MODELLING SOIL EROSION ON WATERSHED BASIS

A Thesis
Submitted to the
Bidhan Chandra Krishi Viswavidyalaya
for the award of the Degree of Doctor of Philosophy
in
AGRICULTURE (SOIL AND WATER CONSERVATION)

By
PRATAP KUMAR DHARA

DEPARTMENT OF AGRICULTURAL ENGINEERING
FACULTY OF AGRICULTURE
BIDHAN CHANDRA KRISHI VISWAVIDYALAYA
MOHANPUR, NADIA, WEST BENGAL
1994

Bidhan Chandra Krishi Viswavidyalaya
FACULTY OF AGRICULTURE

From :

P O. KRISHI VISWAVIDYALAYA
MOHANPUR, NADIA 741 252
W. Bengal, (India)

Ref. No.

Date 17/6/94

Dr. Ranjit Kumar Ghosh
B.Sc.(Hons), B.Sc.Agrill.
Engg & M.Tech.; Ph.D.;
MIE, Life Member ISAE
Professor of Agricultural
Engineering, B.C.K.V.,
Mohanpur, Nadia, W. B.

Dr. Bijan Kumar Mandal
M.Sc.(Ag.), Ph.D., Reader
Department of Agronomy,
Faculty of Agriculture,
B.C.K.V., Mohanpur, Nadia,
W. B.

CERTIFICATE

This is to certify that the work recorded in the Thesis entitled, "Modelling Soil Erosion on Watershed Basis", submitted by Sri Pratap Kumar Dhara for the award of the Degree of Doctor of Philosophy in Agriculture (Soil and Water Conservation) of the Bidhan Chandra Krishi Viswavidyalaya, is the faithful and bonafide research work carried out under our Joint Supervision and guidance. The results of the investigation reported in the thesis have not so far been submitted for any other Degree or Diploma. The assistance and help received during the Course of investigation have been duly acknowledged.

17/6/94
B. K. Mandal
Advisor

RGhosh 17/6/94
R. K. Ghosh
Advisor

TABLE OF CONTENTS

ACKNOWLEDGEMENT

Author expresses his most sincere thanks and deep sense of gratitude to Dr. R. K. Ghosh, Professor of Agricultural Engineering and Dr. B. K. Mandal, Reader in Agronomy under whose able guidance and supervision the present investigation has been carried out. The learned advice and suggestions, liberal help, sound criticism and sympathetic attitude which the author received from them at all stages of the research work have gone a longway in the completion of this work.

The author is deeply indebted to Prof. D. K. Datta, Prof. S. P. Maity, Sri Asit Kumar Chakraborty and Dr. P. K. Tarafdar, Department of Agricultural Engineering, for their help, assistance and encouragement.

The author is highly indebted to Director of Soil Conservation, Mr. Kamal Misra, Joint Director of Soil Conservation Mr. G. C. Basu, Assistant Engineer, Mr. T. R. Jadav, Assistant Hydrologist and Sri Anil Kumar Ghosh, Technical Assistant, Damodar Valley Corporation, Hazaribagh, Bihar for supplying me with all necessary data and giving technical advice from time to time.

The author is grateful to Dr. A. K. Bhattacharyya and Dr. A. Singh, Principal Scientists, W.T.C., IARI, New Delhi 110 012, for amending the manuscript.

The author wishes his thanks to Mr. Subhash Chandra Ghosh for typing this dissertation.

Pratap Kumar Dhara
(PRATAP KUMAR DHARA)

Dated: Kalyani
The 17th June 1994.

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

FIG. NO. DESCRIPTION Page No.

APPENDIX-A

LIST OF ABBREVIATIONS

Agric	Agricultural
Amer	American
A.R.S.	Agricultural Research Service
A.S.A.E.	American Society of Agricultural Engineers
A.S.C.E.	American Society of Civil Engineers
A.W.R.A.	American Water Resource Association
Bull.	Bulletin
ch.	Chapter
Civ.	Civil
Co-opn.	Co-operation
Cons.	Conservation
Deptt.	Department
Div.	Division
D.V.C.	Damodar Valley Corporation
e.g.	As for example
et al.	And others
Engrs	Engineers
Fig.	Figure
Geol.	Geology
Geophys.	Geophysics
H'bag	Hazaribagh
Hy.	Hydrology
IIT	Indian Institute of Technology
Inst.	Institute
IASH	International Assoc. Science Hydrology
ISAE	Indian Society of Agricultural Engineers
Jour.	Journal
Lat.	Latitude
Long.	Longitude
N.P.K.	Nitrogen Phosphate Potash
Proc.	Proceedings
Publ.	Publication
Res.	Research
Sci.	Science
SCD(ED)	Soil Conservation Department (Engineering Division)
Soc.	Society

SPR	Sediment Production Rate
Trans	Transactions
USDA	United State Department of Agriculture
USLE	Universal Soil Loss Equation
UNESCO	United Nations Educational Scientific and Cultural Organisation
Uni.	University
Vol.	Volume.

LIST OF SYMBOLS

a a_o	Co-efficients derived by regression analysis
a'	Matrix of regression co-efficient
A	Drainage area in suitable units
A_c	Column vector of watershed characteristics
A_{cm}	Area of cross section in m^2
A_I	Product of area and precipitation frequency intensity
A_K	Drainage area in sq.km.
A_m	Drainage area in sq.mile
b	Co-efficient derived by regression analysis
b_i	Soil permeability index
b'	Vector of regression coefficient
B_s	Bar soil area ratio
C	Constant of variance
°C	Degree centrigrade
c_f	Cover factor/crop management factor
cm	Centimetre
C	Negative value of log N_s where OR is zero
cc	Cubic centimetre
C_c	Compactness coefficient
d	Co-efficient derived by regression analysis
d_{35}	Particle size at which 35% of the particles are finner (m)
d_{50}	Particle size at which 50% of the particles are finner (m)
d_{84}	Particle size at which 84% of the particles are finner (m)

D	Diameter of soil particles (micron)
D_i	Soil particles greater than 1 mn (%)
D_m	Diameter of soil particles in mm
e	Co-efficient derived by regression analysis
E	Total soil loss
E_{ai}	Soil loss in acre-inch
0_E	Degree E_{east}
E_f	Soil erosion control factor
E_k	Soil loss in ton per km^2 per year
E_{kh}	Soil loss in kg/ha
E_{km}	Soil loss in kg per m per min
E_m	Annual silt rate (m m^{-3}) from 100 sq.km of watershed area
E_{mg}	Soil intercepted in splash samplers during a 30 minute period
E_{mm}	Soil loss (m^3 m^{-1})
E_{ta}	Soil loss in tonnes per acre
E_{th}	Soil loss in tonnes per ha per year
ED	Erodibility index
ED_{rf}	Soil erodibility factor
ED_{rf_1}	Relief and Soil erodibility factor
ED_{rf_2}	
$(ED)_i$	Inherrent erodibility of soil in inches
ED_f	Soil resistance factor which ranges normally from 1.5 to 0.5
EI_{30}	Erosion index related to P_{30}

f	Co-efficient derived by regression analysis
ft	Feet
g	Co-efficient derived by regression analysis
G_i	Ratio of average annual precipitation inch to average annual temp. (°F)
h	Co-efficient derived by regression analysis
ha-m	Hectare metre
H	Constant depending on soil quality (to be found by experience)
H_{ai}	Hypsometric integral
j	coefficient
J	Total time
k	Co-efficient derived by regression analysis
Km	Kilometre
K	Slope of curve with respect to N axis
KE	Kinetic energy of the storm
l	Co-efficient derived by regression analysis
L	slope length of (m)
L_{ck}	Length of main stream in km
L_f	Slope length factor
L_{ft}	horizontal length of land slope, ft.
L_r	Stream length ratio
Lb/Lw	Length width ratio
m	Co-efficient derived by regression analysis
m'	exponent of degree of land slope
mm	Millimetre
n	Co-efficient derived by regression analysis

n_1	roughness coefficient
n'	exponent of horizontal length of land slope
N	Number of years
N_s	Number of streams per 100 hectares
°N	Degree North
O	Co-efficient derived by regression analysis
%	Percentage
OR	Stream orders in reverse order
P	co-efficient derived by regression analysis
p	Annual rainfall in cm
P_{ai}	Mean annual precipitation in inches
P_d	daily rainfall in mm
P_e	rainfall erosivity
P_f	rainfall factor
P_i	length of times the amount of rainfall in inches
P_{ih}	Intensity of rainfall in inch per hour
$P_{i(30)}$	Maximum 30 minutes amount of rainfall
P_{30}	Maximum 30 minutes rainfall intensity of the storm
P_m	the precipitation depth (cm) during the wettest month of the year
P_v	Velocity of raindrop ft/sec.
$P/_Q$	Dimensionless parameter of $(^P/_Q)$ i.e. annual rainfall ÷ annual runoff
$(^P/_Q)_a$	Average annual P/Q values of the present and all preceding years for a particular watershed
$(P/Q)_{cu}$	Cumulative value of P/Q dimensionless

q	Co-efficient derived by regression analysis
Q	Annual runoff in centimetre
Q_a	Average annual runoff
Q_{ac}	Average annual runoff in centimetre
Q_{aft}	Average annual runoff in cubic feet
Q_{ai}	Average annual runoff in inches
Q_{am}	Average annual runoff in mm
Q_{cm}	Runoff in cm
Q_{cu}	Cumulative monthly runoff cm
Q_d	Daily water discharge c.f.s
Q_f	Runoff factor
Q_{fs}	Average discharge in c.f.s.
$Q_{fs(25)}$	25 of years average runoff in c.f.s.
Q_i	Drainage density km/sq.km.
Q_{ft}	Annual runoff in ft^3
Q_{hm}	Average annual runoff in ha m
Q_{mh}	Runoff in m^3 ha^{-1}
Q_{mhr}	Average annual runoff in m^3 hr^{-1} ?/
Q_m	Runoff (m^3 m^{-1})
Q_{mm}	Runoff discharge m^3 per m width per year
Q_{ms}	Average annual runoff in cumec
Q_T	Frequency of runoff
Q_v	Column vector of peak flow at various return periods
q	Co-efficient derived by regression analysis
r	Co-efficient
R	Relief length ratio
R_b	Weighted mean bifurcation ratio

R_c	Circulatory factor
R_f	Rotundity factor
R_{fm}	Relief ratio in feet per mile
RN	Ruggedness number
R_r	Relative relief
R_t	Total relief in metre
s	Co-efficient derived by regression analysis
S	Slope in percentage
S_a	Watershed average slope in percentage
S_b	Shape factor
S_c	Main stream channel slope
S_f	Slope percentage factor
S_{fm}	Main channel slope feet per mile
t	Co-efficient derived by regression analysis
T_m	mean annual temperature in °C
u v	Co-efficient derived by regression analysis
V	Velocity of flow
w	Co-efficient derived by regression analysis
W_a W_z	Independent variables/empirical constants
x y	co-efficient derived by regression analysis
Y	Sediment yield
Y_a	Annual sediment yield in ha-m/km^2
Y_{aa}	Average annual sediment yield in ha-m/km^2

Y_{ai}	Soil aggregation index in percentage
Y_{at}	Average annual sediment load in tons
Y_{atm}	Average annual sediment load in tons/mile^2
Y_{cc}	Sediment discharge cm^3 per cm width per year
Y_{cm}	Sediment discharge in cm
Y_{cu}	Cumulative monthly sediment yield tons/ha
Y_d	Daily sediment load in tons
Y_{hm}	Sediment loss in ha-m per 100 km^2
Y_o	Dimensionless dependent hydrologic response
Y_r	Sediment delivery ratio in percentage of annual gross erosion
Y_s	Sediment load in lb/s/ft
Y_{sm}	Sediment yield lb per min
Y_t	Sediment yield in metric ton
Y_{tm}	Sediment yield tons per mile^2
z	co-efficient derived by regression analysis
Z	Perimeter in miles

ABSTRACT

There are many erosion-producing parameters. But rainfall and watershed characters are considered as the major influencing parameters. These two can again be sub divided into many actually effective components which are neither easily measureable nor are easily available from the records of various organisations engaged in this work. But annual total values of rainfall (P), runoff (Q) and sediment yield (Y_a) or soil loss in a watershed are generally recorded by the organisations. So for future planning and execution of the sustainable agriculture in any ungauged (soil erosion) watershed the models of $Y_a = f\ (P,\ Q)$ may be workable, though may not be very accurate from academic angles.

With this aim in view basic data of eight watersheds in Damodar and Barakar basin (Lat. 23° 3' N to 24° 22' N and Long. 84° 41' E to 86° 43' E) were collected from the records of SCD (ED), DVC, H'bagh 825301, Bihar for a period of 6 to 11 years.

Following trial-error methods, the equations of the form

$$Y_{aa} = W_b - x \left(\frac{P}{Q} \right)_a^y$$

and $$Y_a = W_d - W_e \left(\frac{P}{Q}\right)^y$$

were obtained. Here

Y_{aa} = average annual sediment yield in ha-m per square kilometre

P = annual rainfall in cm

Q = annual runoff in cm

$({}^{P}/Q)_a$ = average values of P/Q

W_b x W_d W_e Y are empirical constants and for estimating annual sediment yield.

The difference between the two models are very subtle. An examinations into the results from these two models reveal that Y_{aa} model is superior than Y_a model. This is not unexpected, too. Because average values have more manoeuvrability than individual values in such heterogeneous and diversified situations.

CHAPTER I

INTRODUCTION

INTRODUCTION

In India as many as 144 million hectares land are subjected to erosion of one kind or the other. The amount that is lost as a result of water erosion alone has been estimated to be about 6000 million tonnes annually. It contains nutrients equivalent to 5.37 million tonnes of N.P.K. (Bose, 1989). Soil erosion on a large scale is not only detrimental to current agricultural production but it is a threat to the survival of a nation. In an untreated agricultural watershed it is obvious that runoff water from upper reaches flows unchecked while transporting the eroded soil to down stream passing through gullies.

Soil erosion is influenced by several environmental factors of which rainfall plays an important role. Rainfall and runoff are related with erosion in an understandable manner. Therefore either or both of these have been used for many years in erosion studies.

Soil loss estimation is of great concern to the watershed managers and soil conservationists. Accurate prediction of sediment yield from watersheds is necessary for undertaking watershed management plans ~~from watersheds is necessary for undertaking watershed management plans~~ on priority basis. A priority approach is imminent in view of vast areas involved with constraint of technical manpower and financial resources.

Although various techniques and tools for predicting the hydrologic responses such as runoff and sediment yield from watersheds are available in literature, all of these are location specific and cannot be universally adopted. Therefore, there is a need for good and accurate techniques for prediction of soil loss based on rainfall, runoff and easily available land parameters.

Keeping the above facts in view, the present study was undertaken to establish watershed-based model(s) for soil loss from the two easily available (or measureable) parameters like annual rainfall and runoff.

CHAPTER II

REVIEW
OF
LITERATURE

REVIEW OF LITERATURE

The principles underlying control of soil erosion, or soil conservation measures in a limited sense are to protect the soil from the impact of raindrops; to reduce the speed and volume of runoff and consequent soil loss. The soil erosion problems started becoming acute specially in the vulnerable areas because of opening up of roads, railway lines deforestation, cultivation of unsuitable lands, overgrazing and various other developmental activities. The disastrous problem began to attract attention of agricultural scientists, forest scientists and also knowledgeable administrators. This awareness appears to have faced mostly in the 1930's or little earlier. This can perhaps be traced to some similar awareness in the U.S.A. To be able to develop a proper plan for controlling soil erosion, it is important to understand the phenomenon of soil loss in depth to make an estimation of the quantum of soil loss due to several, factors of which the three important are probably the rainfall, the watershed characteristics and the runoff. This chapter briefly deals with the review of research work carried out in India and abroad in different years and relevant or remotely relevant to the present works under consideration.

2.1 Quantitative Geomorphology

Quantitative geomorphology has received a great deal of attention. The role of classical descriptive analysis of drainage basins was first discussed by Horton (1945). In early days, it had very limited scope in practical engineering problem. In this connection, a few geomorphologists started to quantify the land Sp form description of the drainage basins. Similar attempts were also made by Strahler (1957, 1958) in which , he highlighted a base system of quantitative geomorphology for dimensional analysis and principles of scale model. In two geometrically similar drainage basins, corresponding length dimensions will be in a fixed ratio. The conception is that in two similar drainage basins, even though different in size, will have correspondingly identifiable dimensionless numbers. In this field some, contributions also made by Maxwell (1955), Melton (1959) and Morisawa (1957, 1962).

2.1.1 Drainage Net work

Strahler (1957) designated the stream orders and drainage net work characteristics as order 1, order 2, order 3 and so on, which were related to hydrologic and erosional processes. All the first unbranched streams were designated order 1. Where two first order streams joined, the subsequent channel segment became order 2. In the same way, a channel segment of order 3 was formed by joining two 2nd order channel segments and so on. Therefore, the main stream was the highest order segment through which all runoff water including sediment passes.

Bifurcation ratio may be defined as the ratio of number of segments of the given order to the number of segments of the higher order. The ratio varied from one order to another due to variation of geometry of watersheds.

Horton (1932) law of stream numbers stated that the number of stream segments of each order formed an inverse geometric sequence with order number. Later, Strahler (1952) modified this law by collecting data from many localities. When logarithm of stream number was plotted against order, most drainage net works showed a linear relationship (Maxwell, 1955).

The bifurcation ratio was highly stable and showed a small range of variation from one region to another except where powerful geologic control dominated.

Tyagi et al. (1970) and Varshney et al. (1970) established a relationship as follows :

$$\text{Log } N_s = K.OR - C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

where, N_s = Number of streams per 100 hectares

K = Slope of curve with respect to N - axis

OR = Stream orders in reverse order

C = Negative value of Log N_s where OR is 0

Miller (1953) studied the frequency distribution of channel segment orders of some drainage basins and observed that the stream lengths were strongly skewed to the right.

Schumm (1956) corrected this skewness by using the logarithm value of the lengths. Horton (1945) defined drainage density as the ratio of cumulative channel segment lengths of a drainage basin to the basin area. He stated that it was closely related with sediment yield. He also defined stream frequency as the ratio of the number of streams in a watershed to its area. He also observed that the intensity of erosion in a watershed increased with the increase in stream frequency in a watershed. Leopold and Miller (1956) and Hack (1957) developed a correlation between stream discharge and basin area. The relationship was depicted in the following manner.

$$Q_{ms} = a\,A^{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

where, Q_{ms} = discharge such as mean annual flood in cumec.

A = Watershed area in suitable units

a and b are constants derived by fitting regression lines to the available data.

Linsley _et al_. (1975) and Varshney (1977) classified and presented different drainage net work patterns.

2.1.2 Basin Shape

Horton (1932) prepared a form factor which was dimensionless ratio of basin area to the square of basin length of a drainage basin. The U.S. Army Corps of Engineers used inverted form of this ratio for the preparation of unit hydro-graph.

Later Horton (1941) also expressed the drainage basin shape and its effect on stream discharge characteristics. High bifurcation ratio of long narrow basins would have attenuated flood discharge periods whereas round basins of low bifurcation ratio would be expected to have sharply peaked flood discharges.

Miller (1953) defined the dimensionless circulatory ratio which was the ratio of basin area to the area of a circle having the same perimeter of the basin. He found that the value of circulatory ratio varied from 0.6 to 0.7 for the first and second order basin in homogeneous shales and dolomites. While it was 0.4 to 0.5 for the flanks of moderately dipping quartzite strata of Clinch Mountain, Virginia.

Schumm (1956) defined elongation ratio of drainage basin. It was the ratio of diameter of a circle of the same area as the basin to the maximum basin length. The value of it runs from 0.6 to 1.0 over a wide range of climatic and geologic types. Values near to 1.0 appeared typical of regions of very low relief; whereas 0.6 to 0.8 were generally strong relief and steep ground slopes.

2.1.3 Topographic Factors

Total watershed relief is the difference in elevation between the most remote point in the divide line and the discharge point of a watershed with reference to a given datum.

Schumm (1956) estimated basin relief along "The longest dimension of the basin parallel to the principal drainage line".

He also stated that erosion intensity increased with the increase of watershed relief. Schumm also estimated dimension less basin relief by dividing the horizontal distance on which it was estimated. Thus relief ratio indicated the overall steepness and erosion intensity of a drainage basin. He found that sediment yield per unit area was closely related with relief ratio.

Strahler (1958) expressed ruggedness number which was a product of total relief and drainage density. High values of the ruggedness number occured when basin slopes were long and steep only. It varied from 0.6 to 1.0 of the Louisians. ??

2.2 Deterministic Modelling of Runoff

Potter (1953) reported a regression relationship of peak stream discharge upon factors of basin area, topography and precipitation for 51 drainage basins in the Appalachian Plateau and established Potter's 'T' factor which indicates basin geometry to be significant in multiple regression with basin area and measures of rainfall frequency and intensity.

Bagley *et al.* (1964) developed an equation for predicting water discharge in Utah by using a relation between runoff and a number of geomorphic variables.

Lull *et al.* (1966) used climatic, topographic and land use variables of 137 watersheds in North-east United States for developing the relationship of average annual and seasonal runoff and daily mean discharge at selected flow durations. He suggested that important variables responsible for annual and seasonal discharge in descending order were precipitation, percentage forest cover, elevation, latitude, July mean maximum temperature and percentage of swamp.

Mustonen (1967) studied the effects of climate and basin characteristics on annual runoff and showed that normal multiple regression was an appropriate method for analysing hydrologic relationships.

Shelton and Sewell (1969) used a set of geomorphic parameters to carry out the analysis of geomorphic interrelations for small agricultural watersheds. They used important component technique and varimax rotation of the factor weight matrix to delete 11 physical variables from the original 17 selected variables from watersheds. They suggested that in the final selection of a variable, consideration should be given to quality of measurement, knowledge of the watershed and relevance to the intended use.

Haan and Read (1970) used water discharge data from 13 small agricultural watersheds in Kentucky and analysed by standard multiple regression techniques. Later they developed an equation for prediction of average annual water discharge by using 21 geomorphic variables. After that Haan and Allen (1972) developed the following equation after eliminating the non-significant independent variables and also comparing the multiple regression and principal component regression for predicting mean annual water discharge in Kentucky.

$$Q_{ai} = -9.65 + 0.43\ P_{ai} + 0.62\ Z + 0.01\ R_{fm} \quad \ldots\ldots\ldots \quad (2.3)$$

where, Q_{ai} = mean annual runoff in inches

P_{ai} = mean annual precipitation in inches

Z = perimeter in miles

R_{fm} = relief ratio in feet per mile.

Raghunath *et al.* (1970) worked on the characteristics of 17 watersheds along with runoff in the Nilgiris and developed the following regression equation for prediction of annual runoff.

$$Q = \frac{P^{1.4}\ A_k^{\ 0.63}\ R_t^{\ 0.66}}{15.19\ R_f^{\ 2.05}\ L_{ck}^{\ 2.05}\ T_m^{\ 1.34}} \quad \ldots\ldots\ldots \quad (2.4)$$

where, Q = annual runoff in cm

P = annual rainfall in cm

A_k = watershed area in sq km

R_t = total relief in m

R_f = rotundity factor ???

L_{ck} = Length of main stream in km

T_m = mean annual temperature in °C

They further regressed R_t, L_{ck} and R_f in terms of watershed area and modified the equation (2.4) to obtain the following

$$Q = \frac{1.511 \quad Z^{1.44}}{T_m^{\quad 1.34} \; R_f^{\quad 0.0613}} \quad \ldots\ldots\ldots\ldots\ldots \; (2.5)$$

They observed that co-efficient of determination and standard error of estimate were 0.81 and 0.086 respectively. Therefore, it was considered to be fairly reliable.

Wong (1979) used twelve hydrologic, geomorphic and meteorologic variables to derive ten dimensionless product through the application of Buckingham-II theorem. Principal component analysis was performed on ten dimensionless products which yielded two dimensionless components that account for almost 70% of the total variance. He derived the following simplified functional relationship for prediction of mean annual runoff in a humid region.

$$\mathrm{Log}_{10} Q_{mhr} = \log_{10} m + a \log A_1 + b \log S_a \quad \ldots\ldots\ldots\ldots \; (2.6)$$

where, Q_{mhr} = Average annual runoff $m^3\ hr^{-1}$

A_1 = Product of area and precipitation frequency intensity

S_a = Watershed average slope in percentage

m = Co-efficient derived by regression analysis.

Jose and Das (1982) derived the following multivariable model for prediction of runoff using three independent variables such as R_f, R_c, C_c from 11 watersheds of Mayurakshi catchment in Bihar, India.

$$\text{Log } Q_{cm} = 2{,}238.43 + 22.12 \log (100 + R_f) - 608.28 \log (100 + R_c) - 530.02 \log (100 + C_c) \quad \ldots\ldots\ldots \quad (2.7)$$

where, Q_{cm} = runoff in cm

R_c = Circulatory factor

R_f = Rotandity factor ???

C_c = Compactness co-efficient.

