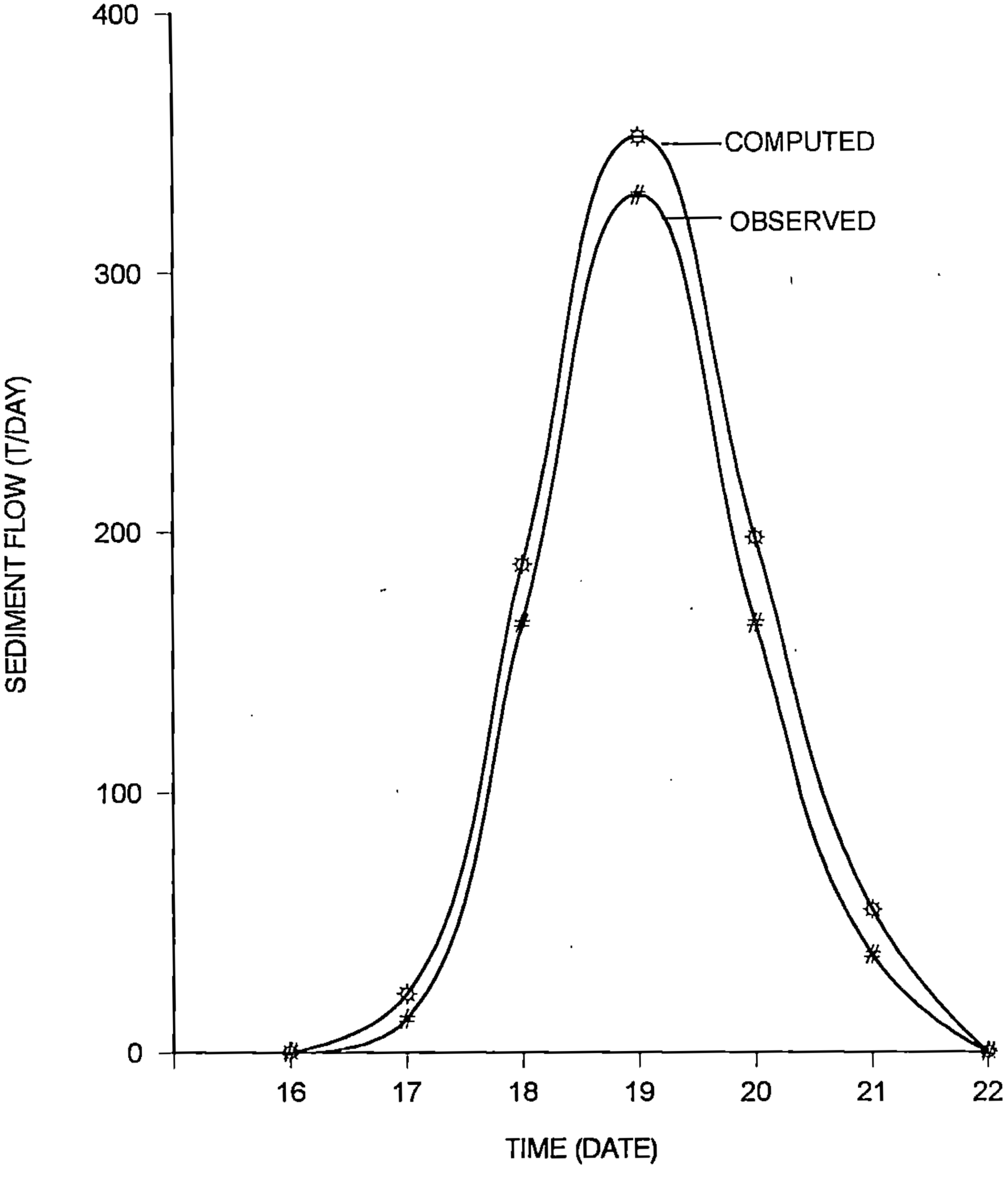


FIG 13. COMPARISON OF OBSERVED AND REGENERATED DIRECT SEDIMENT GRAPHS FOR THE STORM EVENT OF AUGUST 16-22, 1992

duction etc. It is evident from Figs. 14, 15 and 16 that the base length, time to peak, rising, recession and crest segments of the sediment graphs predicted by the model are in close agreement with the observed sediment graph. The little deviations between the predicted sediment graphs and observe sediment graphs may be due to (i) presence of inherent errors in the data, (ii) inadequacy of the assumptions of linearity and time invariances, (iii) the effect of soil conservation measures taken up in the catchment area on sediment production, (iv) fire hazards, road construction, overgrazing, landslides, cultivation practices and (v) the storm events of much later or earlier dates.

Table 9

OBSERVED AND PREDICTED DIRECT SEDIMENT FLOW ORDINATES FOR THE STORM EVENT OF JULY, 19-26, 1993

Date	Observed direct sediment flow ordinates (t/day)	Predicted direct sediment flow ordinates (t/day)
19	0	0
20	27.26	17.98
21	104.96	113.67
22	243.84	245.96
23	392.98	371.24
24	197.35	204.15
25	38.28	24.96
26	0	0

Table 10

OBSERVED AND PREDICTED DIRECT SEDIMENT FLOW ORDINATES FOR THE STORM EVENT OF AUGUST, 11-17, 1993

Date	Observed direct sediment flow ordinates (t/day)	Predicted direct sediment flow ordinates (t/day)
11	0	0
12	72.37	63.41
13	195.63	180.63
14	88.16	104.04
15	30.40	26.24
16	4.69	16.09
17	0	0

Table 11

OBSERVED AND PREDICTED DIRECT SEDIMENT FLOW ORDINATES FOR THE SOTRM EVENT OF OCTOBER, 5-12, 1993

Date	Observed direct sediment flow ordinates (t/day)	Predicted direct sediment flow ordinates (t/day)
5	0	0
6	24.26	26.52
7	104.13	111.20
8	238.88	254.50
9	135.55	140.27
10	50.49	40.84
11	19.41	28.54
12	0	0

4.3. QUANTITATIVE COMPARISON OF PERFORMANCE OF THE MODEL

The accuracy of the model lies with the goodness of fit between the simulated and observed direct sediment values. It is seen that the regenerated sediment graph is almost in constrain with this predicted one and is clear from the Figs. 11 to 16. In this study for further error analysis, certain statistical measures were also employed for a quantitative comparison between the observed sediment graphs and the sediment graphs computed by the model.

