Sediment Transport Predictor in the Ganges River

by

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ABSTRACT

The sediment transport characteristics of the Ganges river have been studied. The peak discharge does not necessarily always coincide with the peak sediment load. There is a phase lag between the peak dischaige and the peak sediment load. The peak sediment load occurs first and then the peak discharge with only exception where the peak sediment load is followed by the peak discharge In some cases, the peak discharge and peak sediment load occur at the same instances The maximum discharge and maximum fine sediment discharge are free from trend but the maximum sand discharge and maximum total sediment discharge show an upward trend beginning from 1992. The percent of fine sediment discharge is about 50 which means that the Ganges river at Hardine bridge gauge station contains a substantial amount of wash loads

The unit stream power formula and modified unit stream power formula have been applied for the estimation and prediction of sediment transports in the Ganges river. The comparison between computed and measured sediment discharge based on Yang's unit stream power formula and modified Yang's formula for high concentration of fine sediments show that Yang's formula over predicts the sediment transport than the modified formula The discrepancy ratio and standard deviation have been used to indicate the accuracy of the sediment transport predictors The modified Yang's formula is better in the sediment laden Ganges river. Comparisons between computed and measured sediment concentrations based on the average logarithm ratio indicate that the goodness of fit of different equations may be affected by selecting statistical parameters

The sediment rating curve of the Ganges river at Hardinge bridge gauge station have been developed by considering discharge, shear stress, stream power and unit stream power as independent variables The discharge and unit stream power when used as independent variables give better curve as compared to shear stress and stream power.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Sediment movement in rivers has been studied by both hydraulic engineers and geologists for centuries because of its importance to the understanding of river hydraulics, river engineering, river morphology and related fields. Sediment transport is complex and often subject to semi-empirical or empirical treatment. Most theoretical treatments are based on some idealized and simplified assumptions that the rate of sediment transport could be determined by one or two dominant factors such as water discharge, average flow velocity, energy slope, and shear stress. Numerous equations have been published. Each equation is supported by limited laboratory data and, occasionally, by field data. The calculated results from various equations often differ drastically from each other and from the measured data. Consequently, none of the published sediment transport equations have gained universal acceptance in confidently predicting sediment transport rates, especially in rivers.

The Ganges is one of the three major rivers in Bangladesh (Figure 1.1). It is a sediment-laden wide meandering river with a bank full width of some 5 km. The river draining the southern slope of the Himalayas has a catchment area of 1,090,000 km^2 and a length of 2,200 km (Delft Hydraulics and DHI, 1996). Sediment transport plays an important role in the regulation and control of rivers. Changes in sediment yield reflect changes in basin conditions including climate, soil erosion rate, vegetation, topography and land use. Fluctuations in sediment load affect many terrestrial and coastal processes including ecosystem responses, because many nutrients and chemicals are also transported along with the sediment load. Information on sediment load is very important for the planning, design and maintenance of any water resources development projects. Knowledge of sediment load carried by a stream is necessary for the solution of most problems associated with rivers (Garde and Ranga Raju, 1985). Ability to accurately estimate sediment transport capacity is a key to the success of water resources projects. A number of relationships have been developed to compute the amount of sediment discharge as a function of the various flow parameters. None of the available equations for the calculation of sediment discharge has gained universal acceptance in confidently predicting sediment transport rate. The calculation of sediment load from various equations often differs drastically from each other for a given set of observed data. This is partly due to inclusion of so many variables that influence sediment transport like the size of sediment, the fall velocity, specific weight, cohesion, porosity of particles etc.

Figure 1.1 Satellite image of the Ganges river in Bangladesh.

The area of the Ganges basin in Bangladesh covers 40,450 km^2 which is approximately 27% of the total area of Bangladesh. This vast area is inhabited by about one fourth of country's population of about 130 million. More than 60% of the area is under cultivation. This deltaic region is unique in many ways. The Sundarban, the single largest mangrove forest in the world, is located in this region spanning an area equal to about 10% of Bangladesh that has extensive biodiversity based economic activities and potential for eco-tourism Sunderban has an outstanding importance of being World Heritage Site and Ramsar Site. The delta has a distinctive landscape feature that it is criss-crossed by a network of rivers and estuaries together with extensive floodplains and wetlands. These water bodies cover 13% of the area. The country is located in the Bengal Basin, which has been gradually filled by sediment washed down from the highlands of the Himalayas. Now the basin has become a low lying very flat delta. The hydro-morphological characteristics of the Ganges river is shown in Table 1.1.

Table 1.1 Hydro-morphological characteristics of the Ganges river.

Parameter	Dimension
Catchment (km^2)	1,090,000
Length (km)	2,200
Length in Bangladesh (km)	275
Mean annual rainfall within the catchment (mm)	1,200
Annual mean discharge (m^3/s) upto 1995	11,163
Avg. maximum discharge (m^3/s) upto1995	49,835
Avg. minimum discharge (m^3/s) upto1995	1,487
Historical Maximum discharge (m^3/s) upto 1995	75,800
Historical Minimum discharge (m^3/s) upto 1995	261
Avg. Maximum water level (m+PWD) upto 1995	14 29
Avg. Minimum water level (m+PWD) upto 1995	6.57
Historical maximum water level (m+PWD) upto 1995	15.05
Historical minimum water level (m+PWD) upto 1995	4.22

Annual sediment transport (million tones/year)	550
Bed material grain size (d_{50} mm)	0.15
Average width (km)	5
Average depth (m)	4.5
Average water level slope (cm/km)	5
Planform	Point-bar meandering

1.2 Background of the Study

The concept that the rate of work done should be related to the rate of energy expenditure was used by Bagnold (1966), among others, to determine the rate of sediment transport under equilibrium conditions. It was demonstrated by Yang (1972) that the rate of sediment transport depends on the unit stream power more than any other hydraulic parameter. The unit stream power is defined as the rate of potential energy expenditure per unit weight of water. A dimensionless unit stream power equation was obtained by Yang (1973) for the computation of total sediment concentration in the sand size range, or the total bed material concentration when wash load is significant. In order to improve the accuracy of the equation for low sediment concentration, criteria for incipient motion were developed (Yang, 1973) and used in the equation. Due to the uncertainties involved in determining the flow conditions precisely at incipient motion, Yang (1979) developed an accurate unit stream power equation for total load, or total bed material load, in the sand size range without using any criteria for incipient motion.

The applicability of Yang's equations to natural rivers in the United States was tested and verified by ASCE task committee (1982) Yang et. al (1996) modified Yang's (1979) stream power formula so that it can be applied to the estimation of sediment transport in a sediment-laden river with a high concentration of fine suspended materials.

In every year large discharge and heavy sediment load in the monsoon cause the river Ganges to be extremely unstable. As the Ganges is a sediment-laden river, it is expected that the formula might be applicable for the estimation of sediment transport in the Ganges In this study, the stream power formulae of Yang (1979) and Yang et al (1996) have been applied for the estimation and prediction of sediment transports in the Ganges river. Because of the high sediment concentration in the Ganges River, it can be presumed that Yang et al (1996) sediment transport equation is more applicable and have been used in this study for the prediction of sediment transport in the Ganges river.

1.3 Objectives

(i) To determine the sediment transport characteristics of the Ganges river.

(ii) To test the applicability of the stream power formulae for the prediction of sediment transport in the Ganges river.

CHAPTER 2

STUDIES OF SEDIMENT TRANSPORT PREDICTORS

2.1 Introduction

Most sediment transport equations were derived under the assumption that sediment transport rate could be determined from a dominant variable In most cases, these equations were supported by limited data collected under carefully designed laboratory conditions Because of the lack of generality of the assumptions used, when such an equation is applied to other flow conditions, the agreement is often poor. The computed results from different sediment transport equations often differ drastically from each other and from measurements. Extensive comparisons of the accuracy of different transport equations have been made by different investigators. A formula that predicts sediment discharge accurately for one river, may predict vary poorly for another river. To ease this difficulty, many of the commonly used transport formula have been tested by different researchers over a wide range of field and laboratory data. The previous studies have been divided into two parts: one part covers application of sediment transport predictors in rivers outside Bangladesh and the other part covers rivers inside Bangladesh.

2.2 Studies of Sediment Transport Predictors outside Bangladesh

In the preparation of the ASCE Manual on Sedimentation Engineering, Vanoni (1971) compared the computed sediment discharges from different equations with the measured results from natural rivers. He studied thirteen formulas and observed that the Colby (1964), Engelund and Hansen (1967) and Tofaletti (1969) formulas gave consistently better agreement than others. Yang (1977) replotted the comparisons of Vanoni (1971) and included Yang (1973) unit stream power formula and found that among fourteen equations, computed results from Yang (1973) unit stream power equation give the best agreement with measurements

White et al. (1975) reviewed sediment transport theories With the exception of Yang's (1973), and Shen and Huang's (1972) equations, most of the available equations at that time were reviewed and compared by them The comparison was based on over 1000 flume experiments and 260 field measurements Comparison made by White et al. (1975) indicate that Ackers and White (1973) equation is the most accurate, followed by Engelund and Hansen's (1972), Rottner's (1959), Einstein's (1950), Bishop, Simons and Richardson's (1965), Toffaleti's (1969), Bagnold's (1966), and Meyer-Peter and Muller's (1948) equations. Yang and Stall (1976) made a similar analysis of 1247 sets of laboratory and river data, and discussed the results of White et al (1975). Because the data used for comparison by Yang and by White et al. are basically the same, the comparison indicate that Yang's (1973) equation can more consistently predict bed-material load in sand size range in laboratory flumes and rivers than Ackers and White's (1973) equations

Alonso (1980) considered over 30 available sediment transport formulas. Selection was based on the following criteria: The selected formula should 1) be framed so that it is easy to apply in computer simulation, 2) give the total load of bed material, knowing the hydraulic and geometric properties of the flow, and 3) provide reliable estimates when applied to channels of any size in which sediment particles are transported by the fluid. The eight formulas Alonso selected for analysis are Ackers and White (1973), Engelund and Hansen (1967), Laursen (1958), Meyer-Peter and Muller (1948) formula for bed load and modified Einstein (1950) formula for suspended load, Yang (1973), Bagnold (1956), Meyer-Peter and Muller (1948) and Yalin (1963). He made the following comments: Yang developed the most reliable equation applicable over the entire range of flow conditions This equation gave predictions that deviated only marginally, with consistently low scatter in all cases. Both the Ackers and White and the Engelund and

Hansen formulas worked reasonably well, without too much scatter. The first formula systematically overestimated the transport rates; however, the second overestimated the field data but under predicted transport in flumes. The Laursen formula worked fairly well in the flume-data range but gave less satisfactory results for the field data. A possible explanation for this behavior may be that the function $f(U_*/\omega)$, where U_* is shear velocity and is ω fall velocity, is not universal as claimed by Laursen, but rather depends on the dimensionless parameters controlling the transport rates

Yang and Molinas (1982) applied basic fluid mechanics and turbulence theories to show that suspended concentration at a given depth of an open channel flow is a function of the turbulence energy production rate at that depth. Comparisons of seven total load equations with 1259 sets of data in the sand-size range indicate that equations proposed by Yang (1979), Engelund and Hansen (1967), and Ackers and White (1973) are more accurate than others under laboratory and field conditions regardless of their sizes. All these equations were derived directly or indirectly from the concept that the rate of sediment transport in an open channel flow should be related to the rate of energy dissipation of the flow. They concluded that agreements between measured and computed results from these equations justify the derivations of a sediment transport equation from power approach.

Based on approaches used in the derivation of the formulas, Vetter (1988) classified sediment transport models into regression and stochastic models, energy models and shear models. Data from seven rivers were used by Vetter to evaluate the accuracies of 19 transport formulas. He found that none of the models can give reliable estimates of wash load, which was considered to have a grain diameter finer than 0.0625 mm. A book describing the procedures for the computation of sediment transport rate for engineering practice using 19 different methods was published by he German Association of Water Resources and Land Improvement (DVWK, 1990). The comparisons made by DVWK and Vetter (1988) indicate that when all data are considered, the regression formula suggested by Karim (1983) and Karim and Kennedy

(1990) has the best estimate overall agreement with measurement. This is partly because of the wide range of data used by Karim and Kennedy in their analyses. If the comparison is limited to sand size range, Yang (1979, 1973) sand formulas and Bagnold (1966) formula provide the best agreement with the measured results. The least reliable formulas are those based on the shear stress approach. These results suggest that although the regression approach alone is not based on the physical process of sediment transport, it can be used to obtain useful formulas if sediment data with proper hydraulic and sediment conditions are used in the regression analyses The physical process-based formulas can give better explanations of the sediment transport process, and can be derived from established theories in fluid mechanics and fluvial hydraulics. However, the coefficients in physical process-based formulas still have to be determine from regression analyses of data, even though the amount of data needed may be much less than those for pure regression formulas.

Nakato (1990) tested eleven sediment transport predictors against data collected from the Sacramento river in California, where the bed grain sizes varies from fine to course sand. He found that the computed values deviate significantly from the measured values except for a very few cases. He commented that the test results clearly demonstrate how difficult a task it is to predict sediment transport in natural rivers

Voogt et al (1991) investigated the predictive capability of the sediment transport formulas of Ackers and White (1973), Engelund and Hansen (1967) and van Rijn (1984). It was found that the Engelund and Hansen and van Rijn formulas predict transport rates with reasonable agreement against the measurements.

Yang and Wan (1991) made a comparison of the over-all accuracy of the prediction formula. They considered different ranges of sediment concentration, Froude number and slope for seven bed-material load formula in their analysis The over-all accuracy of the formula when applied to natural rivers, was in descending order: Yang (1973), Toffaleti (1969), Einstein (1950), Ackers and White (1973), Colby (1964), Laursen (1958), Engelund and Hansen (1967).

Lukanda et al. (1992) studied the applicability of sediment transport theories for the Zaire river. The objective of their study was to identify a suitable sediment transport formula for the analysis of the sediment problems experienced in the inner delta of the Zaire river's maritime reach. The used four formula, namely, Schoklitsch (1943), Shields (1936), Meyer-Peter and Muller (1948) and Bagnold (1966). Bagnold's approach was adopted for application for predicting morphologic changes at local stations.

Van den Berg and van Gelder (1993) studied the prediction of suspended bed material transport in flows over silt and very fine sand for the Yellow river Three equilibrium sand transport formula were tested, namely Ackers and White (1973), Engelund and Hansen (1967) and van Rijn (1984). According to this study, the best results were obtained with the van Rijn formula, except at low flow stages, where better results were produced by the Engelund-Hansen equation The Ackers and White formula seriously over predicted the measured values. Some modifications of the van Rijn formula were proposed for application in flows over fine and silt. In a verification analysis, it was demonstrated that these modifications slightly improve its predicted strength.

2.3 Studies of Sediment Transport Predictors in Bangladesh

Several studies have been carried out in the past on the application of sediment prediction formula in Bangladesh. Bari (1978) studied sediment transport prediction using data from the Ganges river at Hardinge Bridge and from Jamuna at Bahadurabad. He compared five sediment transport formulas, namely, Colby (1957), Engelund-Hansen (1967), Ackers and White (1973) and Inglish and Lacey formula (1967) against the measured data of Bangladesh Water Development Board. He concluded that the Colby (1957) and Engelund and Hansen (1967) formulas may be applicable with appropriate correction factors.