Misra (1987) developed the best fit regression model (Eq. 2.8) for predicting mean annual runoff using one parameter collected from the significant components of ungauged watersheds of upper Damodar Valley.

$$Q_{am} = 30.409\ (A_k)^{0.5}\ (RN)^{-0.27}\ (S_b)^{0.44}\ (S_c)^{0.365} \ldots\ldots \quad (2.8)$$

where, Q_{am} = mean annual runoff mm

R_N = Ruggedness number

S_b = Shape factor and

S_c = main stream channel slope (%)

2.3.1 Sediment Yield Models

Zingg (1940) developed the following soil loss formula

$$E_{ta} = c\ S^{m'}\ L_{ft.}^{n'} \quad \ldots\ldots\ldots\ldots \quad (2.9)$$

where, E_{ta} = Total soil loss, tonnes / acre

c = Co-efficient - derived by regression analysis

S = degree of land slope in per cent

L_{ft} = horizontal length of Land slope, ft

m' = exponent of degree of land slope

n' = exponent of horizontal length of Land slope

Zingg fitted the formula (2.9) on shelby soil at Bethany M. O. after a thorough experiments.

$$E_{ta} = 0.026\ S^{1.37}\ L_{ft}^{\ 1.60} \quad \ldots\ldots\ldots\ldots\ (2.10)$$

Smith (1946) further modified and developed the Zingg's soil loss formula to

$$E_{ta} = c\ S^{1.4}\ \underline{\underline{L_{ft}}}^{\ 0.\underline{\underline{6}}} \quad \text{[illegible]} \quad \ldots\ldots\ldots\ldots\ (2.11)$$

Musgrave (1947) developed the following relationship for estimation of the average soil losses from broder areas.

$$E_{ai} = (ED)_i\ c_f\ S^{1.35}\ L_{ft}^{\ 0.35}\ P_{i(30)}^{\ 1.75} \quad \ldots\ldots\ (2.12)$$

where, E_{ai} = Soil loss in acre-inch

$(ED)_i$ = Inherrent erodibility of soil in inches

c_f = cover factor

$P_{i(30)}$ = Maximum 30 minutes amount of rainfall of 2 years frequency of inches.

Anderson (1957) have illustrated the relationship of watershed variables to the sediment yield. The sediment yield depends upon the geology, topography, land use condition of vegetation and protective and management measures. He also stated that nature of storm and stream flow affect/responsible for yield.

pl check with Ref.

Lanbein *et al.* (1958) developed a relation between average annual sediment production rate per unit area and mean annual precipitation. They reported that the maximum sediment production rates occur at about 30.5 cm of mean annual rainfall because such low rainfall areas normally have little protective cover.

Wischmeier and his associates from 1957 onwards developed universal soil Loss Equation (U.S.L.E.) on agricultural lands using erosion under a set of conditions of slope climate, rainfall, crop management and conservation practices.

$$E = P_f \, ED_{rf} \, L_f S_f \, C_f \, E_f \quad \ldots\ldots\ldots\ldots \qquad (2.13)$$

where, P_f = Rainfall factor, rather the erosion index which is the product of the Kinetic energy of the storm times of the maximum 30 minutes intensity

ED_{rf} = Soil erodibility factor which is the average soil loss per unit area per unit of erosion index from a cultivated fallow plot

L_f = Slope length factor

S_f = Slope percentage factor

E_f = erosion control or soil conservation practices factor (such as strip cropping, contour farming etc.)

The combined $S_f L_f$ factor may be calculated from the graph according to USDA soil Conservation Service.

The values of some of the factors obtained under the soil and climatic conditions of India are as follows : K_f factor

- 0.3 for silty clay loam soil at Dehra Dun; 0.34 for lateritec soil of South India, 0.059 for alluvial soil of Baroda; c factors - Maize 0.73; wheat 0.73; moong 0.465, groundnut 0.374; cowpea 0.327, potato-potato 0.82; potato-barley 0.92, potato-fallow 0.83; P factor - contour cultivation 0.321, bench-terracing 0.076.

The universal soil loss equation overcomes many of the limitations of earlier methods such as the Musgrave (1947) equation and its subsequent modifications. It incorporates (i) a more highly refined rainfall factor (ii) a method of evaluating cropping management effects on the basis of local climatic conditions (iii) a quantitative soil erodibility factor and (iv) a method of accounting for productivity level crop sequences a residue management. Fournier's formula (1960) for prediction of soil loss

$$E_k = ED_{rf_1}^{Pm/P} - ED_{rf_2} \quad \ldots\ldots\ldots \quad (2.14)$$

ED_{rf_1} and ED_{rf_2} the relief and soil erodibility factors (the former ranging from 20 to 100, the latter from 500 to 1000)

E_k = Soil loss in ton per km^2 per year

Pm = the precipitation depth (mm) during the wettest month of the year.

In 1964 Rogers, Barnett and Cobb (quoted by Ghosh, 1993) established one regression equation for soil loss which is as follows :

$$E_{ta} = 0.443\ P_{ih} + 0.011\ P_i - 0.711 \quad \ldots\ldots\ldots \quad (2.15)$$

where P_{ih} = Intensity of rainfall times the amount (inch per hour)

P_i = Length of times the amount of rainfall in inches

Joglekar (1965) derived an equation for prediction of annual silt rate using single parameter as

$$E_m = A_k \frac{0.597}{0.240} \quad \ldots\ldots\ldots\ldots \quad (2.16)$$

where, E_m = annual silt rate (m m^{-3}) from 100 sq km of watershed area

Meyer and Monke (1965) used shearing forces of flowing water on the soil and developed the following model for estimation of soil loss

$$E_{mm} = C_c\ Q_m^{1.5}\ (\sin S)^{2.2}\ d_{50}^{0.5} \quad \ldots\ldots\ldots \quad (2.17)$$

where, E_{mm} = is the soil loss (m^3 m^{-1})
Q_m is the runoff (m^3 m^{-1})
C_c is the compactness coefficient
d_{50} is the particle size at which 50% of the particles are finner.

Fekete & Horn (1965) conducted studies in vineyard plots of 15 by 2 meter size on brown forest soil sloping at 18 per cent in the vicinity of Budapest, Hungary and found in agreement with Gabriel, that the runoff and the volume of eroded soil from plots cultivated along the contourlines were from 40 to 60

ref. 77)

and 20 to 30 per cent, respectively, of that measured on plots with uphill-downhill rows.

In the year 1965 Miller developed a model for estimation of sediment delivery ratios for the Southern Piedmont region of Unite~~s~~d States.

$$\text{Log } Y_r = 4.5 - 0.23 \log_{10} A_m - 0.51 \log \bar{R} - 2.79 \log R_b \quad \ldots\ldots\ldots\ldots \quad (2.18)$$

where, Y_r is sediment delivery ratio in per cent of annual gross erosion.

A_m Drainage area in square miles

R is the relief - length ratio

R_b is the weighted mean bifurcation ratio.

Meyer & Wischmeier (1969) suggested the following formula for estimation of sediment yield

$$Y_s = H\, Q_{fs}^{5/3} \quad S^{5/3} \quad \ldots\ldots \quad (2.19)$$

where, Y_s is sediment yield lb/s/ft

Q_{fs} = average discharge in c.f.s.

H = constant depending on soil quality (to be found by experiments).

Fleming (1969) developed a relation between mean annual suspended load (Y_{at}) in tonnes and mean annual runoff (Q_{ft}) in cubic feet using over 250 catchments throughout the world.

$$Y_{at} = a\, Q_{ft}^{b} \quad \ldots\ldots\ldots\ldots \quad (2.20)$$

Ram Babu, Gupta and Tejewani (1970) expressed that erosion index value with 30 minutes maximum rainfall intensity has the best correlation with soil erosion as compared to 60 minutes intensity products.

$$EI_{30} = \frac{KE \times P_{30}}{100} \quad .... \quad (2.21)$$

where, EI_{30} is erosion index related to P_{30}

KE is Kinetic energy of the storm

P_{30} is maximum 30 minutes rainfall intensity of the storm.

In 1971 Holy (quoted by Starosolszky, 1986) derived the following relationship between the volume of surface runoff; the slope inclination and the rate of erosion for a single rainfall of 10 minutes.

$$E_{kh} = Q_{mh} \sqrt[5]{S_i} \quad .... \quad (2.22)$$

where E_{kh} Soil loss in kg per hectare

Q_{mh} = Runoff in cubic meter per ha

S_i = is slope inclination in percentage

The data from 47 locations in 24 States for sediment yield using wide range of rainfall, soil, slope, crop and management conditions etc. were processed by Meyer (1971) to evaluate the universal soil loss equation (Wischemeir and Smith (1965) on the basis of static analysis.

Meyer also modified the Zingg's equation considering soil particles diameter (D) and obtained following equation.

$$E_{km} = K.L.^{1.9}\ S^{3.5}\ D^{-0.5} \qquad .... \qquad (2.23)$$

where E_{km} = Soil loss in kg per m per min.

Carson and Kirkby (1972) predicted erosion by over land flow on a storm basis

$$E_{mm} = 0.0085\ Q_m^{\ 1.75}\ d_{84}^{-1.11}\ (\mathrm{Sin}^{1.165}\ S)$$

where d_{84} is particle size of which 84% of the particles are finner (m)

The model was based on Eugelunds sediment transport capacity equation and Darcy Weisbach flow velocity formula.

Dong (1974) related the rate of soil erosion, inclination and length of slope by an expression of the form.

$$E_{th} = (ED_f)\ (L_{ft})^a\ (ED_i)^b \qquad .... \qquad (2.24)$$

where E_{th} = Soil loss in tonnes per ha per year
ED_f = Soil resistance factor which ranges normally from 1.5 to 0.5

Adam (1976) performed a series of experiments in the Peli Valley and at Szeksz and in Hungary on lands with lime encrusted chernozyem soils sloping at 10-12 degrees and on which the crop was sunflower. On the 3rd May, 1969 a rainfall of 39 mm depth and 32 minutes duration caused a soil loss of 20 kg/m^2, as determined by surveying the erosion channels, while the sediment volume retained by soil cover and earth dikes showed a value of 10 kg/m^2.

Tixeront (1970) gave an equation for estimation of soil loss (E_k) as

$$E_k = b_i \, c_f^{0.15} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (2.25)$$

where b_i is soil permeability index which ranges from 75 (for coarse-grained sand, clay and adobe soils offering higher resistance to erosion) to 1400 (for readily erodible humus free loose soils)

Gabriel (1976) has equipped five plots of 10 by 2 and five of 20 by 2 meter sizes on sandy boron ?? forest soil sloping at 8.7 per cent in the vicinity of Godollo, Hungary. The crops grown on these plots were winter wheat, maize and alfalfa. His main findings are summarised as follows :

The runoff was 80 per cent higher and the erosion 50 per cent higher from plots treated with herbicides for weed control than from those worked with the hoe.

The runoff was 50 per cent higher and the erosion 70 per cent higher from areas, in which the wheat was sown parallel to the slope as compared to plots ploughed along the contour lines.

The rate of erosion was higher on the long plots than on the shorter ones.

Wishmeier and Smith (1978) indicated that parabola type equation fits the data better than other equations that have been used or suggested. Based on this expression $(0.529 + 0.3635 + .525^{2})$ was substituted for a S in the basic equation for computing soil loss. He used exponent 0.5 for L rather than 0.6 for simplicity. This tended to liberlize the results on steeper slopes.

Morgan (1980) developed a flow erosion model which was showed below.

$$E_{mm} = 0.0061\ Q_{m}^{1.8}\ \sin S^{1.13}\ n_{1}^{-0.15}\ d_{35}^{-1} \quad \ldots\ldots\ldots \quad (2.26)$$

where, n_1 = roughness coefficient

d_{35} = particle size at which 35% of the particles are finner (m)

Singh and Singh (1980) described that soil erosion depends on stage of cultivation and the extent of human interference with nature. Soil erosion from hill 50% to 60% slopes under first year Jhum*, second year of Jhum*, abendoned Jhum* and bamboo forest has been estimated as 146.5, 170.2, 30.2 and 8.2 tonnes/ha respectively (Fig. 2.1). Second year of Jhum* cropping land have been found comparatively more hazardous than first year due to weeding and poor crop canopy.

Balasubramaniam and Sivanappan (1981) formed an exponential relationship between soil erosion and the degree of slope and the rainfall on sandy clay-loam soil, as follows

---

*Shifting cultivation or slash and burn agriculture

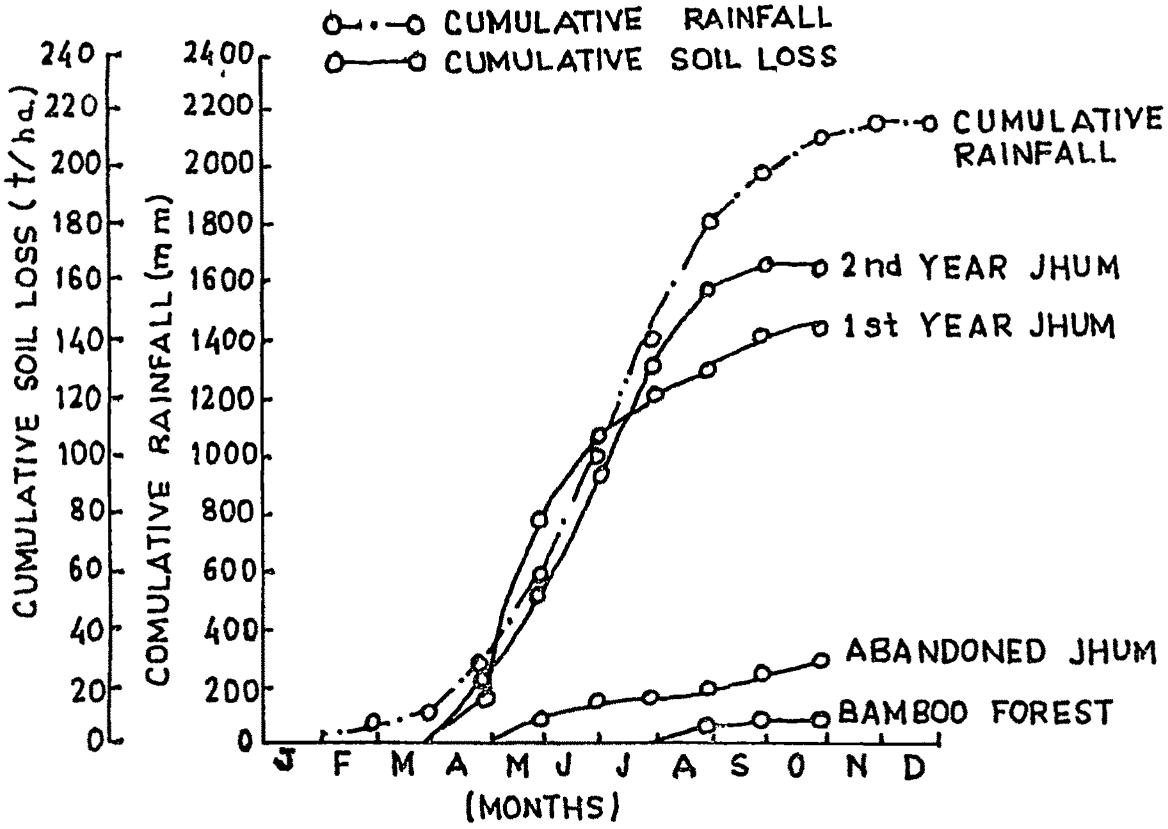

FIG. 2.1 SOIL LOSS FROM 60-70% SLOPE UNDER VARIOUS STAGES OF JHUM CULTIVATION, 1977. SINGH (1980)

Pl check

Singh & Singh (19[illegible])

$$E_{kh} = 0.296\ P_d^{1.325}\ S^{1.514} \quad \ldots\ldots\ldots\ldots \quad (2.27)$$

$$n = 56, \quad R^2 = 0.896^{**}$$

where, E_{kh} = soil loss (kg/ha)

P_d = daily rainfall (mm)

** Significant at 1% level

Ninety per cent

90% of variation in the soil loss was due to rainfall and slope. Moreover soil loss was found to increase significantly with the increase in degree of slope and rainfall. It could be seen from the results that for one per cent change in rainfall, the soil loss would change by 1.325 per cent while for 1 per cent change in slope, the change in soil loss was 1.514 per cent.

Takei et al. (1981) monitored soil loss for over ten years on experimental plots (5 by 20 meter size, 35 degree slope, mountain area, denunded granite rock, mean annual temperature 13°C, mean annual rainfall depth 1650 mm) located in Central Japan in the Tanahami Region. He They found that whereas the sediment yield from bare surfaces was 4500 m^3/km^2 as the annual average, it was no more than 15 m^3/km^2 from the reforested plots, implying that the erosion rate was drastically reduced by afforestation, to 1/300th of that from the bare surface. It is of interest to note further that the sediment yield during the rainy season was only twice as high as during the dry season from the reforested plot while the same ratio was estimated at around 30:1 in the case of the bare plots.

Sharma and Correia (1987) developed a model based on Meyers flow erosion model and Darcy-weischach uniform flow equation

$$E_{mm} = 0.58\ L^2\ E_f\ S^{2.1}\ Q_m \qquad \ldots\ldots\ldots \qquad (2.28)$$

Recheck (Ref) The value of the slope exponent (2.1) is in agreement with that of Kirby (1967) who found a range of the slope exponent from 1.3 to 2.2 for soil erosion by the overland flow. Further in the model L^2 appears due to integration of the conservation of mass equation.

Sonawane and Bengal (1988) developed a correlation between soil loss and runoff. The relationship was of following nature.

$$E_{th} = a \cdot (Q_{cm})^b \qquad \ldots\ldots\ldots \qquad (2.29)$$

It has been observed that soil loss varied from storm to storm within a treatment which correlated with storm erosivity. The following equation was found suitable.

$$E_{th} = e\ (P_e)^d \qquad \ldots\ldots\ldots \qquad (2.30)$$

Storm erosivity (Pe) in Wischmeier and Smith (1978) units by an equation ???

$$P_e = \frac{EI_{30}}{100} \qquad \ldots\ldots\ldots \qquad (2.31)$$

Ellison (quoted by Ghosh, 1993) tried to estimate splash erosion. The equation is

$$E_{mg} = cP_v^{4.33} D_m^{1.07} P_{ih}^{0.65} \quad .... \quad (2.32)$$

where $\overset{E}{F}_{mg}$ = soil intercepted in splash samples during a 30 minute period (gm);

c P_v = velocity of raindrop ft per sec.

D_m = Diameter of soil particles in mm.

2.3.2 Relevant Sediment Yield Modelling Approaches

Flaxman (1972) analysed over 27 watersheds ranging in size from 12 to 54 sq.miles in the Western United States. He developed a relationship between sediment yield and five dominant erosion factors as

$$\begin{aligned} \text{Log}(Y_{tm}+100) = {} & 6.21301 - 2.19133 \log (Gi + 100) \\ & + 0.06034 \log (S_a+100) - 0.01644 \log (D_1+100) \\ & + 0.04250 \log (Y_{ai}+100) \text{......} \quad (2.33) \end{aligned}$$

where, Y_{tm} = Sediment loss rate, in tons per square mile

G_i = ratio of average annual precipitation inch to average annual temperature (°F)

D_I = Soil particles greater than 1 mm (%)

Y_{ai} = Soil aggregation index in percentage

Piest et al. (1972) found that sediment concentration and load were high during early flow, but decrease rapidly after the easily available sediment derived from mass-wasting was removed. Measurements of sediment and water discharge during initial periods of storms over seven years indicate that for a site approximately

350 feet along a channel below an advancing gully head the following relationship exists.

$$Y_{sm} = 50.3\ Q_{fs}^{1.40} \quad \ldots\ldots\ldots \quad (2.34)$$

whereas for a site 700 ft. along a channel below a non-advancing gully head the following relationship is apparent.

$$Y_{sm} = 50.7\ Q_{fs}^{1.53} \quad \ldots\ldots\ldots \quad (2.35)$$

This indicates that during high runoff volumes gully bank erosion is more important than gully head erosion, when sediment concentration was compared with runoff volumes.

where Y_{sm} = Sediment yield lb/min

Jansen and Painter (1974) used data from 79 basins grouped into four major climatic zones and formed linear regression models for prediction of annual average sediment yield. They stated that this model may be applicable for any basin area greater than 5000 sq.km. throughout the world. They reported that factors controlling erosion within each group would vary in local climate, erodibility of geology and soils, topography, vegetation and man made changes.

Dendy and Bolton (1976) utilized data from over 800 reservoirs from all over united states to derive a model. They related sediment yield to the size of the drainage area and mean annual runoff. They stated that watershed area ranged from 1 sq.mile to 30,000 sq.miles and runoff from nearly 2 to 13 inch per year.

Hindall (1976) established the following model for estimation of sediment yields in Wisconsin streams.

$$Y_{atm} = a_o \; A_m^a \; Q_{fs}^b \; Q_{fs(25)}^c \; S_{fm}^d \qquad \ldots\ldots\ldots \qquad (2.36)$$

where, Y_{atm} is average sediment yield in tons/sq mile

$Q_{fs(25)}$ is 25 years average runoff in cfs

S_{fm} is main channel slope in feet per mile.

Komura (1976) developed a model for prediction of soil loss.

$$E_m = \frac{476.B_s.\ ED}{d_{50}} : Q_m^{15/8}.\ \ L^{3/8}\ (\sin^{3/2} S) \ \ldots. \qquad (2.37)$$

where, B_s = bar soil area ratio

ED = erodibility index

or [illegible] (1990) [illegible] check

Varshney (1977) have depicted graphs separately after analysing the actual silt data for northern (Figures 2.2 and 2.3) and for southern rivers (Figures 2.4 and 2.5) because both are found to exhibit distinct characteristics.

Lyngdoh (1980) analysed geomorphic parameters in 7 watersheds of 6 years (1965 - 1970) of upper Damodar Valley of India and developed relationship of these parameters with the sediment production rate as follows

$$Y_{hm} = 0.5\ A_k^{0.916} \qquad \ldots\ldots \qquad (2.38)$$

$$Y_{hm} = 0.043\ Q_i^{0.16} \qquad \ldots\ldots \qquad (2.39)$$

$$Y_{hm} = 1.9 \times 10^{-3}\ Q_{hm}^{0.905} \qquad \ldots\ldots \qquad (2.40)$$

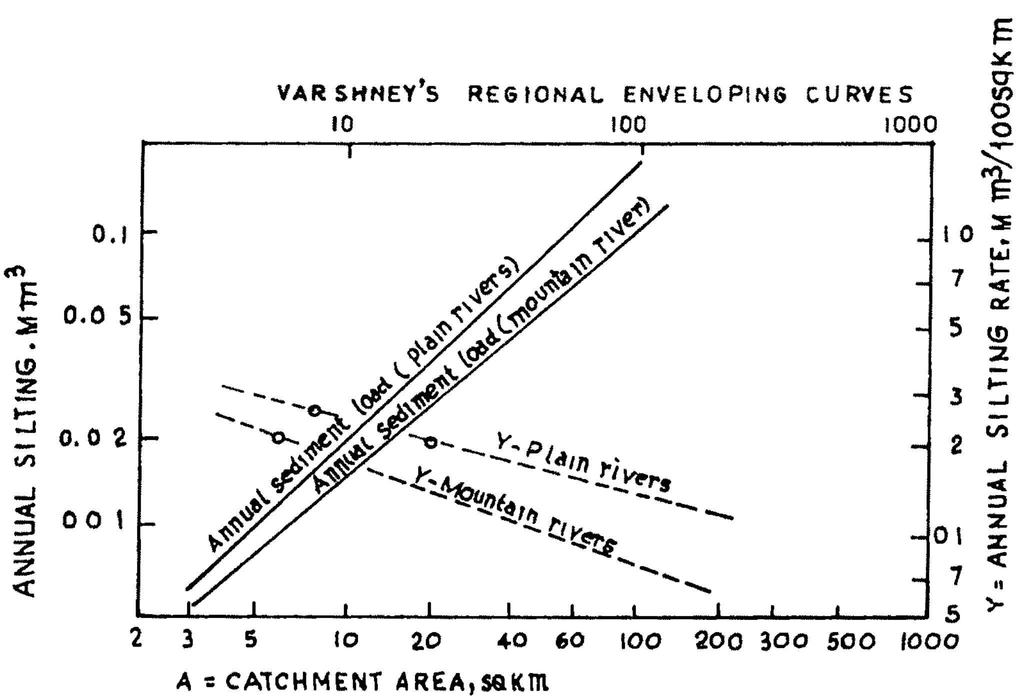

FIG 2.2 SEDIMENTATION RATES FOR NORTH INDIAN CATCHMENTS SMALL BASINS (KUMAR 1990)

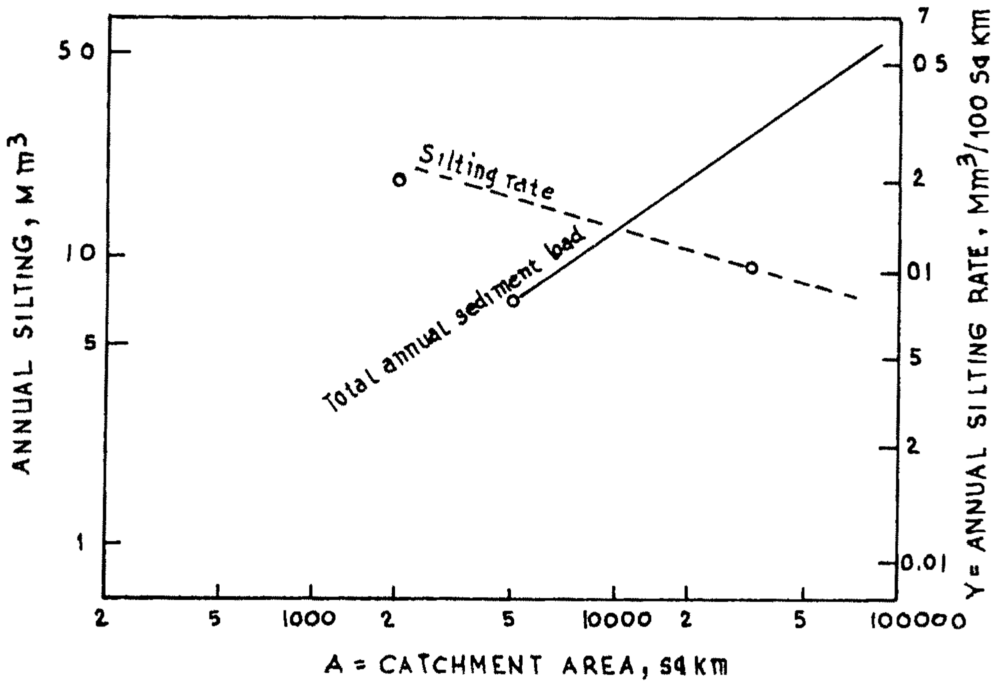

FIG 2.3 SEDIMENTATION RATES FOR LARGE NORTH INDIAN RESERVOIRS (KUMAR 1990)

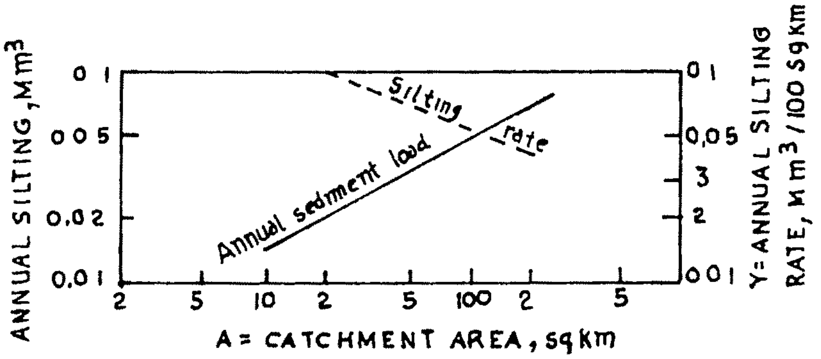

FIG 2.4 SOUTH INDIAN RIVERS-SEDIMENTATION RATE-SMALL CATCHMENTS (KUMAR 1990)

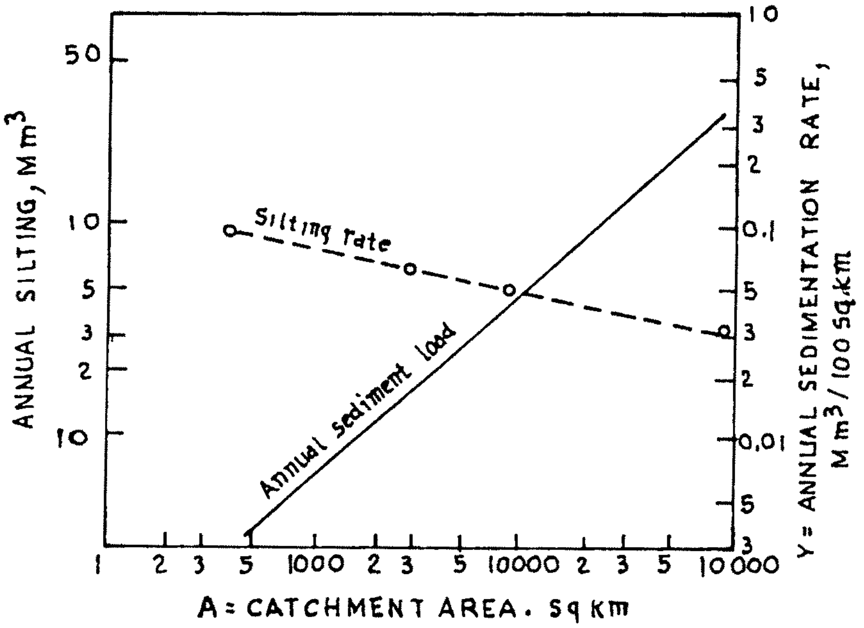

FIG. 2.5 SOUTH INDIAN LARGE RESERVOIRS - SEDIMENTATION RATES (KUMAR 1990)

where, Y_{hm} = sediment loss rate in ha m per 100 sq.km.

