SCHEMATISED SEDIMENT TRANSPORT PREDICTOR FOR STUDY OF ALLUVIAL RIVERS : AN APPLICATION TO THE JAMUNA

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SCHEMATISED SEDIMENT TRANSPORT PREDICTOR FOR STUDY OF ALLUVIAL RIVERS : AN APPLICATION TO THE JAMUNA

BY

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A thesis submitted to the Department of Water Resources Engineering of Bangladesh University of Engineering and Technology, Dhaka in partial fulfilment of the requirements for the degree

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RECOMMENDATION OF THE BOARD OF EXAMINERS

We hereby recommends to the Department of Water Resources Engineering, Bangladesh University of Engineering & Technology (BUET), Dhaka, the acceptance of the thesis, " **Schematised Sediment Transport Predictor for Study of Alluvial Rivers : An Application to the Jamuna**" submitted by **Krishna Chandra Dey** in partial fulfilment of the requirements for the degree of Master of Science in Water Resources Engineering.

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DECLARATION

I hereby declare that the research reported in this thesis was performed by me as a research project in partial fulfilment of the requirements for the degree of Master of Science in Water Resources Engineering from the Bangladesh University of Engineering and Technology (BUET).

This thesis contains no material which has been accepted for the award of any other degree or diploma from any other institution. Further, to the best of my knowledge and belief, the thesis contains no material previously published or written by any other person, except when due reference is made in the text of the thesis.

December 5, 1995

(Krishna Chandra Dey)

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ABSTRACT

This thesis deals with the development of a schematised transport equation applicable for the alluvial rivers. The basis of this schematization considered that the sediment transport is a predominant function of flow velocity. The transport equation is developed based on the available flow and sediment characteristics data collected from the Surface Water Hydrology II, BWDB for the period of 1984-87, in which a total of 582 sets of vertical data of 83 cross sections of the Jamuna river channels have been utilised. Prior to making use of the sediment discharge data, various methods of sediment discharge computation are assessed in the light of recent measurements made by the River Survey Project in Bangladesh. This assessment reflects the reliability of using traditional methods of sediment discharge estimation. The applicability of developed equation has further been verified with an independent set of data for the period of 1993.

An attempt has also been made to compare the developed equation with the selected well known sediment transport predictors against the same data both for verticalwise and normalized channel. In the light of comparison made, it is shown that the developed equation predicts the sediment transport rates more closer to the field data than those of the selected sediment transport predictors. However, the transport predictors namely Hossain, Engelund-Hansen and Bagnold formula are found to be suitable for the application of the Jamuna river.

In addition to this, a separate theoretical investigation has also been carried out to obtain the expressions and the magnitudes of the exponent b of the flow velocity of sediment transport predictors applicable for the case of alluvial rivers. The exponent 'b' obtained from the analysis of the observed data is found to lie within the range derived from the theoretical analysis. All the results are shown in both tabular and graphical forms.

An application of the developed equation have been shown in one dimensional morphological model to demonstrate the influence of exponent 'b' on the propagation of bed level changes. In this application, the constriction of the Jamuna river at the bridge site is considered. It is observed that the exponent 'b' is more sensitive than the variation of grain sizes for the bed level changes. It is expected that the developed equation would be useful for two dimensional sediment transport estimation in large wide rivers. Finally some suggestions for future extension of work have been outlined.

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Symbols	meaning	dimension
a	reference level above the mean bed	(m)
b	exponent of flow velocity	(-)
B	normalised averaged width	(m)
C	overall Chezy coefficient	($m^{0.5}/s$)
C′	grain-related Chezy coefficient	($m^{0.5}/s$)
C_{90}	Chezy roughness coefficient based on d_{90}	($m^{0.5}/s$)
Cs	mean sediment concentration over the vertical	(mg/l)
c_a	reference concentration at level 'a'	(-)
c_i	concentration in point i above the bed	(mg/l)
c_t	total load concentration by weight	(ppm)
c_o	maximum concentration (= 0.65)	(-)
d	point depth	(m)
d	diameter of the sphere	(m)
d_s	representative particle size of suspended sediment	(m)
d_{35}	representative diameter of bed material	(m)
d_{50}	median particle diameter of bed material	(m)
d_{90}	characteristic diameter of bed material	(m)
D_*	dimensionless particle parameter	(-)
e_b	efficiency factor of bed load (= 0.1-0.2)	(-)
e_s	efficiency factor of suspended load (= 0.01-0.02)	(-)
F	shape factor in Van Rijn formula	(-)
g	acceleration of gravity	(m/s^2)
h	water depth	(m)
H	normalised average depth	(m)
k_s	effective bed roughness height of Nikuradse	(m)