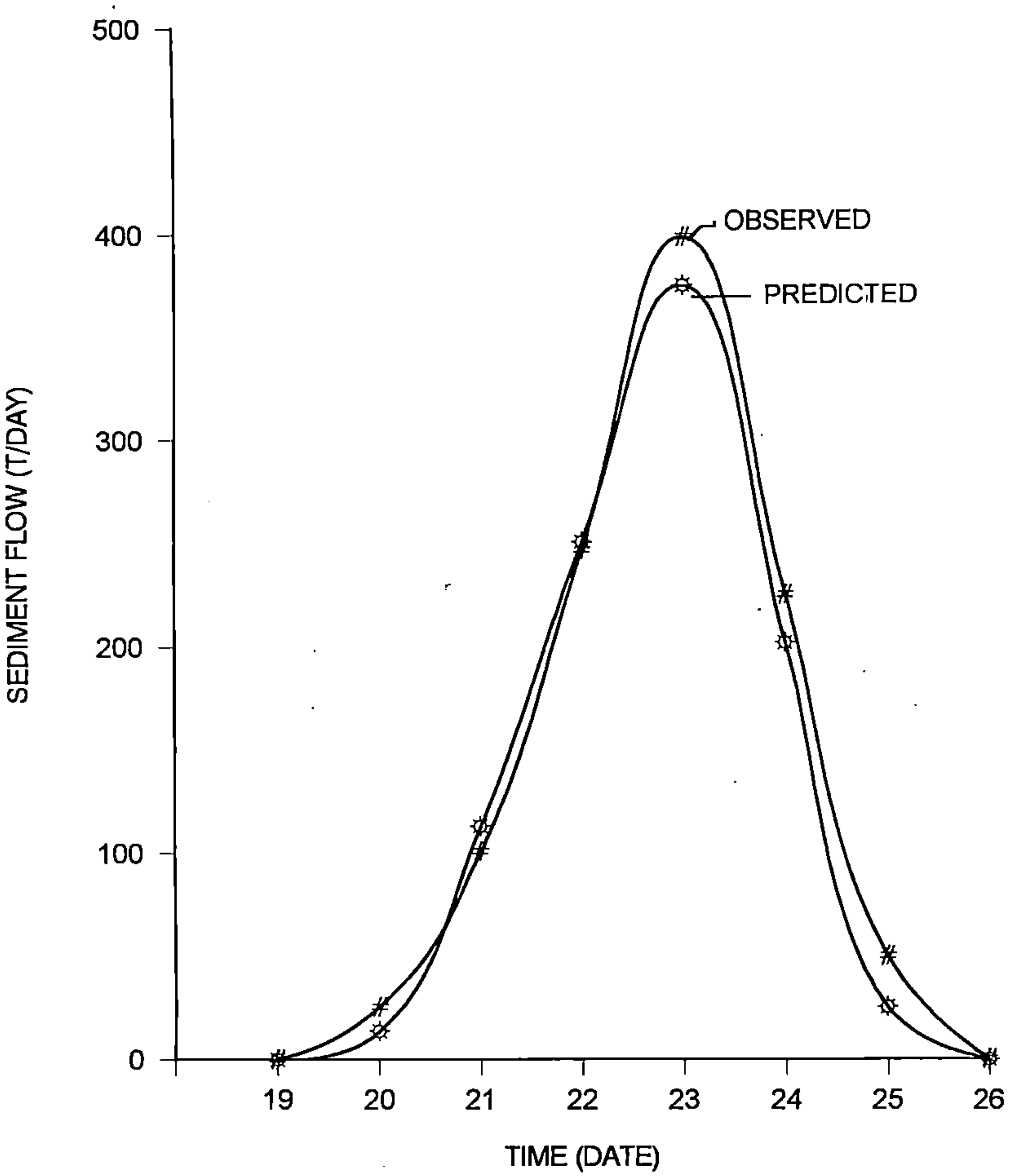


FIG 14. COMPARISON OF OBSERVED AND PREDICTED DIRECT SEDIMENT GRAPHS FOR THE STORM EVENT OF JULY 19-26, 1993

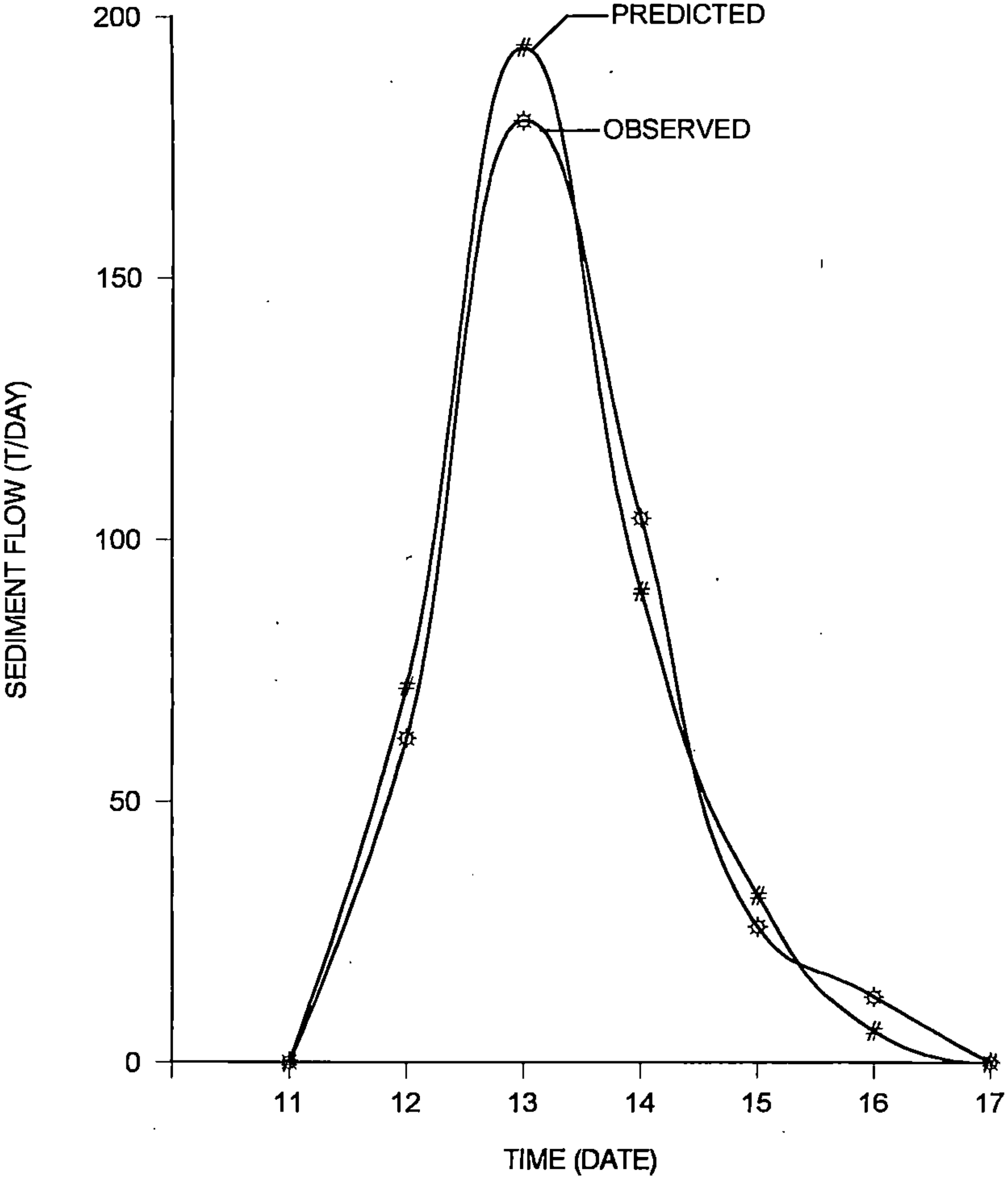


FIG 15. **COMPARISON OF OBSERVED AND PREDICTED DIRECT SEDIMENT GRAPHS FOR THE STORM EVENT OF AUGUST 11-17, 1993**

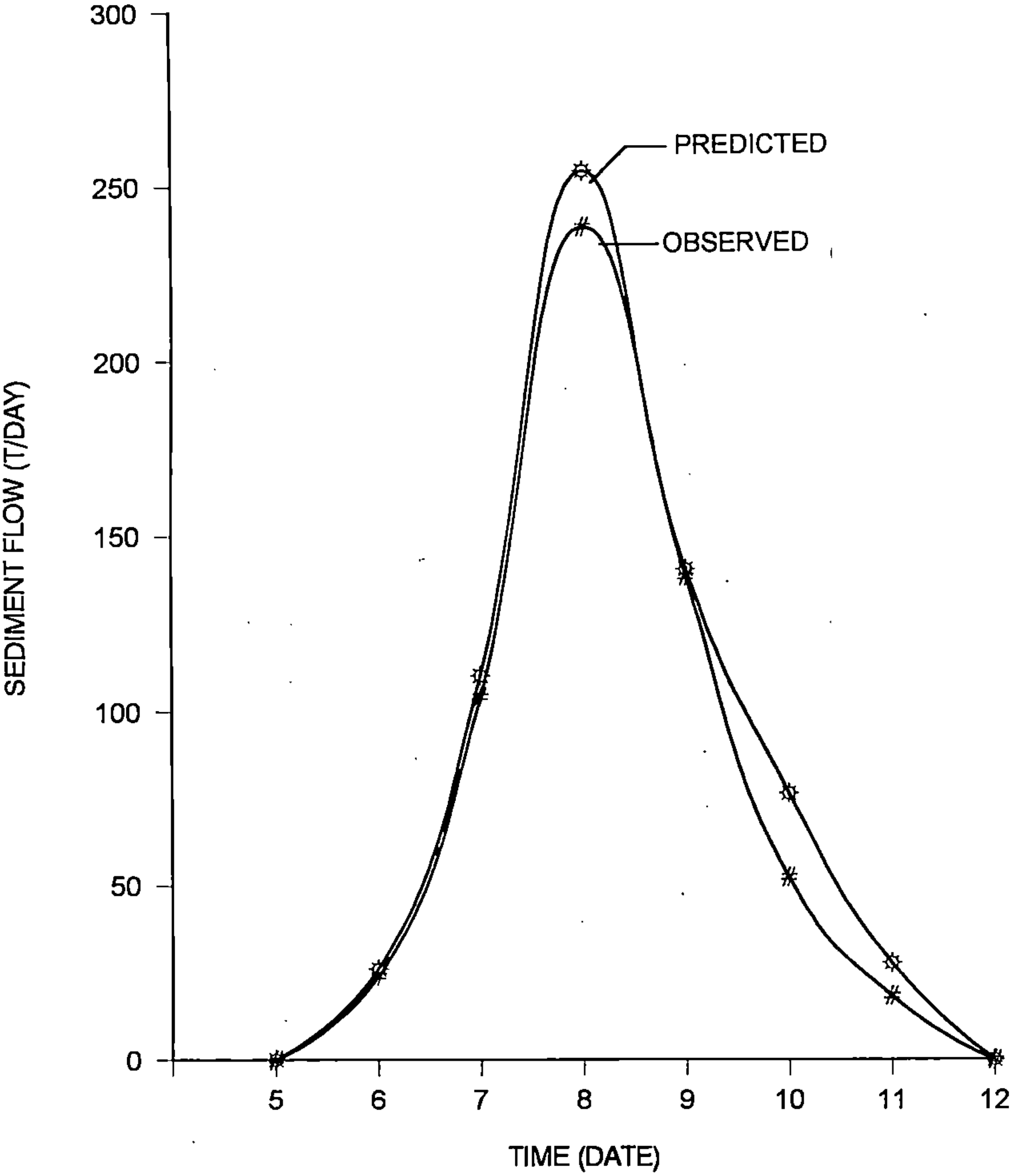


FIG 16. **COMPARISON OF OBSERVED AND PREDICTED DIRECT SEDIMENT GRAPHS FOR THE STORM EVENT OF OCTOBER 5-12, 1993**

4.3.1. PERCENTAGE ABSOLUTE ERROR IN PEAK SEDIMENT FLOW RATE

The percentage absolute errors in peak sediment flow rates were estimated by the equation:

$$\text{PAE peak} = \frac{|\text{Sdop} - \text{Sdcp}|}{\text{Sdop}} \times 100 \qquad (40)$$

where

PAE peak = Percentage absolute error in computed peak flow

Sdop = Observed peak sediment flow rate in t/day

Sdcp = Computed peak sediment flow rate in t/day

The stormwise values of the observed and computed peak sediment flow rates and the percentage absolute error in peak sediment flow rates are given in Table 12.

Table 12

STORMWISE VALUES OF PERCENTAGE ABSOLUTE ERROR IN PEAK SEDIMENT FLOW RATES

Sl No	Date of storm event	Observed peak sediment flow rate (t/day)	Computed peak sediment flow rate (t/day)	PAE peak
1	Sep 15-22, 1986	305.22	276.68	9.3506
2	Oct 11-17, 1986	169.12	159.81	5.4938
3	Nov 4-11, 1986	262.63	237.15	9.7019
4	July 13-18, 1987	104.42	103.77	0.6225
5	Aug 22-30, 1987	344.67	338.10	1.9062
6	Sep 3-8, 1987	64.68	73.24	13.2328
7	Sep 21-27, 1987	242.97	221.76	8.7293
8	Oct 7-13, 1987	64.83	56.42	12.9652
9	Oct 17-23, 1987	209.80	212.62	1.3441
10	Nov 6-12, 1987	243.73	242.81	0.3775
11	June 4-10, 1988	256.12	253.91	0.8551
12	July 3-11, 1988	164.47	167.75	1.9943
13	Aug 11-18, 1988	407.67	405.09	0.6329
14	Sep 8-13, 1988	270.12	281.23	4.1129
15	Oct 21-27, 1988	122.00	110.48	9.4431
16	June 19-26, 1989	138.61	128.52	7.2727
17	July 18-25, 1989	656.93	655.96	0.1477
18	Aug 14-21, 1989	216.46	212.25	1.9449
19	Sep 17-24, 1989	341.69	321.93	5.7832

20	Oct 3-9, 1989	276.68	268.84	2.8336
21	Nov 8-15, 1989	112.66	111.28	1.2249
22	June 11-15, 1990	60.54	62.55	3.3201
23	July 1-7, 1990	243.59	248.48	2.0071
24	Aug 9-15, 1990	264.02	265.91	0.7159
25	Sep 4-10, 1990	110.78	107.23	3.1783
26	Oct 13-19, 1990	87.37	88.56	1.3620
27	Nov 3-11, 1990	221.24	217.51	1.6859
28	June 6-13, 1991	174.77	175.83	0.6065
29	July 18-25, 1991	332.82	331.95	0.2554
30	Aug 12-19, 1991	145.63	147.73	1.4420
31	Oct 5-12, 1991	185.63	170.63	8.0806
32	Nov 13-19, 1991	232.01	231.72	0.1249
33	June 15-22, 1992	317.80	326.04	2.5928
34	July 13-19, 1992	381.92	397.21	4.0008
35	Aug 16-22, 1992	350.17	331.01	5.4716
36	Sep 17-22, 1992	131.79	134.12	1.7679
37	Nov 5-11, 1992	206.39	199.08	3.5418
38	July 19-26, 1993	392.98	371.24	5.5321
39	Aug 11-17, 1993	195.63	180.63	7.6675
40	Oct 5-12, 1993	238.88	254.20	6.4133
Average value		231.24	227.03	3.9934

Out of the forty storm events, the percentage absolute error is less than 10 percent for twelve storm events and for twenty six storm events the error lies below 5 percent. The average percentage absolute error in peak sediment flow of the model is 3.9934 percent, which is comparatively small considering the fact that mobilized sediment is the only source of information used in the model. This show that this generation of the model is clarified.

4.3.2. ABSOLUTE PREDICTION ERROR