Q_i = drainage density km per sq.km.

Q_{hm} = average annual runoff in ha m

Jose and Das (1982) tried to correlate three shape factors with the sediment production rate for predicting average annual sediment load for Mayurakshi catchment in India as follows :

$$\begin{aligned}\text{Log}\,(Y_{hm}) &= 4919.80 + 48.64 \log (100 + R_f) \\ &\quad - 1337.77 \log (100 + R_c) - 1165.64 \log (100 + C_c) \quad \ldots\ldots\ldots \quad (2.41)\end{aligned}$$

They also tried to correlate sediment production rate with runoff as follows :

$$\text{Log}\,(Y_{hm}) = 2.20 \log Q_{am} - 3.09 \quad \ldots\ldots\ldots \quad (2.42)$$

Singh and Chen (1982) developed a linear relation between sediment yield and volume of surface runoff as

$$Y_t = a\, Q_c^{S_c} \quad \ldots\ldots\ldots \quad (2.43)$$

$$\text{or Log } Y_t = \log a + S_c \log Q_c \quad \ldots\ldots \quad (2.44)$$

where, Y_t is sediment yield in metric tons

log a is the intercept

S_c is the slope of the channel, unit ???

The variance explained by this relationship varied from 61% to 95% for 21 watersheds. The slope varied from 1.03 to 1.86 and the co-efficient varied from 0.22 to 37.3 Log a is regressed to various geomorphic characteristics such as elevation, erodibility factor, main channel length and forest area to get a co-efficient of determination of 0.82.

Singh (1985) obtained relationship between per cent slope and soil loss as follows.

$$E_{th} = 17.28 + 4.32 \text{ Sin } \left(\frac{S - 35.1}{26.66} \right) \quad \ldots\ldots\ldots \quad (2.45)$$

The total soil loss observed for the year on slopes of 0, 15, 30, 45, 60, 75 and 100 per cent was 13.15, 13.53, 15.15, 20.47, 21.54, 21.33 and 17.28 T/ha/yr respectively (Fig. 2.6) when soil loss values were plotted against respective slope percentage, a sinusoidal curve (Fig. 2.7) was obtained. The soil loss value increases with the increase in percentage of slope (upto 60%) and then decreases with the increases in percentage of slope. This may be due to the fact that as slope increases, inclined area increases and kinetic energy per unit area decreases. The soil loss (13.15 T/hr/yr) from 0% slope exceeded the soil loss tolerance limit (12.5 T/ha/hr) established by soil conservation services, USDA. | I think this is the result obtained by Singh, A Pl. check

Misra (1987) studied 20 watershed characteristics of Upper Damodar Valley Catchment in India and developed the following model for estimation of sediment production rate.

$$Y_{hm} = 4.909 \; A_k^{0.5} \; R_r^{0.26} \; S_b^{0.181} \; H_{S_i}^{1.044} \quad \ldots\ldots \quad (2.46)$$

where , h_r = relative relief

H_{S_i} = hypsometric integral

The multiple correlation coefficient is found to be 0.956. He reported that the model was highly reliable on the basis of F-test.

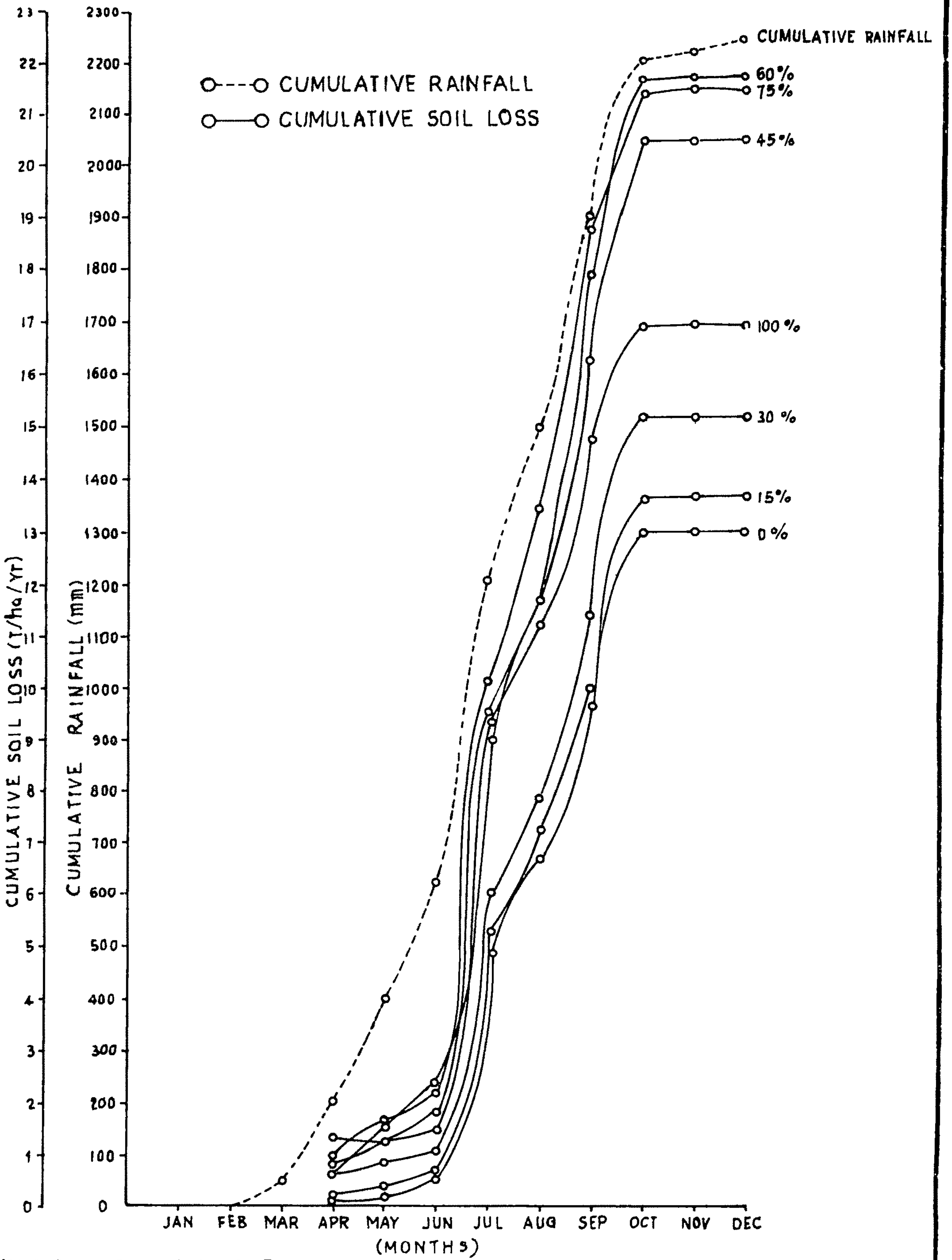

FIG 2·6 SOIL LOSS FROM 0, 15, 30, 45, 60, 75 AND 100 PERCENT SLOPES (SINGH 1985)

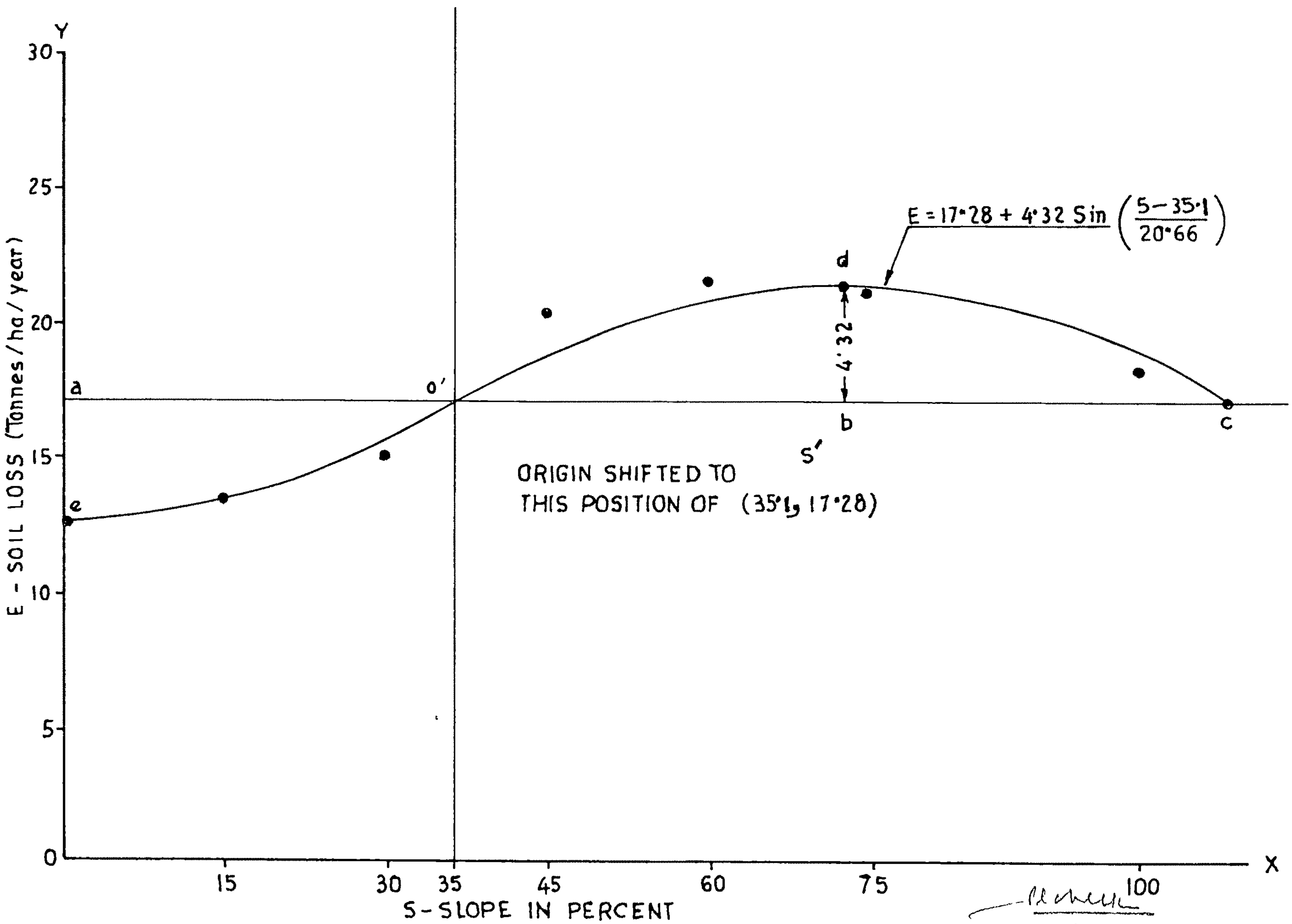

FIG.2·7 EFFECT OF SLOPE ON SOIL LOSS (SINGH 1985)

Bhowmik (1988) referred Bhowmik et-al (1986) to illustrate the observation of sediment yield of main stem stations of the Illinois and Mississippi Rivers. and recommended the station relationships used for determining the sediment loads for these rivers

$$Y_d = a\, Q_d^b \quad \ldots\ldots\ldots\ldots \qquad (2.47)$$

where Y_d = daily sediment load in tons; Q_d = daily runoff c.f.s.

Bhowmik (1984) and Bhowmik [illegible] (1984) noted the same type of relationships between annual sediment load and annual water discharges at any particular gauging station for each of the river basins studied

$$Y_t = a\, Q_{ft}^b \quad \ldots\ldots\ldots \qquad (2.48)$$

Bhowmik (1988) also established correlation between the average annual sediment load and drainage area at 90 different locations with in Kankakee River basin in Illinois

$$Y_{at} = a(A_m)^b \quad \ldots\ldots\ldots \qquad (2.49)$$

Kumar (1990) developed dimensionally homogeneous and statistically optimal models in either of the following linear or log linear forms by applying multiple regression techniques for Hirakud, Mayurakshi, Damodar Valley and the region for prediction of mean annual runoff and SPR

$$Y_o = a_o + aW_a + bW_b + cW_c + dW_d + eW_e \quad \ldots\ldots\ldots \qquad (2.50)$$

where W_a .... W_e are independable variables

a .... e are co-efficients derived by regression analysis

$$Y_o = a_o\, W_a^a \quad W_b^b \quad W_c^c \quad W_d^d \quad W_e^e \quad \ldots\ldots\ldots\ldots \qquad (2.51)$$

where, Y_o = dimensionless dependent hydrologic response.

The regional mean annual runoff model is developed using only the data sets of 43 watersheds. Seven Watersheds MK_4, H_5, M_4; M_{12}, D_5, D_{16} and D_{21} are kept out of the analysis for later validation of the model. The developed best fit optimal model is as follows

$$Q_f = \frac{Q_a}{\sqrt{A}} = -7.755 + 0.401\ P_f + 1.827\ S_a + 4.608\ S_b - 7.841\ R_b + 57.772\ H_{Si} \quad \ldots. \quad (2.52)$$

The best fit optimal model is developed for estimation of SPR in case of Mayurakshi catchment as follows

$$\frac{Y}{\sqrt{A}} = 0.0679\ (S_c)^{0.262}\ (S_b)^{0.327}\ (R_b)^{-1.404}\ (H_{S_i})^{0.113}\ (Q_f)^{0.987} \quad \ldots\ldots \quad (2.53)$$

where, Q_f = runoff factor, Q_a = average annual runoff.

Regional average SPR model for prediction of average annual SPR from small ungauged watersheds of the eastern red soil region.

$$Y = 0.0749(A)^{0.5}\ (S_c)^{0.236}\ (Lb/Lw)^{0.044}\ (Lr)^{-0.20}\ (H_{Si})^{0.393}\ (Q_f)^{0.665} \quad \ldots\ldots \quad (2.54)$$

where, Y = Sediment yieldrate, unit ??

Lb/Lw = Length width ratio

L_r = Stream length ratio

Ghosh and Swain (1993) expressed black-box type model as

$$Y_{cc} = a\ Q_{mm}^{b} \quad \ldots\ldots\ldots \quad (2.55)$$

where, Y_{cc} = sediment discharge cm^3 per cm width per year

Q_{mm} = runoff discharge m^3 per m width per year

sometimes a is separated into two parts multiplied together

$$a = a_o \tan S \quad \ldots\ldots\ldots \quad (2.56)$$

If Y_{cc} and Q_{mm} are expressed in terms of depth units

$$Y_{cm} = m\ Q_{cu}^{n} \quad \ldots\ldots\ldots \quad (2.57)$$

where Y_{cm} = sediment discharge in cm

The equation (2.57) is the alternative to the equation 2.55 Considering Q_{cu} as the cumulative monthly runoff cm and Y_{cu} as the cumulative monthly soil loss (tons/ha), the following equation

$$Y_{cu} = c\ Q_{cu}^{d} \quad \ldots\ldots\ldots \quad (2.58)$$

may be used. This gives better results than equation 2.57

2.4 Regional Frequency Analysis

Regional analysis in hydrology indicates the techniques of possible estimation of magnitudes at sites where no observation have been taken. The gauging records used for the purpose are usually shorter than the return period of interest.

Benson (1962) related flood flow (Q) with drainage area (A) for serving the above purpose as

$$Q = a\ A^{b} \quad \ldots\ldots\ldots \quad (2.59)$$

Another types of empirical equations, such as rational formula related flood-flow to rainfall intensity and area. The aim of all these equations was to extrapolate from gauged basins to ungauged basins by use of parameters which could be estimated from maps.

He observed three drawbacks found in the index flood method and discussed thoroughly.

Benson (1962) & Cruff & Rantz *et al.* (1965) have modified original index-flood method by increasing the number of independent variables. Two types of variables were used such as (a) Physiographic characteristics, drainage area, elevation, slope, per cent of basin covered by lakes and swamps and (b) hydrometeorologic variables i.e. mean annual precipitation and mean annual temperature.

Many researchers have carried out the general relationships between discharge at specified return periods and basin characteristics.

$$Q_T = f(W_a^a \quad W_b^b \quad W_c^c \; .... W_z^z) \quad .... \qquad (2.60)$$

where, $W_a \quad W_b \quad W_c$ .... W_z are independent variables.

Decoursey (1973) derived a multiple regression matrix relationship between peak flow and watershed characteristics as follows.

$$Q_v = a' A_c + b' \quad .... \qquad (2.61)$$

where, Q_v = column vector of peak flow at various return periods

A_c = column vector of watershed characteristics

a' = matrix of regression coefficient

b' = vector of regression co-efficient

This approach preserves the the intercorrelation between the dependent variables in vector Q_v.

Golden and Price (1976) regionalized flood frequency data for stream, less than 20 sq mile in Georgia, using multiple regression analysis involving 10 physical and climatological characteristics of gauged basins as independent variables. They reported that drainage basin site was the only significant variable if individual equations were developed for five regions having different runoff characteristics.

Chong and Moore (1983) used annual runoff data of 22 gauging stations in Southern Illinios and depicted a regional flood frequency curve and also compared five types of analytical probability distribution functions. They found best function by comparing the residual sum of squares obtained from each function and selecting the function for which residual sum of squares was minimum.

Haq (1985) used multiple regression analysis as a method of presenting the regional flood frequency for available annual peak discharge of series of 23 catchments of Cauvery basin subzone. He related frequency of runoff, Q_T to catchment area, slope, per cent area of tanks and climatic parameters of frequency rainfall of 24 hours, He claimed that the frequency formulae based on catchment area, slope and per cent area of tanks provide better and reliable flood frequency estimates.

Glen et al. (1989) presented flood frequency relations for physiographic parameters from many sites throughout Georgia using four methods as rainfall runoff models, regional regression equations and map model combination and compared these methods.

2.5 Uncertainty and Risk in Hydrologic Design

Vicens et al. (1975) stated that inadequate structure of the hydrologic model gives rise to model uncertainty. Data uncertainty results due to model parameters from imperfect data and estimation methods. So, parameter estimation and calibration was the most important aspect of hydrologic modelling.

Kuczera (1982) found that parameter uncertainty was of primary importance relative to bias due to random error in rainfall data.

Beck (1987) analysed uncertainty in water quality modelling.

Edwards and Haan (1989 a) used probabilistic nature of parameters of SCS unit hydrograph model for estimation of ungauged watersheds. The parameters were regressed against geomorphic parameters of 15 watersheds in South Central Oklahoma. They distinctly accounted the uncertainty of two parameters for in a flood estimation technique for ungauged watersheds and was translated into confidence limits on the flood frequency curves.

Riggs (1961) derived a relation between magnitude, design period in years and probability of not exceeding that magnitude in the design period. He also represented the statistical interpretation and the graphical representation of the relation.

Yen (1970) expressed the risk associated with hydrologic structure for a given design event by using basic probability theory. In every cases risk of failure involved for any hydrologic design with a certain return period and expected life of project, has been calculated.

Tung and Mays (1980) considered composite risk like static and dynamic for development of any hydraulic structure design.

Stedenger (1983) pointed out the permissible risk for designing flood capacity of a structure and in the distribution of peak flows.

Edward and Haan (1989 b) also pointed out the permissible risk for designing flood capacity of a structure. They also reported a procedure of using the SCS unit hydrograph models to estimate peak flow distribution and basic probability theory to compute the peak flow corresponding to a given permissible risk and expected life time.

2.6 Concluding Remark

There is ample literature available on soil erosion studies as well as mathematical or empirical models for estimation of soil loss. Soil erosion is an extremely complex phenomenon, depending on rainfall and watershed characteristics. Some of the soil and vegetation factors continuously change with time and their proper evaluation in engineering units has not yet been possible. Considerable amount of work has been done by various investigators in studying the effect of certain factors on soil erosion since 1930 or little earlier. Quantitative prediction of soil loss under a given set of conditions has not yet been possible except by purely empirical analysis for estimating soil loss caused by impact of rain drops. Model laws from laboratory studies under simulated rainfall conditions has also been developed. However, the limitations of dimensional analysis should always be remembered since it does not explain the inside process of any physical phenomenon, though it is better than any simple empirical relation.

The works which have direct bearing on the present project are listed among the references (Flexman, 1972; Piest et al., 1972; Hindall, 1976; Komura, 1976; Lyngdoh, 1980; Jose and Das, 1982; Singh and Chen, 1982; Singh, 1980; Misra, 1987; Bhowmik, 1984; 1986, 1988; Kumar 1990; Ghosh and Swain, 1993). A number of empirical formulae or mathematical models have been made using single or multiple parameters with numerical values of constants. The numerical values of these constant are changed according to soil type and watershed characteristics. These values along with number of parameters must be verified according to local condition. Therefore, catchment wise models are needed for picturing the real world situations to be really useful for the users.

CHAPTER III

MATERIALS
AND
METHODS

MATERIALS AND METHODS

In India more than 70% of watershed area is below hills and hillocks of varying slopes, which are badly eroded and degraded due to deforestation and uncontrolled grazing during past three decades. According to land capability classification the area can be classified into Class III and IV land.

This chapter deals with data collection and the methods used in the analysis and development of specific models for prediction of soil loss rate on watershed basis. The watersheds are in the Damodar and Barakar catchments in India. Various federal and state agencies are engaged in collection of data on point or non point sources. Consequently, a large amount of data in various forms has been generated and reported in the literatures by different workers such as Singh _et_ _al_. (1978); Singh _et_ _al_. (1979), Das _et_ _al_. (1979); Samuel _et_ _al_. (1981 a); Subramaniyan _et_ _al_. (1982); Das _et_ _al_. (1984) and Singh _et_ _al_. (1986).

Data on annual soil loss, rainfall, runoff data and relevant information of Damodar and Barakar Catchments are collected from the records of Soil Conservation Department (Engineering Division) Damodar Valley Corporation, Hazaribagh 825 301 Bihar (India). The climate is subhumid tropical with annual rainfall ranging from 900 mm to 1400 mm. During summer months maximum temperatures vary between 42°C and 48°C with severe dry spells occuring often in the entire catchments. Rainy season lasts for about four months from June to September, but maximum rainfall occurs during mid July to mid-September. Winter is moderately cold (3.3°C).

The correctness of any model depends largely upon the accuracy of data sets with relevant information and methodology adopted. The hydrologic process like sediment yield and runoff, the causative factors such as climate, soil type, land use, topography geology and morphological characteristics are to be known along with the hydrological time series data. But long period and adequate data for a complete and comprehensive analysis are not always available. However, short period and inadequate data may be taken as representative till long period data are available.

3.1 Some information on catchments

3.1.1 Damodar catchment

Six watersheds of Damodar catchment (Table 3.1) are chosen for analysis of sediment yield. In general the area is undulating and slopes gently from west to east. There are many tributaries flowing either in SW-NE or NW-SE direction and ultimately met with the Damodar river which flows from west to east (Fig. A-7).