Klaassen and Vermeer (1988) compared the measured sediment transport of the Jamuna river with the Engelund and Hansen (1967) formula and found that the measured sediment transport of the period 1968-1970 can be well represented by the Engelund-Hansen formula multiplied by 2

Khan (1986) studied sediment transport in the river Gorai-Modhumati He selected five equations, namely Yang (1973), Ackers and White (1973), Engelund-Hansen (1967), Hossain (1985) and Mantz (1983) for analyzing the sediment transport in the Gorai-Modhumati river. He found that the Hossain and the Engelund-Hansen equations produced better predictions of sediment transport for that river. The total load as computed by the Engelund-Hansen and Hossain formula were respectively found to be 30.4% and 18.3% higher than the measured suspended load. Galappatti (1993) used the Engelund-Hansen formula for the development of 1-D morphological model for the Jamuna river.

Dey (1995) developed a schematized sediment transport predictor for study of alluvial rivers and applied it to the Jamuna river The basis of the schematization is that the sediment transport is a function predominant function of flow velocity He compared the developed equation with the selected well known sediment transport predictors It was found that the developed equation predicts the sediment transports closer to the field data than those of the selected sediment transport predictors. However, the transport predictors namely Hossain (1985), Engelund and Hansen (1967) and Bagnold (1966) formulas are found to be suitable for the application of the Jamuna river.

Ahmed (1996) studied applicability of sediment transport predictors in the Jamuna river by measured shear velocity He used five sediment transport equations, namely, Meyer-Peter and Muller (1948), Bagnold (1968), Engelund and Hansen (1967), Ackers and White (1973), van Rijn (1984) and Hossain (1985) for assessing the impact of shear stress in predicting the sediment transport in the Jamuna river. He found that the performance of sediment transport equations improves significantly when using measured shear stress. The improvement in the predictive values are found through the use of measured shear velocity as 42, 81, 63, 55 and 74 percent in the case of van Rijn, Bagnold, Engelund and Hansen, Ackers and White and Meyer-Peter and Muller respectively.

FAP 24 (1996) developed a sediment transport equation for both Ganges at Hardinge Bridge and Jamuna at Bahadurabad. The Suggested Dimensionless Sediment Transport Equation for the Jamuna river was derived on the basis of measured data from the jamuna river from 1984-1987. They used an independent data set of Bangladesh Water Development Board from the period 1993-1994 The result indicated that the Suggested Equation slightly over predicts the sediment transport rate. They applied a correction factor of 0.75 to adjust this variation. A comparison of the developed equation and five selected sediment transport prediction formulas show an accuracy in the following descending order are: Suggested equation, Bagnold (1966), Engelund and Hansen (1967), Yang (1973), van Rijn (1984) and Acker and White (1973). They, however, did not compare the performance of the Suggested equation with the measured data of the Ganges at Hardinge due to the inaccuracy of the data.

2.4 Concluding Remarks

There are various assumptions used in the development of transport equations. The assumption that sediment transport rate or concentration should be related to the rate of energy dissipation used in transporting sediment is more generally applicable than the approaches using water discharge, average flow velocity, energy slope, or shear stress as the dominant variable. There are three ways of expressing the rate of energy dissipation in transporting sediments. The stream power concept introduced by Bagnold (1966), and later used by Engelund and Hansen (1967) and Ackers and White (1973) is based on power per unit bed area The unit stream power concept introduced by Yang (1973) is based on power per unit weight of water and Valikanov's (1954) parameter is based on the gravitational theory. The validity and generality of the power concept may be one of the basic reasons why the equations of Engelund and Hansen (1967), Ackers and White (1973) and Yang (1973, 1979) are generally more accurate than others. Another reason is that all the parameters used in these equations are dimensionless, which means that they are not sensitive to the scale difference between laboratory flumes and large rivers. The stream power concept is based on general physics without needing any rigorous derivation from fundamental fluid mechanics On the other hand, the unit stream power concept is not only shown to be more generally applicable based on data confirmation but also can de derived directly from basic theories in fluid mechanics and turbulence. It can be shown that bed-load, suspended-load and total load concentrations are directly related to unit stream power. The generality of assumption used in the development of the unit stream power equations, the dimensionless parameters used in these equations and vast amount of data used in the calibration of the dimensionless parameters may be the basic reasons why, in general, the unit stream power equations are more accurate than others for non-cohesive materials under most laboratory and field observations. As Yang et al (1996) formula has been developed for high concentration of sediment and the fact that the Ganges River contains high sediment concentration, it can be presumed that Yang et al (1996) sediment transport equation is more applicable and have been used in this study for the prediction of sediment transport in the Ganges river.

CHAPTER 3

DERIVATION OF YANG'S UNIT STREAM POWER FUNCTION

3.1 Evaluation of Basic Assumptions

With the exception of probabilistic and regression approaches, most sediment transport equations were derived from the assumption that sediment transport rate or concentration could be determined by a dominant variable such as water discharge, average flow velocity, energy or water surface slope, shear stress, stream power per unit bed area, unit stream power. Yang (1972) used the data collected by Guy et al. (1966) from a laboratory flume to examine the validity of the assumptions. He found that more than one value of total sediment discharge can be obtained for the same value of water discharge, velocity, slope, or shear stress. The validity of the assumption that total sediment discharge of a given particle size could be determined from water discharge, velocity, slope, or shear stress is open to question. Because of the weakness of these assumptions, the generality and applicability of any equation derived from one of these assumptions is also questionable. To overcome this, Yang (1972) introduced the concept of unit stream power

3.2 Concept of Unit Stream Power

Yang (1972) defines the unit stream power as the velocity (V)- slope (S) product as VS. The rate of energy per unit weight of water available for transporting water and sediment in an open channel with reach length x and total drop of Y is

$$\frac{dY}{dt} = \frac{dx}{dt}\frac{dY}{dx} = VS \tag{3.1}$$

Yang argued that the rate of work being done by a unit weight of water in transporting sediment must be related to the rate of work available to a unit weight of water. Thus, the total sediment concentration or total bed-material load must be directly related to unit stream power Yang emphasized the power available per unit weight of fluid to transport sediments.

3.3 Theoretical Analysis

To determine total sediment concentration, Yang (1973) considered a relation between the relevant variables of the form

$$\phi(C_t, VS, U_*, \nu, \omega, d) = 0 \tag{3.2}$$

where

C_t = total sediment concentration, with wash load excluded (in ppm by weight)

VS = unit stream power

U_* = shear velocity

ν = kinematic viscosity

ω = fall velocity of sediment

d = median particle diameter

Using Buckingham's π theorem, C_t in Eq. (3.2) can be expressed in the following dimensionless form.

$$C_t = \phi'\left(\frac{VS}{\omega}, \frac{U_*}{\omega}, \frac{\omega d}{\nu}\right) \tag{3.3}$$

Because a critical unit stream power $V_{cr}S$ is required at incipient motion, Eq. (3.3) is modified to

$$C_t = \phi''\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}, \frac{U_*}{\omega}, \frac{\omega d}{\nu}\right) \quad (3.4)$$

From the analysis of laboratory flume data, Yang (1973) found the best form of Eq. (3.4) to be

$$\log C_t = I + J\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \quad (3.5)$$

I and J in Eq. (3 5) are dimensionless parameters reflecting the flow and sediment characteristics. Based on Eq (3 5) and analysis of flume data,

$$I = a_1 + a_2\log\frac{\omega d}{\nu} + a_3\log\frac{U_*}{\omega} \quad (3.6)$$

$$J = b_1 + b_2\log\frac{\omega d}{\nu} + b_3\log\frac{U_*}{\omega} \quad (3.7)$$

where a_1, a_2, a_3, b_1, b_2, b_3 = coefficients.

The coefficients in Eq. (3.6) and (3.7) were determined by considering log C_t as the dependent variable, and log ($\omega d/\nu$), log (U_*/ω), log (VS/ω - $V_{cr}S/\omega$), log ($\omega d/\nu$) log (VS/ω - $V_{cr}S/\omega$), and log (U_*/ω) log (VS/ω - $V_{cr}S/\omega$) as independent variables, and running a multiple regression analysis for 463 sets of laboratory data The equation thus obtained is

$$\log C_t = 5.435 - 0.286\log\frac{\omega d}{\nu} - 0.457\log\frac{U_*}{\omega}$$
$$+\left(1.799 - 0.409\log\frac{\omega d}{\nu} - 0.314\log\frac{U_*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \quad (3.8)$$

The critical dimensionless unit stream power $V_{cr}S/\omega$ is the product of the dimensionless critical velocity V_{cr}/ω and the energy slope S. The dimensionless critical velocity at incipient motion can be computed by

$$\frac{V_{cr}}{\omega} = \begin{cases} \dfrac{2.5}{\log(U_*d/\nu) - 0.06} + 0.66 & for\ 1.2 < \dfrac{U_*d}{\nu} < 70 \\ 2.05 & for\ 70 \le \dfrac{U_*d}{\nu} \end{cases} \quad (3.9)$$

When the sediment concentration is low, it is necessary to include criteria describing the flow condition at incipient motion. As the rate of sediment transport increases, the need to include incipient motion criteria in a sediment transport equation decreases. For sediment concentrations higher than about 100 ppm by weight, Yang (1979) introduced the following unit stream power equation:

$$\log C_t = 5.165 - 0.153\log\frac{\omega d}{\nu} - 0.297\log\frac{U_*}{\omega}$$
$$+\left(1.780 - 0.360\log\frac{\omega d}{\nu} - 0.480\log\frac{U_*}{\omega}\right)\log\left(\frac{VS}{\omega}\right) \quad (3.10)$$

The basic form of Eq. (3.8) and (3.10) can be theoretically derived from turbulence theories (Yang and Molinas, 1982) and dimensional analyses (Yang, 1973). The coefficients in (3.8) and (3.10) were determined from laboratory flume data in the United States. The applicability of these two equations to natural rivers in the United States and Europe has been independently tested and verified by the ASCE Task

Committee (1982), the German Association for Water Resources and Land Improvement (1990), the U.S. Department of Agriculture National Sedimentation Laboratory (Alonso, 1980), and University of the German Federal Army (Vetter, 1989), among others. Yang (1996) modified Eq. (3.10) for computing sediment transport in the Yellow River. The modification is described below.

3.4 Non-equilibrium High Concentration Sediment Transport

Most of the sediment transport functions or equations are intended for the estimation of sediment transport rate or concentration at an equilibrium condition with no scour nor deposition, at least from a statistical point of view. It is assumed that the amount of wash load depends on the supply from upstream and is not a function of the hydraulic conditions at a given station. It is also assumed that the amount of wash load is not high enough to significantly affect the fall velocity of sediment particles, flow viscosity, or the relative density of sediment and fluid in a river in comparison with these values in clear water. When the wash load or concentration of fine material is high (e.g. Yellow river in China, Ganges river in Bangladesh), non-equilibrium bed-material sediment transport may occur, and its amount is a function of wash load (Yang, 1996). So sediment transport function should not be applied directly without taking the effects of wash load into consideration. Eq. (3.10) was developed for sediment transport in fairly clear water without too much wash load. Before (3.10) can be applied to a river with high concentration of fine sediments, it is necessary to change the values of fall velocity, kinematic viscosity, and relative specific weight to reflect the situation of sediment transport in flows with high concentrations of suspended load (including wash load).

3.4.1 Modification of Fall Velocity

An increase of suspended sediment concentration will reduce a sediment particle's fall velocity in a sediment-laden flow. Richardson and Zaki (1954) proposed the following relationship:

$$\frac{\omega_m}{\omega} = (1 - C_v)^k \tag{3.11}$$

where,

ω, ω_m = sediment particle fall velocity in clear water and sediment–laden flow, respectively,

C_v = suspended sediment concentration by volume, including wash load, and

k = a parameter

The value of **k** varies with the sediment particle Reynolds number. Wang (1984) conducted experiments on sediment fall velocity in a sediment-laden flow with a median particle diameter of 0.15 mm. The experiment suggested a value of 7 for the Yellow river. The value of k for the Ganges river would be calibrated while computing sediment load

3.4.2 Modification of Viscosity

The viscosity of water is a function of water temperature. In addition to water temperature, the viscosity of a sediment-laden flow is also a function of the suspended sediment concentration, size distribution of suspended sediment particles, percent of fine suspended sediment concentration, particle surface roughness, cohesiveness of sediment particles, etc The equation derived by Einstein and Chien (1955) for flows with non cohesive uniform spherical sediments is

$$\mu_r = \frac{\mu_m}{\mu} = 1 + 2.5C_v \tag{3.12}$$

where,

μ, μ_m = dynamic viscosity of water and sediment-laden flow, respectively;

μ_r = relative dynamic viscosity; and

C_v = sediment concentration by volume, including wash load

The experimental relationship obtained by Zhang et al (1980) for hyper concentration flows in the Wei River and Lo River in China is

$$\mu_r = \frac{0.63\gamma_s C_v + 1}{\left(1 - 1.11\gamma_s C_v \beta^{0.362}\right)^{1.4}} \tag{3.13}$$

where,

γ_s = specific weight of sediment=2.65 g/cm^3; and

β = percentage of sediment with particle diameter smaller than 0.025 mm.

It is apparent that the μ_r value is sensitive to the percentage of suspended fine materials in a sediment-laden flow. Qian et al (1980) obtained the following exponential relationship using field data from Yellow river

$$\mu_r = e^{5.06 C_v} \tag{3.14}$$

The kinematic viscosity of the sediment-laden Yellow river becomes

$$\nu_m = \frac{\rho}{\rho_m} e^{5.06 C_v} \tag{3.15}$$

where, ρ, ρ_m = specific density of water and sediment-laden flow. The coefficient of C_v in the above equation would be calibrated for the Ganges river The value of ρ_m can be expressed as

$$\rho_m = \rho + (\rho_s - \rho)C_v \tag{3.16}$$

Eqs. (3.15) and (3.16) are used to reflect the influence of suspended sediment including wash load, on the viscosity of the sediment-laden flow.

3.4.3 Modification of Specific Weight

Yang's unit stream formulas were originally derived for sediment transport in clear water. When the unit stream power is applied to the transport of solid in other types of fluid, it should be modified to reflect the relative specific weight between solid and fluid According to Bagnold (1996), the power required to maintain sediment particles in suspension should be balanced by the power generated by the turbulent flow supporting the suspended particles, i.e

$$W_s \omega_m = \tau V (1 - e_b) e_s \tag{3.17}$$

where,

W_s = submerged weight of suspended materials;

ω_m = particle fall velocity in a sediment-laden flow,

τ = shear stress per unit bed area = γ_m DS,

γ_m = specific weight of sediment-laden flow,

D = flow depth,

V = average flow velocity; and

e_b, e_s = efficiency coefficients for bed load and suspended load transport, respectively.

The suspended material transport rate per unit channel width is

$$g_s = W_s u_s \tag{3.18}$$

where,

g_s = transport rate in submerged weight per unit bed area; and

u_s = average velocity of suspended sediments. From Eqs. (3.17) and (3.18), it can be shown that

$$g_s = \gamma_m DVS \frac{u_s}{\omega_m} e_s (1 - e_b) \tag{3.19}$$

If sediments are transported in a sediment-laden flow with high concentrations of fine materials, Eq. (3.19) can be rewritten as

$$C_v = (1 - e_b) \frac{\gamma_m}{\gamma_s - \gamma_m} \frac{VS}{\omega_m} \tag{3.20}$$

where,

γ_s, γ_m = specific weight of sediment and sediment-laden flow, respectively.