κ	Von Karman constant (= 0.4)	(-)
K	weighing factor for the i th sample	(-)
L_D	damping length	(m)
L_P	wave length	(m)
m, n	coefficients in Ackers and White formula	(-)
N	sum of the weighing factors at a vertical	(-)
q_b	bed load transport	(m^2/s)
q_s	suspended load transport	(m^2/s)
q_t	total load transport	(m^2/s)
Q	measured water discharge	(m^3/s)
Q_c	assessed discharge	(m^3/s)
$s\ (= \rho_s/\rho)$	specific density	(-)
S	slope of energy gradient	(-)
T	dimensionless bed-shear stress parameter in Van Rijn formula	(-)
u	depth averaged velocity	(m/s)
u_*	current-related bed-shear velocity	(m/s)
u_i	velocity at the i th measuring point	(m/s)
u_{cr}	depth-averaged velocity at initiation of motion	(m/s)
V	cross sectional average velocity	(m/s)
w	settling velocity of the sediment load	(m/s)
w_r	settling velocity for a representative sediment size	(m/s)
w_s	fall velocity (based on d_{50} of bed material)	(m/s)
Y	particle mobility parameter	(-)
Y_{cr}	critical particle mobility parameter	(-)
z	suspension number	(-)
z_o	zero velocity level	(m)
z_i	height above the bed of point i	(m)
α_2	coefficient according to Parker and Klingeman	(-)
β	ratio of sediment and fluid mixing coefficients	(-)
$\tan\beta$	bottom slope in Bagnold equation	(-)
γ_s	specific weight of the sediment particle	(kg/m^3)

γ_f	specific weight of the fluid particle	(kg/m^3)
ρ	fluid density	(kg/m^3)
ρ_s	sediment density	(kg/m^3)
Δ	relative density	(-)
$\tan\phi$	dynamic friction coefficient(= 0.6)	(-)
ϕ_{50}	dimensionless flow parameter in Parker and Klingeman formula	(-)
θ	dimensionless Shields parameter	(-)
θ'	dimensionless shear stress parameter based on grain roughness	(-)
μ	bed-form factor or efficiency factor	(-)
μ	dynamic viscosity of the fluid	(kg/sm)
τ_b	overall current-related bed-shear stress	(N/m^2)
τ_b'	effective bed-shear stress	(N/m^2)
$\tau_{b,cr}$	critical bed-shear stress according to Shields	(N/m^2)
ν	kinematic viscosity coefficients	(m^2/s)
λ_s	adaptation length of the sediment transport and bed topography	(m)
λ_w	adaptation length of the main flow	(m)
Ψ	dimensionless sediment transport	(-)
Ψ	stratification correction in Van Rijn formula	(-)
σ_s	geometric standard deviation of bed material	(-)
σ	standard deviation	(-)

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CHAPTER ONE

INTRODUCTION

1.1 General

The term "alluvial" is usually applied to streams in which the moving sediment and the sediment in the underlying bed is of the same character. An alluvial channel has a mobile bed, composed of non-cohesive granular materials. Such material are unconsolidated silts, sands and gravels. The channel banks are usually composed of clay, silt or sand. Many natural water courses, and the majority of man made canals are examples of alluvial channels.

The morphology of natural channels and rivers are determined by the interaction of the fluid flow with the erodible materials of the channel boundary. This interaction involves the distinct processes of erosion, entrainment, transportation and deposition. Thus there is a problem in defining this interaction in both qualitative and quantitative terms. Certainly, the basic mechanical principles are well established. However a complete analytical solution is still a long way off, if, indeed, it is attainable. This is because the existence of natural or quasi-natural streams represent the movement of a fluid-solid mixture within boundaries that are themselves deformable. Even the motion of a single particle is a random process, difficult to describe adequately. Also, the problem becomes more complex when the boundary material is in any way cohesive.