The soils of the watershed area have derived from decomposed granite gneiss and isolated patches of hornblande schists. The former soil group is mostly yellowish brown to red in colour, light surface texture underlain by moderately heavy subsoil and are slightly acidic in reaction. Soils developed from hornblends schists have olive brown colour, moderately heavy surface texture underlain by heavy sub soil neutral to alkaline in reaction. The soil series in this area consist of Rorekacha sandy loam, Bandhadih sandy loam, Bhubi loam, Bhogabandh sandy loam, Talgaria sandy loam chamsalead clay loam etc., top soil structure are mostly crumb, granular and subangular blocky, permeability is moderate to rapid.

The western part of the Damodar Valley is covered with moderately dense forest, the intensity decreasing towards the east. The dominant species in the forest area are Sal (Shorea robusta), Palash (Butea monosperm) other associated species are Ber (Zizuphys jujuba), Keud (Diospyrous melanoxylon), Neem (Azadirachta indica), Karanj (Pongemia glabra). Arjun (Termindia arjuna).

3.1.2 Barakar catchment

Two watersheds of Barakar catchment (Table 3.1) are taken for the present analysis. Major soils come under red loam group which are light to heavy in texture from surface to sub-surface and acidic in reaction. Patches of grey calcarious soils heavy in texture and alkaline in reaction are observed. Clayee soil are found in scattered locations. The soil is well drained and very vulnerable to erosion.

Table 3.1 Location and slope of some selected watersheds of Barakar and Damodar catchments

Catchment		Name of Watersheds	Location		Slope in percentage
Name	No.		Longitude	Latitude	
	1	Deonad[+]	84°41'E	23°40'N	1-15
D*amodar	15	Gola	85°43'E	23°33'N	1-5
	17 B	Rajatar	86°0' E	23°43'N	1-5
	20 A	Pindrajora	86°12'E	23°30'N	1-5
	23 B	Nildhi*	86°43'E	24°11'N	1-5
	23 B	Santhaldih	86°34'E	23°3' N	1-5
B**arakar	26	Jogiatila	85°37'E	24°22'N	1-5
	36	Lokaisakra	86°29'E	24° 4'N	1-5

* Drainage system of Damodar Valley Catchment may be glanced through Fig. A-7

** For contour and drainage map of Barakar basin as a whole vide Figs. A-1 & A-2

[+] For contour and drainage map vide Figs. A-3 to A-6.

Surface drainage is fair to moderate. Mainly surface flow exists during the lean period, resulting a perinial flow. Main stream flows in the easternly direction while the tributaries draining to main streams either flow north easternly or northernly direction. The length of the catchment is 24 miles while the length of tributeries is 26 miles. Flash floods in major streams often occur in June to October due to southwest monsoon while the flow dries up in summer i.e. April to May. The catchment is extremely vulnerable to erosion because of extensive grazing and over exploitation of forest. Paddy is cultivated in bench-terraced portion of the catchment and in other areas farming practices simply "add insult to the injury" i.e. enhances soil erosion.

3.2 Data collection and analysis

A good net work of stream gauging and sediment yield observation posts are under operation in the catchments of DVC by the centrally sponsored schemes of soil conservation in the catchment of River Valley Projects.

3.2.1 Runoff

The runoff is computed by velocity area method (Fig. 3.1). Weirs with head walls having crest height of 0.30 to 0.45 meter above bed level of the stream with stage level recorder are also installed. As illustrated in Fig. 3.1 each channel cross-section was divided into five subsections. Velocity(V) of flow in each cross-section was determined by current meter and the corresponding cross-sectional area of flow by graphical method after obtaining the salient measurements. Discharge in each subsection was determined as (cross sectional area X velocity of flow). The total discharge was obtained by adding all discharge through all sub-sections. All such values were averaged for each year to get average annual runoff (Q_{ms}) in cumec.

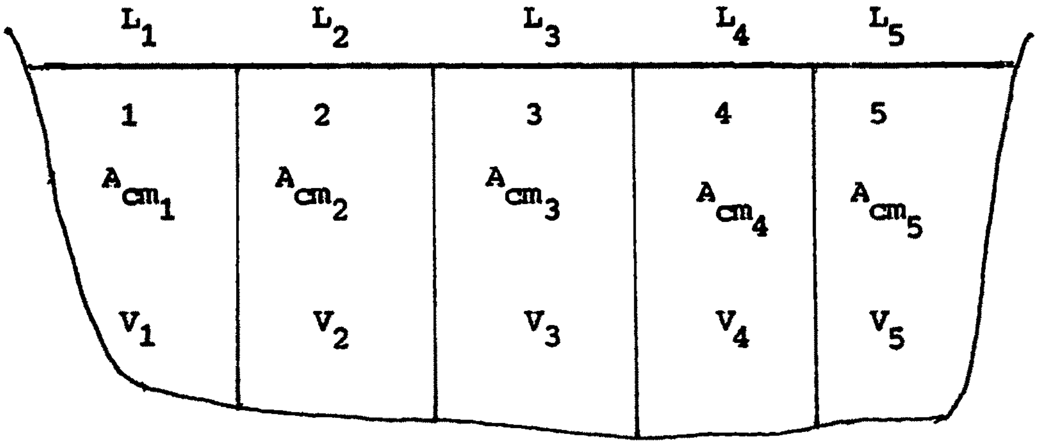

Fig. 3.1 Flow measurements by velocity area method

3.2.2 Sediment yield

For the purpose of analysis, the total sediment load is often splitted into two parts : bed load and suspended load. Bed load is defined as that sediment in the bed layer moved by saltation (Jumping), rolling or sliding. The bed layer is a flow layer several grain diameters thick immediately above the bed. The bed layer thickness is usually taken as 2 grain diameters (Einstein, 1950). Suspended load is defined as that sediment load that is moved by upward components of turbulent currents and that stays in suspension for a considerable time. The silt samples are collected using Punjab bottles/USDH-48/USDH-49 depth intergrating samplers. A depth-intergrating sampler is designed to accumulate a water-sediment sample from a stream vertical at such a rate that the velocity in the nozzles at the point of intake is always as nearly identical to the immediate stream velocity as possible, while running the vertical at a uniform speed. A simple depth intergrating sampler collects and accumulates the sample as it is lowered to the bottom of the stream and raised back to the surface. The sampler must be moved at a uniform rate in a given direction but not necessarily at equal in both directions. The sediment samples are analysed in the silt laboratory for finding out coarse, medium, fine silt and also clay contents of discharge samples. These samples, however, do not account for the bed load. As the streams predominantly have sand as bed material and silt concentration in runoff from medium to high. 2.5 to 15% of the suspended load is added as bed load (Singh et al., 1990) in order to calculate the total sediment production rate.

$$\text{Sediment yield} = \frac{\text{Sediment (c.c/m}^3\text{) x Runoff (m}^3\text{/day) x 365}}{100 \text{ x } 100 \text{ x } 100 \text{ x } 10{,}000}$$

Table 3.2 Physiographic characters of eight watersheds of Damodar and Barakar Catchments

Catchment Name	No.	Name of watersheds	Area in Km^2	Size* km^{-1}	Shape	Drainage+ density km/km^2	Character of flow
	1	Deonad	205.26	272.26/205.26	Traingular	0.327	Surface fed intermittent
Damodar	15	Gola	261.90	166.66/261.90	Rectangular	0.383	- Do -
	17 B	Rajatar	230.04	207.02/230.04	Triangular	0.371	Perinial
	20 A	Pindrajora	267.91	180.72/267.91	Do	0.365	Surface fed intermittent flow
	23 B	Nildhi	071.69	490.14/071.69	Rectangular	0.284	- Do -
	23 B	Santhaldih	077.34	490.14/077.34	Triangular	0.451	- Do -
Barakar	26	Jogiatila	149.60	238.58/149.60	Rectangular	0.327	- Do -
	36	Lokaisakra	144.55	145.22/144.55	Triangular	0.612	- Do -

* Size = Length up to the gauging point ÷ total area

\+ Drainage density is the ratio of cumulative channel segment lengths of the drainage basin to the basin area.

Table 3.3 Yearwise rainfall, runoff and sediment yield of Deonad watershed of Damodar catchment

Year	Annual rainfall (cm)	Annual runoff (cm)	Annual sediment yield in (ha m per km^2)
	P	Q	Ya
1965	084.86	47.12	0.378
1966	086.33	47.60	0.454
1967	136.93	79.32	0.467
1968	140.26	58.98	0.502
1969	076.12	41.35	0.195
1970	129.03	72.90	1.000 ?
1971	141.53	83.95	0.693
1973	081.86	43.94	0.192

Table 3.4 Yearwise rainfall, runoff and sediment yield of Rajatar watershed of Damodar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Annual sediment yield (ha m per km^2) Ya
1964	132.28	60.00	0.416
1965	111.94	47.17	0.499
1966	074.57	22.43	0.119
1967	107.67	53.47	0.266
1968	086.34	45.95	0.430
1969	087.07	38.41	0.190
1970	110.08	38.53	0.215

Table 3.5 Yearwise rainfall, runoff and sediment yield of Gola watershed of Damodar catchment

Year	Annual rainfall in cm P	Annual runoff in cm Q	Annual sediment yield (ha m per km^2) Ya
1964	093.98	53.37	0.229
1965	111.94	76.91	0.207
1966	074.57	40.13	0.169
1967	107.67	66.55	0.101
1968	106.10	46.10	0.101
1969	069.24	41.76	0.107
1970	108.71	53.19	0.206
1971	087.43	46.08	0.379
1972	088.70	46.66	0.222
1973	130.15	82.73	0.186
1974	102.59	59.06	0.139

Table 3.6 Yearwise rainfall, runoff and sediment yield of Pindrajora watershed of Damodar catchment

Year	Annual rainfall in cm P	Annual runoff in cm Q	Annual sediment yield (ha-m per km^2) Ya
1964	111.74	54.94	0.348
1965	092.41	40.49	0.224
1966	084.07	32.49	0.230
1967	131.95	60.81	0.371
1968	117.07	66.70	0.357
1969	086.56	34.21	0.152
1970	096.90	66.42	0.469
1971	092.89	52.55	0.429
1972	089.61	51.31	0.384
1973	139.83	83.92	0.733
1974	104.04	67.59	0.516

Table 3.7 Yearwise rainfall, runoff and sediment yield of Nildhi watershed of Damodar catchment

Year	Rainfall (cm) P	Runoff (cm) Q	Sediment yield (km m/km^2) ha-m per-km Ya
1964	074.04	46.74	0.235
1965	075.82	24.44	0.132
1966	089.89	28.96	0.047
1967	137.14	75.29	0.313
1968	087.91	46.76	0.195
1969	082.04	49.20	0.095
1970	115.16	33.35	0.144
1971	086.08	49.84	0.231
1973	112.37	56.49	0.178

Table 3.8 Yearwise rainfall, runoff and sediment yield of Santhaldih watershed of Damodar catchment

Year	Rainfall (cm) P	Runoff (cm) Q	Sediment yield (ha m / km^2) Ya
1964	088.54	43.43	0.182
1965	079.10	28.50	0.139
1966	055.65	14.58	0.066
1967	111.86	63.45	0.096
1968	136.37	64.11	0.091
1969	082.09	25.71	0.067

Table 3.9 Yearwise rainfall, runoff and sediment yield of Jogiatila watershed of Barakar catchment

Year	Rainfall (cm)	Runoff (cm)	Sediment yield (ha m / km^2)
	P	Q	Ya
1964	085.04	41.78	0.435
1965	102.03	50.42	0.488
1966	062.10	28.35	0.177
1967	089.10	54.41	0.699
1968	123.55	83.26	0.627
1969	094.46	64.80	0.330
1970	070.54	49.86	0.453
1971	104.70	65.35	0.524
1972	093.50	61.27	1.017
1973	144.02	95.48	0.702
1974	090.04	49.30	0.205

Table 3.10 Yearwise rainfall, runoff and sediment yield of Lokaisakra watershed of Barakar catchment

Year	Rainfall (cm) P	Runoff (cm) Q	Sediment yield (ha-m / km^2) Ya
1965	073.94	34.39	0.183
1966	073.53	44.98	0.434
1967	091.19	51.66	0.492
1968	119.74	73.91	0.540
1969	077.03	53.16	0.278
1970	069.98	50.88	0.288
1971	180.06	136.20	0.630

3.2.3 Rainfall

Daily rainfall is being recorded in each observation posts of DVC by recording type of rain gauges. These data are pooled and averaged monthwise. Such monthly and yearly data are available in DVC records.

3.3 Data

Raw data were collected from the records of DVC, Hazaribagh and were suitably converted to the present units such as CGS and MKS. Physiographic character of all the eight watersheds considered herein may be viewed through the data served in the Table-3.2. Stationwise data on P (annual rainfall), Q (annual runoff) and Y_a (annual sediment yield) for the period of 1964 to 1974 in general are presented in Tables 3.3 to 3.10.

3.4 Analysis

3.4.1 Analysis for average annual sediment yield

Model for prediction of average annual sediment yield are developed for six watersheds of Damodar and two watersheds of Barakar catchments. The annual rainfall (P) and annual runoff (Q) are available in depth units. Thus dimensionless parameter (P/Q) is formed for each year and considered against each annual sediment yield (Y_a) in ha m/km^2.

Step I : The Y_a values are arranged in an ascending order. That is the lowest value in the top of the column and highest at the bottom of the column (vide 8th column, Table 3.11). The ($\frac{P}{Q}$) values corresponding to each actual Y_a values are retained (vide 7th column, Table 3.11). In the process vertical columns prepared for $\frac{P}{Q}$ and chronological years lost any specific order. But each row of the 6th, 7th and 8th column of Table 3.11 represent the recorded value for the year mentioned in the 6th column of the said Table.

Step II. The cumulative values of $\frac{P}{Q}$ marked as $(\frac{P}{Q})_{cu}$ and Y_a marked as $(Y_a)_{cu}$ are prepared from the two columns of $(\frac{P}{Q})$ and Y_a as these stand in Step I (vide 9th and 10th column of Table 3.11).

Step III. Following graphical methods values of $(Y_a)_{cu}$ and $(\frac{P}{Q})_{cu}$ of Step II are fitted in

$$(Y_a)_{cu} = x \left[\left(\frac{P}{Q} \right)_{cu} \right]^{y} \quad \ldots \quad \ldots \quad (3.1)$$

where x is the intercept of the best fit straight line on $(Y_a)_{cu}$-axis of the logarithmic plot of $(Y_a)_{cu}$ against $(P/Q)_{cu}$ and $y = \tan \theta$ where θ is the inclination of the best fit straight line with the $(^P/_Q)_{cu}$ axis.

Step IV. For Deonand, Rajatar, Pindrajora, Jogiatila and Lokaisakra the values of x and y obtained have been averaged and taken as one equation for all the five watersheds catchments. Following same procedure another equation for the watersheds Gola, Nildhi & Santhaldi has been established.

After testing these two equations it is found that the results obtained are very poor. Hence applying trial and error ??? NC method is established for both seperately. That means average

$$Y_{aa} = W_b - x \left[\left(\frac{P}{Q} \right)_a \right]^{y} \quad \ldots \quad \ldots \quad (3.2)$$

Table 3.11 Yearwise normal and cumulative form of rainfall, runoff and sediment yield of Pindrajora watershed of Damodar catchment

Year	Yearwise normal arrangement of data sets				Rearrangement on the basis of ascending of order of Y_a				
	Rainfall (cm) P	Runoff (cm) Q	Sediment yield in ha m / km^2 Y_a	Values of P/Q	Year	P / Q	Y_a	Cumulative	
								$(P/Q)_{cu}$	$(Y_a)_{cu}$
1964	111.74	54.94	0.348	2.034	1969	2.530	0.152	2.530	0.152
1965	092.41	40.49	0.224	2.282	1965	2.282	0.224	4.812	0.376
1966	084.07	32.49	0.230	2.588	1966	2.588	0.230	7.400	0.606
1967	131.95	60.81	0.371	2.207	1964	2.034	0.348	9.434	0.954
1968	117.07	66.70	0.357	1.757	1968	1.757	0.357	11.191	1.311
1969	086.56	34.21	0.152	2.530	1967	2.207	0.371	13.398	1.677
1970	096.90	66.42	0.469	1.459	1972	1.747	0.384	15.145	2.061
1971	092.89	52.55	0.429	1.768	1971	1.768	0.429	16.913	2.486
1972	089.61	51.31	0.384	1.747	1970	1.459	0.469	18.372	2.956
1973	136.83	83.92	0.733	1.678	1974	1.539	0.516	19.911	3.468
1974	104.04	67.59	0.516	1.539	1973	1.678	0.733	21.589	4.199

x and y remain unchanged and another constant W_b is introduced as in Eq (3.2).

Ultimately two models of the type Eq (3.2) are obtained for all the eight watersheds.

To illustrate the above four steps the data of Pindrajora watershed may be considered as an example in the first five columns of Table 3.11. The remaining five columns of the same table are rearranged on the basis of ascending order of Y_a. Using Eq(3.1) $x = 0.05$ and $y = 1.483$ are obtained. Similarly $x = 0.16$ and $y = 1.57$ for Deonand; $x = 0.016$ and $y = 1.963$ for Rajatar; $x = 0.10$ and $y = 1.57$ for Jogiatila; $x = 0.094$ and $y = 1.732$ for Lokaisakra and hence average $x = 0.084$ and $y = 1.651$ are obtained. By trial and error $W_b = 0.621$ is chosen for these five catchments.

3.4.2 Analysis for annual sediment yield

One may not be interested in the average annual sediment yield but instead may require individual annual values. Accordingly the same is tried here following the steps I to III of Art. 3.4.1. Afterwards the two more steps as given below are followeds

Step A : Suppose N is the number of years for which the data of P, Q and Y_a available. The total sediment yield of the period (N) under consideration is obtained at the bottom of the column of $(Y_a)_{cu}$ mentioned in step I (vide last row of the last column, Table 3.11. This gives 11 years total and N = 11).

If Y_{aa} assumed as average annual soil loss and P/Q for N years and $(^{P}/Q)_a$ is taken as average annual P/Q value of the present and all preceding years, then from the functional relationship of Eq(3.1).

$$Y_{aa}\,N = x\left[N(P\,/\,Q)_a\right]^{y} \quad \ldots\ldots$$

$$\text{or}\quad Y_{aa} = x.N^{y-1}\left[(P/Q)_a\right]^{y} \quad \ldots\ldots \quad \ldots\ldots \quad (3.3)$$

$$= W_c\,(P/Q)_a^{y} \quad \ldots \quad \ldots \quad \ldots\ldots \quad (3.4)$$

may be obtained.

Step B. The Eq (3.4) does not give good results. Hence it is transformed once again as through trial and error method. Only

$$Y_a = W_d - W_e\,\left[P/Q\right]^{y} \quad \ldots \quad \ldots \quad (3.5)$$

y has been obtained by curve fitting as in Eq(3.1). W_d and W_e are chosen arbitrarily to suit the requirement. This is more or less same as in Eq(3.2).

where, Y_a = annual sediment yield, ha m/km^2

P/Q = annual (P/Q), dimensionless.

To illustrate this the data of Pindrajora (the last two columns of Table 3.11) are fitted in Eq(3.5) to obtain

$$Y_a = 0.6853 - 0.121\,(P/Q)^{1.483} \quad \ldots\ldots\ldots \quad (3.6)$$

Table 4.10 shows all such results.

3.4.3 Miscellaneous analysis

In order to judge the efficacy of the methods and the corresponding results of the principles explained in Articles 3.4.1

and 3.4.2 miscellaneous graphical attempts were made for only three watersheds and are shown in Figs. 4.3 to 4.11. The Figs. 4.3 to 4.8 are self explanatory. In Figs. 4.9, 4.10 and 4.11 the term percentage (%) rainfall is obtained as annual rainfall divided by N Year total rainfall multiplied by hundred. (N is the number of years for which rainfall data are available). None of these trials help one to obtain a reasonable model.

CHAPTER IV

RESULTS
AND
DISCUSSION

RESULTS AND DISCUSSION

Two types of models namely (i) average annual sediment yield as a function of average annual rainfall and runoff (ii) annual sediment yield based on annual rainfall and runoff are tried herein. In the process a large number of known and unknown variables operating in the phenomena are being ignored. Consequently these may possess more defects than the qualities. It is expeditious to have a soil erosion model based on only two parameters viz. annual rainfall and annual runoff from the whole catchment area, because these are easily measureable. The average annual estimated and observed values of sediment yield (Y_{aa}) tally well. The empirical constant W_b of Eq (3.2) varies from 0.233 to 0.621; the exponent y varies from 1.590 to 1.651 and constant x varies from 0.014 to 0.084. This variation of constants are mainly due to other (not considered herein) erosion influencing factors of the watersheds. The best-fit models have been chosen on the basis of minimum standard error and maximum correlation coefficient.

4.1 Results

As discussed in Article 3.4.1 the models obtained for all the watersheds presented in Table 4.1. In order to compare the recorded and estimated values of Y_{aa} (average annual sediment yield) the Tables 4.2 through to 4.9 are prepared and shown here for each watershed.

Table 4.1 Watershed based models for prediction of average annual sediment yield

Catchment		Name of watershed	Models
Name	No.		
Damodar	1	Deonad	$Y_{aa}=0.621-0.084(^{P}/Q)_{a}^{1.651}$
Damodar	17 B	Rajatar	
Damodar	20 A	Pindrajora	
Barakar	26	Jogiatila	
Barakar	36	Lokaisakra	
Damodar	15	Gola	$Y_{aa}=0.233-0.014(^{P}/Q)_{a}^{1.59}$
Damodar	23 B	Nildhi	
Damodar	23 B	Santhaldi	

Table 4.2 Observed and estimated average values of sediment yield of Deonad watershed of Damodar catchment

Year of observation from 1965 to	Average values of P/Q	Sediment yield in ha-m / km^2		Percentage deviation
		Observed average*	Estimated average*	
1966	1.786	0.416	0.404 0.402	0.402 03.37
1967	1.766	0.433	0.405 0.406	06.24
1968	1.758	0.450	0.408	09.33
1969	1.775	0.399	0.404	01.25
1970	1.774	0.499	0.405	18.84
1971	1.761	0.527	0.407	29.48
1973	1.774	0.485	0.405	16.50
Mean	1.771	0.458		
Sd	0.1009	0.043		

*Average of the present and all preceding years

Table 4.3 Observed and estimated average values of sediment yield of Gola watershed of Damodar catchment

Year of observation from 1964 to	Value of average P/Q	Sediment yield in ha-m/km^2		Percentage deviation
		Observed average*	Estimated average*	
1965	1.608	0.218	0.203	06.88
1966	1.691	0.202	0.201	00.00
1967	1.673	0.176	0.201	14.21
1968	1.799	0.161	0.197	22.36
1969	1.775	0.152	0.198	30.26
1970	1.814	0.160	0.197	23.13
1971	1.824	0.187	0.197	05.35
1972	1.833	0.191	0.196	02.62
1973	1.807	0.191	0.197	03.14
1974	1.800	0.186	0.197	05.91
Mean	1.762	0.182		
Sd	0.073	0.019		

*Average of the present and all preceding years

Table 4.4 Observed and estimated average values of sediment yield of Rajtar watershed of Damodar catchment

Year of observation from 1964 to	Value of average P/Q	Sediment yield in ha-m/km^2		Percentage deviation
		Observed average*	Estimated average*	
1965	2.289	0.458	0.291	36.46
1966	2.628	0.345	0.207	40.00
1967	2.474	0.325	0.246	24.31
1968	2.355	0.346	0.276	20.23
1969	2.341	0.320	0.279	12.81
1970	2.414	0.305	0.261	14.43
Mean	2.417	0.350		
Sd	0.111	0.050		

*Average of the present and all preceding years

Table 4.5 Observed and estimated average values of annual sediment yield of Pindrajora watershed of Damodar catchment

Year of observation from 1964	Value of average P/Q	*Average annual sediment yield ha-m / km^2		Percentage deviation
		Observed	Estimated	
1965	2.158	0.286	0.322	12.59
1966	2.301	0.267	0.289	08.24
1967	2.278	0.292	0.294	00.69
1968	2.174	0.305	0.318	04.26
1969	2.232	0.280	0.305	08.93
1970	2.122	0.206	0.330	07.27
1971	2.078	0.322	0.340	05.59
1972	2.041	0.328	0.348	06.10
1973	2.005	0.369	0.356	0.352
1974	1.963	0.382	0.365	04.45
Mean	2.138	0.314		
Sd	0.109	0.036		

*Average of the present and all preceding years.