The absolute prediction error proposed by the World Meteorological Organisation (1975) statistics for evaluating the model performance was used in this study for quantitative comparison of the model which is given as

$$APE = \frac{\sum_{i=1}^{n} \left| Sdi(i) - Sdo(i) \right|}{\sum_{i=1}^{n} sdo(i)} \times 100 \qquad (41)$$

where

APE = The absolute prediction error, percent

Sdo(i) = ith value of observed sediment flow

Sdc(i) = ith value of computed sediment flow

n = number of values in the series

The absolute prediction error of all the forty storm events are given in Table 13. As seen from the table, the absolute prediction error for twenty five storm events is less than 10 percent. The average value of the absolute prediction error of the model is 9.007 percent which is comparatively small considering the fact that mobilized sediment is the only source of information used in the model. This reveals the correct performance of the model developed.

Table 13

ABSOLUTE PERCENTAGE ERROR (APE), INTEGRAL SQUARE ERROR (ISE), AND CORRELATION COEFFICIENT (R) OF THE STORM EVENTS

Sl No	Date of storm event	APE	ISE	R
1	Sep 15-22, 1986	17.4763	10.0508	0.9976
2	Oct 11-17, 1986	11.8739	7.3443	0.9954
3	Nov 4-11, 1986	21.2796	11.0643	0.9957
4	July 13-18, 1987	8.6665	5.9090	1.0000
5	Aug 22-30, 1987	4.9271	3.5177	0.9971
6	Sep 3-8, 1987	17.3329	15.3800	0.9990
7	Sep 21-27, 1987	16.0065	9.0640	0.9992
8	Oct 7-13, 1987	17.9209	16.4123	1.0000
9	Oct 17-23, 1987	4.6699	2.8274	0.9991
10	Nov 6-12, 1987	2.3905	1.5231	0.9989
11	June 4-10, 1988	4.8189	3.0593	0.9992
12	July 3-11, 1988	2.5918	1.4732	0.9996
13	Aug 11-18, 1988	2.0452	0.0206	0.9989
14	Sep 8-13, 1988	9.5079	6.6468	0.9975
15	Oct 21-27, 1988	10.8026	5.9208	0.9886
16	June 19-26, 1989	13.3263	6.7736	0.9872
17	July 18-25, 1989	5.7775	3.3496	0.9986
18	Aug 14-21, 1989	5.9236	2.7838	0.9942
19	Sep 17-24, 1989	14.4089	7.3863	0.9928

20	Oct 3-9, 1989	11.8144	7.2234	0.9883
21	Nov 8-15, 1989	10.9401	5.4193	0.9978
22	June 11-15, 1990	11.7682	9.9431	1.0000
23	July 1-7, 1990	2.7460	1.3948	0.9976
24	Aug 9-15, 1990	6.1616	4.0222	0.9953
25	Sep 4-10, 1990	9.3893	5.0883	0.9897
26	Oct 13-19, 1990	3.3972	2.1002	0.9994
27	Nov 3-11, 1990	9.2715	4.9427	0.9979
28	June 6-13, 1991	6.4407	4.2570	0.9928
29	July 18-25, 1991	5.2413	2.7147	0.9996
30	Aug 12-19, 1991	9.9674	5.2125	0.9906
31	Oct 5-12, 1991	11.2429	6.7149	0.9944
32	Nov 13-19, 1991	3.1034	1.8596	0.9797
33	June 15-22, 1992	4.7633	2.7423	0.9992
34	July 13-19, 1992	6.5087	3.6434	0.9952
35	Aug 16-22, 1992	10.1537	5.2017	0.9992
36	Sep 17-22, 1992	8.1283	1.0823	0.9862
37	Nov 5-11, 1992	9.3496	5.0015	0.9990
38	July 19-26, 1993	6.1325	2.9330	0.9959
39	Aug 11-17, 1993	14.1613	6.7822	0.9674
40	Oct 5-1, 1993	7.5862	3.8590	0.9946
	Average value	9.0007	5.3286	0.9951

4.3.3. INTEGRAL SQUARE ERROR

The goodness of fit of the computed sediment graphs to the observed sediment graphs was also estimated by the integral square error, given by the equation.

$$ISE = \frac{\left(\sum_{i=1}^{n}[(Sdo(i) - Sdc(i)]^2\right)^{1/2}}{\sum_{i=1}^{n} Sdo(i)} \times 100 \qquad (42)$$

where ISE is the integral square error in percent. Table 13 gives the integral square error values in percentage of the model considered in this study. The average values of integral square error is 5.3286. The result reveals that the model simultate the direct sediment graphs more accurately.