It can be seen from Eq. (3.20) that when the unit stream power concept is applied to estimate sediment transport in sediment-laden flows, a modified dimensionless unit stream power $[\gamma_s/(\gamma-\gamma_m)]VS/\omega_m$ should be used. The modified unit stream power formula for sediment-laden flows becomes

$$\log C_t = 5.165 - 0.153 \log \frac{\omega_m d}{\nu_m} - 0.297 \log \frac{U_*}{\omega_m} + \left(1.780 - 0.360 \log \frac{\omega_m d}{\nu_m} - 0.480 \log \frac{U_*}{\omega_m}\right) \log\left(\frac{\gamma_m}{\gamma_s - \gamma_m} \frac{VS}{\omega_m}\right) \tag{3.21}$$

The coefficients in Eq. (3.21) are identical to those in (3.10). However, the values of fall velocity, kinematic viscosity, and relative specific weight are modified for sediment transport in sediment-laden flows with high concentrations of fine suspended materials.

CHAPTER 4

DATA COLLECTION, ANALYSIS AND DISCUSSION

4.1 Sources of Data

Discharge, sediment loads of the Ganges river at Hardinge bridge gauge station (Figure 4.1) have been collected from the Directorate of Surface Water Hydrology of Bangladesh Water Development Board (BWDB). The sediment data of the Ganges river at Hardinge bridge which have been available since 1966 contains only suspended sand discharge. This means that the sample was not separated in the wash load (also called fine fraction) and suspended bed material load (also called sand fraction). The wash load consists of the silt and the clay fraction. The sand fraction consists of the sediment particles larger than 0.063 mm. The sediment load comprises of only suspended load as BWDB does not measure any bed load on regular basis. The sediment data used for this study are of 1983 - 1988, 1992 -1994. These data are separated in the wash load and the suspended bed material load. The data on width, average flow depth, cross-sectional velocity have also been collected from Directorate of Surface Water Hydrology of Bangladesh Water Development Board (BWDB). The data ou longitudinal bed slope and water temperature are missiug. The longitudinal slope has been obtained from the literature as 5.5×10^{-5} (FAP 24, 1996).

4.2 Measurement of Sediment

The sediment samples are collected at the same time when the discharge measurements are performed. A Binckley Silt Sampler is used to collect a one litre sample of the river water. The samples are taken in a number of verticals in a gauging transect and from several points in each vertical The sand and silt fractions of a sample are separated in a conical elutriator. The sand fraction are collected in a tube attached to the elutriator after 100 s. The weight of the sand fraction of a sample is determined by the weight of that tube, full of water with and without the sediment sample.

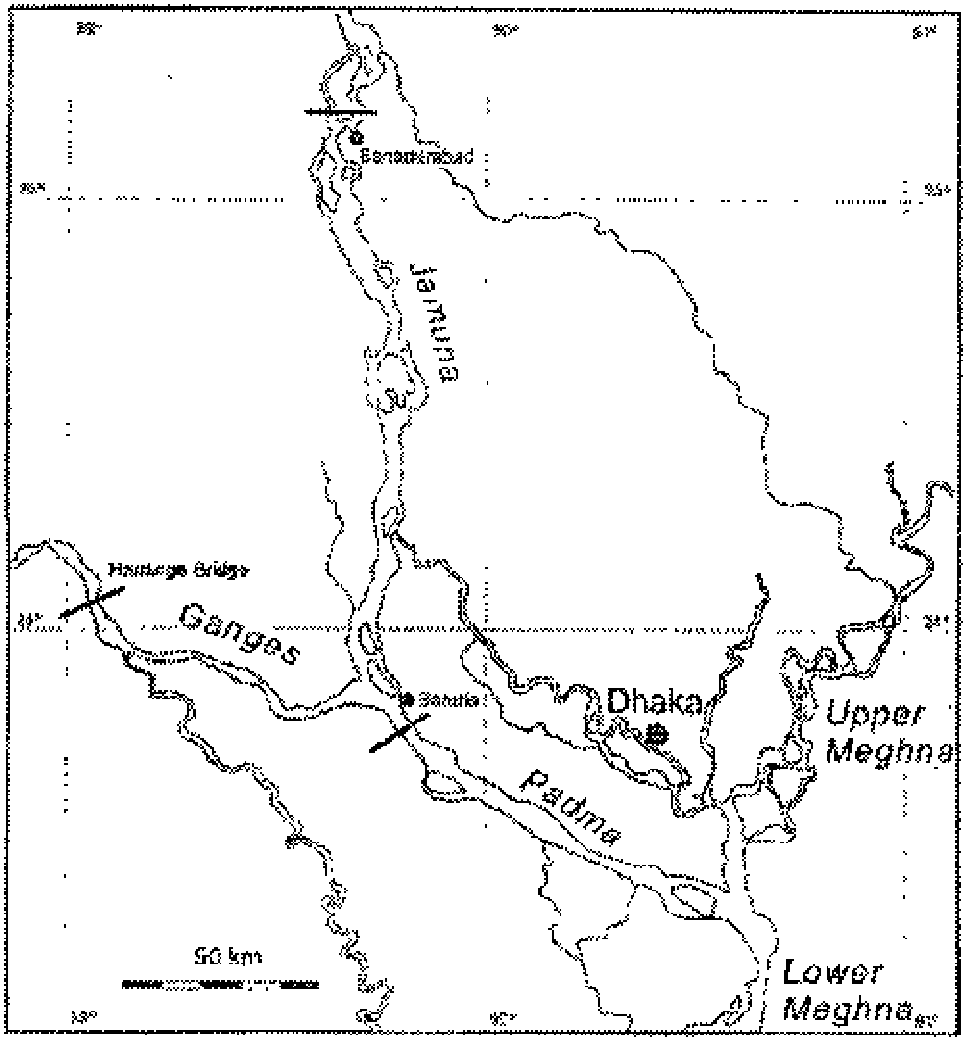

Figure 4.1 Location of the Gauging Station of the Ganges at Hardinge Bridge.

4.3 Sediment Transport Characteristics

The yearly variations of discharge, suspended sand discharge, suspended fine discharge and total suspended discharge are shown in Appendix A. The peak discharge does not necessarily always coincide with the peak sediment load. There is a phase lag between the peak discharge and the peak sediment load. The peak sediment load occurs first and then the peak discharge (Figure A1, A4, A7) with only exception as can be seen in Figure A8 where the peak sediment load is followed by the peak discharge. In some cases, the peak discharge and peak sediment load occur at the same instances (Figure A2, A3, A5, A6, A9). Figure 4.2 shows the yearly variation of annual maximum discharge, suspended sand discharge, suspended fine discharge and total suspended discharge. The maximum discharge and maximum sand discharge appears to be free of trend but the maximum fine discharge and maximum total sediment discharge show an upward trend beginning from 1992. But without the data of the subsequent years it is not possible to conclude whether the trend really exists. Figure 4.3 shows the yearly variation of the percent of fine suspended discharge with respect to the total suspended discharge. On an average, the percent of fine sediment discharge with respect to total sediment discharge is about 50 which means that the Ganges river at Hardine bridge gauge station contains a substantial amount of wash loads. So the modified Yang's equation can be applied to compute sediment transport in the Ganges river.

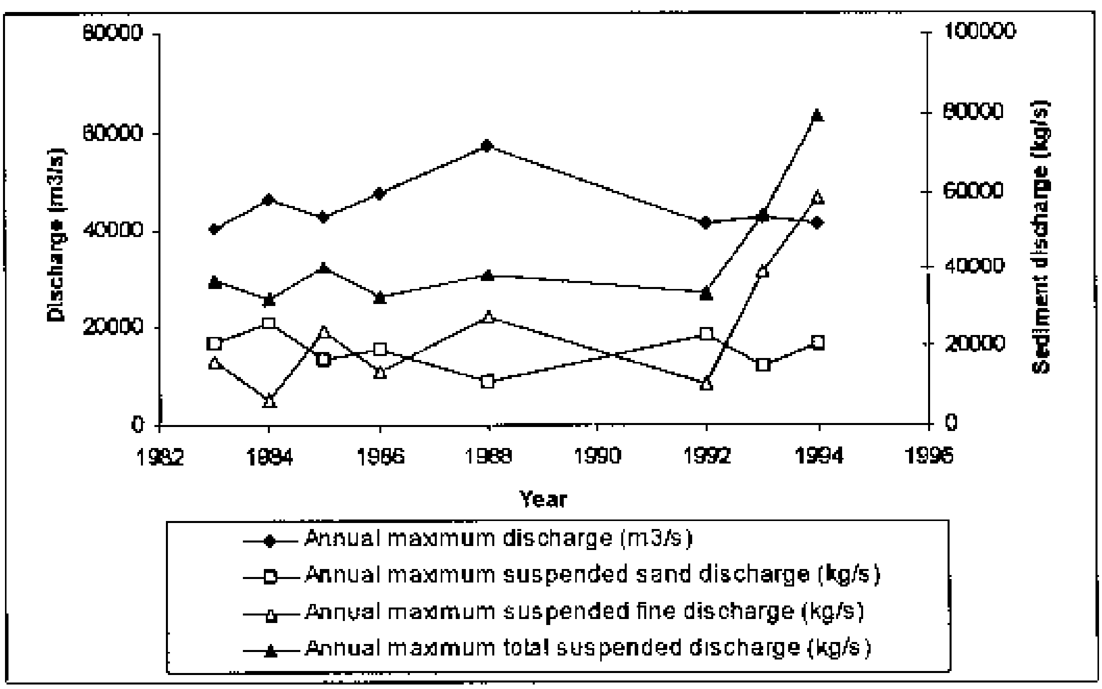

Figure 4.2 Yearly variation of annual maximum discharge, suspended sand discharge, suspended fine discharge and total suspended discharge.

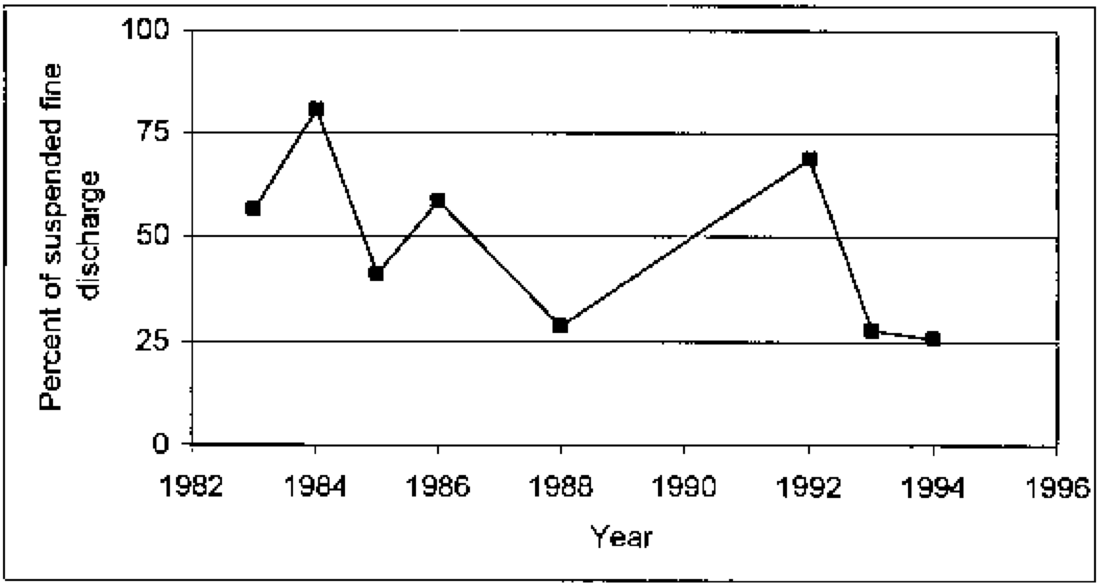

Figure 4.3 Yearly variation of percent of suspended fine discharge of total suspended discharge.

5.4 Computation of Sediment Transport

Based on measured data, sediment transports have been computed using Yang's (1979) formula and modified Yang's formula (Yang et al, 1996). Figures 4.4 and 4.5 show the comparison between computed and measured sediment discharge based on Yang's unit stream power formula and modified Yang's formula for high concentration of fine sediments. In case of Yang (1979) formula, most of the points lie above the 45^0- line which implies that the formula over predicts the sediment transport. But in case of the modified formula, the points are more or less distributed along the 45^0 - line. In both the figures there are scattering of the points. Computed values from are the theoretical values under equilibrium conditions. The Ganges river is constantly undergoing the process of scour and deposition Consequently, measured sediment transport at a given time can be higher or lower that the computed values Part of the scattering shown in Figures 4.4 and 4.5 reflect this phenomenon. Another reason for the scattering is the unavoidable errors of field measurements.

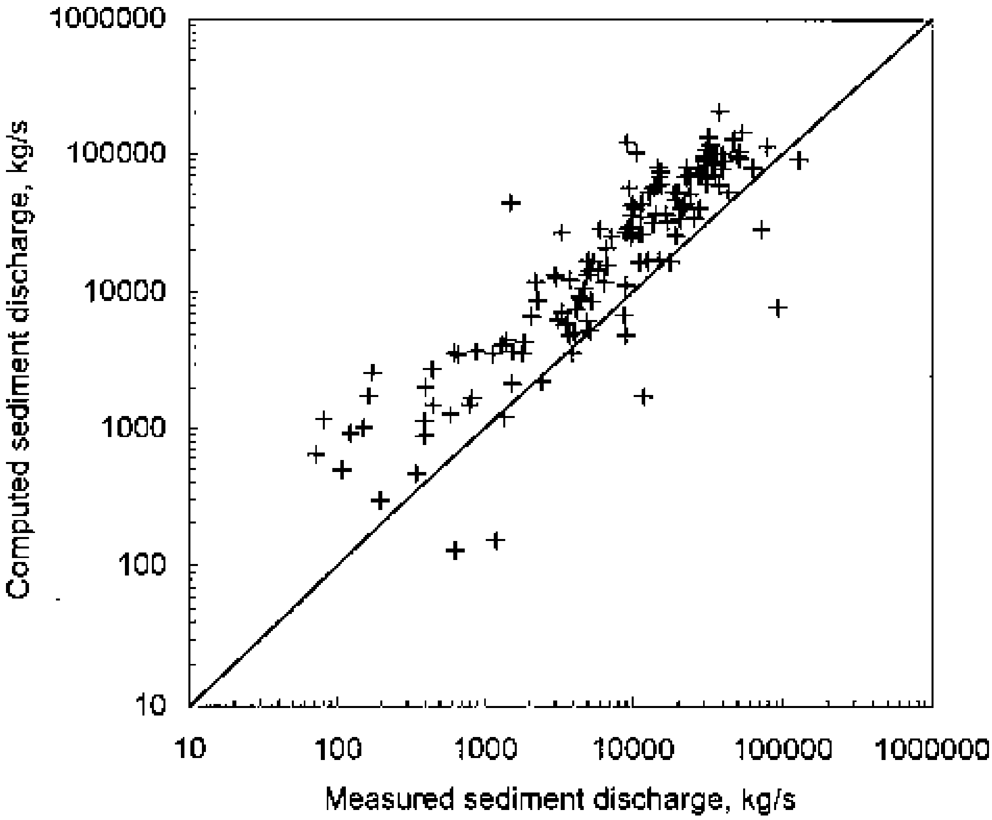

Figure 4.4 Comparison between computed and measured sediment discharge based on Yang's (1979) unit stream power formula.

Due to the uncertainty of the accuracy of measurements and the fact that flow and sediment conditions in the Ganges river cannot be maintained at true equilibrium, the scattering in Figures 4.4 and 4.5 should not be a surprise. Another fact is the location of the gauging station of the Ganges at Hardinge Bridge which is artificially narrowed down FAP 24 (1996) observed that the present gauging station should be free from artificially narrowed channels, and should be away from an upstream confluence. At Hardinge bridge point, the contraction scour of the river bed induces a yearly variation in the sediment transport which is not representative for the whole reach of the Ganges river. The sediment data collected from this constriction will not lead to good estimates of the overall sediment budget. Also, upstream of Hardinge Bridge, there is a bend, which again implies that this station is not well suited for sediment gauging.