Table 4.6 Observed and estimated average values of sediment yield of Nildhi watershed of Damodar catchment

Year of observation from 1964 to	Values of average P/Q	*Average sediment yield in ham / km^2		Percentage deviation
		Observed	Estimated	
1965	2.344	0.183	0.179	02.19
1966	2.597	0.138	0.169	22.46
1967	3.204	0.182	0.144	20.88
1968	2.299	0.184	0.180	02.17
1969	2.194	0.170	0.184	08.24
1970	2.373	0.166	0.178	07.23
1971	2.293	0.174	0.181	04.02
1973	2.259	0.175	0.182	04.00
Mean	2.445	0.172		
Sd	0.307	0.014		

*Average of the present and all preceding years

Table 4.7 Observed and estimated average values of sediment yield of Santhaldhi watershed of Damodar catchment

Year of observation from 1964 to	Values of average (P/Q)	Sediment loss rate in ha-m / km^2		Percentage deviation
		Observed average*	Estimated average*	
1965	2.407	0.161	0.176	09.32
1966	2.877	0.129	0.158	22.48
1967	2.599	0.121	0.169	39.67
1968	2.504	0.115	0.173	50.44
1969	2.619	0.107	0.168	36.30
Mean	2.601	0.127		
Sd	0.157	0.019		

*Average of the present and all preceding years

Table 4.8 Observed and estimated average values of sediment yield of Jogiatila watershed of Barakar catchment

Year of observation from 1964 to	Average values of (P/Q)	Sediment yield in ha-m/km^2		Percentage deviation
		Observed average*	Estimated average*	
1965	2.030	0.461	0.351	23.86
1966	2.083	0.367	0.339	07.63
1967	1.972	0.432	0.363	15.97
1968	1.874	0.456	0.384	15.79
1969	1.805	0.435	0.398	09.30
1970	1.750	0.438	0.409	06.62
1971	1.731	0.448	0.413	07.81
1972	1.708	0.433	0.418	03.46
1973	1.688	0.460	0.422	08.26
1974	1.701	0.436	0.419	03.90
Mean	1.834	0.437		
Sd	0.139	0.026		

*Average of the present and all preceding years

Table 4.9 Observed and estimated average values of sediment yield of Lokaisakra watershed of Barakar catchment

Year of observation from 1965 to	Values of average P / Q	*Average sediment yield ha-m/km^2		Percentage deviation
		Observed	Estimated	
1966	1.893	0.309	0.279	09.71
1967	1.850	0.370	0.300	18.92
1968	1.793	0.412	0.327	20.63
1969	1.724	0.386	0.359	07.00
1970	1.666	0.369	0.385	04.34
1971	1.617	0.406	0.407	00.25
Mean	1.757	0.375		
Sd	0.098	0.034		

*Average of the present and all preceding years

A token graphical comparison of the Y_{aa} observed and estimated is made in Fig. 4.1 for Pindrajora in order to understand the situation from visual angle. As discussed in Article 3.4.2 the models on annual sediment yield based on annual rainfall for the eight watersheds are presented in Table 4.10. Comparisons of Y_a (annual sediment yield) recorded (observed) and generated from the models are shown in Tables 4.11 to 4.18.

Figure 4.2 illustrates the above mentioned comparison through graphs for Pindrajora watershed as a sample case.

Miscellaneous graphical results (Article 3.4.3) are displayed in Figs. 4.3 to 4.11.

4.2 Discussion

The average annual values on sediment yield are useful for conservation planning and executions. The value for a particular year is not of any help for such purposes. From this view point average annual model is important, specially if it gives the correct picture (more or less) of the real world situation. Hence the estimated average annual sediment yields are compared with observed values in Tables 4.2 to 4.9. In most of the cases the variation ranges in between 0 to ± 40.00 per cent. In most of the events average sediment yield rates were high during lower values of $(P/Q)_a$ but decreases with the increase of average $(P/Q)_a$ values. It is quite obvious because low P/Q indicates high runoff

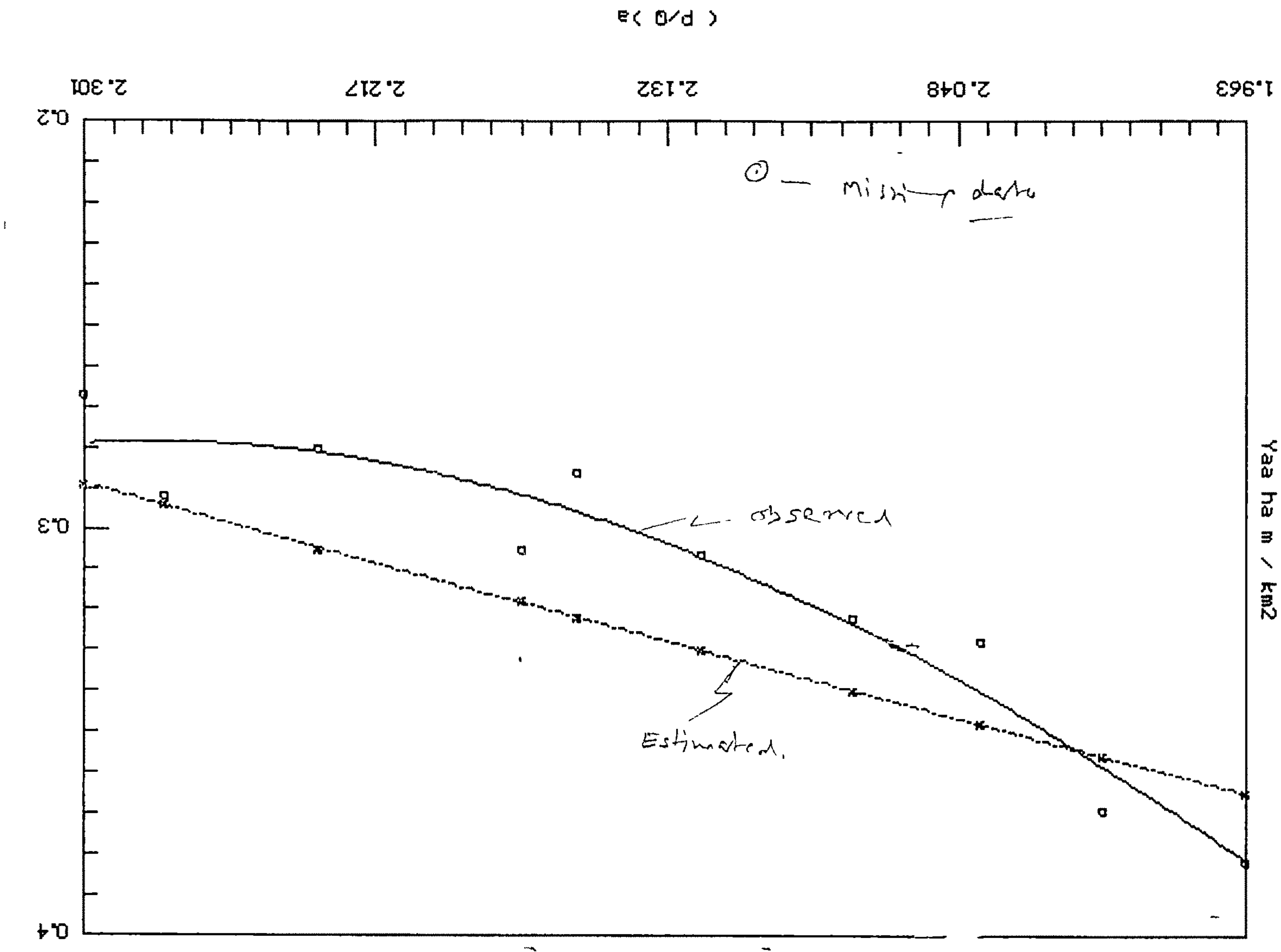

FIG. 4.1 PICTORIAL COMPARISON OF Y_{aa} GENERATTED AND OBSERVED AGAINST $(P/Q)_a$ FOR PINDRAJORA. THE DISCONTINUOUS LINE WITH CROSS MARKS REPRESENTS THE GENERATED DATA SETS & OPEN CIRCLES THE RECORDED DATA POINTS VIDE TABLE 4.5 FOR TABULAR COMPARISON

Orientation 4.1 L 4.11

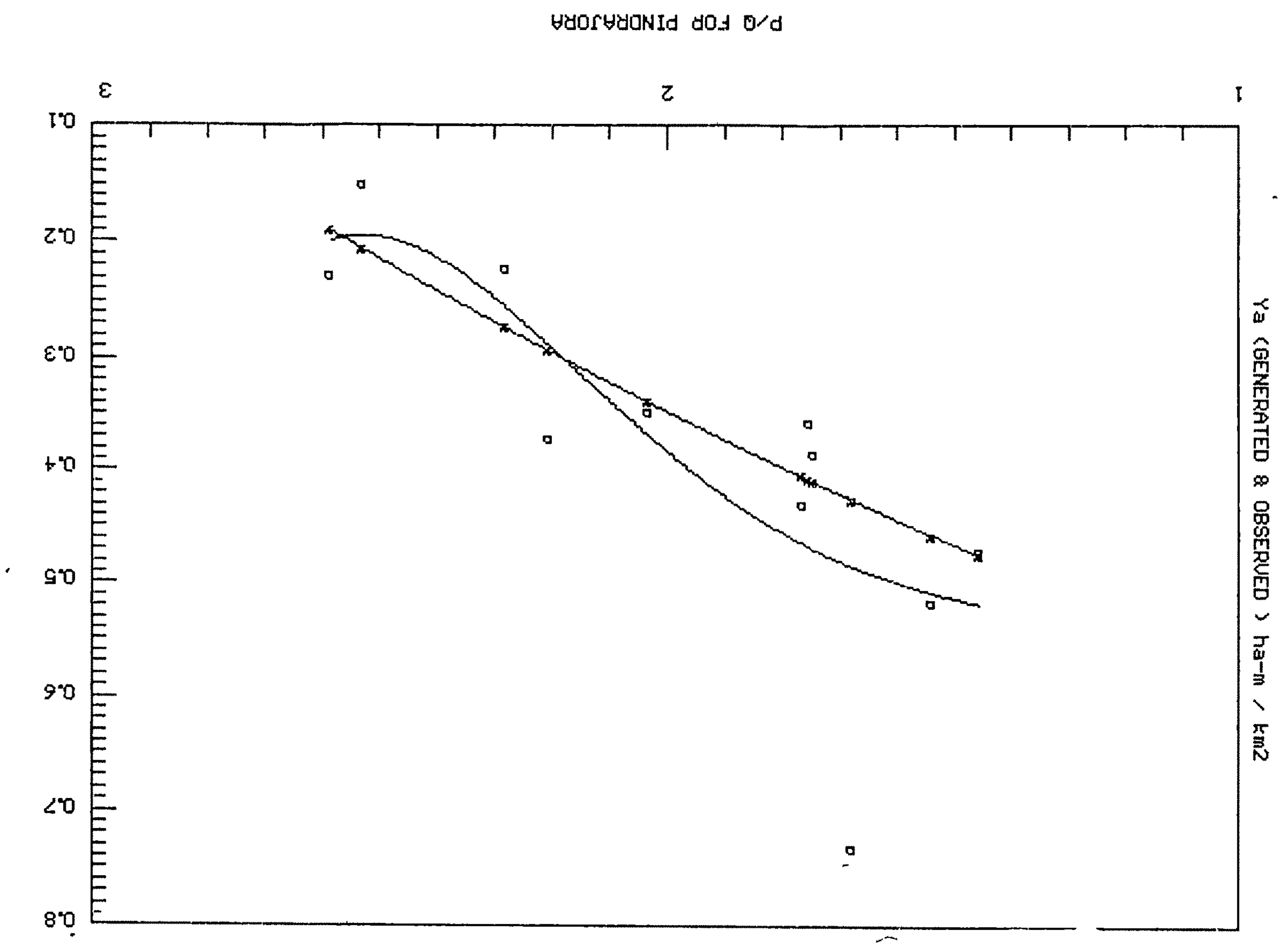

FIG. 4.2 GRAPHICAL COMPARISON OF Y_a GENERATED AND OBSERVED AGAINST P/Q FOR PINDRAJORA. THE SOLIDLINE ALONG WITH CROSS MARKS REPRESENTS THE GENERATTED DATA SETS AND OPEN CIRCLES ARE OBSERVED (RECORDED) DATA POINTS VIDE TABLE 4.14 FOR TABULAR COMPARISON