4.3.4. CORRELATION COEFFICIENT

The correlation coefficient is a measure of the degree of closeness of the linear relationship between two variables. It was used in this study to describe the association between the observed sediment flows and the sediment flows computed by the model. The correlation coefficient (R) is given by

$$R = \frac{n \sum_{i=1}^{n} Sdo(i) \times Sdc(i) - \sum_{i=1}^{n} Sdo(i) \sum_{i=1}^{n} Sdc(i)}{[n \sum_{i=1}^{n}(Sdo(i)^2 - (\sum_{i=1}^{n} Sdo(i))^2]^{1/2} \times [n \sum_{i=1}^{n}(Sdc(i)^2 - (\sum_{i=1}^{n} Sdc(i))^2]^{1/2}} \qquad (43)$$

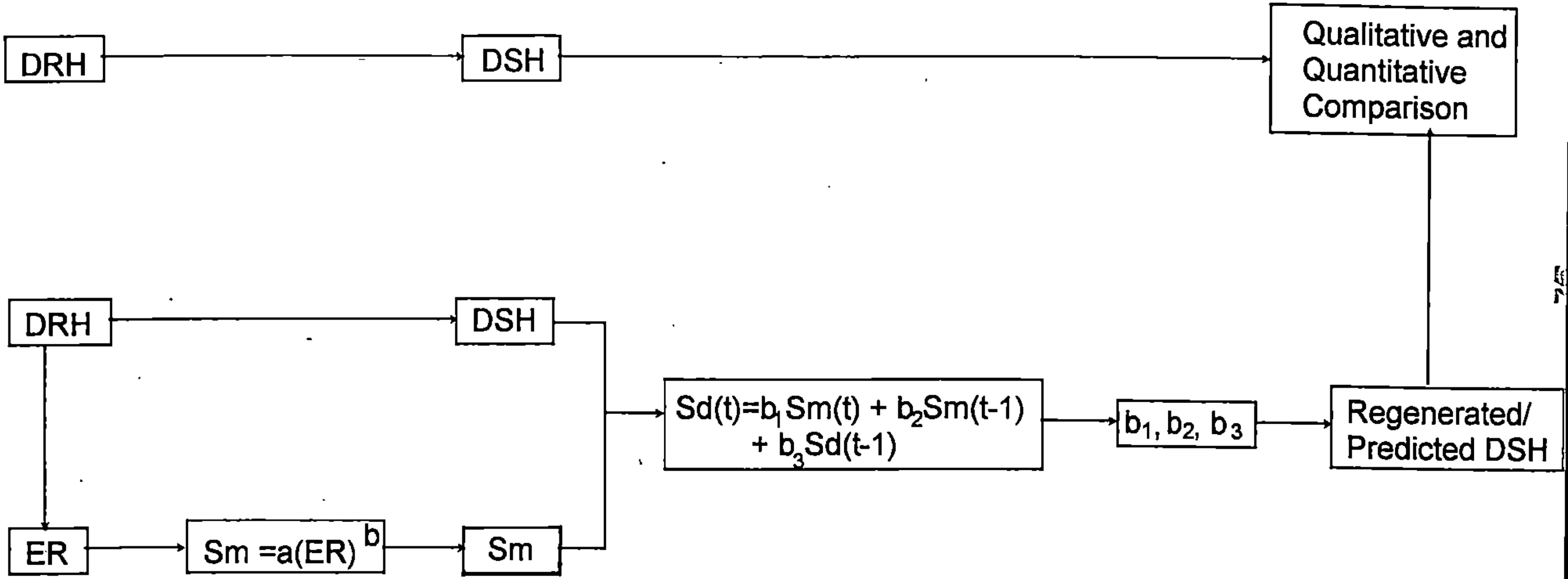
The values of correlation coefficient of the model is given in Table 13. The average value of correlation coefficient is 0.9952. This result indicates that the flow estimated by the model have the highest degree of association with the observed flows.

4.3.5. COEFFICIENT OF EFFICIENCY

Nash and Sutcliffe (1970) introduced the term coefficient of efficiency to describe the degree of association between the observed and computed sediment flow. The coefficient of efficiency of the model was determined by the equation.

$$CE = \frac{\sum_{i=1}^{n} (Sdo(i) - Sdo)^2 - \sum_{i=1}^{n} (\bar{S}do(i) - Sdc(i))^2}{\sum_{i=1}^{n} (Sdo(i) - \bar{S}do)^2} \qquad (44)$$

where CE is the coefficient of efficiency of the model. The values of coefficient of efficiency of the model is given in Table 14. Out of forty storm events the coefficient of efficiency is less than 0.9 for three storm events and for thirty seven storm events considered the coefficient of efficiency is greater than 0.9. The average coefficient of efficiency of the model is 0.9659. These results indicate that the performance of the model is good. Fig.17 shows the procedure used in model verification (regeneration/prediction).



Events used to estimate the model parameters

FIG 17. PROCEDURE USED IN MODEL VERIFICATION (REGENERATION /PREDICTION)

Table 14
COEFFICIENT OF EFFICIENCY (CE) FOR THE STORM EVENTS

Sl No.	Date of storm event	Mobilized Sediment (t/km^2)	Total Sediment flows t/day		CE
			Observed	Computed	
1	Sep 15-22, 1986	9.03	443.98	370.22	0.9614
2	Oct 11-17, 1986	5.83	275.04	242.38	0.9738
3	Nov 4-11, 1986	10.20	548.33	431.09	0.8836
4	July 13-18, 1987	3.63	181.94	170.51	0.9605
5	Aug 22-30, 1987	14.46	703.80	665.89	0.9916
6	Sep 3-8, 1987	2.00	106.19	134.68	0.8855
7	Sep 21-27, 1987	7.09	365.56	305.37	0.9679
8	Oct 7-13, 1987	2.16	130.12	93.10	0.7930
9	Oct 17-23, 1987	7.40	360.93	372.21	0.9959
10	Nov 6-12, 1987	8.67	418.59	415.59	0.9987
11	June 4-10, 1988	11.10	580.03	553.23	0.9807
12	July 3-11, 1988	7.20	362.62	371.68	0.9986
13	Aug 11-18, 1988	18.05	907.82	934.68	0.9963
14	Sep 8-13, 1988	8.13	442.48	480.10	0.9834
15	Oct 21-27, 1988	5.60	307.01	277.32	0.9442
16	June 19-26, 1989	5.56	295.68	278.12	0.9852
17	July 18-25, 1989	28.50	1550.41	1450.88	0.9877
18	Aug 14-21, 1989	11.40	595.42	619.31	0.9861
19	Sep 17-24, 1989	15.19	856.31	745.12	0.9365

20	Oct 3-9, 1989	9.57	599.99	528.98	0.9477
21	Nov 8-15, 1989	5.86	340.17	289.93	0.9560
22	June 11-15, 1990	2.83	106.93	116.64	0.9137
23	July 1-7, 1990	11.56	694.82	681.95	0.9951
24	Aug 9-15, 1990	10.55	503.56	525.06	0.9669
25	Sep 4-10, 1990	4.63	220.05	219.50	0.9779
26	Oct 13-19, 1990	2.93	152.44	150.87	0.9975
27	Nov 3-11, 1990	9.58	533.61	482.43	0.9735
28	June 6-13, 1991	8.30	396.73	416.82	0.9809
29	July 18-25, 1991	16.50	791.07	751.31	0.9928
30	Aug 12-19, 1991	7.28	311.76	317.77	0.9774
31	Oct 5-12, 1991	6.70	375.31	331.46	0.9698
32	Nov 13-19, 1991	8.43	413.25	402.02	0.9979
33	June 15-22, 1992	13.98	719.54	758.12	0.9928
34	July 13-19, 1992	14.40	790.84	810.45	0.9881
35	Aug 16-22, 1992	15.0	817.43	729.45	0.9596
36	Sep 17-22, 1992	4.27	251.94	286.46	0.9254
37	Nov 5-11, 1992	7.90	437.99	393.40	0.9690
38	July 19-26, 1993		1004.67	977.69	0.9911
39	Aug 11-17, 1993		391.25	390.41	0.9641
40	Oct 5-12, 1993		572.72	601.57	0.9863
	Average value				0.9659