Consider an alluvial channel in a given location. Its nature results from an integration of the upstream factors of geology, climate and land use. These determine the type of sediment, and the manner in which water is supplied from the source area. At times the upstream factors remain constant for the drainage area. Then the river morphology is likely to remain stable, although the channel may not be static. Such stability is reflected in the many empirical generalisations which have been proposed. These seek to relate both the adjustment of the river form to the processes involved, and to provide the relations among the various aspects of channel form.

Of the many branches of hydraulic science that which concerns the transport of sediment laden water is possibly the most complex and inexact. This complexity arises from the number of independent factors which can influence the geometry of a channel for a given discharge. Of these, among the more important are density and the size of the particles, the settling velocity of the particles and the sediment concentration. Both the average fall velocity of the particles and their mean size may have to be regarded as variables, because of different shape characteristics.

The geometry of an alluvial channel can be altered by the flow conditions. This alteration of geometry always tends towards a configuration that is in equilibrium for the currently obtaining flow. Potentially, a stream channel in alluvium is constantly subject to change in its boundary configuration. Its cross-sectional dimensions and slope are all free to adjust in response to the action of the flowing water. Thus, the boundary of channel can either remain stable, i.e no nett movement of materials occurs or there may be nett erosion from the boundary with the material then transported in the direction of flow. Conversely, there may be nett deposition.

A number of hydraulic parameters govern the physical characteristics of a channel and the parameters are interrelated. The hydraulic characteristics of an alluvial channel are affected by the stream discharge, sediment load, longitudinal slope, bed and bank resistance and other factors. A detailed knowledge of the hydraulic characteristics of different types of streams are of great importance when dealing with river training works, flood control works, location of bridges, navigation, loop cutting, channel improvements etc.

The alluvial plains of Bangladesh is composed of the sediments brought by the three major river systems; the Ganges, the Brahmaputra and the Meghna. The sediment carried by these river systems are supplied from the erosion of their enormous catchment areas outside and inside of the country.

In Bangladesh most of the river courses being of alluvial nature, proper quantification of the extent of erosion, deposition and changes in channel form of such alluvial courses still has been a subject of considerable research. For planning and design of water development projects it is often required to estimate the extent of the nature of possible future changes in river geometry in which transport of sediment plays a dominant role.

A systematic study on the flow and sediment characteristics of the alluvial rivers of Bangladesh is, therefore, of utmost importance from the standpoint of improved planning and design of water development projects. Also knowledge of the rate of total sediment transport for given flow, fluid and sediment characteristics in a stream is essential in the solution of practically associated with the flow in alluvial channels.

1.2 Importance of Schematised Transport Relation

The most common schematised transport relation is the sediment rating curves which can be represented by the sediment transport as a function of the water discharge. The sediment rating curve, which is an exponential function, can be determined either by regression analysis or from a graph with the data points (discharge versus sediment transport) on a logarithmic scale. The curve is widely used to estimate the sediment concentration or the sediment transport for periods during which discharge data are available and where the measurements of sediment transport data are not available.

A sediment rating curve assumed an unique relationship between the average flow velocity in a cross-section and the shear stress at the river bed. This unique relationship exists in a steady uniform flow with a fully developed boundary layer. In these flows the vertical flow velocity profile is described with a logarithmic or a power law profile and with an assumption that the river cross-section is more or less of prismatic nature.

However, in an accelerating or decelerating flows, deviations in a sediment transport rating curve can be expected. These types of flow occur in bends, near bifurcations and confluences of the channel of a braiding river and during the rising and receding limbs of the hydrograph. Consequently the sediment rating curves fitted in the main river system in Bangladesh are regression lines fitted to strongly elongated cloud of data points. Moreover sediment transport and water discharge relation makes spurious correlation as because pocket width at each vertical is multiplied with sediment transport per unit width and discharge per unit width per vertical.