Should have appeared after Table 4.14

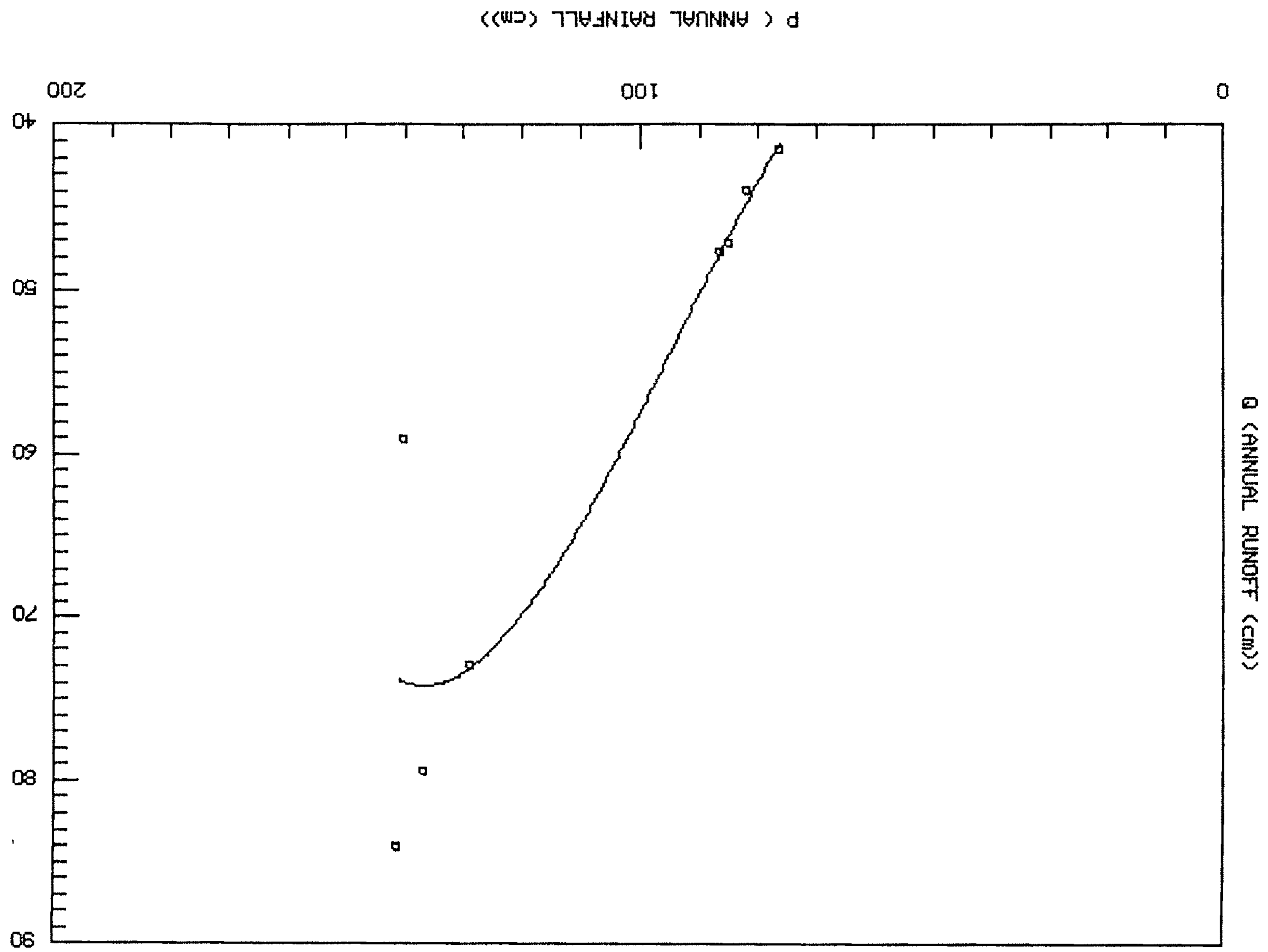

FIG. 4.3 RAINFALL VS. RUNOFF RELATIONSHIPS OF DEONAD WATERSHED OF DAMODAR CATCHMENT FOR 1965 TO 1973

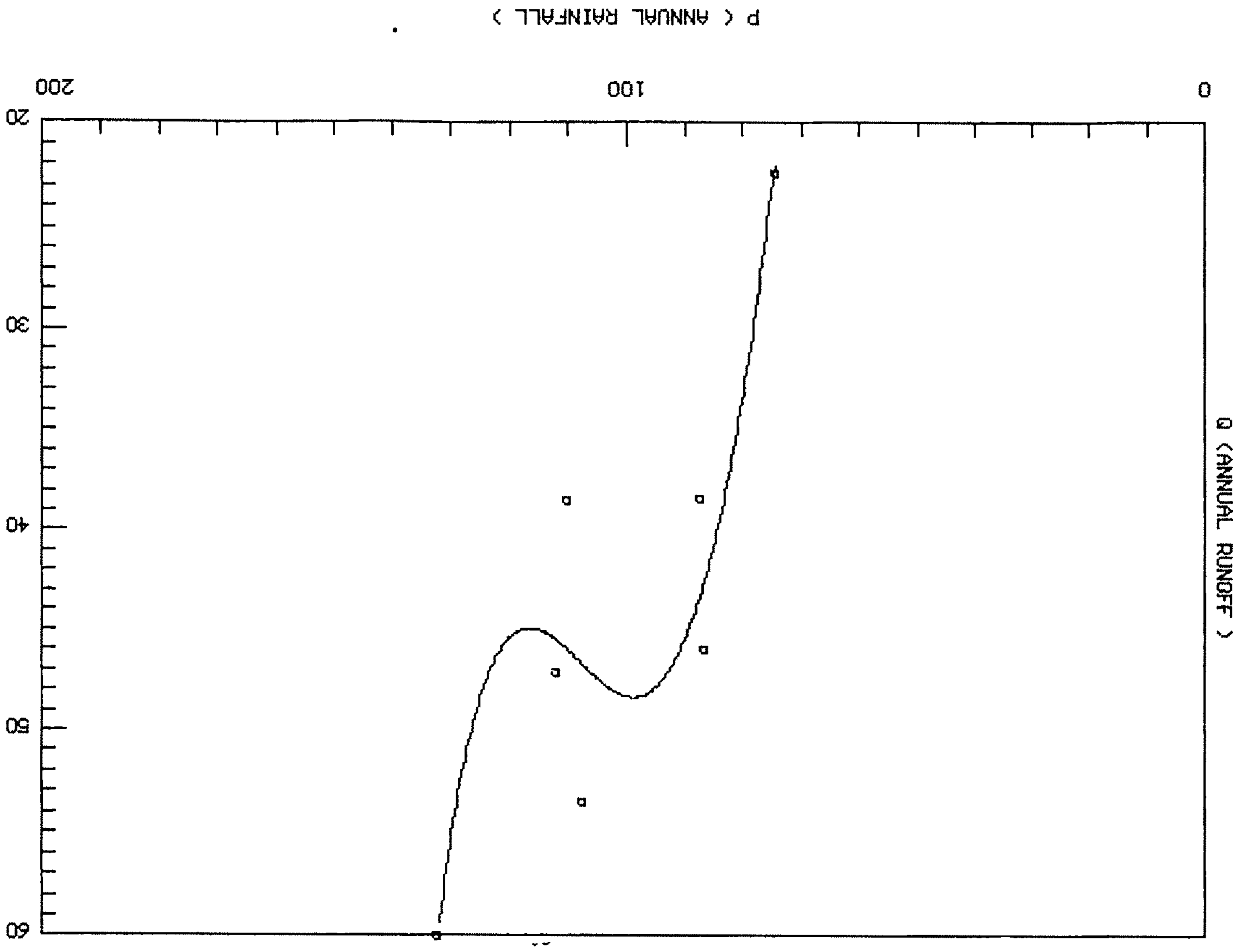

FIG. 4.4 RAINFALL VS. RUNOFF RELATIONSHIP OF RAJATAR WATERSHED OF DAMODAR CATCHMENT FOR 1964 TO 1970

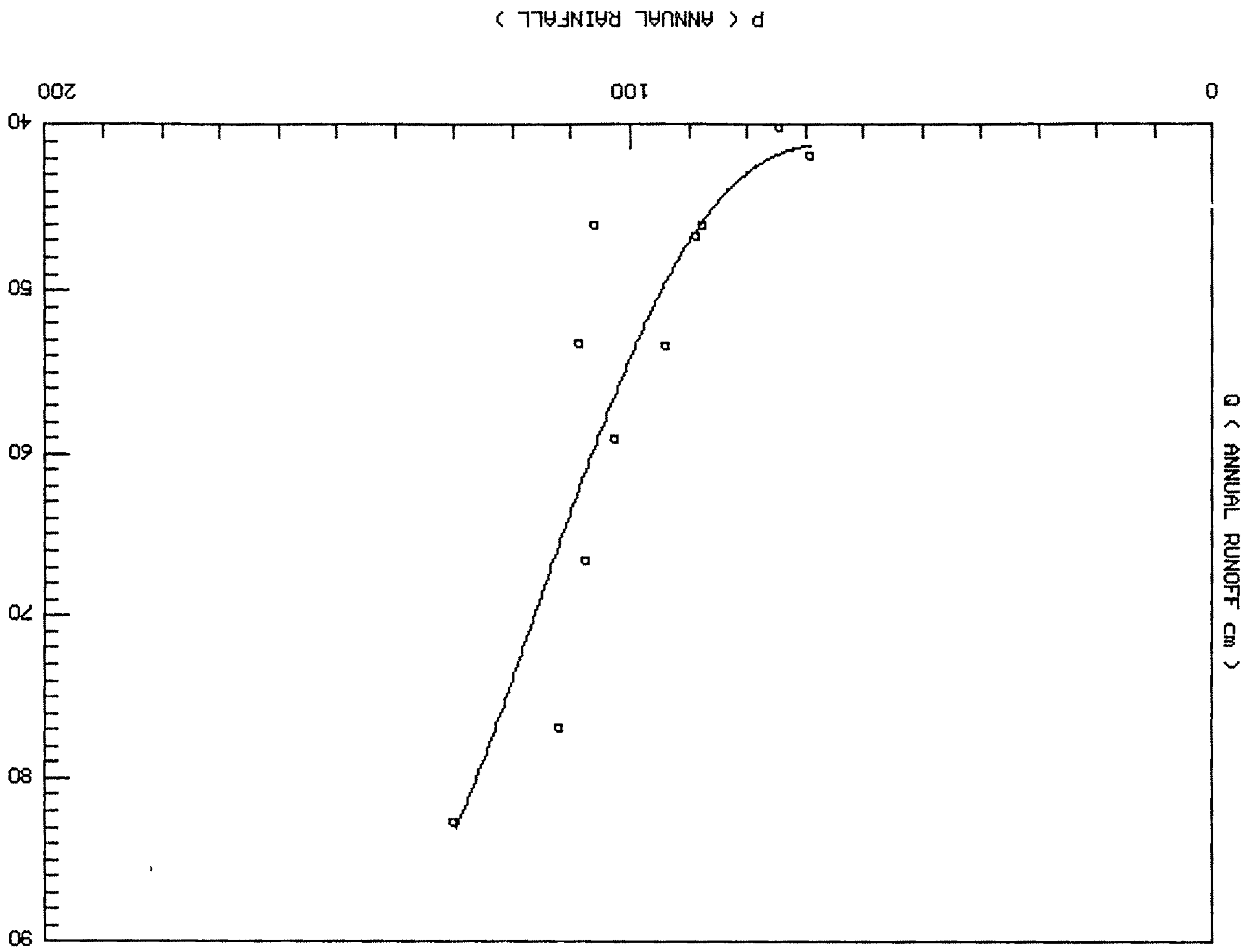

FIG. 4.5 RAINFALL VS. RUNOFF RELATIONSHIP OF GOLA WATERSHED OF DAMODAR CATCHMENT FOR 1964 TO 1974

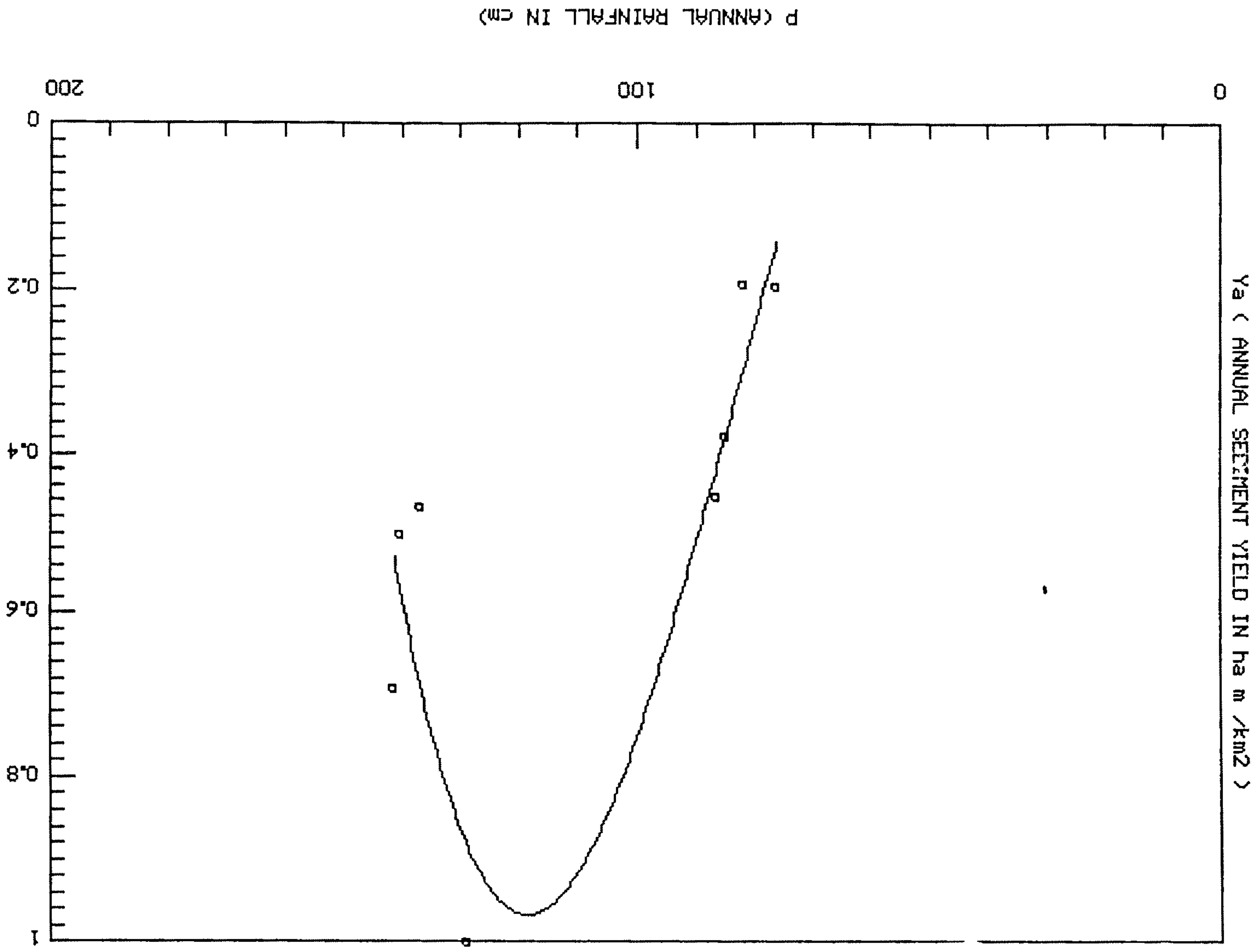

FIG. 4.6 RAINFALL VS. SEDIMENT YIELD RELATIONSHIP OF DEONAD WATERSHED OF DAMODAR CATCHMENT FOR 1965 TO 1973

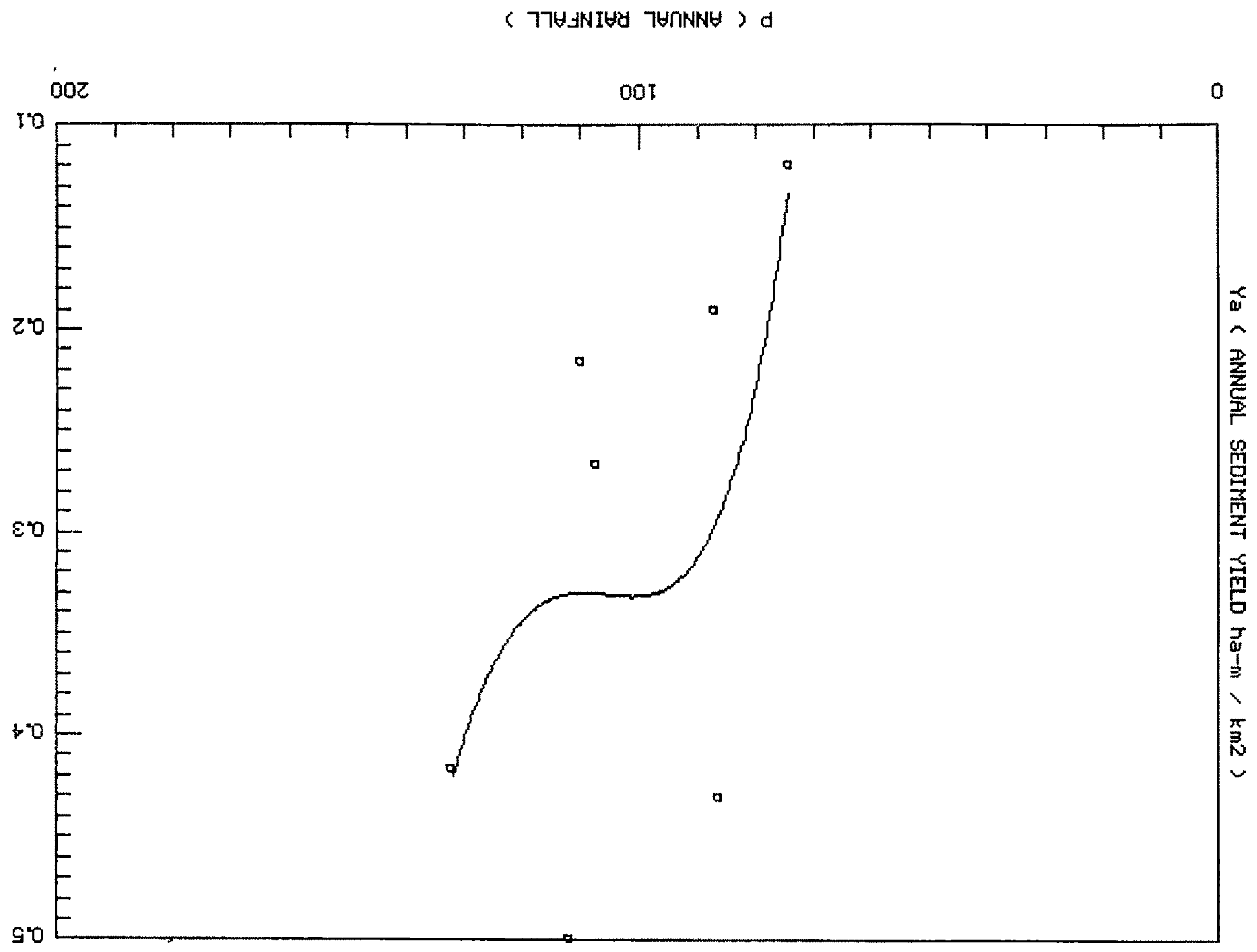

FIG. 4.7 RAINFALL VS. SEDIMENT YIELD RELATIONSHIP OF RAJATAR WATERSHED OF DAMODAR CATCHMENT FOR 1964 TO 1970

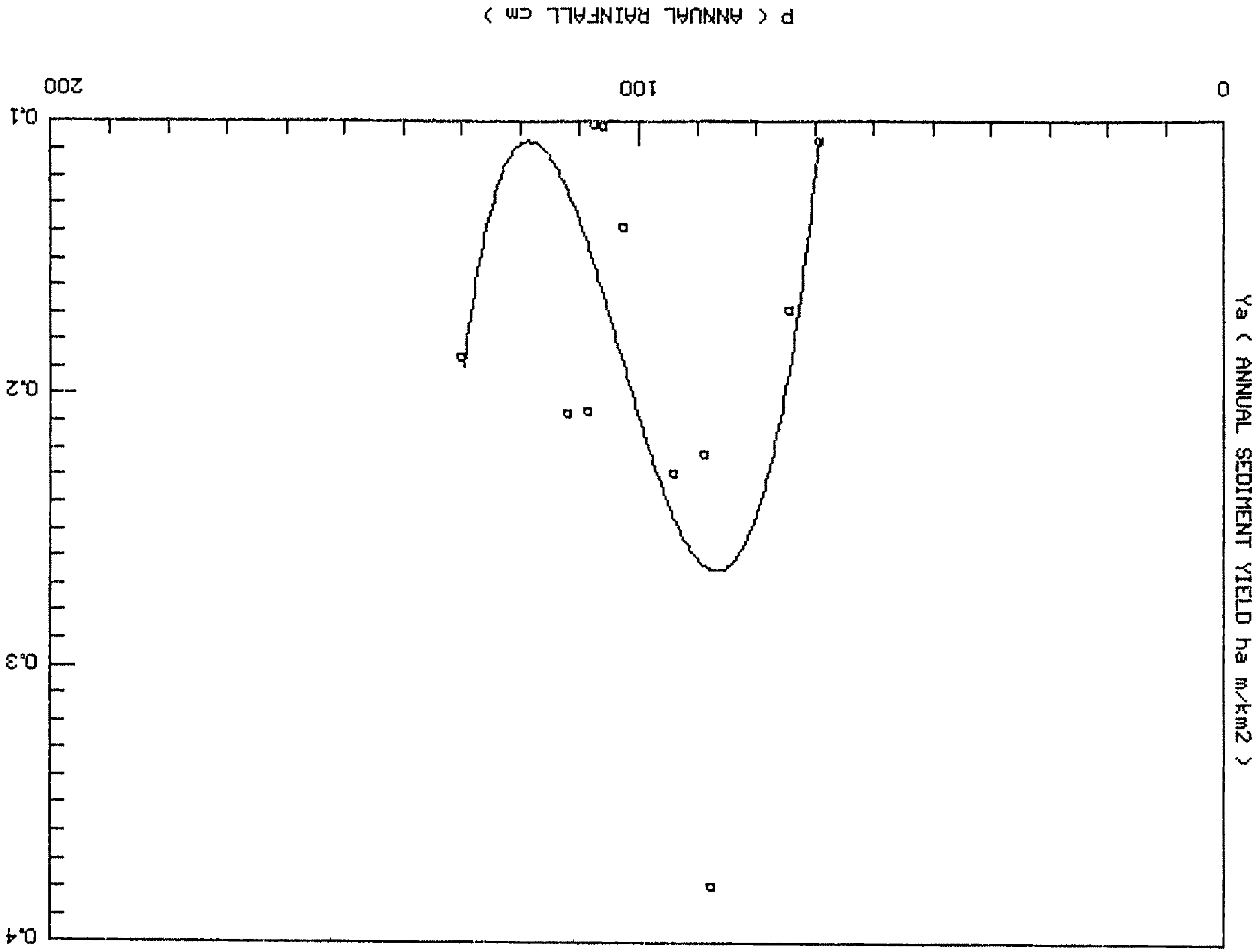

FIG. 4.8 RAINFALL VS. SEDIMENT YIELD RELATIONSHIP OF GOLA WATERSHED OF DAMODAR CATCHMENT FOR THE YEAR 1964 TO 1974

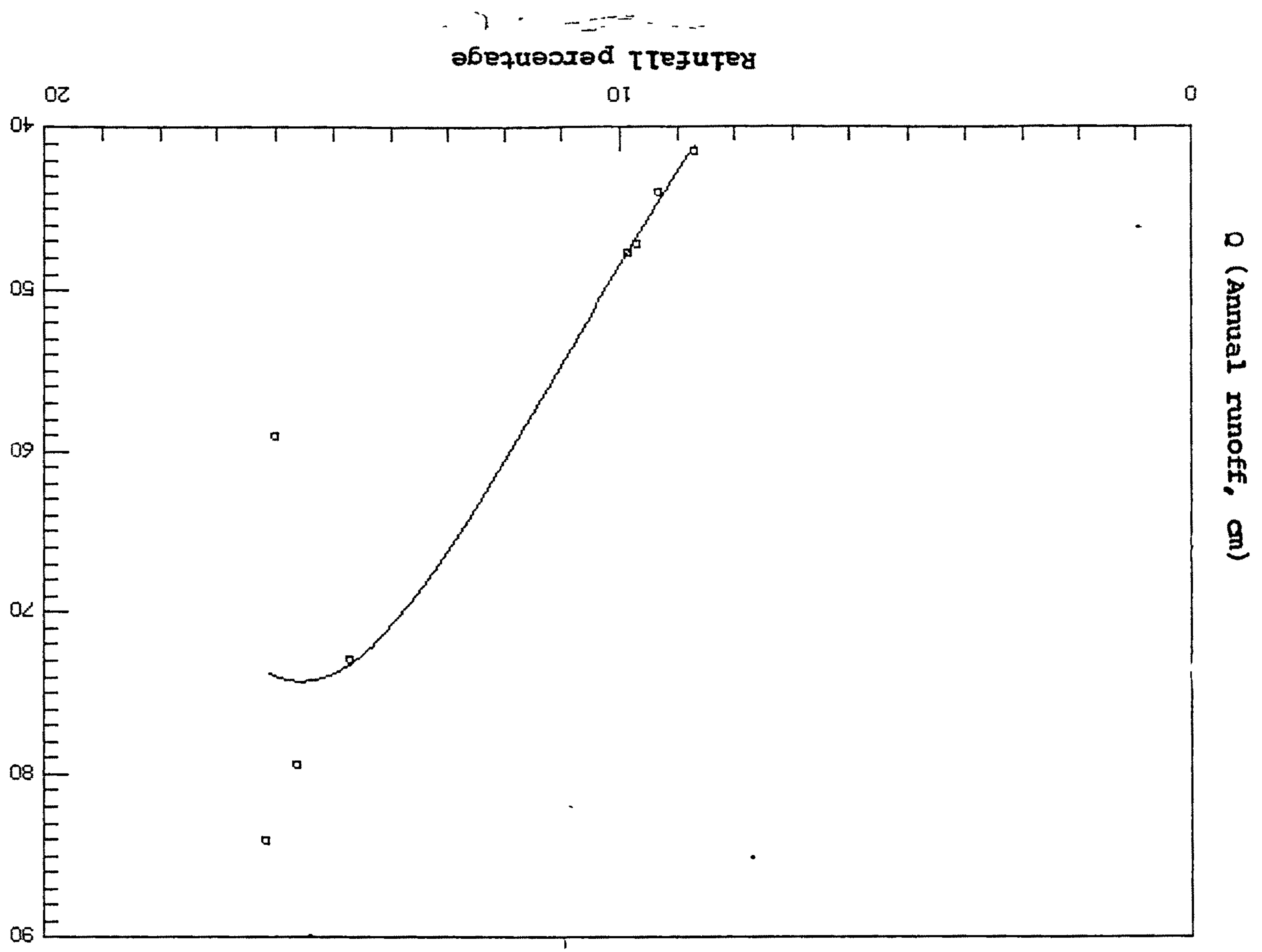

FIG. 4.9 VARIATION OF ANNUAL RAINFALL PERCENTAGE VS. ANNUAL RUNOFF FOR RELATIONSHIP OF DEONAD WATERSHED OF DAMODAR CATCHMENT FOR 1965 TO 1973

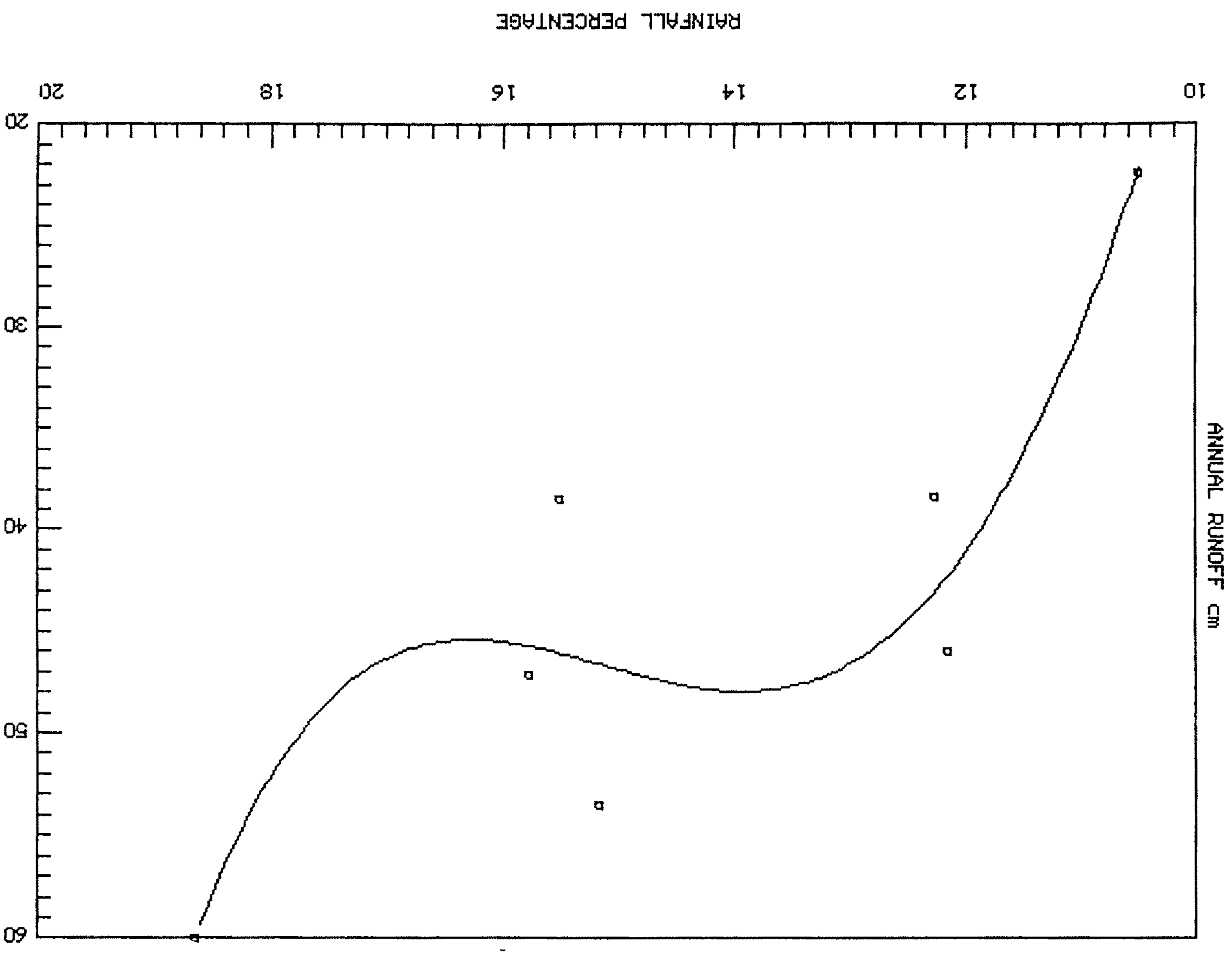

FIG. 4.10 VARIATION OF ANNUAL RAINFALL PERCENTAGE VS. ANNUAL RUNOFF RELATIONSHIP OF RAJATAR WATERSHED OF DAMODAR CATCHMENT FOR 1964 TO 1970

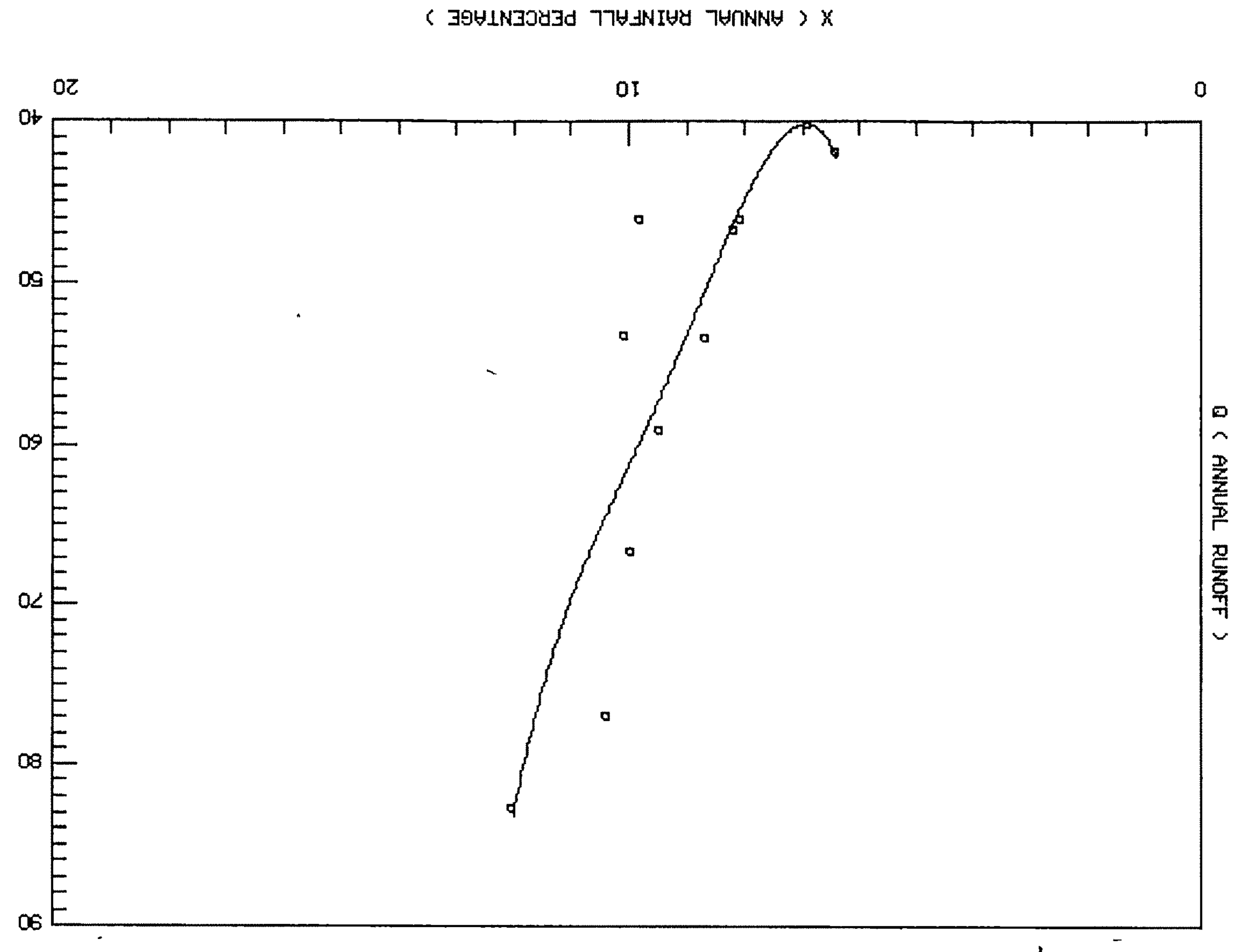

FIG. 4.11 VARIATION OF ANNUAL RAINFALL PERCENTAGE VS. ANNUAL RUNOFF OF GOLA WATERSHED OF DAMODAR CATCHMENT FOR 1964 TO 1974

Table 4.10 Watershed based models for annual sediment yield

Name of catchment	No. of Catchment	Name of Watershed	Models
Damodar	1	Deonad	$Y_a = 5.4000 - 1.950(P/Q)^{1.600}$
Damodar	15	Gola	$Y_a = 0.2027 - 0.014(P/Q)^{1.400}$
Damodar	17 B	Rajatar	$Y_a = 0.3734 - 0.019(P/Q)^{1.960}$
Damodar	20 A	Pindrajora	$Y_a = 0.6853 - 0.121(P/Q)^{1.483}$
Damodar	23 B	Nildhi	$Y_a = 0.2400 - 0.022(P/Q)^{1.840}$
Damodar	23 B	Santhaldi	$Y_a = 0.1643 - 0.015(P/Q)^{1.570}$
Barakar	26	Jogiatila	$Y_a = 0.9650 - 0.230(P/Q)^{1.570}$
Barakar	36	Lokaisakra	$Y_a = 0.7800 - 0.177(P/Q)^{1.732}$

which increases erosion and vice-versa. Thus choosing (P/Q) as a single major parameter to explain soil erosion is quite reasonable.

The other model predicts the annual sediment yields based on annual rainfall and runoff. But the variation with the noted values are too high (0 to ± 93.68 per cent) as shown in Tables 4.11 to 4.18. We have considered 8 watersheds for a maximum period of 11 years. The predicted items are 70. A scan to the above Tables it is revealed that out of 70 such events the variation is ± 40.0 % for 50. That means majority events can be predicted with this model too; hence the model on average annual sediment yield is superior than this.

Soil erosion have been documented in the literatures from various angles viz. storm basis, plot basis, soil basis etc. But very few workers have viewed this problem from gross values on large or medium watershed basis which is actually important for anti ? erosion measures. The present study is quite important from these points of view.