4.4. RELATIONSHIP BETWEEN MOBILIZED SEDIMENT AND EFFECTICE RAINFALL

The total amount of mobilized sediment during the storm event must be known or estimated,inorder to generate a sediment graph for a particular storm event. To compute the mobilized sediment during the storm event, a relationship between mobilized sediment and excess rainfall was developed. Thirty seven hydrographs and sediment graphs measured at the gauging station on a storm basis were considered. Based on this data, the following regression equation was obtained.

$$Sm = 0.3865\ ER^{0.8909} \qquad (45)$$

$(r = 0.9205)$

and this is graphically represented in Fig. 18.

where

Sm = mobilized sediment in t/Km^2

ER = effective rainfall in mm

r = coefficient of correlation

This equation and graph serve useful tools for the estimation of total mobilized sediment on the basis of known or predicted excess or effective rainfall.

4.5. RELATIONSHIP BETWEEN COMPUTED SEDIMENT FLOWS AND OBSERVED SEDIMENT FLOWS

The relationship between computed sediment flow estimated by the model and observed sediment flow for Thuthapuzha drainage basin was established and the result was obtained which is represented by this equation.

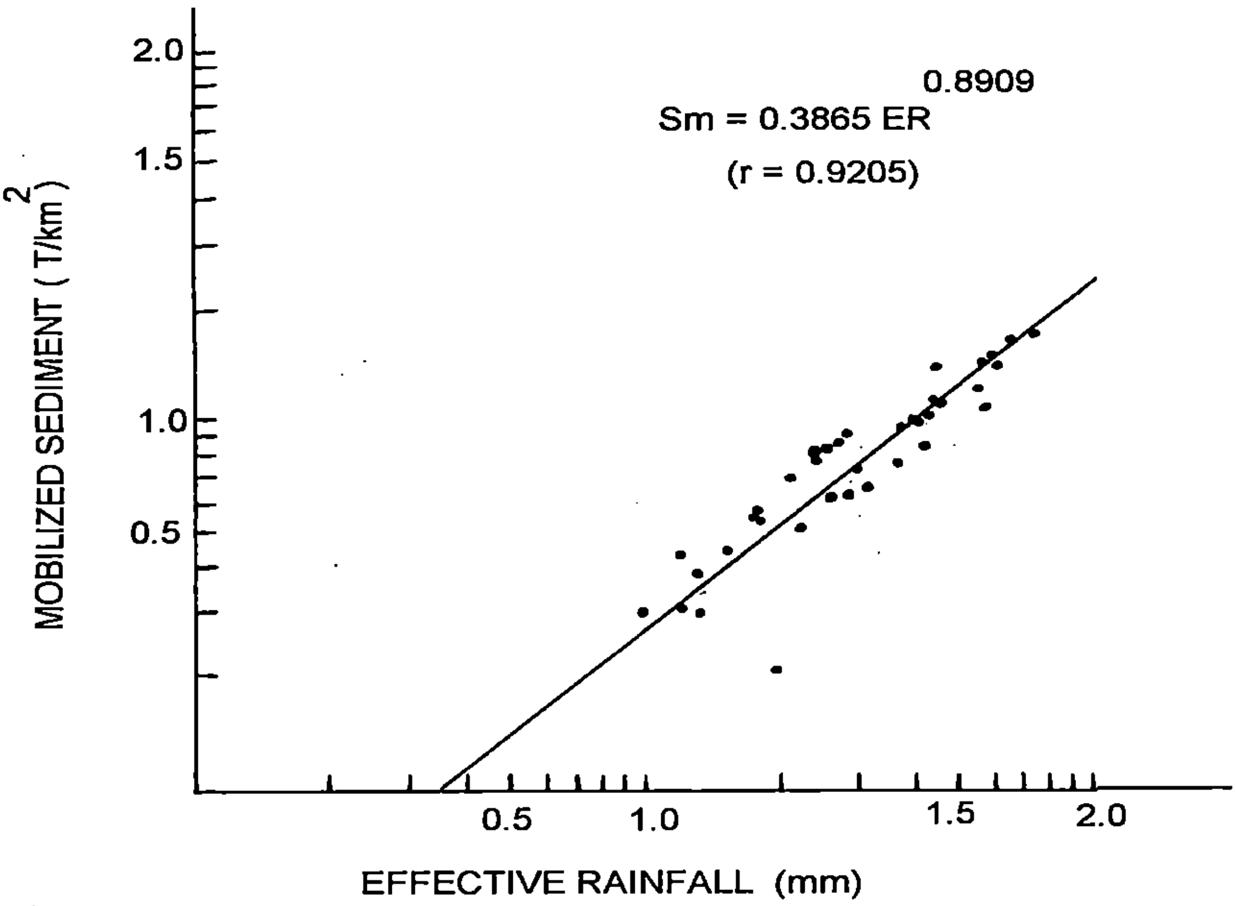


FIG. 18 RELATIONSHIP BETWEEN MOBILIZED SEDIMENT AND EFFECTIVE RAINFALL

$$Sdc = 4.9983 + 0.9446\ Sdo \qquad (46)$$

$(r = 0.99024)$

where

Sdc = computed sediment flow in t/day

Sdo = observed sediment flow in t/day

The subscript of Sdc refers to the model used for estimating sediment flow rate. For the model, the value of correlation coefficient is almost equal to one which indicate very close agreement, between the observed and estimated flow rates. This reveals the accuracy of the performance of the model.

4.6. RELATIONSHIP BETWEEN SEDIMENT FLOW RATES, EFFECTIVE RAINFALL AND MOBILIZED SEDIMENT

The relationship between sediment flow rate, effective rainfall and mobilized sediment is useful to determine the sediment flow rate from a watershed if effective rainfall and mobilized sediment are known for a storm event. The observed sediment flow and sediment flow computed by the model are related with effective rainfall and mobilized sediment by the following equations.

$$Sdo = 1.1191\ (ER)^{3.3629}\ (Sm)^{-2.6570} \qquad (47)$$

$(r = 0.9153)$

$$Sdc = 3.928\ (ER)^{1.9684}\ (Sm)^{-3.5732} \qquad (48)$$

$(r = 0.9035)$

where

Sdo = observed sediment flow in t/ day
Sdc = computed sediment flow in t/ day
ER = effective rainfall in mm
Sm = mobilized sediment in t/km^2

The correlation coefficient r equal to 0.9153 for the relationship of observed sediment flows with effective rainfall and mobilized sediment and r = 0.9053 for the relationship of computed sediment flows with effective rainfall and mobilized sediment. The correlation coefficients **r** close to one indicates very high dependence of sediment flows on effective rainfall and mobilized sediment.

4.7 DISCHARGE - SEDIMENT RATING CURVE

A rating curve for the discharge and sediment production rate was developed.from the rating curve, one can find out the sediment production rate for a given discharge if the sediment concentration measurements were not available. Discharge and sediment concentration measured out at the gauging station from the year 1986 to 1993 were considered for the development of the relationship. Based on this data, the following regression equation was developed.

$$y = 8.32\, x^{1.25} \qquad (49)$$

$$(r = 0.92)$$

and this is graphically represented in Fig 19.

where

y = sediment production rate in ton/ day
x = discharge in M m^3/ day
a, b = constants

Once the relationship is established the subsequent procedure consists of measuring the discharge and reading the sediment production rate from the rating curve.