For general application in morphological studies, either by mathematical analysis or by scale modelling it is attractive to use the schematised sediment transport formula in a form which can be defined as the sediment transport per unit width is a function of the flow velocity to the power 'b' or the dimensionless sediment transport is a function of the Shields parameter to the power b/2. Most of the prediction formula can be converted to such schematised form. In general, the power 'b' which is the exponent of the flow velocity varies between 3 and 7 and even more (high values for low transport rate), with 'b' equal to 4 to 5 for high sediment rates (Breusers, 1988). The exponent 'b' depends on the Shields parameter, which is a dimensionless shear stress parameter.

The importance of exponent 'b' had been demonstrated by Jansen et al (1979), Struiksma et al (1985), Struiksma and Klaassen (1988), Struiksma and Crosato (1989). They have shown that point bar formation in channel bends, bar dimensions, transition between meandering and braiding and the braiding index are closely linked to the exponent 'b'. Beside these, in morphological computations, the exponent 'b' influences the prediction of the river bed response by any morphological model. de Vries (1986) demonstrated that the slope and the flow depth of an alluvial river are dependent on the value of exponent 'b'.

Erosion and deposition of an alluvial rivers are characterised by the spatial variation in sediment transport and this is fully governed by the non-linearity of the sediment transport formula which describes the relation between the flow characteristics and the quantities of the bed material being moved. The importance of this schematised transport equation is that such simplified relationship can be combined with other equations to arrive at analytical expressions that provide increased insight into the morphological behaviour of an alluvial river.

1.3 Related Previous Investigations

Review of pertinent literature shows that several attempts have been made to establish sediment rating curves relating sediment discharge with water discharge. Such attempts have been made by many researchers such as Vanoni (1977), Bari (1978), Alam (1988), Klaassen et al (1988), Hossain (1992), Matin and Mohiuddin (1994) and others. Most of their studies mainly concentrated on the quantitative assessment of sediment transport in a river but did not make sufficient attempts to establish a schematised transport equation based on dimensionless sediment transport and dimensionless Shields parameter from the measured data.

In connection with the sediment discharge computation, BWDB is measuring suspended coarse and fine sediment discharge in the major rivers in Bangladesh since 1966. In practice suspended sediment samples are collected at 0.2 and 0.8 of the total depth in a vertical. In order to convert the observed concentration at 0.2 and 0.8 depth to the mean concentration in a vertical, Straub method is being used which is valid for all streams with moderate slope. But the accuracy of this method is still unknown to the hydraulic engineer. Because sufficient information about the accuracy of this method were not obtained from the literature.

In the previous article, the importance of the exponent 'b' for various morphological studies have been envisaged. An attempt had been made to derive the exponent 'b' as a function of the Shields parameter for the Meyer-Peter and Mueller bed load transport formula (Vries, 1987). But for the other prediction formula, no such relationships were found in the literature reviewed for this study.

1.4 Scope and Objectives of the Present Study

In the previous section, it was mentioned that no studies have been carried out to verify the accuracy of the Straub method used by BWDB for sediment discharge computation. But at the present time, River Survey Project (FAP 24) is collecting suspended sediment samples from several measuring points (multipoint) in a vertical. The use of this data could provide better opportunity to verify the accuracy of the Straub method with other method such as Chinese standard (WMO 1989) and to compare with the measured multipoint methods.

In most of the prediction formulae, the exponent 'b', the power to the flow velocity, plays an important role in estimating sediment transport. The importance of exponent 'b' is well understood by the investigators in this field, but its significance in each prediction formula is not well explained. Even it is not known in most of the prediction formulae, the range of exponent 'b' and its sensitivity with different hydraulic parameters. In this study, attempts have been made to derive the exponent 'b' analytically for other prediction formula. As the analytical solution is not always easy to schematise the prediction formula due to the complexity of various parameters of the equation, some numerical solution is often required. Hence in the present investigation on the exponent 'b' as a function of the Shields parameter (θ) will be made either analytically or numerically to derive the exponent 'b' of the flow velocity. In addition to this, a development of schematised transport equation based on the dimensionless sediment transport (ψ) with the dimensionless Shields parameter (θ) from the measured data, will be attempted.