There are many factors responsible for soil erosion. For example rainfall erosivity, runoff volume, relief, slope angle, slope length, slope shortening (terraces, ridges) length of wind fetch, shortening of fetch (shelter-belts), Soil erodibility, infiltration capacity, soil management (use of fertilizers tillage practices), population density (pressure on land) plant

Table 4.11 Observed and estimated values of annual sediment yield of Deonad watershed of Damodar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Value of P / Q	Sediment yield in ha-m/km^2 Y_a		Percentage deviation
				Observed	Estimated	
1965	084.86	47.12	1.801	0.378	0.401	+ 06.09
1966	086.33	47.60	1.771	0.454	0.534	+ 17.62
1967	136.93	79.32	1.726	0.467	0.730	+ 56.30
1968	140.26	58.98	1.734	0.502	0.696	+ 38.65
1969	076.12	41.35	1.841	0.195	0.223	+ 14.36
1970	129.03	72.90	1.770	1.000	0.538	- 46.20
1971	141.53	83.95	1.686	0.693	0.902	+ 30.16
1973	081.86	43.94	1.863	0.192	0.123	- 35.94

Table 4.12 Observed and estimated values of sediment yield of Gola watershed of Damodar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Values of P / Q	Sediment yield in ha-m/km^2		Percentage deviation
				Observed	Estimated	
1964	093.98	53.37	1.761	0.229	0.172	- 24.78
1965	111.94	76.91	1.455	0.207	0.179	- 13.53
1966	074.57	40.13	1.858	0.169	0.169	00.00
1967	107.67	66.55	1.618	0.101	0.175	+ 73.27
1968	106.10	46.10	2.301	0.101	0.158	+ 56.44
1969	069.24	41.76	1.658	0.107	0.174	+ 62.62
1970	108.71	53.19	2.044	0.206	0.165	- 19.90
1971	087.43	46.08	1.897	0.379	0.168	- 55.67
1972	088.70	46.66	1.901	0.222	0.168	- 24.32
1973	130.15	82.73	1.573	0.186	0.176	- 05.78
1974	102.59	59.06	1.737	0.139	0.172	+ 23.74

Table 4.13 Observed and estimated annual sediment yield of Rajatar watershed of Damodar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Values of P / Q	Sediment yield (ha-m / km^2)		Percent deviation
				Observed	Estimated	
1964	132.28	60.00	2.205	0.416	0.284	- 31.73
1965	111.94	47.17	2.373	0.499	0.270	- 45.29
1966	074.57	22.43	3.325	0.119	0.173	+ 45.38
1967	107.67	53.47	2.014	0.266	0.299	+ 12.41
1968	086.34	45.95	1.879	0.430	0.308	- 28.37
1969	087.07	38.41	2.267	0.190	0.279	+ 46.84
1970	110.08	35.53	2.857	0.215	0.225	+ 04.65

Table 4.14 Observed and estimated annual sediment yield of Pindrajora watershed of Damodar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Values of P / Q	Sediment yield ha-m/km^2		Percentage deviation
				Observed	Estimated	
1964	111.74	54.94	2.034	0.348	0.339	- 02.59
1965	092.41	40.49	2.282	0.224	0.274	+ 22.32
1966	084.07	32.49	2.588	0.230	0.190	- 17.39
1967	131.95	60.81	2.207	0.371	0.294	- 20.76
1968	117.07	66.70	1.757	0.357	0.406	+ 13.73
1969	086.56	34.21	2.530	0.152	0.206	+ 35.53
1970	096.90	66.42	1.459	0.469	0.473	+ 00.85
1971	092.89	52.55	1.768	0.429	0.404	- 05.83
1972	089.61	51.31	1.747	0.384	0.409	+ 06.51
1973	139.83	83.92	1.678	0.733	0.425	- 42.02
1974	104.04	67.59	1.539	0.516	0.456	- 11.63

Table 4.15 Observed and estimated values of annual sediment yield of Nildhi watershed of Damodar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Values of P / Q	Sediment yield (ha-m/km^2) Y_a		Percentage deviation
				Observed	Estimated	
1964	074.04	46.74	1.584	0.235	0.189	- 19.58
1965	075.82	24.44	3.103	0.132	0.063	- 42.33
1966	089.89	28.96	3.104	0.047	0.063	+ 34.04
1967	137.14	75.29	1.822	0.313	0.174	- 44.41
1968	087.91	46.76	1.880	0.195	0.170	- 12.82
1969	082.04	49.20	1.668	0.095	0.184	+ 93.68
1970	115.16	33.35	3.453	0.144	0.025	- 82.64
1971	086.08	49.84	1.727	0.231	0.180	- 22.08
1973	112.37	56.49	1.989	0.178	0.162	- 08.99

Table 4.16 Observed and estimated annual sediment yield of Santhaldi watershed of Damodar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Values of P / Q	Sediment yield in ha-m/km^2		Percentage deviation
				Observed	Estimated	
1964	088.54	43.43	2.039	0.182	0.118	+ 35.17
1965	079.10	28.50	2.775	0.139	0.090	- 35.25
1966	055.65	14.58	3.817	0.066	0.041	- 37.88
1967	111.86	63.45	1.763	0.096	0.128	+ 33.33
1968	136.37	64.11	2.127	0.091	0.115	+ 26.37
1969	082.09	25.71	3.194	0.067	0.071	+ 05.97

Table 4.17 Observed and estimated annual sediment yield of Jogiatila watershed of Barakar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Values of P / Q	Sediment yield in ha-m/km^2 Y_a		Percentage deviation
				Observed	Estimated	
1964	085.04	41.78	2.035	0.435	0.263	- 39.54
1965	102.03	50.42	2.024	0.488	0.269	- 44.88
1966	062.10	28.35	2.191	0.177	0.177	00.00
1967	089.10	54.41	1.638	0.699	0.466	- 33.33
1968	123.55	83.26	1.484	0.627	0.538	- 14.20
1969	094.46	64.80	1.458	0.330	0.549	+ 66.36
1970	070.54	49.86	1.415	0.453	0.568	+ 25.39
1971	104.70	65.35	1.602	0.524	0.483	- 07.82
1972	093.50	61.27	1.526	1.017	0.518	- 49.07
1973	144.02	95.48	1.508	0.702	0.527	- 24.93
1974	090.04	49.30	1.826	0.205	0.373	+ 81.95

Table 4.18 Observed and estimated annual sediment yield of Lokaisakra watershed of Barakar catchment

Year	Annual rainfall (cm) P	Annual runoff (cm) Q	Values of P / Q	Sediment yield (ha-m/km^2) Y_a		Percentage deviation
				Observed	Estimated	
1965	073.94	34.39	2.150	0.183	0.114	- 37.71
1966	073.53	44.98	1.635	0.434	0.365	- 15.90
1967	091.19	51.66	1.765	0.492	0.307	- 37.60
1968	119.74	73.91	1.620	0.540	0.372	- 31.11
1969	077.03	53.16	1.449	0.278	0.444	+ 59.71
1970	069.98	50.88	1.375	0.288	0.473	+ 64.24
1971	180.06	136.20	1.322	0.630	0.493	- 21.75

cover (crops, improved and natural pasture, forest), amenity value (pressure of use) and land management. But some of these are interdependent; many are not easily measureable. Hence attempts to model this phenomena from easily measureable variables may be appreciated but undoubtedly it will be full of weaknesses too. This has exactly happended in the present set of two types of models with high degree of empiricism. For the sake of simplicity one may not agree to digest such weaknesses.

Moreover though two types of models have been prescribed here but in effect it is 10 because all the constants, coefficients and exponents are different from each other. Had there been only two models, then it would have been better. But it is not so. This is another drawback.

But some how we are partially successful in case of Y_{aa}-model. For eight watersheds we could arrive at two models instead of one.

Probable causes of high percentage deviation between observed and estimated annual sediment yield may be due to many reasons.

Table 4.11 shows that for nearly same values of P/Q i.e., 1.771 and 1.770 the values of Y_a are 0.454 and 1.00 ha-m per square kilometre for the year 1966 and 1970 respectively. This seems to be puzzling but may be explained as -

(1) In many developing countries, because of shortage of resources, sediment sampling programmes are often based on a regular time schedule viz., once or twice a day. The method has two principal defects.

Firstly in many rivers or nalas by far the largest proportion of the total sediment load is carried during flood events. Sampling at regular intervals can miss the peak of such flood and this is more pronounced with small catchments with large drainage areas this effect is less important, but because of the obvious difficulties in sampling during times of peak flow sediment sampling is often not carried out. Thus in both cases the flood events are missed resulting in an under estimate of the total sediment flux.

Secondly, in many depth integrated and point sampling programmes no distinction is made between fine sediment (wash load) and coaser sediment (suspended bed material load). The transport of these two fractions depends on different controlling parameters wash load is more evenly distributed in the cross section and its concentration is dependent on the rate of supply as dictated by climate, soil type, vegetative cover, land use etc. Suspended bed material load, concentration on the other hand varies more markedly through the depth and is dependent on the stream carrying capacity in addition to the supply rate (both from the basin and the channel bed upstream). These distinctions are rarely made and the resulting correlation between sediment concentration and water discharge is often very poor.

Runoff (cm) against rainfall (%)* are plotted in Fig.4.9, 4.10, 4.11. This shows that same percentage of rainfall does not produce same runoff or soil loss (Fig. 4.6, 4.7, 4.8). The relationship between these two are not very good. It is an well known fact that rainfall is a vital parameter for sediment loss. Here rainfall itself is not accurately interrelated either with runoff or soil loss. It is, therefore, very difficult to get high correlation in the models established herein. This happens because annual total could not accommodate minor details of other characteristics of this phenomena.

(2) Rainfall intensity (amount per unit time (mm sec^{-1}) and velocity of rainfall, size of raindrops and pattern or distribution of rainfall throughout the year are components of rain-factor influencing soil erosion. Rain can be either erosive or non erosive. The duration of erosive rainfalland its intensity are the important factors causing soil erosion.

Erosion index (EI) has been found to be a good index of erodibility of rain and to have a good correlation with the soil losses (E^I is the product of kinetic energy of the storm times the maximum 30 minutes intensity). Here we have considered total amount of annual precipitation which consists of several spell of individual precipitation. Therefore, it is reasonable that nearly same value of P/Q offers different sediment flow rate.

---

*Rainfall percentage is obtained as annual rainfall divided by N year total rainfall multiplied by hundred

Some of the major weaknesses of the present models may be summarised as follows :

(1) Soil erosion is determined by several factors like rainfall, runoff, slope, vegetation and soil. But in this model slope, vegetation and soil factors of watersheds are not considered either separately or in combination.

(2) Same values of P/Q may give different sediment flow rate. This is the major draw back of these models. Because total amount of annual precipitation consist of several spells of individual precipitation. The rainfall intensity and/or other characteristics of individual spells are not equal which is the major factor of soil erosion.

If two watersheds having different characteristics are considered for same P/Q, on both, it is certain that runoff or soil loss will differ. Similarly if sediment yield or runoff comes out to be same, the P/Q and watershed characteristics may also differ.

(3) Prediction of soil loss itself is subject to large inaccuracies even when the data used for the prediction is both reliable and comprehensive. Therefore, if only a small proportion of the sediment load is depositing in a river system, it can be ignored without significantly imparing the accuracy of the sediment yield predictions.

(4) Failures of the models because of anomalies due to rainfall characteristics are quite obvious and widely documented in the concerned literatures. The present models are not free from such encumbrances.

Inspite of all these main defects it is worthwhile to record that the two Y_{aa} models as established here for the eight watersheds (Table 4.1) are quite good. The generated and observed values tally well for these two. Hence these two are the best product out of the whole lot under so many constrains.

CHAPTER V

SUMMARY
AND
CONCLUSION

SUMMARY AND CONCLUSION

In the present concept since 1930 a lot of works on soil loss has been done. Only a part of this has been reviewed in the present study. It is noted that models (Mathematically/statistical/empirical) on soil loss based on individual storm, slope percentage, slope length drainage area, soil compactness, cover factor, soil particle size, runoff, relief length ratio circulatory factor, shape factor and velocity of raindrop are now available. But what is important for the planners is the gross average soil loss from a catchment based on gross total rainfall and/or runoff. Such useful models are rarely available. This is convenient too, because the data of gross total rainfall and/or runoff are easily available.

Accordingly an attempt has been made in the present thesis. The data for watersheds viz. Santhaldih (1964-1969), Lokaisakra (1965 - 1971); Rajatar (1964 - 1970); Deonad (1965 - 1971 + 1973); Nildhi (1964 - 1971 + 1973); Gola (1964 - 1974) Pindrajora (1964-1974) and Jogiatila (1964 - 1974) belonging to Damodar and Barakar basins (vide Tables 3.3 to 3.10) have been collected from Soil Conservation Department (Engineering Division). Damodar Valley Corporation, Hazaribagh 825301, Bihar, India. The data on annual rainfall, runoff and sediment yield are available from these records. These were processed through all the known methods. But a combination of trial and error along with statistical method yielded the best results such as Eqs. (3.2) and (3.5).

Tables 3.3 to 3.10 give a clear picture about the sediment load carried by the rivers and streams from their respective catchments or sub-catchments. The models developed here will be useful for management practices essential for sustained agriculture in ungauged watersheds which are similar to the studied watersheds. Reservoirs are essential in watershed planning and management. For prolonged use of these reservoirs, one is compelled to measure the silting-up positions of the reservoir. This is a time consuming and costly process. The models developed in the present thesis are useful to avoid the actual measurements to make the things cheaper and quicker.

Sixty two events of average annual sediment yield rates of eight watersheds are recorded and presented in the Tables 4.2 to 4.9. From the generated data using Eq (3.2), it is noted that percentage deviation between the prediction obtained from models and observed values are within ± 40.0. Similarly Eq (3.5) describes eight watersheds to predict annual sediment yield. From the generated data using Eq (3.5) it is seen that percentage deviation is within ± 40% for 50 events out of 70. For both cases such deviations are reasonable due to reasons explained in Article 4.2, the gist of which are as follows :

i) Sediment sampling programmes are often based on a regular time schedule viz. one or twice a day. Beyond this some valuable events remain unrecorded.

2) In many depth integrated and point sampling programms no distinctions is made between fine and coarser sediment.

3) Rain can be either erosive or non erosive which is important factor causing soil erosion. Here we have considered total amount rainfall which consists of several spell of individual rainfall having different erosion producing characters.

It may, therefore, be said that models developed for the respective catchment could well be utilized for said purposes. Such types of empirical models for sediment yield rate warns us about the soil conservation measures on watershed basis. Within each watershed there is much diversity and heterogenity and there is a need for further improvement and development in models to permit more meaningful and purposeful uses. These techniques are aimed at providing information for management of soil and water resources.

Inspite of so many constrains the Eq(3.2) plus Table 4.1 is a silver lining in the whole exercise. It would have been best to arrive at a single model for all eight watersheds. But somehow we could arrive at two models. Thus it is better, if not the best. The generated and observed values for these two models tally far better than the many other models known to us.

From the present study the following conclusions may be drawn. Equation 3.2 (vide Table 4.1) may be used to predict average annual soil loss from a catchment on the basis of average annual rainfall and runoff data and Eq 3.5 (vide Table 4.10) may be used for generating data on annual soil loss from an watershed just from the records of annual rainfall and runoff.

CHAPTER VI

SUGGESTION FOR FUTURE RESEARCH WORK

SUGGESTIONS FOR FUTURE WORK

1. Similar models may be developed on the basis of geomorphic factors responsible for soil loss;
2. These models may be developed using data for more number of watershed stations and of longer periods
3. These models may be used for other watersheds of physiographically similar characters.
4. Percentage deviation of the models need to be reduced again whenever data for longer periods become available.

BIBLIOGRAPHY

BIBLIOGRAPHY

✓Adam, L., 1976 : Erosion of the Top soil cover in the Szekszard Region (in Hungarial), Foldrujzi Ertesito.

✓Anderson, H.W. 1957. Relating sediment yield to watershed variables. Trans. American. Geophysics Union 38(6) : 921 - 924.

✓Bagley, J. M., R. W. Jeppson and C. H. Milligan, 1964. Water yields in Utah. Special Report 18, Utah Agricultural Exp. Station. Utah State University. Logan (original not seen, cited in wong, 1963).

✓Balasubramaniam, G. and Sivanappan, R. K. (1981). Effect of degree of slope and rainfall erosivity on soil erosion and the influence of mulching on runoff and soil loss, Proc. South. East Asian Regional Symposium on problems of soil Erosion and Sedimentation. Asian Institute of Technology Bangkok : 29 - 36.

✓Beck, M. B. 1987. Water quality modelling. A review of the analysis of uncertainty water Resource Research 23(B) : 1393 - 1442.

✓Benson, M. A. 1962. Factors influencing the occurrence of floods in a humid region of diverse terrain. USGS, WSP 1580-B Washington DC (original not seen cited in Kite, 1974).

✓Bhowmik, N. G. 1984. Relationship between the geomorphic parameters and the sediment transport characteristics of the Spoon River Basin in Illinois. 1984. Symposium of Surface Mining, Hydrology, Sedimentology, Reclamation University of Kentucky, Lexington, Dec. 2-7.

Bhowmik, N.G.; J. R. Adams and R. E. Sparks, 1986. Fate of Navigation Pool on Mississippi River. American Society of Civil Engineers Journal of Hydraulic Engineering Volume 112, No. 10, October.

✓Bhowmik, N. G. 1988. Sediment Transport in streams and Rivers. Journal of Applied Hydrology Vol.1, No.1, 1988. pp. 25 - 62.

✓Carson, M. A. and Kirkby, M. J. 1972. Hillslipe form and process Cambridge University Press.

✓Bose, S.S.; and R. K. Sivanappan 1989. Runoff and Soil Loss On Red and Black Soils of Coimbatore District. Indian Journal of Soil Conservation. Vol. 17, No.2, August 1989.

✓Chong, S. K. and S. M. Moore. 1983. Flood frequency analysis of small watersheds in Southern Illinois, Water Resour. Bulletin 19(2) : 279 - 282.

✓Cruff, R. W. and S. E. Rantz, 1965. A comparison of methods used in flood frequency studies for coastal basins in California, USGS, WSP 1580 E (original not seen, cited in Kite, 1974).

Das, D. C. and S. Singh 1979. Soil Conservation for Moderation of Flood and Sedimentation. Hydrology Reviced 1 HO Indian National Committee Vol. (1, 2, 3 & 4), New Delhi, 1979.

Das, D.C.; S. Subramanian, J. C. Samuel and C. S. Ramasesha, 1984. Guidelines and status of Hydrologic Sediment Monitoring of Watersheds in Selected River Valley Catchments. Technical Series No. 1/H & S/1984, Ministry of Agriculture, Department of Agricultural & Co-operation, 1984, New Delhi.

✓ Decoursey, D. G. 1973. Objective regionalization of peak flow rates. Proc. of Second International symposium in Hydrology. WRP, Fort Collins, Colarodo : 395 - 405. (Original not seen, cited in Kite, 1974).

✓ Dendy, F. E. and Bolton, G. C. 1976. Sediment yield runoff drainage area relationships in the USA. Journal of Soil and Water Conservation 31(6) : 264 - 266.

✓ Dong, C. X., 1974. Regularities in the Development of Erosion, Thesis for the title of Candidate of Technical Sciences (in Hungarian), Budapest.

✓ Edwards, D. R. and C. T. Haan. 1989 a. Confidence limits on peak flow estimates for ungauged watersheds. Transactions. American Society of Agricultural Engineers. 32(1) : 120 - 126.

✓ Edwards, D. R. and C. T. Haan. 1889 b. Risk-based hydrologic design under uncertain conditions. Trans. ASAE 32(4):1335-1341.

Einstein, W. A. (1950). The Bed-Load Function for Sediment Transportation in Open channel Flows. U. S. Department of Agriculture, Soil Conservation Services, Technical Bulletin 1026.

Fekete, Z., and Horn, E., 1965 : Examination of Contourline in Vine yards at Budaors-Kamaraerdo (in Hungarian), Kerteszeti es Szoleszeti Foiskola. Ko zlemenyel.

✓Flaxman, E.M. 1972. Predicting sediment yield in western US Proceeding ASCE, Jour. of Hydrology Division 98(12): 2073-2085.

✓Fleming, G. 1969. Design curves for suspended load estimation. Proc. Institution Civ. Engineers 43 : 1-9.

✓Fournier, F., 1960 : Climat et Erosion, Presse Universitaire de France, Paris, (in French).

✓Gabriel, A., 1976 : The Rate of Erosion and the critical Runoff from sloping Areas (in Hungarian). Hidrologiai Kozlony, No. 3.

✓Ghosh, R.K. and Swain, S. 1993 : Practical Agricultural Engineering Naya Prokash Publication Calcutta, Vol.II, Chapter 3, PP. 81.

✓Glen W. Hess and Mc Glone Price. 1989 : Comparison of methods for estimating flood magnitudes on small streams in Georgia. Water Resour. Bull. American Water Resource Association 25(1) : 149 - 154.

✓Golden, H. G. and Mc Glone Price. 1976. Flood frequency analysis for small natural streams in Georgia. USGS Open file Report 76-511, Washington DC : 75 (Original not seen cited in Glenetal, 1989).

✓Haan, C. T. and Read 1970. Prediction of monthly seasonal and annual runoff. Volumes for small agricultural watersheds in Kentucky, Bull. 711. Kentucky Agri. Experiment Station, Lexington (Original not seen, cited in Haan et al., 1972).

✓Haan, C. T. and David, M. Allen, 1972. Comparison of multiple regression for predicting water yields in Kentuoky. Water Resour. Res. 8(6) : 1593 - 1596.

✓Hack, J. T. 1957. Studies on longitudinal streams profiles in Virginia and Maryland. USGS Professional paper 294-B (Original not seen, cited in Chow, 1964).

✓Haq, S. M. 1985. Regional flood frequency analysis of Cauvery zone. Proc. 52nd Annual R & D Session Vol. 11, CBIP : 3-6.

✓Hindall, S. M. 1976. Prediction of sediment yields in Wisconsin streams. Proc. 3rd Federal Inter-Agency Sedimentation Conference : 1.205 - 1.218.

✓Horton, R. E. 1932. Drainage basin characteristics. Trans. Am. Geophys. Union 13 : 350 - 361.

✓Horton, R. H. 1941. Sheet erosion : Present and past. Trans. Am. Geophys. Union. 22 : 299 - 305.

✓Horton, R. E. 1945. Erosional development of streams and their drainage basin : hydrological approach to quantitative morphology. Geol. Soc. Am. Bull. 56 : 275 - 370.

✓ Jansen, J.M.L. and R. B. Painter. 1974. Predicting sediment yield from climate and topography. Jour. of Hydrology 21(4): 371 - 380.

✓Joglekar, D. V. 1965. Irrigation Research in India. Publication No. 78, CBIP.

✓Jose, C. Samel and D. C. Das 1982. Geomorphic prediction models for sediment production and inter-se priorities of watersheds in Mayurakshi catchment. Proc. of the International Symposium on Hydrological Aspects of Mountainous watersheds. School of Hydrology, University of Roorkee, Vol. 1 : 15 - 23.

✓Kirkby, M. J. 1967. Erosion by water on hill slopes in water earth and Man (ed.) M. J. Chorley, London Methuen : 98-107.

Kite, G. W. 1974. Frequency and Risk Analysis in Hydrology. WRP, Ottawa : 156 - 210.

✓Komura, S. 1976. Hydraulics of slope erosion by overland flow. Journal of the hydraulics Division A.S.C.E. 102 (Hy 10) 1573 - 1586.

✓Kuczera, G. 1982. On the relationship between the reliability of parameter estimates and hydrologic time series data used in Calibration. Water Resour. Res. 18(1) : 146 - 154.

✓Kumar, V. 1990. Hydrologic response models for prediction of runoff and sediment yields from small watersheds. Indian Journal of Soil Conservation. Vol. 19, No. 1 & 2.

✓Langbein, W. B. and S. A. Schumm, 1958. Yield of sediment in relation to mean annual precipitation. Trans. Am. Geophys. Union 39 : 1036 - 1084.

Leopold, L. B. and J. P. Miller, 1956. Ephemeral streams : Hydraulic factors and their relation to drainage net. USGS Professional paper 282A (oroginal not seen, cited in Chow, 1964).

Linsley, R. K., M. A. Kohler and J. L. H. Paulhus, 1975. Hydrology for Engineers. New Delhi : Mc Graw Hill Series in Water resources and environmental engineering.

Lull, H. W. and Williams E. Sopper. 1966. Factors that influence stream flow in the northeast. Water Resour. Res. 2(3): 371 - 379.

Lyngdoh, P. S. 1980. Hydrological investigation of mini watersheds for efficient watershed management, Unpublished M. Tech. Thesis, IIT, Kharagpur (India).

Maxwell, J. C. 1955. The bifurcation ratio in Honton's law of stream numbers. Trans. Am. Geophys. Union 36 : 520.

Melton, M. A. 1959. A derivation of Strahler's channel - Ordering system. Jour. of Geology 67(3) : 345 - 346.

Meyer, L. D. 1971. Soil erosion by water on upland areas from river mechanics book. Chapter. 27. Pt. Collins Colorado, 1971.

Meyer, L. D. and Monke, E. J. 1965. Mechanics of soil erosion by rainfall and overland flow. Trans. A.S.A.E. Vol. 8 pp. 572 - 577. 580.

Meyer, L. D. and Wischmeier, W. H., 1969. Mathematical Simulation of the Process of Soil Erosion by water. Trans. of the Am. Soc. of Agricultural Engineering, Vol. 12.

Miller, Carl, R. 1965. Advances in sedimentation relevant to watershed problems. Trans. ASAE 8 : 146 - 152.

✓Miller, V. C. 1953. A quantitative geomorphic study of drainage basin characteristics in the clinch mountain area, Virginia and Tennesses. Dept. of Navy Office of Naval Research, Technical Report 3, Project NR 389-042 Wasington DC (original not seen, cited in Chow, 1964).

✓Misra, N. 1987. Modelling runoff and sediment yields from small watersheds. Unpublished Ph.D. Thesis, Agril. Engg. Dept. IIT, Kharagpur (India).

✓Morgan, R.P.C. 1980. Field studies of sediment transport by overland flow. Earth Surface Processes, 5 : 307 - 316.

✓Morisawa, M. E. 1957. Accuracy of determinations of stream lengths from topographic maps. Trans. Am. Geophys. Union 38 : 86 - 88.

✓Morisawa, M. E. 1962. Quantitative geomorphology of some watersheds in the Appalachian plateau. Geological Soc. Am. Bull. 73. 1025 - 1046.

✓Musgrave, G. W. 1947. The quantitative Evaluation of Factors in water erosion, A first approximation. Jl. Soil and Water Conservation. Vol. 2. pp. 133 - 138.

✓Mustonen, Seppo E. 1967. Effects of climatologic and basin characteristics on annual runoff. Water Resour. Res. 3:123-130.

✓Piest, R. E.; Bradford, J. M. and Sporner, R. G. 1972. Mechanisms of Erosion and Sediment Movement from Gullies. In Proc. Sediment yield Workshop. U.S.D.A. Sediment Laboratory Oxford, Mississippi, U. S. A. ARS-S-40.

✓Potter, W.D. 1953. Rainfall and topographic factors that effect runoff. Trans. Am. Geophys. Union. 34 : 67 - 73.

✓Raghunath, B.D.C. Das and P. K. Thomas 1970. Some results of investigations on hydrology of sub-watersheds in the Nilgiris (India). Symposium on the results of research on representative experimental basin IASH, UNESCO-3 : 136 - 162.

✓Ram Babu, Gupta, S. K. and Tejwani, K. G. 1970. Correlation of soil loss with various energy intensity products. Indian Forester. 96(10) : 771 - 774.

✓Riggs, H. C. 1961. Frequency of natural events, Proc. ASCE. Jour. of Hy. Div. 87(HYI) : 15 - 26.

Samuel, J. C. and D. C. Das 1981 a. Watershed and Sediment load Relationship for Damodar Barakar and its comparison with Existing Formulae 18th Annual Convention of ISAE, Karnel, February 26-28, 1981.

Samuel, J.C.; G.C. Basu, S. Bhan and D. C. Das 1981 b. Runoff Silt load Prediction Models for Damodar Watersheds. Indian Journal of Soil Conservation, Dehradun, Vol. 9, No. 1, pp. 33 - 42, April, 1981.

Schumm, S. A. 1956. Evaluation of drainage systems and slopes in bad lands at perth Ambry. New Jersey. Bull. Geol. Soc. Am. 67 : 597 - 646.

Sharma, K. D. and Correia, J. F. 1987. Use of weighted slope instead of mean slope with soil loss relationship in the humid steep hill basin. Journal of the Indian Society of Soil Science 35 : 171 - 173.

Shelton, C. H. and J. I. Sewell. 1969. Parameter screening for watershed analysis. Trans. ASAE 2(4) : 533 - 539.

Singh, M. D. 1985. Rainfall runoff and soil loss relationships on varying degrees of hill slope. Unpublished Masters' thesis, Assam Engineering College, Gauhati.