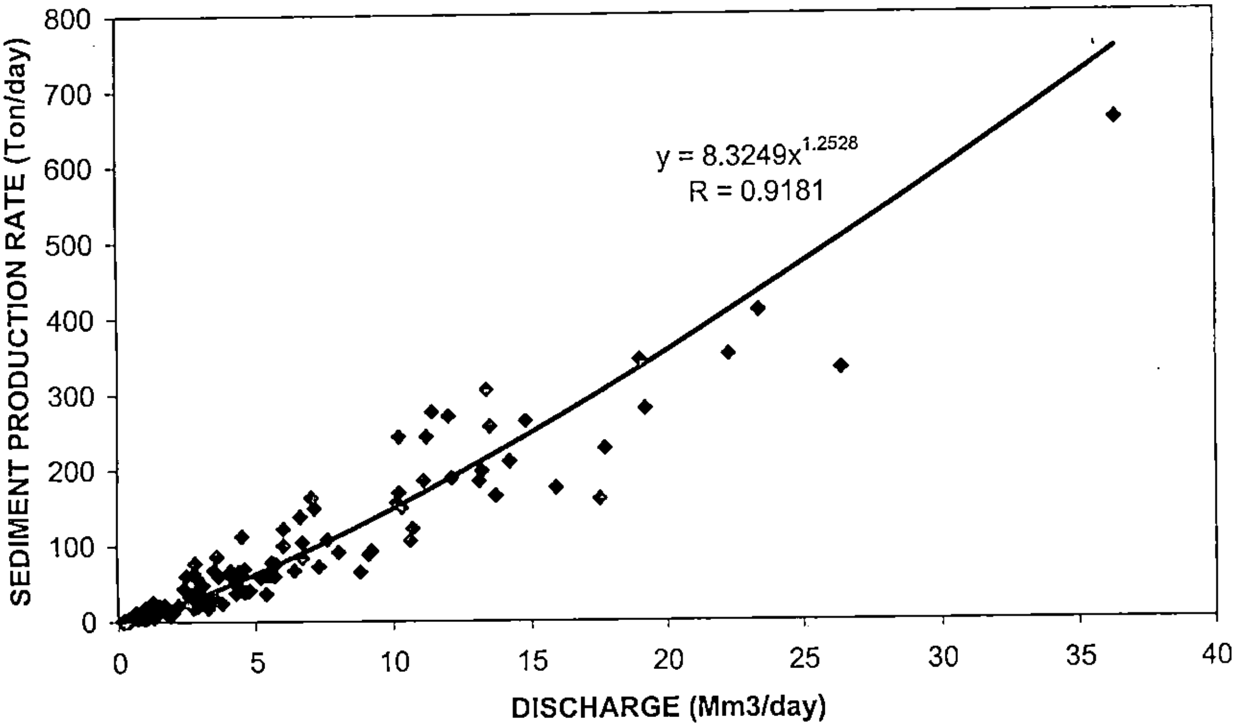


FIG 19 DISCHARGE- SEDIMENT RATING CURVE

Summary and Conclusion

SUMMARY AND CONCLUSION

Erosion and sedimentation are the major problems, that reduce the productivity of crop land, degrade water quality, carry polluting chemicals, reduce the capacity of water conveyance and storage structures. For the efficient design of soil and water conservation structures and water quality modelling, the storm wise temporal distribution of suspended sediment in surface runoff is important.

Most of the available sediment yield prediction models predict only average annual sediment yield. The prediction of sediment yield based on individual storm is more accurate than the annual prediction procedures. Therefore the Muskingum sediment yield model is developed with parameters determined from the mobilized and direct sediment data of Thuthapuzha drainage basin using Lagrange multipliers method. The model is used to compute temporal distribution of suspended sediment yield on storm basis and their performance was evaluated both qualitatively and quantitatively. Mathematical relationships of mobilized sediment with effective rainfall, computed sediment flow rates with oberved sediment flow rates, and observed and computed sediment flow with effective rainfall and mobilized sediment are also established.

Based on the above investigations the following results were obtained:

1. The Muskingum sediment yield for Thuthapuzha drainage basin with parameters estimated by Lagrange multipliers method is

$$Sd(t) = 41.0975\ Sm(t) - 41.0851\ Sm(t-1) + 0.9876\ Sd\ (t-1)$$

2. The qualitative comparison shows that the base length, time to peak, rising, crest and recession segments of direct sediment graphs generated by the model are in close agreement with those of the observed direct sediment graphs. The slight variation between the observed sediment graphs and regenerated sediment graphs may be due to inadequacy of the assumption of linearity or presence of noise in the data.

3. The visual observation of predicted sediment flow graphs and observed sediment flow graphs shows that the sediment flow graphs predicted by the model conformed reasonably well with the observed sediment flow graphs.

4. For Thuthapuzha drainage basin, the Muskingum sediment yield model is recommended for computation of peak sediment flows needed for the design of soil conservation practices and hydraulic structures, as it has the lowest average Percentage Absolute Error of 3.9934 percent in peak sediment flow rates. However, for the simulation of whole sediment graphs, Muskingum sediment yield model can be applied as the model records the lowest Absolute Prediction Error 9.0007 percent, lowest Integral Square Error of 5.3286 and the highest Correlation Coefficient of 0.9951.

5. The model result in Coefficient of Efficiency of 0.9659, justifying the use for prediction of the complete sediment graph.

6. The mobilized sediment was related to effective rainfall on storm basis by the following equation.

$$Sm = 0.3865\ ER^{0.8909}$$

$$(r = 0.9205)$$

This relationship may be useful for computation of mobilized sediment from effective rainfall of a storm event for which sediment graph is required.

7. The relationship between computed and observed sediment flow rates for the drainage basin is described by the equation.

$$Sdc = 4.9983 + 0.9446\ Sdo$$

$$(r = 0.99024)$$

8. The observed sediment flow as a function of effective rainfall and mobilized sediment is expressed as

$$Sdo = 1.1191\ (ER)^{3.3629}\ (Sm)^{-2.6570}$$

$$(r = 0.9153)$$

9. The relationship of computed sediment flows with effective rainfall and mobilized sediment is

$$Sdc = 3.928\ (ER)^{1.9684}\ (Sm)^{-3.5732}$$

$$(r = 0.9035)$$

The correlation coefficient of all the equations are close to one indicating very high dependence of sediment flow on effective rainfall and mobilized sediment.

10. The discharge was related to sediment production rate on storm basis by the following equation

$$Y = 8.32\ X^{1.25}$$

$$(r = 0.92)$$

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* *Originals not seen*

Appendix

APPENDIX I
SALIENT INFORMATION ABOUT DATA

1. Date of commencement of observation.

Gauge	: 24-05-1985
Discharge	: 17-02-1986
Sediment	: 28-08-1986

2. Discharge observation

Maximum stage	: 18.50 m.
Corresponding discharge	: 1380 m^3/s.
Maximum observed discharge	: 1072 m^3/s.
Minimum stage	: 11.00 m.
Minimum discharge	: 0.00 m^3/s.
Maximum point velocity	: 2.1835 m/s.
Maximum flood discharge	: 1380 m^3.

3. Sediment observation

a) Maximum concentration	: 0.514 gm/lit.
b) Minimum concentration	: 0.001 gm/lit.
c) Quantity of sediment carried in a year	
i) Maximum	: 138242
ii) Minimum	: 45212
d) Quantity of sediment carried during mansoon.	
i) Maximum	: 137639
ii) Minimum	: 32544

4. Bed material sample analysis.

	Max-size in mm	Min-size in mm	Silt factor
a) Pre-mansoon	24.0	0.06	2.31
b) Mansoon	22.0	0.06	2.01
c) Post Mansoon	24.0	0.06	2.54

APPENDIX II

OBSERVED AND COMPUTED DIRECT SEDIMENT GRAPH ORDINATES OF THE STROM EVENTS

Date	Observed runoff (X10^5m^3/day)	Effective Rainfall (mm)	Mobilized Sediment (t/Km^2)	Observed direct sediment production rate (t/day)	Computed Sediment producion rate (t/day)
Sep'86					
15	0.0			0.0	0.0
16	2.76			0.75	1.45
17	57.37	3.8	1.27	75.72	52.93
18	133.87	20.2	6.73	305.22	276.68
19	54.00	5.1	1.03	61.58	39.08
20	3.37			0.71	0.08
21	1.73			0.31	0.005
22	0.0			0.0	0.0
Oct'86					
11	0.0			0.0	0.0
12	3.74			1.496	0.882
13	27.76	4.2	1.4	63.16	59.01
14	101.98	11.6	3.87	169.1	159.81
15	28.33	1.7	0.57	39.4	22.25
16	2.85			1.88	0.43
17	0.0			0.0	0.0
July'87					
13	0.0			0.0	0.0
14	4.63			3.96	2.56
15	66.94	7.3	2.43	104.42	103.77
16	24.09	2.5	0.83	43.94	36.77
17	5.69	0.1	0.03	9.49	3.56
18	0.0			0.0	0.0

Aug'87

22	0.0			0.0	0.0
23	13.24			5.68	6.13
24	27.63			18.41	21.05
25	131.10	16.6	4.15	184.59	188.74
26	189.96	31.4	7.84	344.67	388.10
27	106.35	9.0	2.25	106.40	104.27
28	47.92	0.8	0.19	41.11	18.34
29	17.64		12.38		10.31
30	0.0		0.0		0.0