Thus, the present study is directed towards the development of an appropriate schematised sediment transport equation for the data collected for the alluvial Jamuna river at Bahadurabad. Other various well recognized sediment transport equations such as Ackers & White (1973), Bagnold (1966), Engelund-Hansen (1967), Hossains (1985), Van Rijn (1984) and Yang (1973) have also be transformed to a form of schematised equation in order to compare with the developed schematised transport equation from the measured data. Further, if appropriate, one of these equations is to be adjusted to obtain an appropriate sediment transport predictor for the river Jamuna.

Summarizing above, the specific objective of this study can be set as follows:

(1) To compare critically the method of sediment discharge computation adopted by BWDB (two point) with that of multipoint procedures.

(2) To investigate the value of exponent 'b' as a function of the Shields parameter (θ) for various prediction formula and thereby develop a schematised sediment transport equation based on field measurements.

(3) To compare the various well known sediment transport prediction formulae based on the developed schematised transport equation to assess the suitability of application for the Jamuna river.

(4) Finally to apply the developed schematised transport equation for the prediction of morphological changes of river bed due to human interference.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 General

"What sediment transport formula should we recommend to estimate suspended sediment discharge in river reaches?" This question always arises from hydraulic and environmental engineers who are engaged in various sediment-control projects such as the River Survey Project, dealing with wide range of objectives for sediment-discharge prediction in natural movable-bed rivers in Bangladesh.

It is not possible to determine positively which one gives the more realistic result. To ease this difficulty many of the commonly used transport formulae have been tested by different researchers over a wide range of field and laboratory data. Notably these are :

(a) The ASCE Task Committee for preparation of sedimentation manual (1971).

(b) White et al of the Hydraulic Research Station (H.R.S), Wallingford (1973).

The Task Committee have studied thirteen formulae and observed that Colby (1964), Engelund-Hansen (1967) and Tofaletti (1969) formulae gave consistently better agreement than others. However, in presenting their results they continued that " these are not conclusions but recommendations or suggestions presented for guidance until more complete studies can be made". On the other hand Wallingford's studies are the most comprehensive and recent. They have tested nineteen transport formulae against about 1000 laboratory and 270 field measurements. They divided the theories into four groups, namely A, B, C and D according to general performance. It was found that out of the nineteen theories the total load formulas such as Engelund-Hansen (1967), Ackers & White (1973) and Rottner (1959) bed load formulas are most reliable and applicable for a wide range of flow conditions and sediment characteristics.

Numerous theoretical and semi-empirical approaches have been developed for the calculation of sediment transport rates, for example, Einstein (1950), Yalin (1963), Bagnold (1966); Engelund-Hansen (1967), Ackers & White (1973), Yang (1973), Van

Rijn (1984), Hossain (1985); mainly based on observation on laboratory experimental flumes and small streams. However, few attempts were made to test their applicability in large sand bed rivers, where the river morphology may strongly control the transport rates.

A formula that predicts sediment discharges adequately for one river, does very poorly for the other river. For example, the Inglis-Lacey formula (Inglis 1968) seems to predict sediment transport for the Colorado river quite well but for Niobrara river is extremely high, in spite these two rivers have very similar energy slopes and and a similar geometric mean diameters of the grain size.

Based on stream power concept, Yang (1977) developed a sediment transport equation. He compared his equation with ten other sediment transport equations against 154 sets of field and 1093 sets of laboratory data. He found that Yang's equation is superior to others. According to his evaluation, his equation was followed by Shen-Hung, Ackers and White, Engelund-Hansen and the other equations.

Eleven sediment transport formulae were tested by Nakato (1990) against the field data measured at two United States Geological survey (USGS) gauging stations along the Sacramento River in California. The bed material sizes of these two rivers were classified ranging from fine sand to coarse sand. The equations included were Ackers and White, Einstein-Brown, Engelund-Fredsoe, Engelund-Hansen, Inglis-Lacey, Karim, Meyer-Peter and Mueller, Van Rijn, Schoklitsch, Toffaleti and Yang's formulas. General flow and sediment input variables required by each transport function, as well as dependent variables were summarized and detailed and measured hydraulic and sediment quantities including bed material size distributions were presented. The computed sediment discharge were tabulated for comparison and were directly compared against the measured suspended sediment discharges. The computed values, however, are found to deviate significantly from the measured values except a very few cases. The test results clearly demonstrate how difficult a task it is to predict sediment discharges in natural rivers.