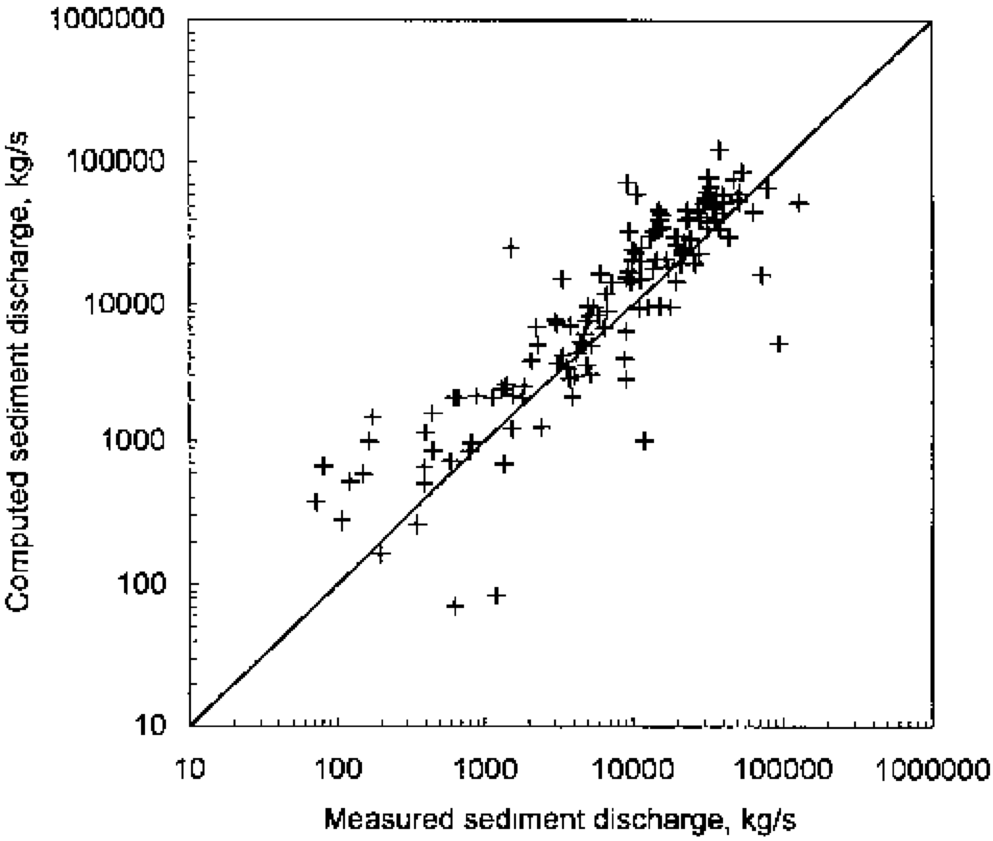

Figure 4.5 Comparison between computed and measured sediment discharge based on Yang et al (1996) unit stream power formula.

4.5 Performance Evaluation of the Sediment Transport Predictors

The discrepancy ratio and standard deviation are used to indicate the accuracy of the sediment transport predictors. The discrepancy ratio indicate the goodness of fit between the computed and measured results. The discrepancy ratio can be expressed as

$$R_t = \frac{\psi_c}{\psi_m} \tag{4.1}$$

where,

ψ_c = computed sediment concentration

ψ_m = measured sediment concentration

The mean value R and standard deviation σ of the discrepancy ratio are

$$\overline{R} = \frac{\sum_{i=1}^{j} R_i}{j} \tag{4.2}$$

and

$$\sigma = \sqrt{\frac{\sum_{i=1}^{j} \left(R_i - \overline{R}\right)^2}{j}} \tag{4.3}$$

Figure 4.4 shows the comparison between measured and computed sediment transports based on Yang's 1979) with $\overline{R}$ = 3.210 and σ = 3.216. Figure 4.5 shows a similar comparison based on Yang et al (1996) with $\overline{R}$ = 1.866 and σ = 1 869 The change of mean discrepancy ratio from 3.210 to 1.866 indicates that Yang et al (1996) unit stream power formula is better in the sediment laden Ganges river.

Table 4.1 Summary of comparisons between computed and measured sediment concentrations.

Formula	Mean, $\overline{R}$	Standard deviation, σ
Yang's formula (1979)	3 210	3 216
Modified Yang's formula (1996)	1.866	1 869

Another way to measure the goodness of fit is the use of average discrepancy ratio and standard deviation based on the average value of the logarithm ratio between computed and measured results using the following parameters.

$$D_i = \log\left(\frac{\psi_c}{\psi_m}\right) = \log\psi_c - \log\psi_m \tag{4.4}$$

$$\overline{D}_a = \frac{\sum_{i=1}^{j} D_i}{j} \tag{4.5}$$

$$\sigma_a = \sqrt{\frac{\sum_{i=1}^{j}\left(D_i - \overline{D}_a\right)^2}{j-1}} \tag{4.6}$$

For a perfect fit, $\overline{D}_a = 0$ and $\sigma_a = 0$.

Comparisons between computed and measured sediment concentrations based on the average logarithm ratio are summarized in Table 4.1. Yang et al (1996) is more accurate based on $\overline{D}_a$ but less accurate based on σ_a when compared with Yang's (1979) Results in Table 4.1 and 4.2 indicate that the goodness of fit of different equations may be affected by selecting statistical parameters. The above tests for goodness of fit suggest that the modified unit stream power formula can be used as sediment transport predictor for the Ganges river. The Yang et. al (1996) sediment transport function can be used in modeling sediment load in the Ganges river

If the sediment load computed by the Yang's (1979) formula is adjusted with a multiplying factor of 2, then it can be seen that the match between computed and measured sediment loads fits pretty well. So the Yang's (1979) can also be used in stead of Yang et al (1996) after adjusting the computed sediment load by an appropriate multiplying factor.

Table 4.2 Summary of comparisons between computed and measured sediment concentrations.

Formula	$\overline{D}_a$	σ_a
Yang's formula (1979)	0.350	0.351
Modified Yang's formula (1996)	0.142	0.377

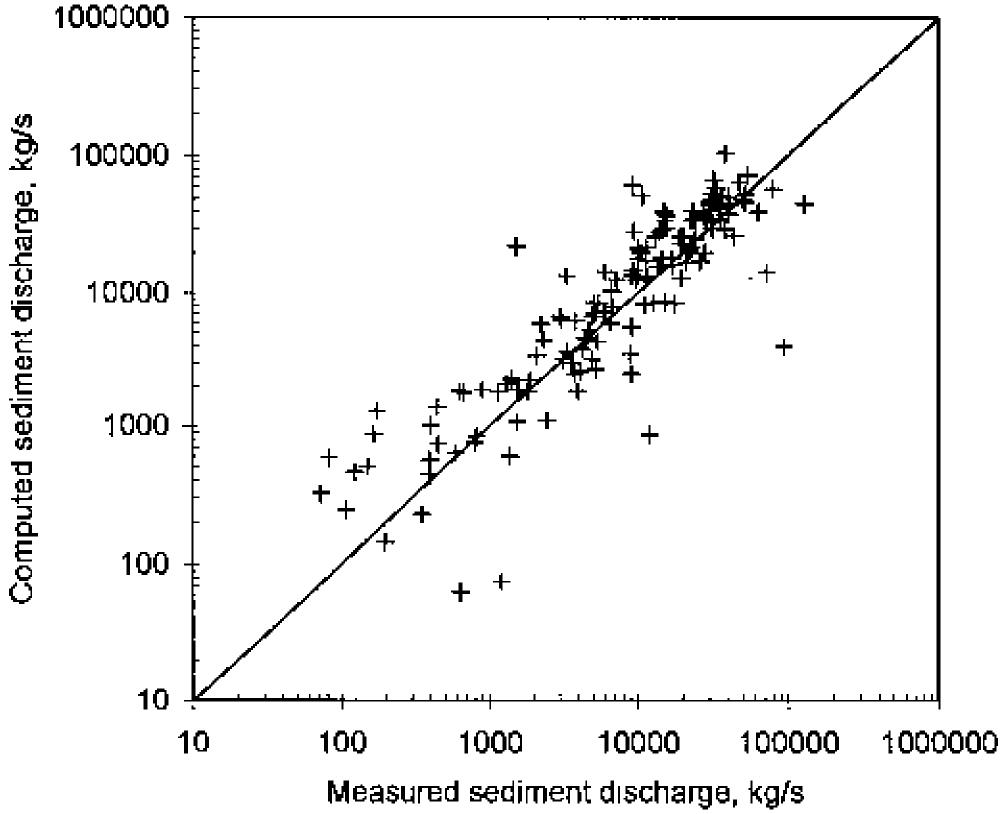

Figure 4.6 Comparison between computed and measured sediment discharge based on Yang et al (1979) unit stream power formula after adjusting the computed sediment load with a multiplying factor of 2.

4.6 Sediment Rating Curve

The relationship between the discharge and the sediment transport, which is calculated from the samples taken in a transit, can be expressed by an average curve. This curve, generally referred to as a sediment rating curve, is often an exponential function, which can be determined either by a regression analysis or from a graph with the data points (discharge, sediment transport). These curves are widely used to estimate the sediment concentration or the sediment transport for periods where discharge data are available, but sediment data are not. The reliability of the sediment transport calculated from a rating curve depends upon the quantity and reliability of data used to define that rating curve, and whether the data are representative for the discharge and sediment transports occurring during the period for which sediment transports have to be estimated. Furthermore, a sediment rating curve between sediment discharge, S_T and water discharge, Q assumes a unique relationship between the average flow velocity in a cross-section and the shear stress at river bed. This unique relationship is requires more or less prismatic cross-sections with only one channel in a cross-section of the river. However, in an accelerating flow, deviations can be expected relative to a sediment transport rating curve

Yang (1996) evaluated the assumptions used in the development of most sediment transport equations. He noticed that, with the exception of probabilistic and regression approaches, most sediment transport equations were derived from the assumption that sediment transport rate or concentration could be determined by a dominant variable. The dominant variables are water discharge, average flow velocity, energy or water surface slope, shear stress, stream power per unit bed area, unit stream power. When none of the existing sediment transport formulas can give satisfactory results, sediment rating curve can be developed for the prediction of sediment discharge. Conventional sediment rating curve establishes relationship between sediment load, S_T as dependent variable and discharge, Q as independent variable (FAP 24, 1996a; Hossain, 1992; CBJET, 1991). But according to Yang (1996), the basis of establishing sediment rating curve should be as follows. The existing data on sediment load or concentration collected from a river station should be plotted against water discharge, shear stress, stream power and unit stream power. The least scattered curve without systematic deviation from a one-to-one correlation between dependent and independent variables should be selected as the sediment rating curve for the station Thus the sediment rating curve would be one of the following four equations

$$S_T = AQ^B \tag{4.7}$$

$$S_T = A\,\tau^B \tag{4.8}$$

$$S_T = A(\tau V)^B \tag{4.9}$$

$$S_T = A(VS)^B \tag{4 10}$$

where A is the coefficient and B is the exponent of the sediment rating curves.

In this study, the data of sediment load has been plotted against discharge, shear stress, stream power and unit stream power to find the least scattered curve. The curve having the highest coefficient of determination is taken as the sediment rating curve.

Appendix B shows the plots of sediment discharge against water discharge, shear stress, stream power and unit stream power. Tables 4.3, 4.4, 4.5 and 4.6 show the equations and the coefficients of determination of the sediment rating curves for different years with discharge, shear stress, stream power and unit stream power as independent variables respectively. The coefficients and exponents of the sediment rating curves vary with year to year to a large extent. This suggests that the sediment rating curve should be updated for each year This is because the Ganges river is very unstable and undergoes process of erosion and deposition. The discharge and unit stream power when used as independent variables give better curve as compared to shear stress and stream power. In some years, sediment discharge shows better correlation with discharge (Figure B2, B4, B7, B8, and B9). In other years, the sediment discharge shows better correlation with unit stream power (Figure B1, B3, B5 and B6). This suggests that the yearly rating curve should be developed by taking discharge and unit stream power as independent variables The curve showing better correlation should be taken as the rating curve for that particular year. The Figures 4.6, 4 7, 4 8 and 4.9 show the variation sediment discharge with discharge, shear stress, stream power and unit stream power by taking into consideration of all the years. As can be seen the correlation between sediment discharge and unit stream power is better than discharge or shear stress or stream power

Table 4.3 Sediment rating curve of the Ganges: discharge as independent variable.

Year	Sediment rating curve	r^2
1983	$S_T = 1E\text{-}06Q^{2.3231}$	0 9025
1984	$S_T = 1E\text{-}06Q^{2.3017}$	0.8983
1985	$S_T = 0.0328Q^{1.2853}$	0.7502
1986	$S_T = 0.0004Q^{1.6741}$	0.7143
1987	$S_T = 0.3396Q^{0.9951}$	0.7477
1988	$S_T = 3.9238Q^{0.7805}$	0.4096
1992	$S_T = 4E\text{-}05Q^{2.0174}$	0.8862
1993	$S_T = 0.0026Q^{1.5639}$	0.9330
1994	$S_T = 5E\text{-}06Q^{2.2254}$	0.9608

Table 4.4 Sediment rating curve of the Ganges for shear stress as independent variable.

Year	Sediment rating curve	r^2
1983	$S_T = 0.0002\tau^{6.6715}$	0.5889
1984	$S_T = 8E\text{-}08\tau^{9.7236}$	0.8694
1985	$S_T = 0.8838\tau^{3.5607}$	0.6451
1986	$S_T = 0.0114\tau^{4.9452}$	0.7074
1987	$S_T = 0.3457\tau^{3.6945}$	0.6633
1988	$S_T = 3.9675\tau^{2.8758}$	0.1925
1992	$S_T = 9E\text{-}09\tau^{11.106}$	0.5712
1993	$S_T = 0.0005\tau^{5.9885}$	0.6369
1994	$S_T = 11.065\tau^{2.5405}$	0.9161

Table 4.5 Sediment rating curve of the Ganges for stream power as independent variable.

Year	Sediment rating curve	Coefficient of determination
1983	$S_T = 11.459(\tau V)^{2.3765}$	0.9056
1984	$S_T = 10.316(\tau V)^{2.3324}$	0.8991
1985	$S_T = 252.58(\tau V)^{1.3041}$	0.7514
1986	$S_T = 51.241(\tau V)^{1.6983}$	0.7141
1987	$S_T = 328.92(\tau V)^{1.0294}$	0.758
1988	$S_T = 765.07(\tau V)^{0.8414}$	0.4317
1992	$S_T = 23.31(\tau V)^{2.2904}$	0.8773
1993	$S_T = 74.719(\tau V)^{1.5669}$	0.9137
1994	$S_T = 11.065(\tau V)^{2.5405}$	0.9161

Table 4.6 Sediment rating curve of the Ganges for unit stream power as independent variable.