Sep'87

3	0.0		0.0	0.0	
4	7.44	0.5	0.17	14.65	18.21
5	30.87	4.3	1.43	64.78	73.24
6	12.82	1.2	0.4	20.38	30.02
7	5.01			6.45	13.21
8	0.0			0.0	0.0

Sep'87

21	0.0			0.0	0.0
22	10.51			5.02	2.54
23	41.82	3.3	1.09	66.96	49.75
24	112.49	15.9	5.29	242.97	221.76
25	31.31	2.1	0.69	47.91	30.027
26	4.08			2.70	1.29
27	0.0			0.0	0.0

Oct'87

7	0.0			0.0	0.0
8	2.24			1.65	0.09
9	46.20	4.6	0.52	38.55	23.08
10	88.21	11.8	1.34	64.83	56.42
11	38.21	2.6	0.29	24.18	12.58
12	3.96		0.91	0.51	
13	0.0			0.0	0.0

Oct'87

17	0.0			0.0	0.0
18	16.51	0.5	0.125	19.60	23.84
19	64.11	6.0	1.5	67.19	75.86
20	142.39	19.4	4.85	209.80	212.62
21	43.27	3.8	0.95	52.24	49.77
22	13.15			12.10	10.12
23	0.0			0.0	0.0

Nov'87

6	0.0			0.0	0.0
7	20.40			14.07	16.86
8	60.30	6.4	2.13	99.49	101.43
9	102.20	16.8	5.6	243.73	242.81
10	43.20	2.8	0.93	49.24	47.94
11	18.70			12.06	6.55
12	0.0			0.0	0.0

June'88

4	0.0			0.0	0.0
5	55.30	3.7	0.93	60.83	59.05
6	103.08	12.3	3.08	149.47	148.45
7	134.79	22.7	5.68	256.1	253.91
8	91.48	5.7	1.43	88.74	75.76
9	31.50			24.89	16.06
10	0.0			0.0	0.0

July'86

3	0.0			0.0	0.0
4	9.80			17.64	21.81
5	34.84	2.9	0.58	32.45	35.12
6	57.47	6.5	1.31	59.47	61.65
7	137.05	19.5	3.9	164.47	167.75
8	51.95	6.1	1.22	58.19	55.58
9	28.12	2.5	0.52	25.62	25.31
10	9.51			4.48	4.46
11	0.0			0.0	0.0

Aug'88

11	0.0			0.0	
12	54.21			36.54	43.06
13	107.17	10.1	2.52	122.53	139.65
14	234.01	36.1	9.02	407.67	405.09
15	176.56	19.1	4.78	226.59	225.93
16	92.06	6.7	1.67	93.43	95.37
17	15.08			21.1	25.58
18	0.0			0.0	0.0

Sep'88

8	0.0			0.0	0.0
9	28.40	2.8	0.93	76.68	79.52
10	120.05	17.8	5.93	270.12	281.23
11	66.79	3.8	1.27	84.15	86.30
12	14.24			11.53	33.05
13	0.0			0.0	0.0

Oct'88

21	0.0			0.0	0.0
22	12.20			11.71	8.96
23	35.70	4.9	1.63	85.68	78.55
24	60.00	7.3	2.43	122.00	110.48
25	35.12	4.5	1.54	68.44	70.92
26	14.73			19.18	8.41
27	0.0			0.0	0.0

June '89

19	0.0			0.0	0.0
20	3.63			3.02	1.98
21	12.35			8.86	7.34
22	36.72	3.2	1.07	59.40	52.72
23	66.0	8.8	2.93	138.60	128.52
24	25.24	4.8	1.59	60.48	71.89
25	12.81			25.32	15.67
26	0.0			0.0	0.0

July'89

18	0.0			0.0	0.0
19	28.77			57.54	40.39
20	192.33	18.0	4.53	278.88	241.77
21	364.96	58.6	14.65	656.93	655.96
22	264.99	28.0	7.01	331.23	333.61
23	175.82	9.4	2.35	159.99	138.46
24	43.89			65.84	40.19
25	0.0			0.0	0.0

Aug'89

14	0.0			0.0	0.0
15	11.92			24.99	31.65
16	75.4	9.2	2.3	102.59	119.20
17	170.44	18.0	4.5	216.46	212.25
18	94.00	14.6	3.65	169.20	174.74
19	57.88	3.6	0.9	63.67	59.60
20	19.08			18.51	21.87
21	0.0			0.0	0.0

Sep'89

17	0.0			0.0	0.0
18	22.96			22.73	13.54
19	63.81	8.5	2.12	134.00	109.57
20	253.11	29.3	7.32	341.69	321.93
21	134.09	16.5	4.12	221.25	186.52
22	82.07	6.5	1.62	121.46	81.51
23	15.65			15.18	13.94
24	0.0			0.0	0.0

Oct'89

3	0.0			0.0	0.0
4	25.87			34.14	17.38
5	70.41	7.1	2.37	163.68	131.12
6	114.16	17.3	5.76	276.68	268.84
7	45.64	4.3	1.43	112.27	87.63
8	13.21			24.63	27.79
9	0.0			0.0	0.0

Nov'89

8	0.0			0.0	0.0
9	12.23			8.19	6.28
10	30.33	5.5	1.38	69.75	64.81
11	86.08	10.1	2.53	112.66	111.28
12	47.46	6.1	1.53	79.26	68.83
13	29.91	1.7	0.43	31.10	22.79
14	14.26			13.22	4.84
15	0.0			0.0	0.0

June'90

11	0.0			0.0	0.0
12	30.23	2.2	0.47	26.29	23.19
13	63.06	6.4	1.36	60.54	62.55
14	31.84	4.8	1.02	38.20	47.81
15	0.0			0.0	0.0

July'90

1	0.0			0.0	0.0
2	62.0	2.4	0.48	67.0	52.57
3	121.00	12.4	2.48	151.37	148.37
4	165.03	24.8	4.96	243.59	248.48
5	124.65	14.4	2.88	164.82	159.98
6	70.65	4.0	0.80	68.04	72.55
7	0.0			0.0	0.0

Aug'90

9	0.0			0.0	0.0
10	24.81			20.73	22.92
11	79.34	7.2	1.8	89.84	94.45
12	192.02	24.0	6.0	264.02	265.91
13	77.86	9.6	2.4	96.71	114.74
14	22.56	1.2	0.3	32.26	27.04
15	0.0			0.0	0.0

Sep'90

4	0.0			0.0	0.0
5	5.83			6.51	9.53
6	35.22	3.8	1.27	50.39	58.63
7	58.55	7.4	2.47	110.75	107.23
8	25.77	2.6	0.87	43.02	40.18
9	5.82			9.38	3.93
10	0.0			0.0	0.0

Oct'90

13	0.0			0.0	0.0
14	5.53			6.73	7.19
15	17.59	1.2	0.40	25.78	23.09
16	36.82	6.0	2.05	87.37	88.56
17	19.58	1.6	0.53	26.83	27.07
18	3.16			5.76	4.96
19	0.0			0.0	0.0

Nov'90

3	0.0			0.0	0.0
4	18.06			9.75	8.49
5	24.11			16.39	13.42
6	72.41	8.7	2.18	112.29	105.78
7	111.29	19.7	4.93	221.24	217.51
8	69.93	8.3	2.08	103.85	97.75
9	43.58	1.7	0.43	49.85	28.75
10	20.68			20.24	10.73
11	0.0			0.0	0.0

June’91

6	0.0			0.0	0.0
7	42.71	2.6	0.52	37.61	43.35
8	72.29	8.6	1.72	72.29	86.47
9	159.46	19.6	3.92	174.77	175.83
10	80.36	10.0	2.00	91.29	94.79
11	29.84	0.6	0.12	20.77	16.38
12	5.46			4.33	1.87
13	0.0			0.0	0.0

Aug’91

12	0.0			0.0	0.0
13	4.86			4.62	6.08
14	38.76	4.9	1.23	43.41	55.11
15	112.89	14.0	3.50	145.63	147.73
16	75.82	7.4	1.85	74.28	78.13
17	37.52	2.8	0.73	39.39	29.93
18	3.54			4.39	0.79
19	0.0			0.0	0.0

Oct’91

5	0.0			0.0	0.0
6	20.21			12.06	9.05
7	45.52	4.7	1.18	69.37	60.41
8	112.89	15.5	3.88	185.63	170.63
9	56.15	6.3	1.58	78.16	74.04
10	13.49	0.1	0.03	25.43	9.24
11	4.49			4.69	8.09
12	0.0			0.0	0.0