The predictive capability of the sediment transport formulae of Ackers-White, Engelund-Hansen and Van Rijn at high flow velocities was investigated by Voogt et al (1991). Total load transport at high velocities over a fine sand bed (100-400 μm) was studied by analysing data collected from various literatures and new flume and field measurements. Flume experiments were performed to measure flow velocity and sand concentration profiles in a self-eroding flow initially free of sediment. The measured flow velocities were found upto 2.7 m/s. A two dimensional vertical mathematical model for suspended sediment was applied to compute the equilibrium transport rates. Finally predicted transport rates were compared with measured transport rates under flume and field conditions. It was found that the formulae of Engelund-Hansen and Van Rijn predict transport rates with reasonable agreement against the measurements.

Yang and Wan (1991) made a comparison of the overall accuracy of the prediction formula. They considered different ranges of sediment concentration, Froude number and slope for seven bed-material load formulae in their analysis. Four formulae that can compute bed-material load transport by size fractions were used to determine the particle size distribution of the bed-material in transportation. A total of 1119 sets of laboratory data and 319 sets of river data in the grain size range were used to evaluate and compare the accuracy of these formulae. The overall accuracy of formulae in descending order were Yang, Engelund-Hansen, Ackers and White (d_{50}), Laursen, Ackers and White (d_{35}), Colby, Einstein and Toffaleti formulae, when applied to laboratory flumes. The accuracy in descending order when applied to natural rivers were Yang, Toffaleti, Einstein, Ackers and White (d_{50}), Colby, Laursen, Engelund-Hansen and Ackers and White (d_{35}). However, these ratings may vary depending on the values of sediment concentration, Froude number and slope of the data used in comparison. The study also indicated that Yang's formula by size fractions can accurately predict the size distribution of bed-material in transportation while Einstein's hiding and lifting correction factors overcorrected the effect of non uniform size distribution of bed material on total bed-material transport.

Lukanda et al, (1992) studied the applicability of sediment transport theories for the world's second largest Zaire river. The objective of their study was to find a sediment transport formula useful for the analysis of the sediment problems experienced in the inner delta of the Zaire river's maritime reach. They used four formulae which were Schoklitsch, Shields, Meyer-Peter & Muller and Bagnold. According to their study, Bagnold's approach has been adapted for application in local stations for predicting morphologic changes.

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

2.1.1 Sediment transport and morphological studies in Bangladesh

Many studies have been done in the past on the application of sediment transport equations in Bangladesh. From the literature review, it has been found that Bari (1979) worked with the sediment prediction formula using the Ganges river data at Hardinge Bridge. His study indicates that sediment transport rate by Colby equation shows a closer match with the measured values and Engelund-Hansen formula gives consistent results. He also established a power law relation between sediment and water discharge.

Waliuzzaman (1986) selected five equations namely Yang (1973), Ackers and White (1973), Engelund-Hansen (1967), Hossain (1985) and Mantz (1983) for analysing the sediment transport in the river Gorai-Madhumati. He concluded that Hossain and Engelund-Hansen equation produced better prediction of sediment transport for the river Gorai-Madhumati.

The measured sediment transport for the Jamuna river is compared with the Engelund-Hansen formula for at a station condition (Klaassen et al. 1988). It was found that the measured sediment transport of the period 1968-1970 can be well represented by the Engelund-Hansen formula multiplied by 2, when channel dimensions are determined by the analysis of the measured BWDB cross-sections.

Alam and Hossain (1988) made a quantitative evaluation of the sediment transport rate for the Jamuna river and they also performed a comparative assessment of the applicability of few well-known formulae. Of all the formulae considered for their study, Colby and Hossain's formula gave consistent results. They showed that sediment discharge may satisfactorily be expressed as a function of water discharge and flow velocity.