Singh, A. and Singh, M. D. 1980. Effect of various stage of shifting cultivation on soil erosion from steep slopes. Indian Forester Vol. 106 No. 2 pp. 115 - 121.

Singh, S. and D. C. Das 1979. Runoff and sediment prediction for priority Delineation in soil Conservation Programmes. Indian Journal of Soil Conservation, Vol. 7, No. 2, 1979. pp. 66 - 79 Dehradun.

Singh, S.; C. M. Pandey and D. C. Das 1990. Sedimentation in Small Watersheds. Technical Series No. 4/H & S/1990. Min of Agri. Dept. of Agri. & Co. Opn. New Delhi, 1990.

Singh, S.; S. Subramaniyan and D. C. Das 1978 Analysis of Hydrologic and Sediment Data. A case study of small watershed on the catchment of Damodar, XIV Annual Convention of Indian Society of Agricultural Engineering at I.I.T., Kharagpur, 1978.

✓ Singh, V. P. and V. J. Chen. 1982. On the relationship between sediment yield and runoff volume. In Singh, V. P. (Ed.) Modelling components of hydrologic Cycle. Water Resour. Publications Littleton, Colorado : 555 - 570.

Singh, S.; S. Subramaniyan and D. C. Das 1978. Analysis of Hydrologic and Sediment Data. A case study of small watershed on the catchment of Damodar. XIV Annual Convention of Indian Society of Agricultural Engineering at I.I.T., Kharagpur, 1978.

Singh, V.P. and V. J. Chen. 1982. On the relationship between sediment yield and runoff volume. In Singh, V. P. (Ed.) Modelling components of hydrologic Cycle. Water Resour. Publications Littleton, Colorado : 555 - 570.

Repeat

Repeat

Singh, S. and C. M. Pandey 1986. Status of Hydrologic & sediment Monitoring in C.S.s. for the Catchment Stabilisation. Seminar on Environmental Consideration in Planning of Water Resources Project Univ. of Roorkee April. 1986. Roorkee.

✓ Smith, D. D. 1946. Interpretation of soil conservation data for field used. Unpublished report. USDA. Sc. 9. 1946.

Sonawane, M. G. and Bengal, G. B. 1989. Effect of Irregular slope shapes on runoff and soil loss. Indian Journal of Soil Conservation. 17(3) 6-10.

Starosolszky, O. 1986. Applied Surface Hydrology. Water Resources Publications, Colorado. Ch. 15.

Stendenger, J. R. 1983. Design events with specified flood risk. Water Resour. Res. 19(2) : 511 - 522.

Strahler, A. N. 1952. Hyposometric (area-altitude) analysis of erosional topography. Bull of Geol. Soc. Am. 63 : 1117 - 1143.

Strahler, A. N. 1957. Quantitative analysis of Watershed geomorphology. Trans. Am. Geophys. Union. 38 : 913 - 920.

Strahler, A. N. 1958. Dimensional analysis applied to fluvially eroded landforms. Bull. of Geol. Soc. Am. 69 : 279 - 300.

Subramaniyan, S.; D. C. Das, and Jose, C. Samuel 1982. Hydrologic and sediment Response Variations in Watersheds of River Valley Project catchments. International Sym. On Hydrological Aspects of Mountainous Watersheds. Uni. of Roorkee. Nov. 1982.

Takei, A., *et al.* full 1981 : Erosion and Sediment Transport Measurement in a Watershed Granite Mountain Area, Erosion and Sediment Transport Measurement, Symposium, Florence, IAHS No. 133.

Tixeront, J., 1970 : Taux d' Abrasion et Teneur en Suspension des cours d' Eav d' Algerie et de Tunisie, Etude (in French).

Tung, Yeou-Koung and Larry, W. Mays, 1980. Risk analysis for hydrologic design. Proc. ASCE. Jour. of Hy. Div. Hy (5): 893 - 913.

Tyagi, N. K., B. Raghunath and V. Lakshman. 1970. Study of watershed characteristics affecting the hydrologic performance. Jour. Soil and Water Cons. in India 18(1 & 2).

Varshney, K.G., D. C. Das and B. Raghunath. 1970. Hydrological performance of watersheds in the Nilgiris. 8th Annual Meeting of ISAE held at Ludhiana (India)

Varshney, R. S. 1977. Engineering Hydrology. Roorkee (India) : Nem. Chand and Brothers. Publications.

Vicens, G., I. Rodriguez-Iturbe and J. C. Shaak 1975. A Bayesian framework for the use of regional information in hydrology. Water Resour. Res. 11(3) : 405 - 414.

Wischmeier, W. N. (1959) A rainfall erosion index for universal soil loss equation. Soil Sci. Sac. Amer. Proc. V. 23). 246 - 249.

Wischmeier, W. H. and Smith, D. D. 1965. Predicting rainfall erosion losses from cropland east of the Rocky mountains guide for selection of practices for soil and water conservation. Agricultural Hand Book No. 282. USDA.

✓Wischmeier, W. N. and Smith, D. D. (1978). Predicting rainfall erosion losses A guide to conservation planning Agricultural Hand Book No. 537. USDA.

✓Wong, S. T. 1979. A dimensionally homogeneous and statistically optimal model for predicting mean annual flood. Jour. of Hydrology 42 : 269 - 279.

✓Yen, Ben Chie. 1970. Risks in hydrologic design of engineering projects. Proc. ASCE, Jour. of Hy. Div. HY (4):959-965.

✓Zingg, A. W. (1940) Degree and length of land slope as it affects soil loss in runoff, Agr. Eng. 21. 59 - 64.

① uniformity of pattern is missing

③

APPENDIX

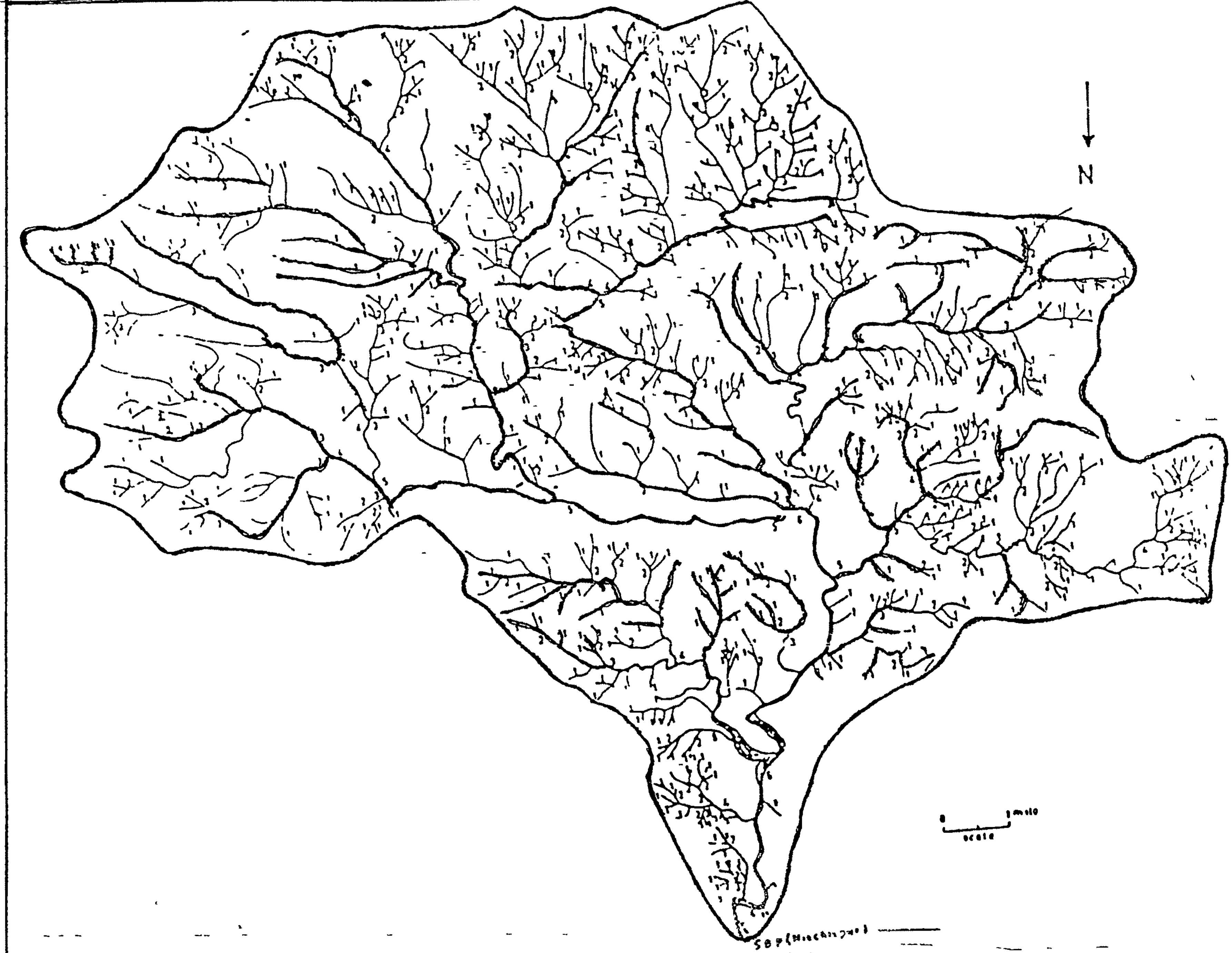

FIG. A_1 DRAINAGE MAP OF BARAKAR CATCHMENT

FIG.A 2 CONTOUR MAP OF BARAKAR CATCHMENT

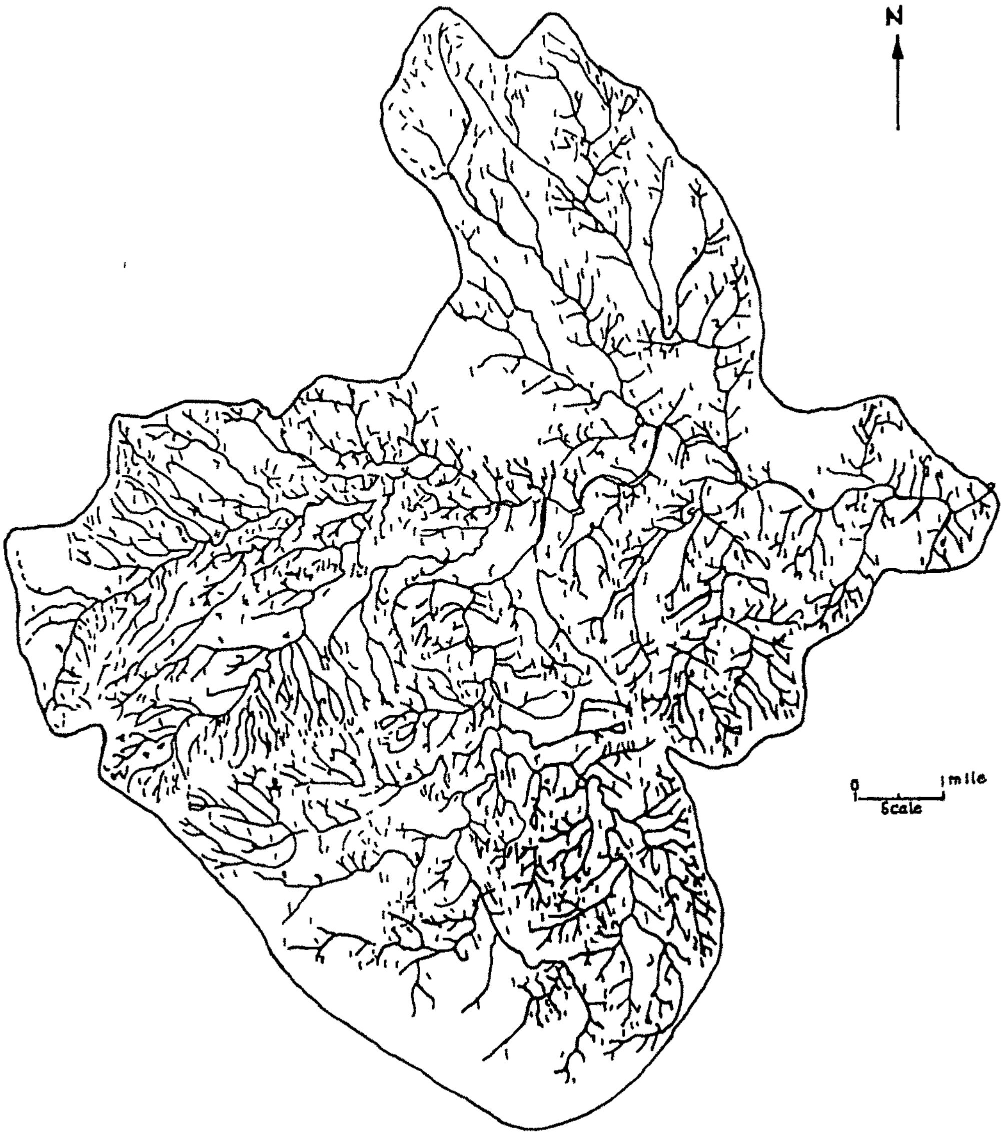

FIG A 3 DRAINAGE MAP OF DEONAD WATERSHED OF DAMODAR CATCHMENT

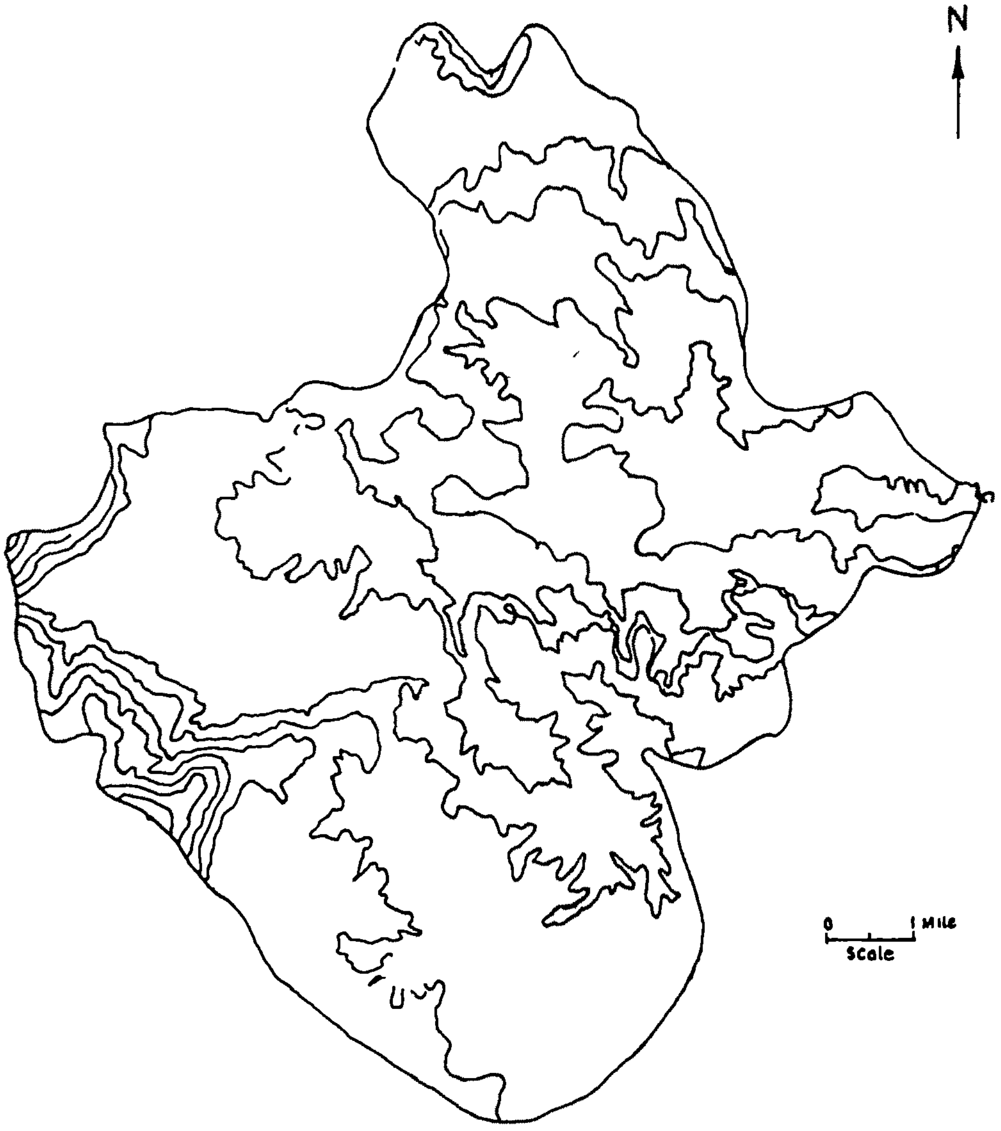

FIG A 4 CONTOUR MAP OF DEONAD WATERSHED OF DAMODAR CATCHMENT

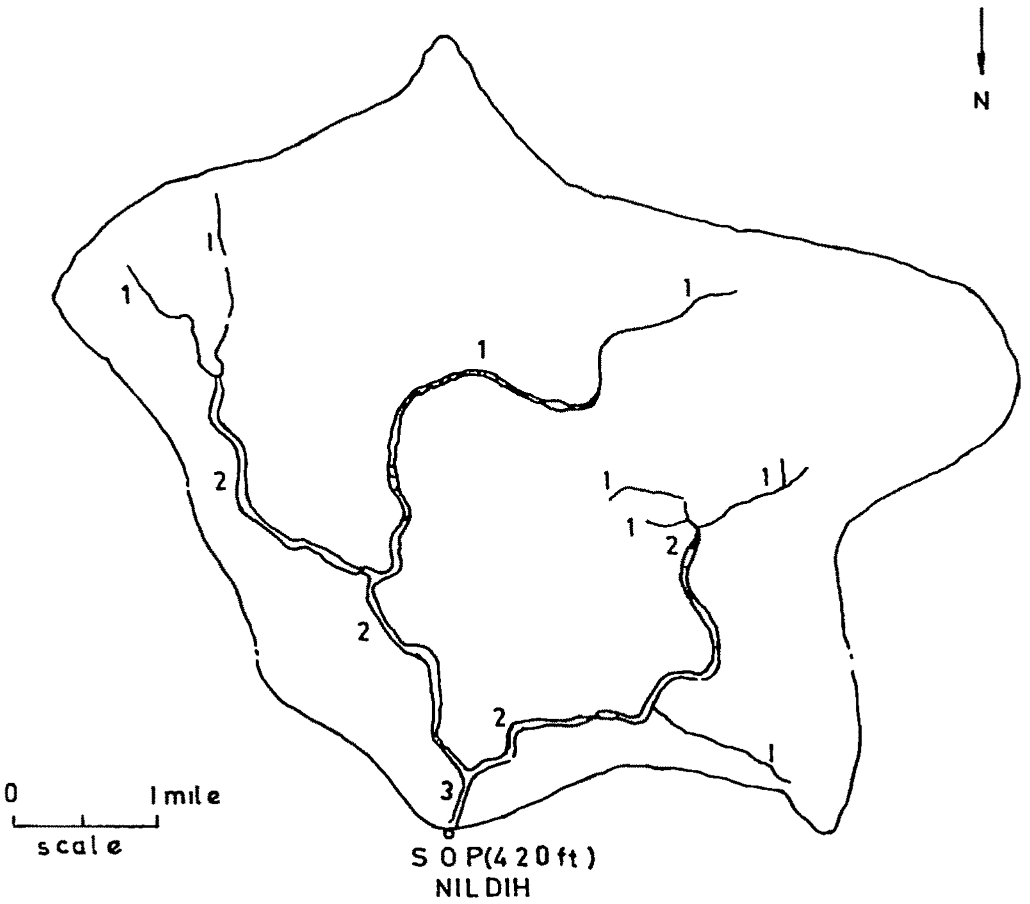

FIG.A 5 DRAINASE MAP OF NILDIH WATERSHED OF DAMODAR CATCHMENT

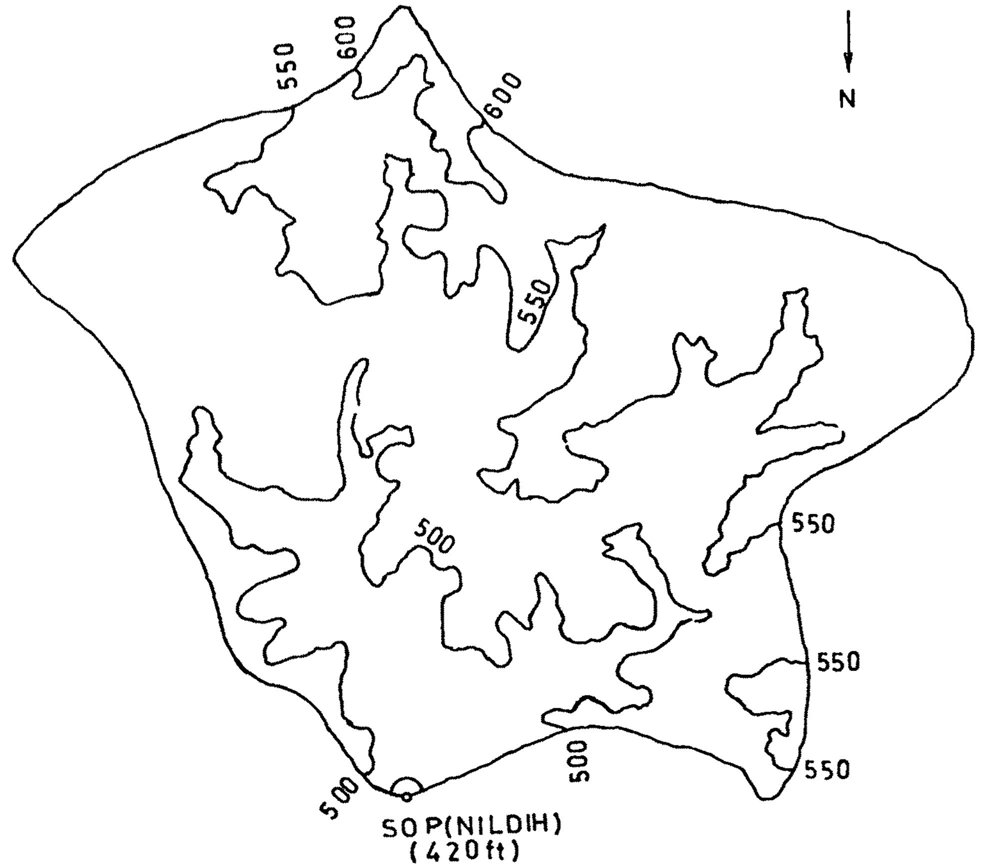

FIG.A. 6 CONTOUR MAP OF NILDIH WATERSHED DAMODAR CATCHMENT

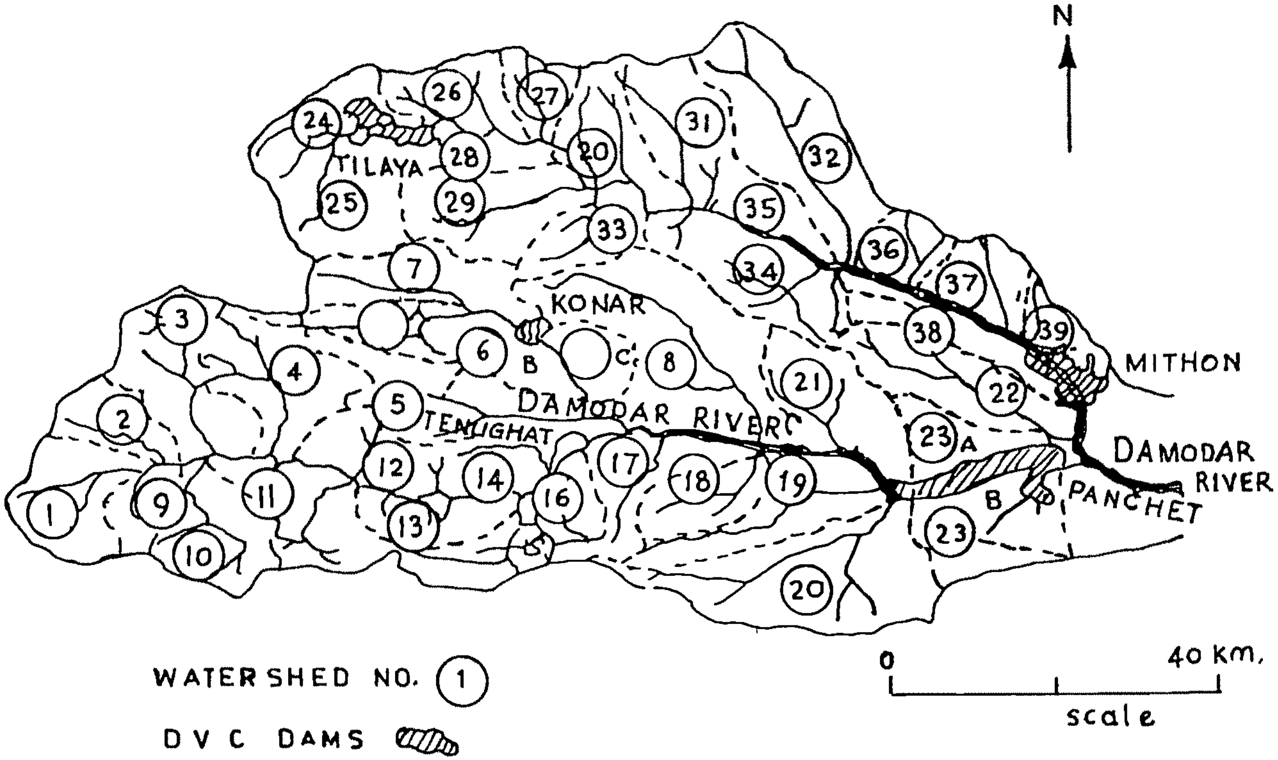

FIG.A.7 PRINCIPAL DRAINAGE SYSTEM OF DAMODAR CATCHMENT