Year	Sediment rating curve	Coefficient of determination
1983	$S_T = 9E+13(VS)^{3.1456}$	0.9210
1984	$S_T = 3E+13(VS)^{3.0134}$	0.8922
1985	$S_T = 1E+10(VS)^{1.922}$	0.7592
1986	$S_T = 3E+11(VS)^{2.3853}$	0.6618
1987	$S_T = 2E+08(VS)^{1.409}$	0.7846
1988	$S_T = 2E+07(VS)^{1.0837}$	0.4834
1992	$S_T = 3E+12(VS)^{2.6712}$	0.8857
1993	$S_T = 1E+10(VS)^{1.9369}$	0.9235
1994	$S_T = 6E+12(VS)^{2.7533}$	0.9463

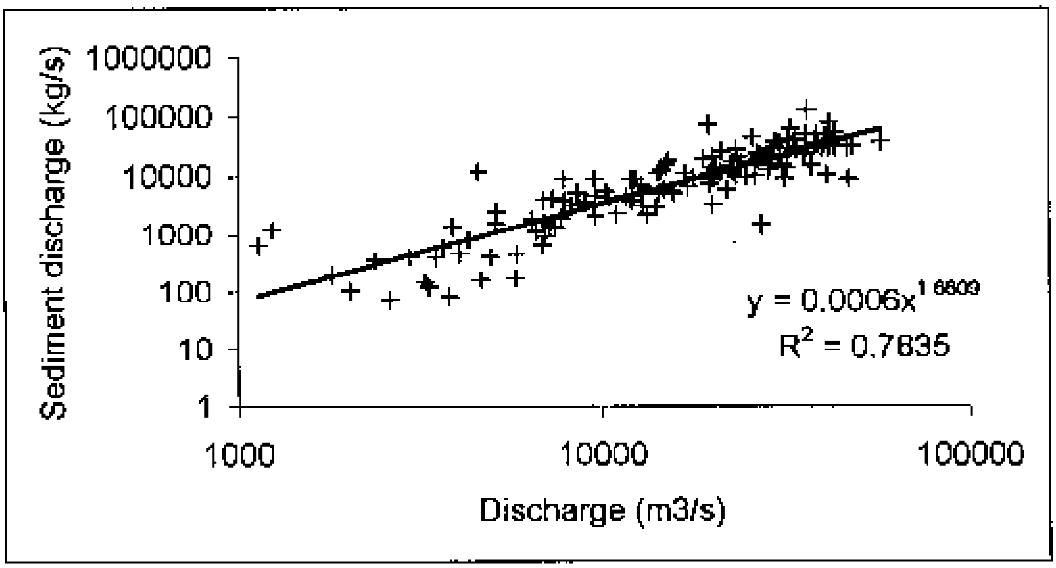

Figure 4.7 Sediment rating curve of the Ganges: discharge as independent variable.

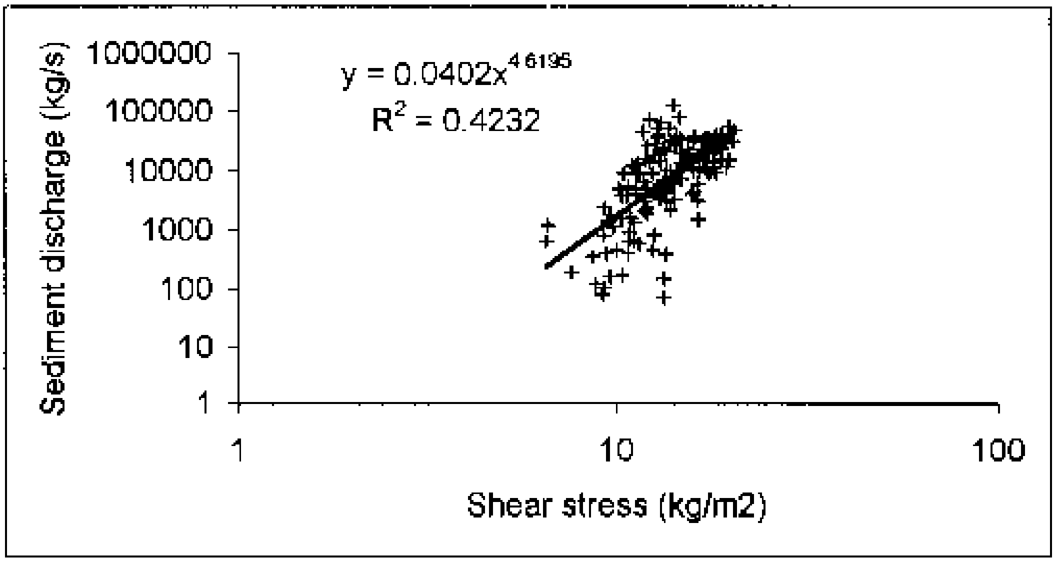

Figure 4.8 Sediment rating curve shear stress as independent variable.

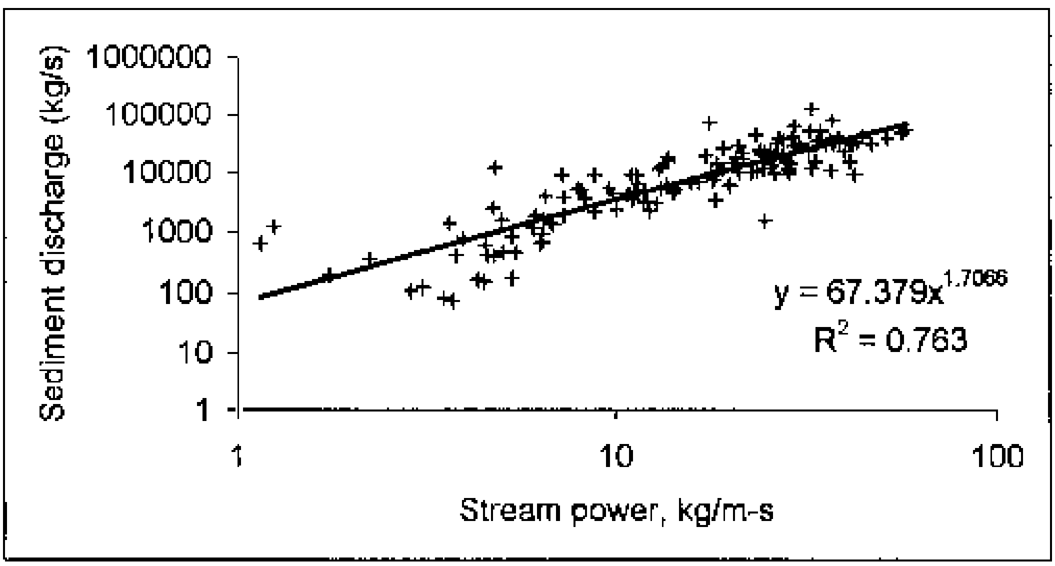

Figure 4.9 Sediment rating curve. stream power as independent variable

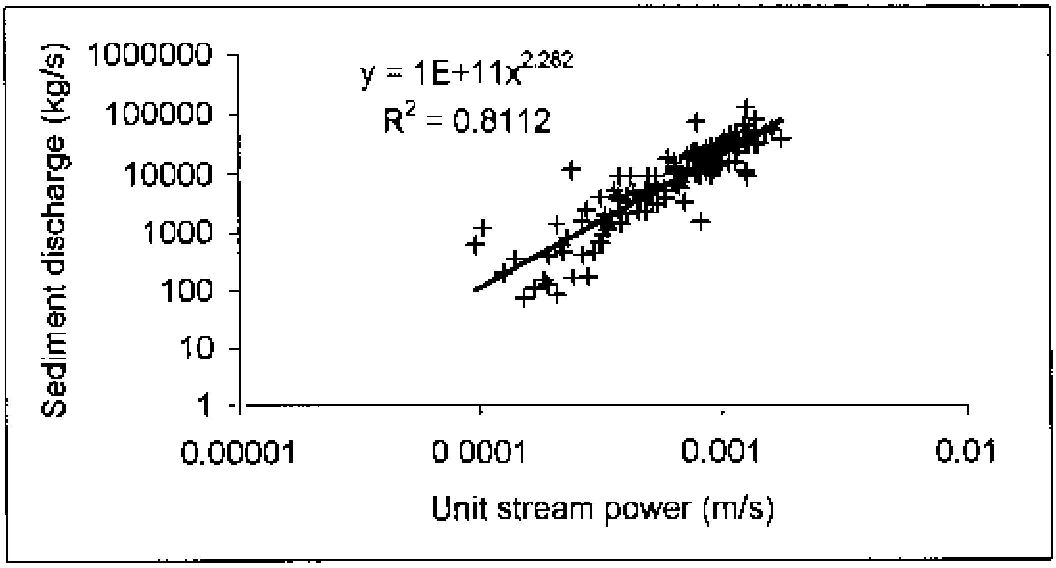

Figure 4.10 Sediment rating curve: unit stream power as independent variable.

CHAPTER 5

CONCLUSIONS

In this study, the sediment transport characteristics of the Ganges river have been studied. The unit stream power formula and modified unit stream power formula which is applicable for high concentration of fine sediments have been applied for the estimation and prediction of sediment transports in the Ganges river.

The peak discharge does not necessarily always coincide with the peak sediment load. There is a phase lag between the peak discharge and the peak sediment load The peak sediment load occurs first and then the peak discharge with only exception where the peak sediment load is followed by the peak discharge. In some cases, the peak discharge and peak sediment load occur at the same instances The yearly variation of annual maximum discharge, suspended sand discharge, suspended fine discharge and total suspended discharge suggest that the maximum discharge and maximum sand discharge are free from trend but the maximum fine discharge and maximum total sediment discharge show an upward trend beginning from 1992. The yearly variation of the percent of fine suspended discharge with respect to the total suspended discharge shows that the percent of fine sediment discharge is about 50 which means that the Ganges river at Hardine bridge gauge station contains a substantial amount of wash loads.

Based on measured data, sediment transports have been computed using Yang's stream power formula and modified Yang's formula The comparison between computed and measured sediment discharge based on Yang's unit stream power formula and modified Yang's formula for high concentration of fine sediments show that Yang's formula over predicts the sediment transport than the modified formula. The discrepancy ratio and standard deviation have been used to indicate the accuracy of the sediment transport predictors. The discrepancy ratio and standard deviation suggest that modified Yang's formula is better in the sediment laden Ganges river. Comparisons between computed and measured sediment concentrations based on the average logarithm ratio indicate that the goodness of fit of different equations may be affected by selecting statistical parameters. The modified Yang's sediment transport function can be used in modeling sediment load in the Ganges river. The Yang's formula can be used in stead of the modified Yang's formula after adjusting the computed sediment load by an appropriate multiplying factor.

The sediment rating curve of the Ganges river at Hardinge bridge gauge station have been studied by establishing power relations between sediment transport as dependent variable and discharge, shear stress, stream power and unit stream power as independent variable separately. It is found that the sediment rating curve should be updated for each year. The discharge and unit stream power when used as independent variables give better curve as compared to shear stress and stream power.

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APPENDIX A

Year-wise variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge

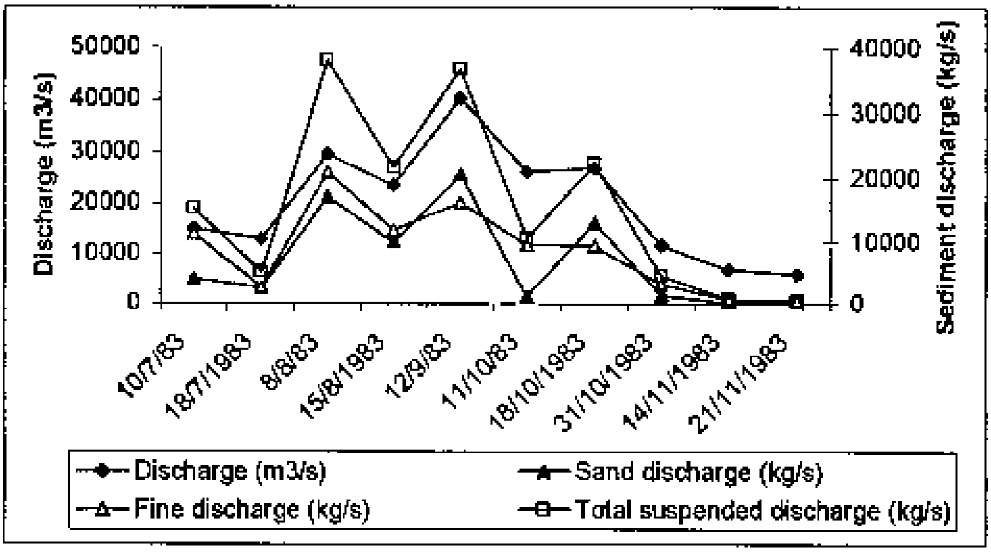

Figure A1 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1983

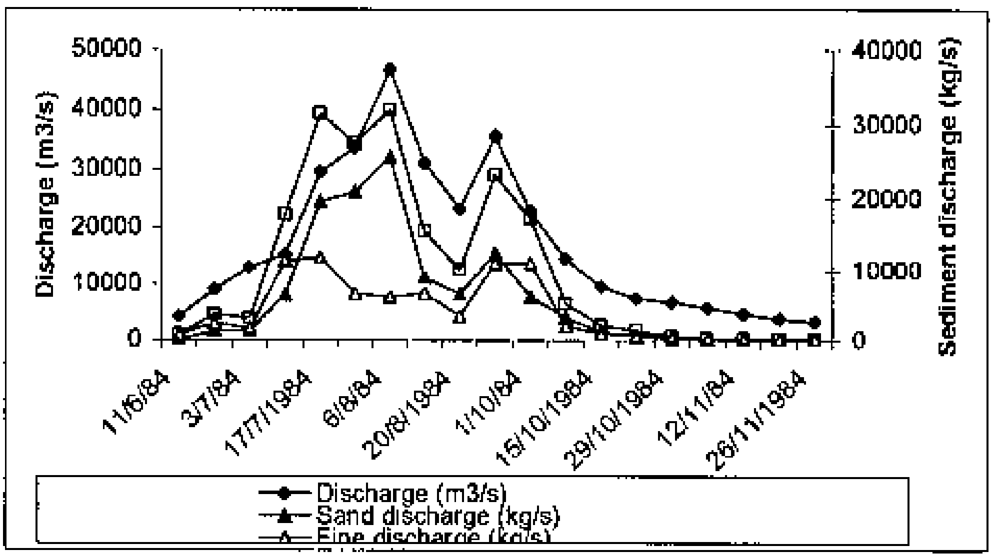

Figure A2 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1984

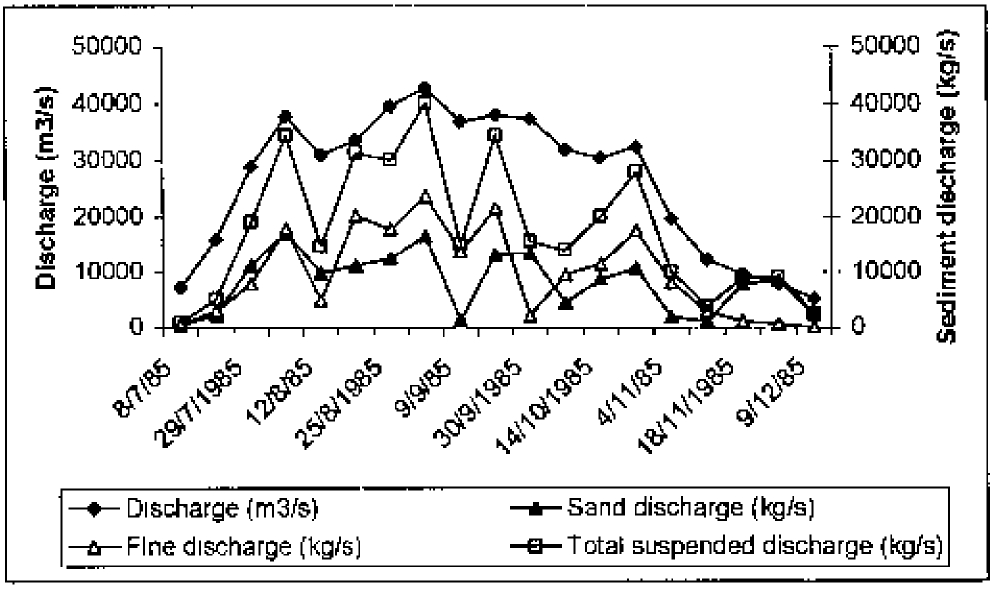

Figure A3 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1985.