Nov'91

13	0.0			0.0	0.0
14	13.04			13.69	10.64
15	44.35	4.1	1.37	74.24	69.82
16	124.61	16.0	5.33	232.01	231.72
17	440.0	5.2	1.73	78.85	80.96
18	11.87			14.46	8.88
19	0.0			0.0	0.0

June'92

15	0.0			0.0	0.0
16	54.89	3.6	0.90	76.29	84.23
17	109.85	12.8	3.20	155.98	169.88
18	230.29	28.2	7.05	317.82	326.04
19	86.79	11.2	2.80	145.81	147.42
20	36.42			23.66	30.55
21	7.56			5.40	4.96
22	0.0			0.0	0.0

July'92

13	0.0			0.0	0.0
14	15.82			18.60	16.24
15	60.41	6.3	2.10	145.85	141.66
16	193.32	25.1	8.36	381.92	397.20
17	113.68	11.7	3.90	218.72	209.09
18	22.75			25.00	46.26
19	0.0			0.0	0.0

Aug'92

16	0.0			0.0	
17	22.92			21.76	14.57
18	121.52	13.9	3.48	188.36	164.51
19	223.04	30.3	7.58	350.17	331.01
20	132.49	15.3	3.85	197.41	172.89
21	44.25	0.3	0.08	59.73	46.47
22	0.0			0.0	0.0

Sep'92

17	0.0			0.0	0.0
18	24.13	1.3	0.43	45.50	49.82
19	79.12	7.8	2.60	131.79	134.12
20	23.02	3.8	1.27	56.67	77.83
21	11.59			17.98	24.69
22	0.0			0.0	0.0

Nov'92

5	0.0			0.0	0.0
6	16.17			15.19	10.13
7	58.82	5.4	1.35	81.76	70.48
8	125.09	18.0	4.50	206.39	199.08
9	61.85	6.8	1.74	87.2	81.59
10	35.15	1.4	0.35	47.45	32.12
11	0.0			0.0	0.0

APPENDIX III

COMPUTATION OF EFFECTIVE RAINFALL AND MOBILIZED SEDIMENT.

Storm event - June 6-13, 1991.

Total direct sediment $= 390.12 \times 10^5 \text{ m}^3$

Runoff depth (mm) $$= \frac{\text{Total direct runoff}(\text{m}^3)}{\text{Catchment area } (\text{Km}^2) \times 1000}$$

$$= \frac{390.12 \times 10^5}{940 \times 1000}$$

$= 41.5$ mm

Total rainfall $= 58.4$ mm

Infiltration (mm) = Total rainfall - runoff depth

$= 58.4 - 41.5$

$= 16.9$ mm.

0 index $$= \frac{\text{Infiltration (mm)}}{\text{Duration of rainfall excess (day)}}$$

$$= \frac{16.9}{5}$$

$= 3.4$ mm/day

Effective rainfall (mm) = Total rainfall - 0 index x duration of rainfall excess

$= 41.5$ mm

Runoff depth = effective rainfall

Volume of hyetograph = Effective rainfall (mm) x Area which mobilize the sediment (km^2)

= Total volume of sediment produced (tonnes)

Volume of hyetograph = 2.6x + 8.6x + 19.6x + 10x + 0.6x

Total volume of sediment produced = 500.20 tonnes

2.6x + 8.6x + 19.6x + 10x + 0.6x = 500.2

x = 12.05 km^2, area which mobilize the sediment

Total area which mobilize the sediment = duration of excess rainfall x area which mobilize the sediment

= 5 x 12.05

= 60.26 km^2

Quantity of sediment mobilized by 41.5 mm effective rainfall per unit area

$$= \frac{500.20}{60.26}$$

= 8.3 t/km^2

Sm(t-1) + Sm(t) + Sm(t+1) + Sm(t+2) + Sm(t+3) = 8.3 t/km2.

Quantity of sediment mobilized per unit effective rainfall per unit area.

$$= \frac{8.3}{41.5}$$

= 0.2 $t/mm/km^2$.

Sm(t-1) = 0.2 x 2.6 = 0.52
Sm(t) = 0.2 x 8.9 = 1.72
Sm(t+1) = 0.2 x 19.6 = 3.92
Sm(t+2) = 0.2 x 10 = 2.0
Sm(t+3) = 0.2 x 0.6 = 0.12

```
C       APPENDIX IV
C       PROGRAM LISTING FOR GAUSS JORDAN ELIMINATION METHOD
        DIMENSION A(9,10),C(9)
        DOUBLE PRECISION A,C,D
        WRITE(*,*)'ENTER THE NO. OF UNKNOWNS'
        READ(*,*)N
        WRITE(*,*)'ENTER THE MATRIX OF COEFFICIENTS'
        DO 1 I=1,N
        READ(*,*) (A(I,J),J=1,N)
  1     CONTINUE
         WRITE(*,*)'ENTER THE VECTOR OF CONSTANTS'
C        DO 2 I=1,N
        READ(*,*) (C(I),I=1,N)
  2     CONTINUE
        WRITE(*,*)'ENTERED MATRIX OF COEFFICIENTS IS ....'
        DO 63 I=1,N
        WRITE(*,39) (A(I,J),J=1,N)
  63    CONTINUE
        WRITE(*,*)'ENTERED VECTOR OF CONSTANTS IS....'
C       DO 4 I=1,N
        WRITE(*,10) (C(I),I=1,N)
  4     CONTINUE
C       ****************************************************
C       GAUSS JORDAN ELIMINATION
C       ****************************************************
        DO 3 I=1,N
        A(I,N+1)=C(I)
  3     CONTINUE
        DO 6 I=1,N
  23    D=A(I,I)
        IF (D) 19,20,19
  20    DO 34 NF=I+1,N
        IF(A(NF,I).NE.0)THEN
        DO 35 M=1,N+1
        A(I,M)=A(I,M)+A(NF,M)
  35    CONTINUE
        `GOTO 23
        ENDIF
  34    CONTINUE
        WRITE(*,*) 'SORRY! THE MATRIX IS SINGULAR-NO SOLUTION'
        STOP
  19    DO 7 J=I,N+1
  7     A(I,J)=A(I,J)/D
        DO 8 K=1,N
        IF(K.NE.I)THEN
```

```
      E=A(K,I)
      DO 9 J=I,N+1
    9 A(K,J)=A(K,J)-A(I,J)*E
      ENDIF
    8 CONTINUE
    6 CONTINUE
      WRITE(*,*) 'THE SOLUTION OF THE VECTOR IS.....'
C     DO 75 I=1,N
      WRITE(*,10) (A(I,N+1),I=1,N)
   75 CONTINUE
   39 FORMAT(10F8.3/)
   10 FORMAT(1X,F10.5)
      STOP
      END
```

A MATHEMATICAL MODEL FOR SEDIMENT YIELD IN AGRICULTURAL WATERSHED

By

BABU V.

ABSTRACT OF THE THESIS

**Submitted in partial fulfilment of the
requirement for the degree**

Master of Technology
in
Agricultural Engineering

**Faculty of Agricultural Engineering
Kerala Agricultural University**

**Department of
Water Resources and Conservation Engineering
EGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY**
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1998

ABSTRACT

The knowledge of temporal distribution of sediment yield is required in the design and operation of soil and water conservation programmes on watershed basis. For the project planning purposes, the estimates made are mostly based on experience. Such estimates are very approximate and grossly inadequate for engineering analysis. Therefore there is an urgent need for rational analysis of erosion data from catchments, inorder to obtain relationship for erosion rate. Therefore a mathematical daily sediment yield model is developed for Thuthapuzha drainage basin (940 km^2) of Bharathapuzha basin, corresponding to Muskingum routing equation. The model is based on combined approach of translation and routing for simulating sediment graphs. Thirty seven selected storm events of the drainage basin observed during 1986-92 are used for estimation of model parameters by Lagrange multipliers method and three storm events of 1993 are used for verification of the model.

The model is used to compute temporal distribution of suspended sediment yield on storm basis and their performance is evaluated both qualitatively and quantitatively. Mathematical relationships of mobilized sediment with effective rainfall, computed sediment flow rates with observed sediment flow rates and observed and computed sediment flow with effective rainfall and mobilized sediment were also established. The Correlation Coefficient of all those equations are found to be close to one. The statistical measures of Percentage Absolute Error in peak sediment flow rates, Absolute Prediction Error, Integral Square Error, Correlation Coefficient and Coefficient of Efficiency of the model are obtained as 3.9934, 9.0007, 5.3286, 0.9951 and 0.9659 respectively. The study reveals that the developed model is a very effective tool in the real time forecasting of sediment yield in Thuthapuzha drainage basin.