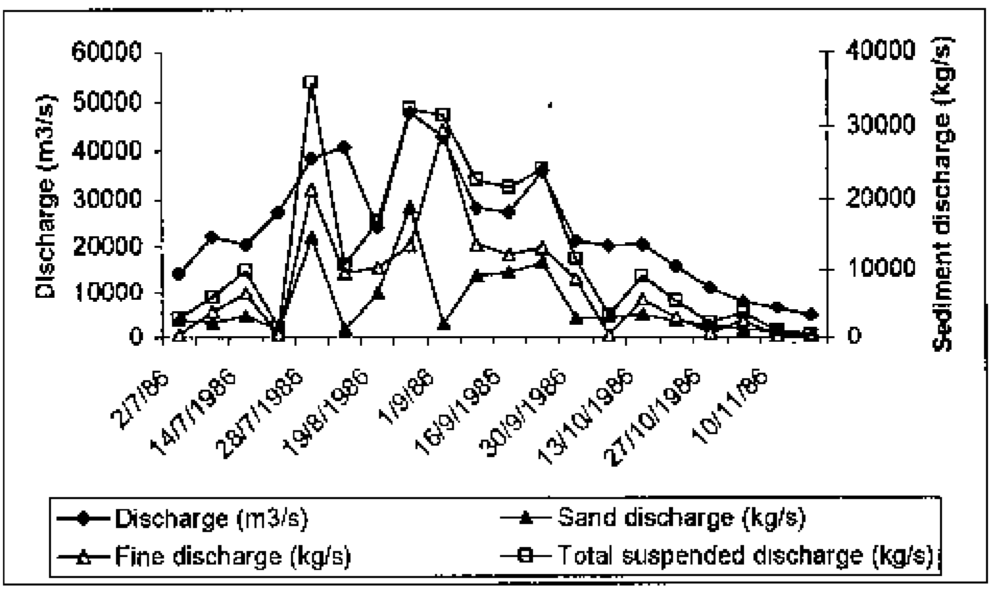

Figure A4 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1986.

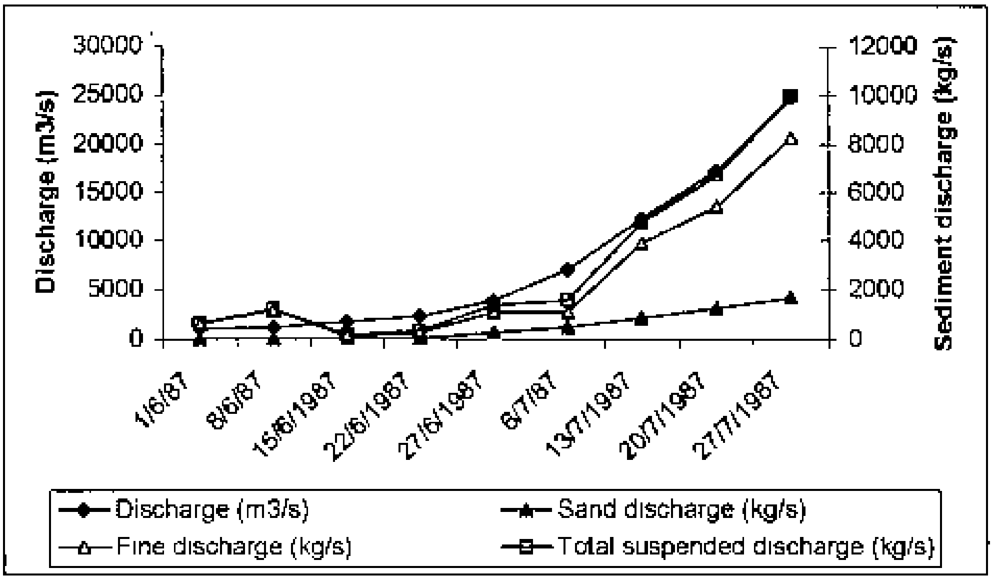

Figure A5 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1987

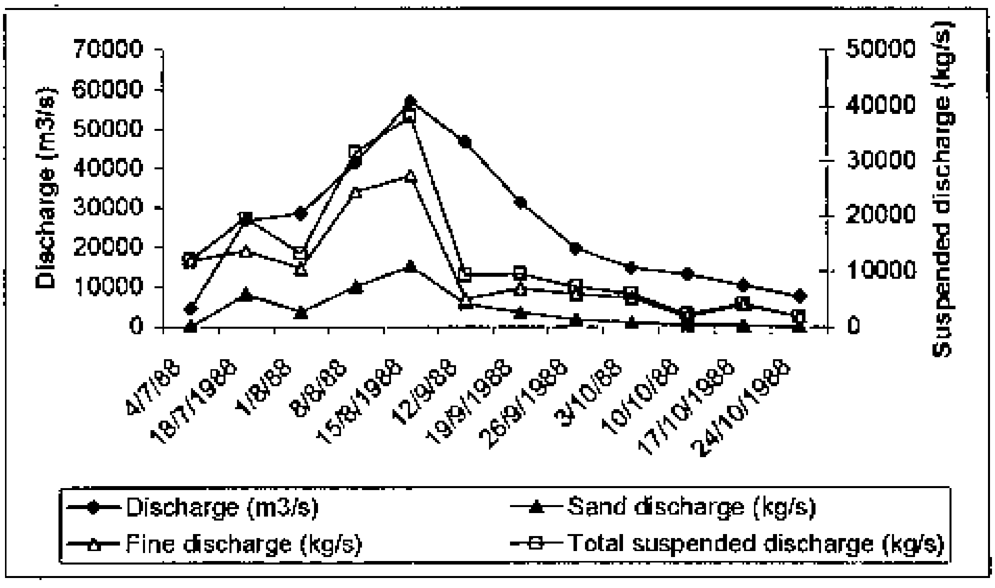

Figure A6 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1988

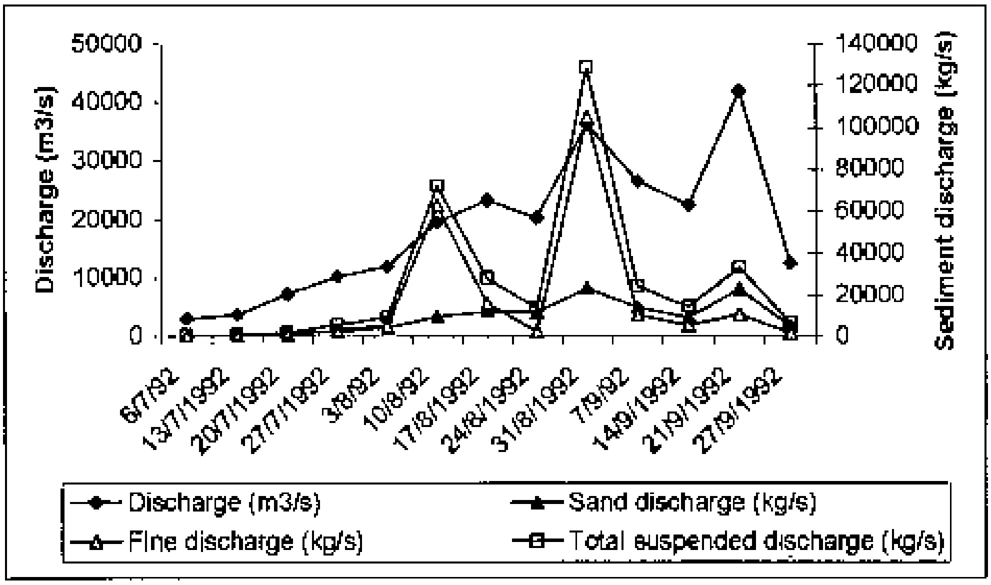

Figure A7 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1992

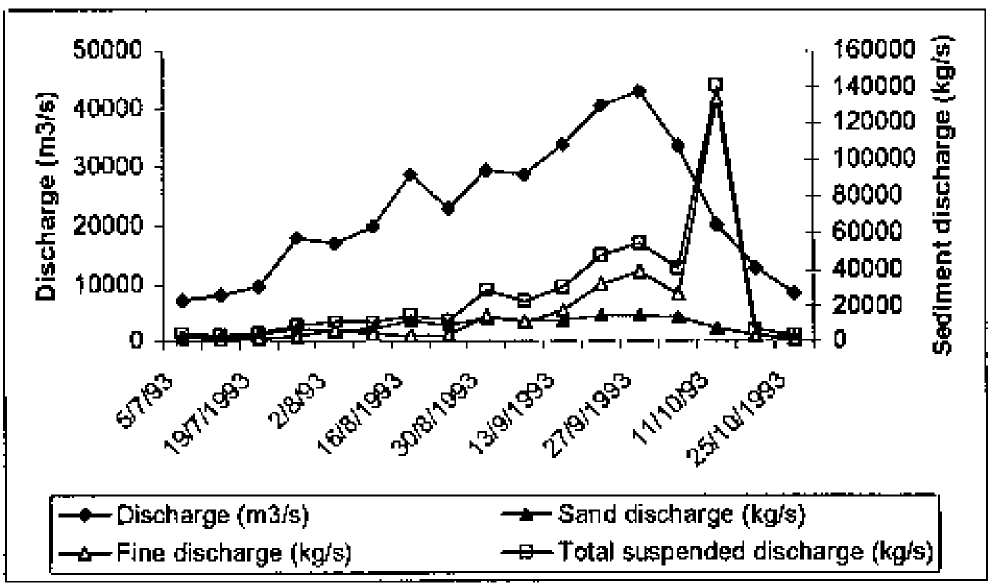

Figure A8 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1993

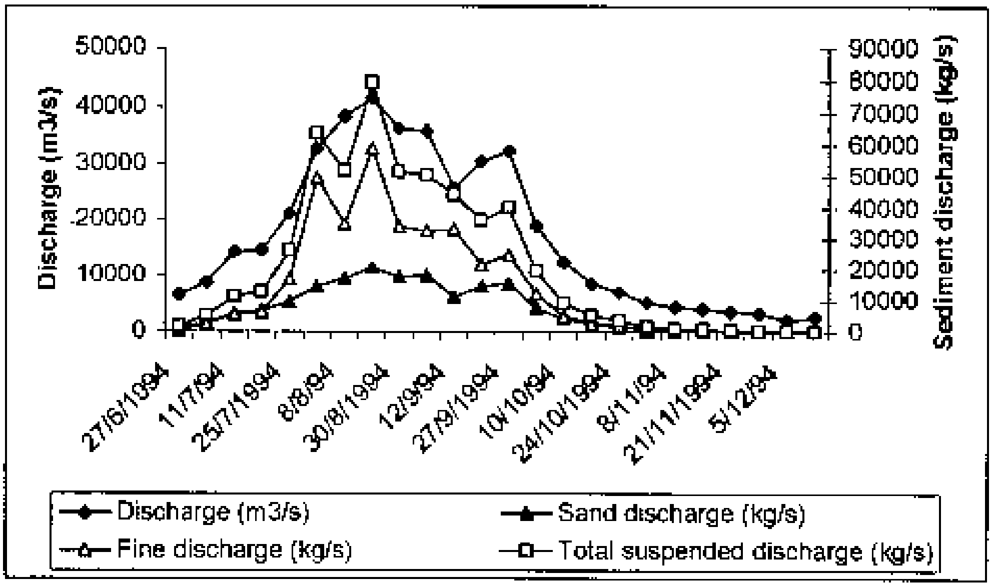

Figure A9 Variation of discharge, suspended sand discharge, suspended find discharge and total suspended discharge for the year 1994

APPENDIX B

Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for different years.

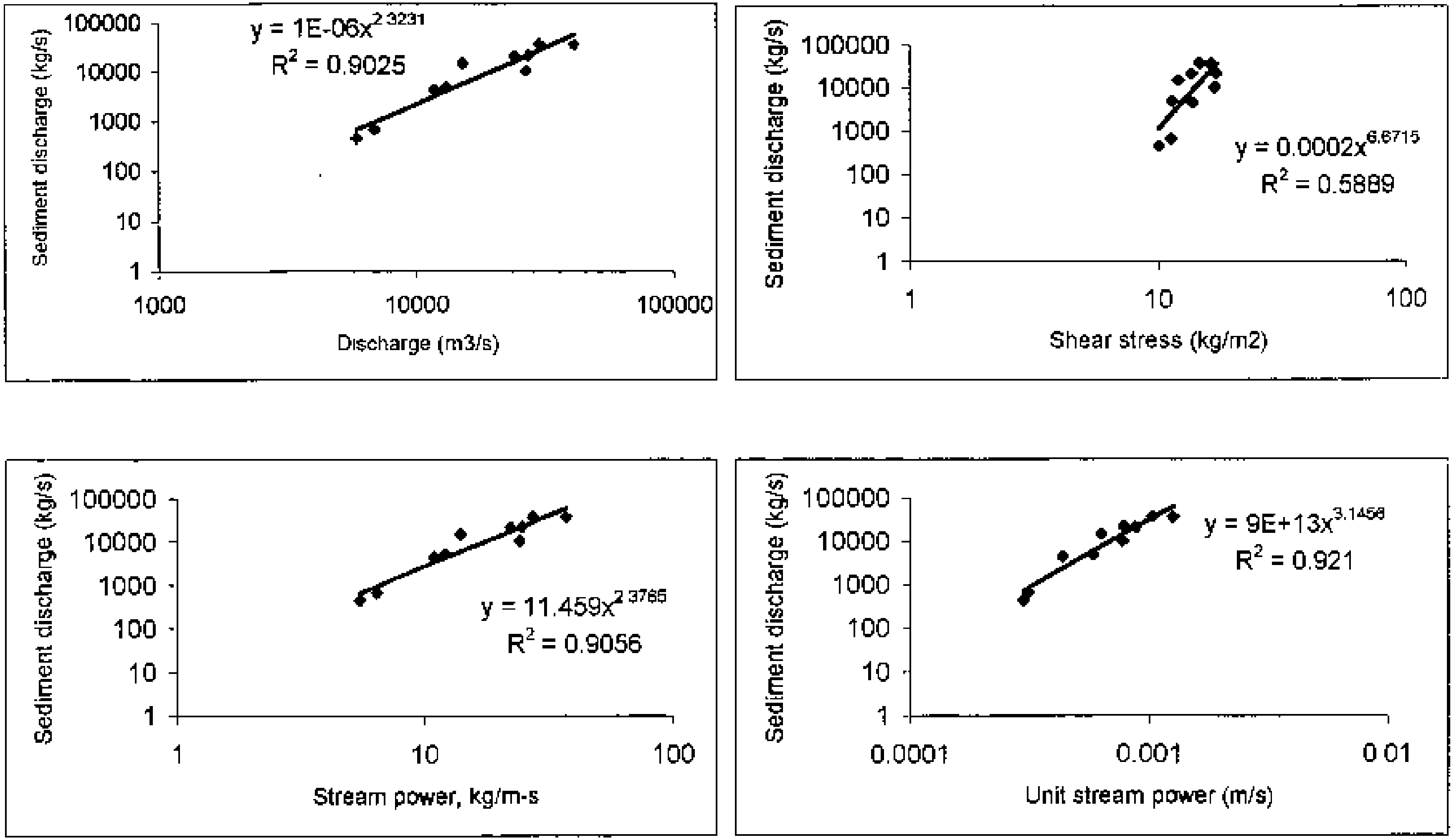

Figure B1: Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1983.

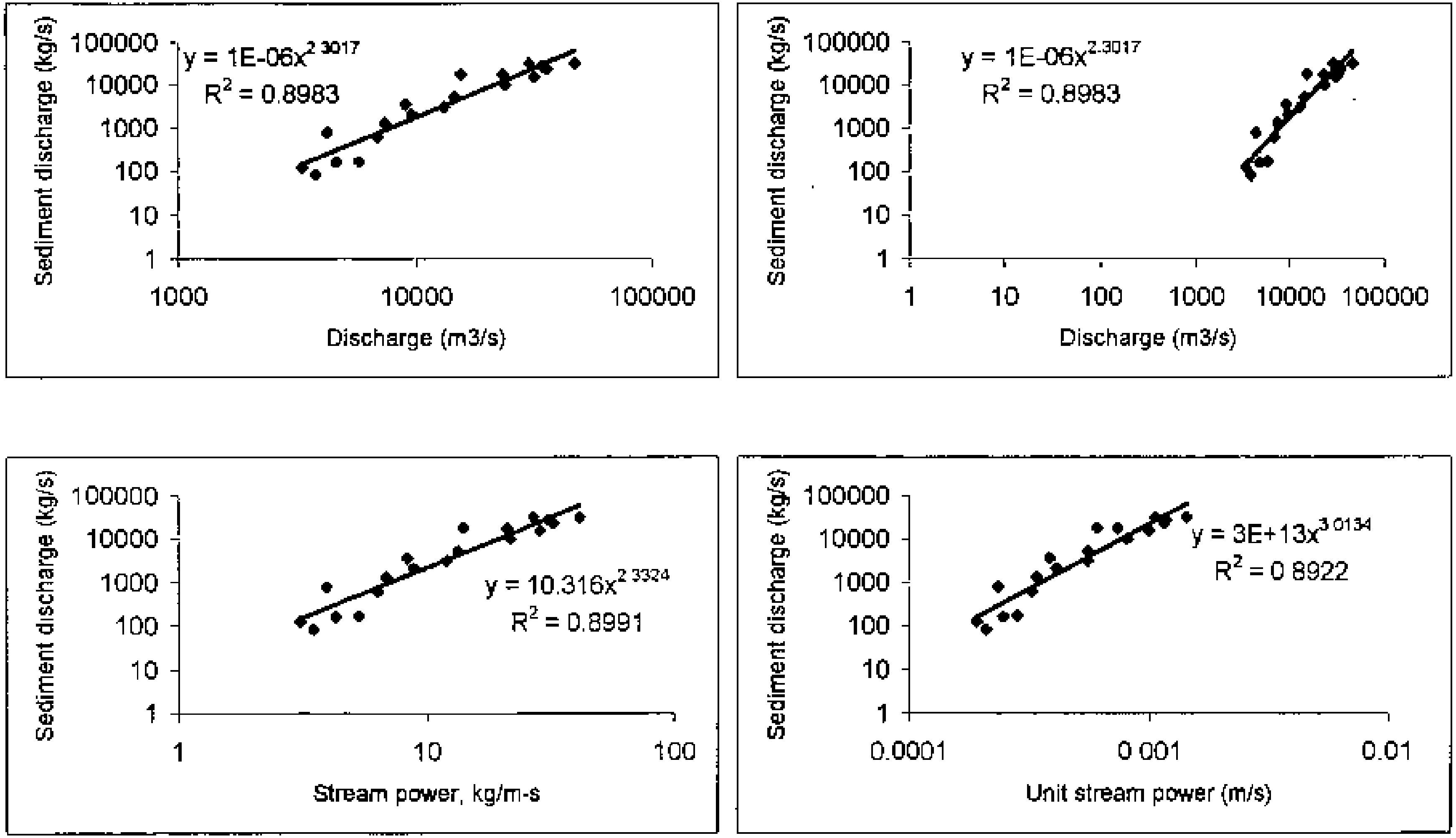

Figure B2 Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1984.

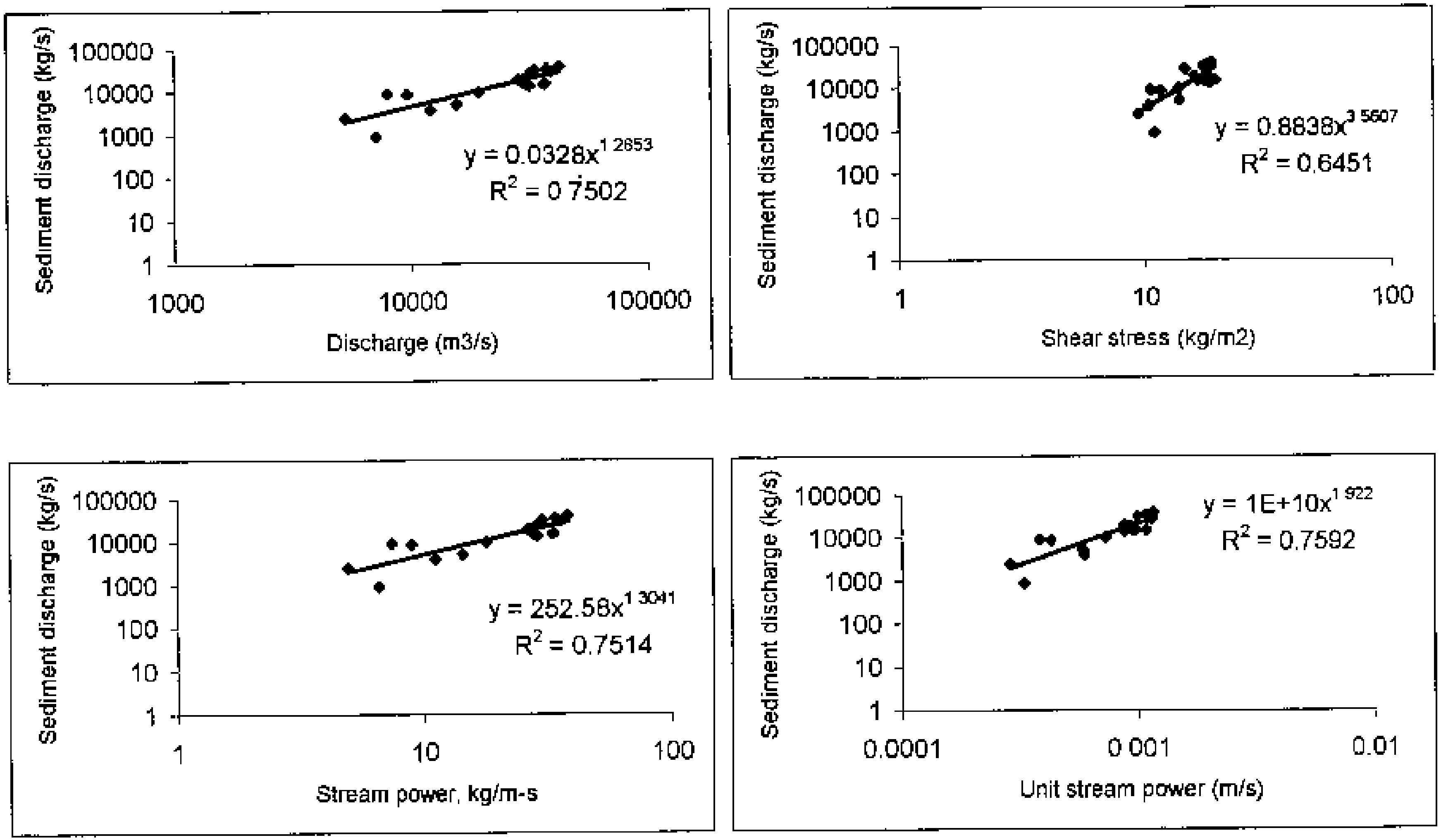

Figure B3: Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1985.

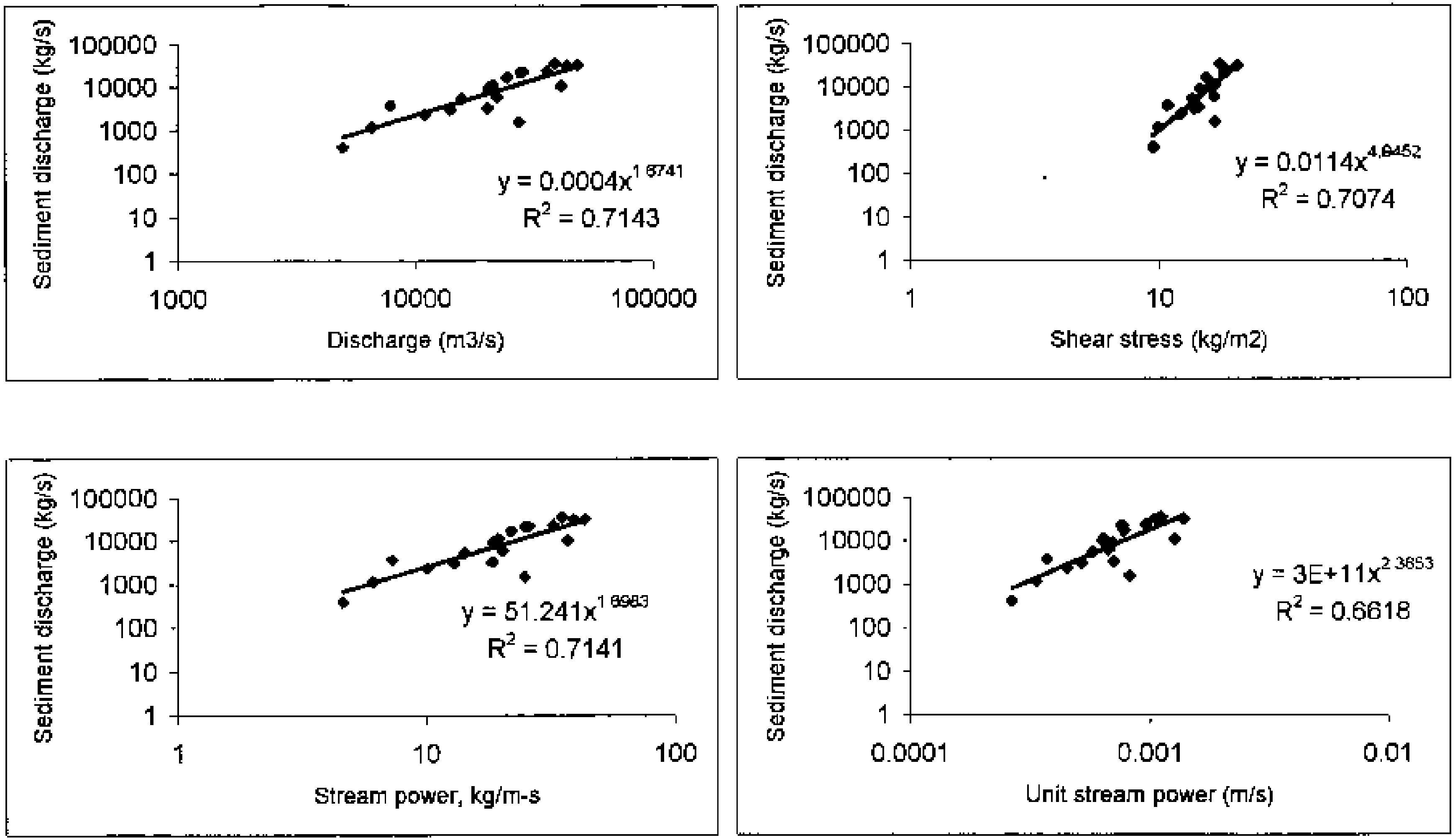

Figure B4: Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1986.

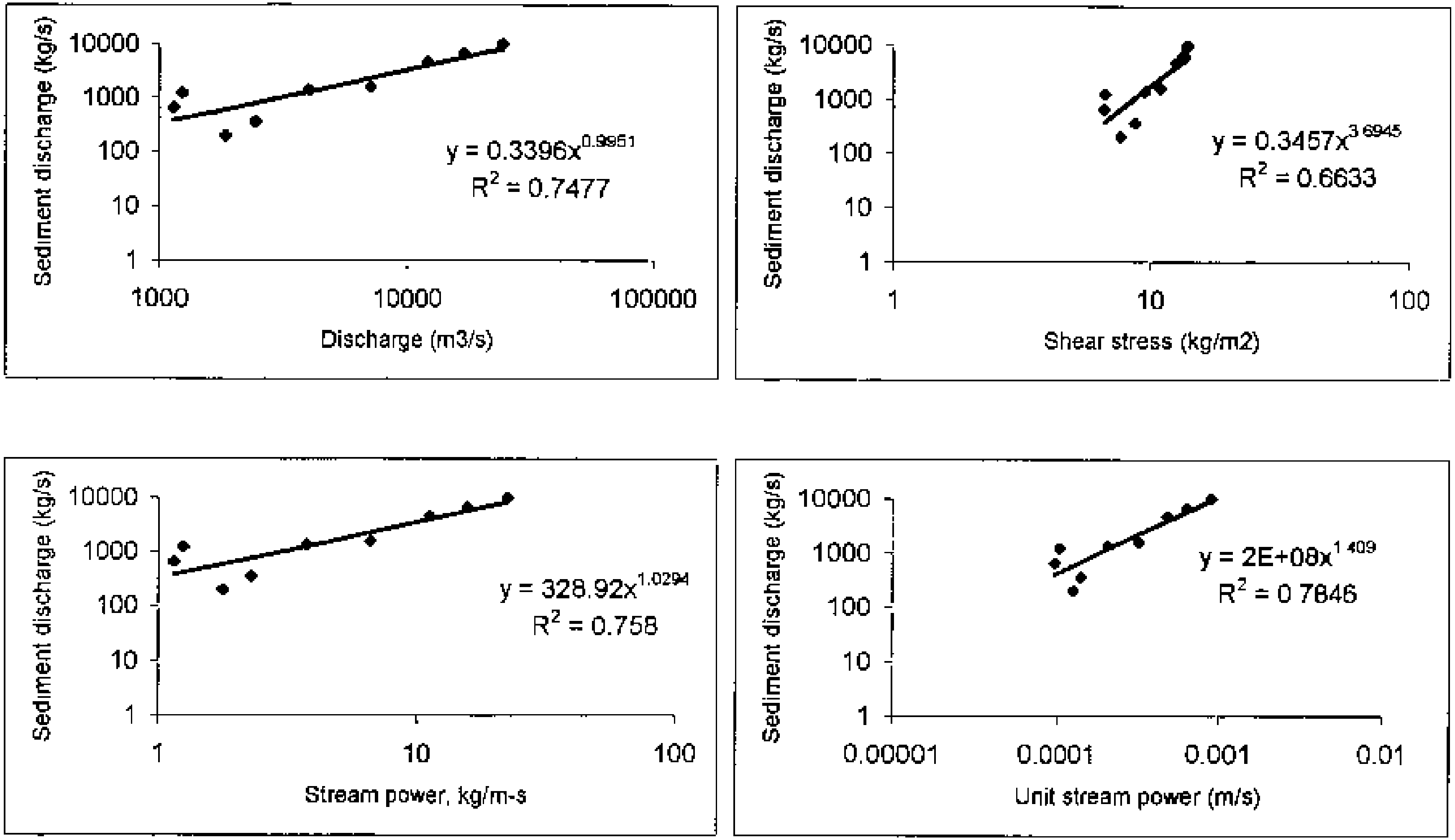

Figure B5. Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1987

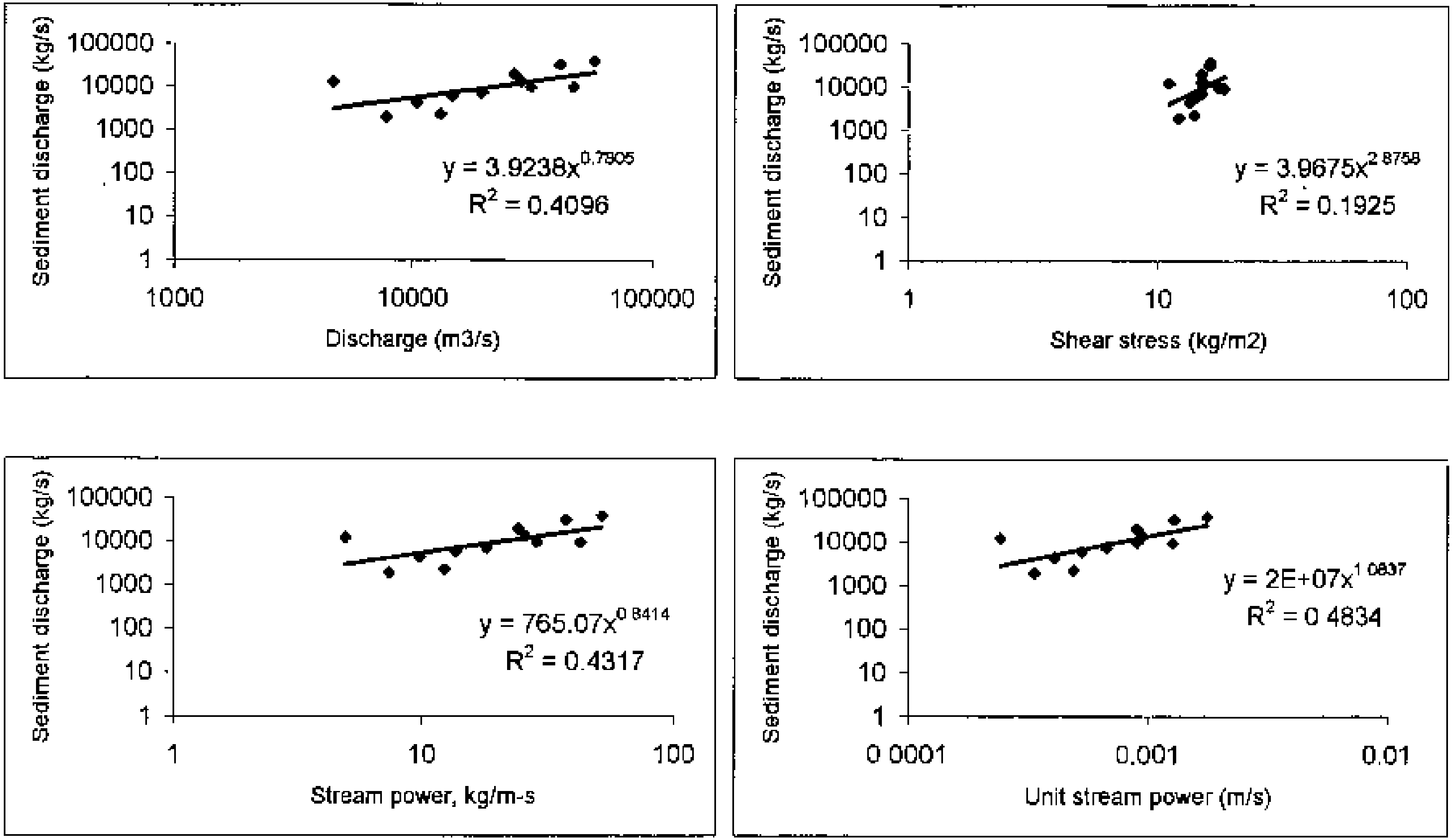

Figure B6: Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1988.

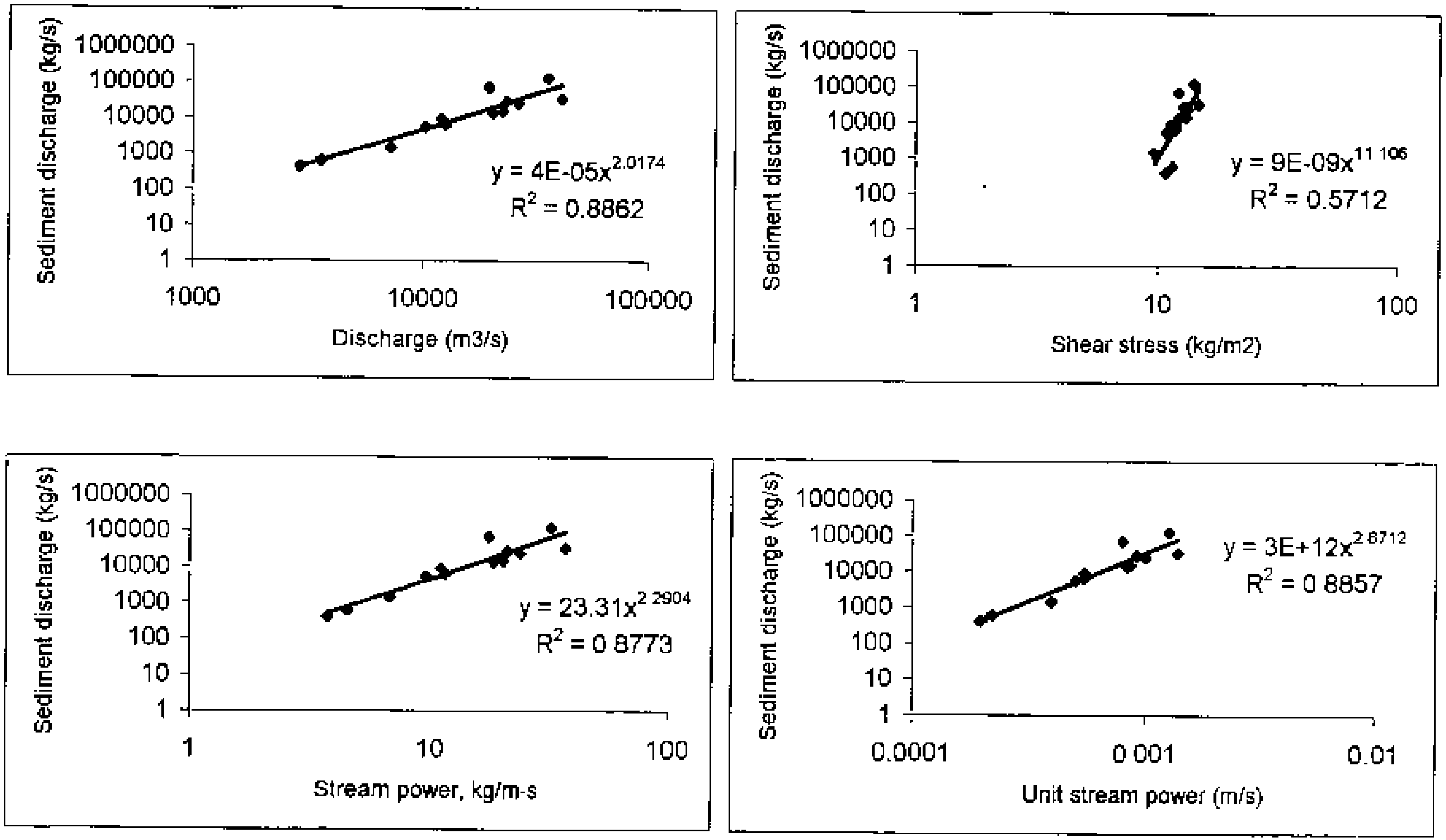

Figure B7 Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1992.

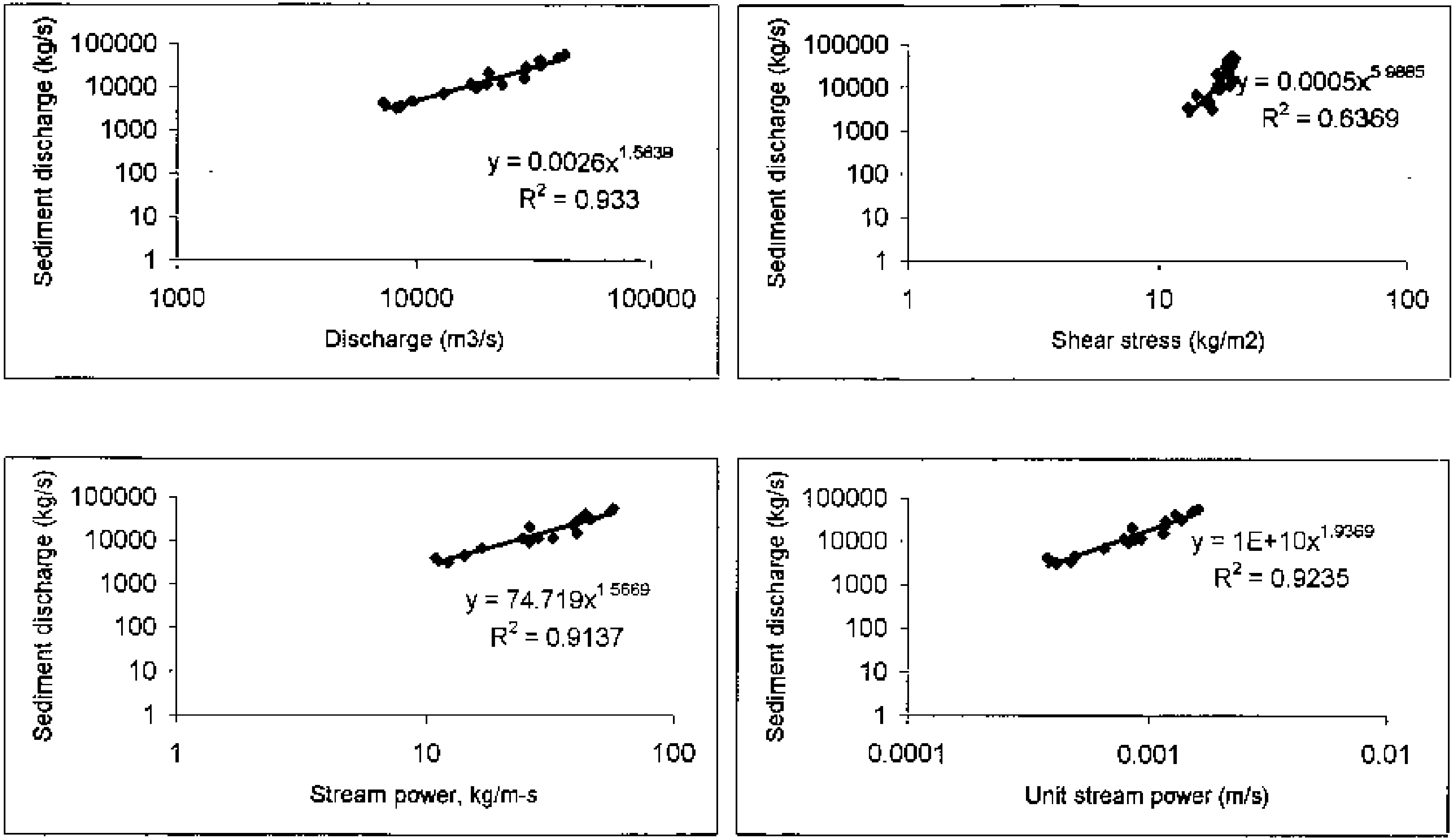

Figure B8: Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1993.

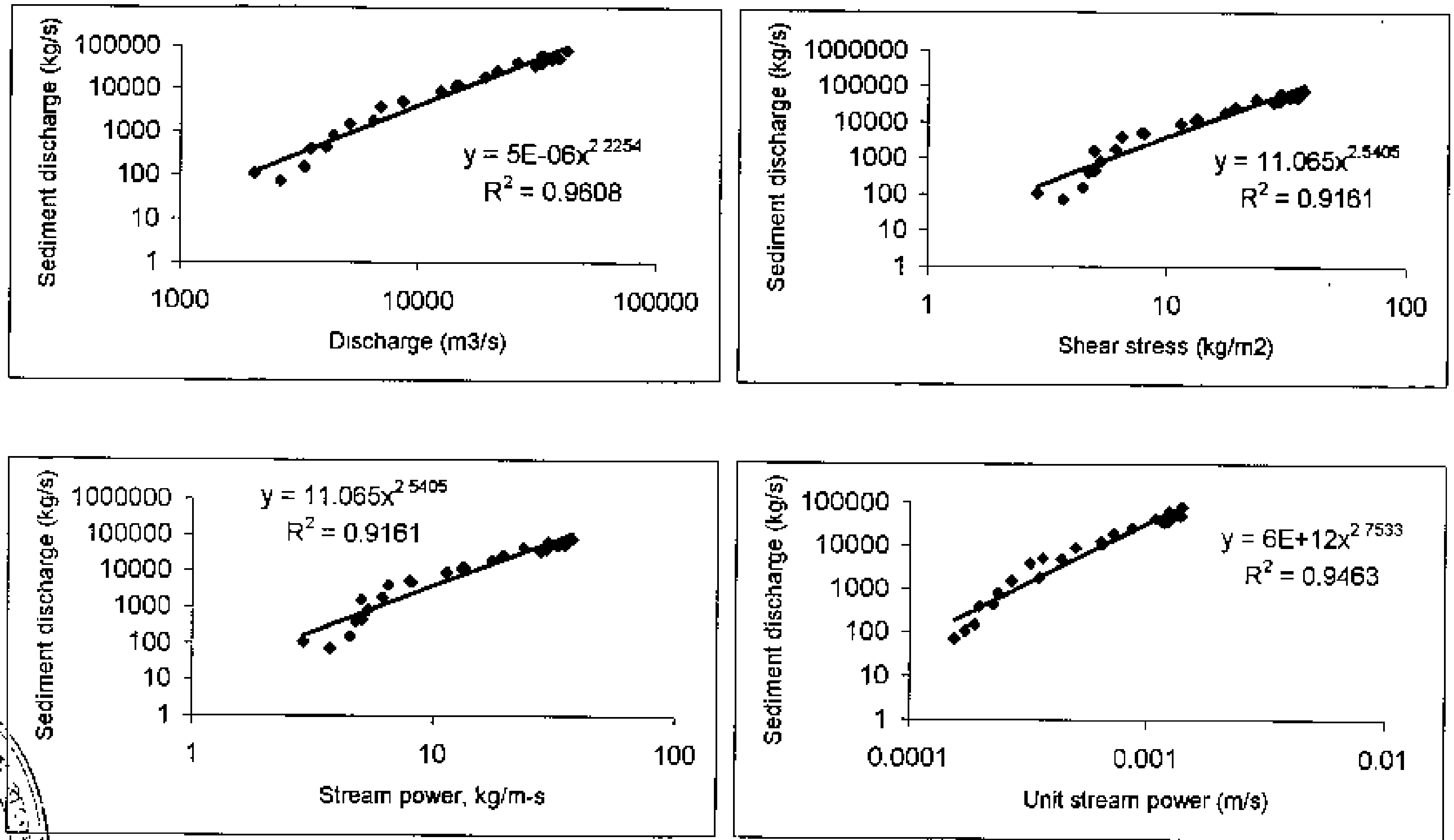

Figure B9· Plots of sediment discharge against discharge, shear stress, stream power and unit stream power for 1994.