Hossain and Barr (1988) compared eight well known transport equations against the data collected from various sources throughout the world. They considered Yang, Colby, Engelund-Hansen, Ackers and White, Einstein-Brown, Toffaletti, Holtroff and Hossain equation through systematic comparison against 800 field data and 3480 laboratory data. It was concluded that Hossain equation was superior to others considering all criteria of testing the efficiency against these large number independent data sets.

In connection with the design of the Teesta Barrage Project, BUET-BWDB (1988) conducted a study on the sediment transport characteristics of the river Teesta. They selected Yang, Engelund-Hansen and Colby's equation and concluded that Yang's equation was superior to others.

Hossain (1989) analyzed the data of the Ganges using more recent data of 1980 to 1988. He also found that Hossain and Engelund-Hansen formula produced more consistent and reliable results. Nilufer (1989) also concluded that Hossain's equation was more appropriate against the data of the Brahmaputra.

Based on non-dimensional considerations, a power type equation using regression technique was developed by Hossain (Hossain, 1992). He applied his approach for the Ganges river data at Hardinge Bridge and the Jamuna river data at Bahadurabad. His study was mainly concentrated to assess the applicability of few well-known sediment transport equations against the data of the Ganges and the Jamuna. According to him, the sediment transport equations which produced reasonable degree of accuracy were the Hossain, the Colby and the Engelund-Hansen equations.

More recently, some well-known sediment transport prediction formulae have been utilised and compared for the application in Bangladesh for morphological study. Galappatti (1993) used the Engelund-Hansen formula for the development of 1D morphological model for the Jamuna river. Islam (1994) also used Ackers and White, Engelund-Hansen, Engelund-Fredsoe and Van Rijn formulae for studying the bed level changes for the Ganges river by using one dimensional morphological model (MIKE 11). It has been found that the Engelund-Hansen formula is resonably good for predicting the bed level changes.

In FAP 1 (Annex 1, 1993), two prediction formulae such as the Engelund-Fredsoe and the Van Rijn formula have been used to calculate the sediment transport in the Brahmaputra River. These formulae were used for mathematical modelling of bend scour. The two formulas predict slightly larger transport rates than the Engelund-Hansen formula.

Based on measured data Matin and Mohiuddin (1994) attempted to develop a schematised transport equation applicable for the north-west regional rivers of Bangladesh. The relationship obtained were also compared with the schematised form of Engelund-Fredsoe (1976) and Van Rijn (1984) equations. It reveals from the study that Van Rijn predictor is comparatively found suitable for the prediction of sediment transport.

2.2 Exponent "b" in Schematised Transport Equation

As mentioned earlier that an approximate relationship between the exponent 'b' and the Shields parameter (θ) had been derived for the Meyer-Peter and Mueller transport formula which is later corrected for form roughness (Struiksma and Klaassen, 1988) and presented in Figure 2.1. This figure shows that Shields parameter (θ′) decreases with the increased value of exponent 'b' and vice versa. This evaluation indicated that the exponent 'b' is not always constant but is a function of (θ′), except for the case of Engelund-Hansen equation where 'b' equals to 5. The corrected expression for θ′ reads as :

$$\theta' = \frac{C^2}{C_{90}^2} \cdot \frac{u^2}{C^2 \Delta d_{50}} = \mu\theta \qquad (2.1)$$

where

$$C_{90} = 18 \log \left(\frac{12h}{d_{90}}\right) \qquad (2.2)$$

$$C = 18 \log \left(\frac{12h}{k_s}\right) \tag{2.3}$$

in which, θ is the dimensionless shear stress parameter based on grain roughness, θ is the dimensionless Shields parameter, C_{90} is the Chezy coefficient based on d_{90}, C is the overall Chezy coefficient based on k_s, Δ is the relative density, d_{50} is the median particle size of bed material, u is the depth averaged flow velocity, μ is the ripple factor, k_s is the Nikurradse roughness height and h is the water depth.

Struiksma and Klaassen (1988) studied the equilibrium bed topography in curved channels and developed the criteria for the spatial amplification of steady bed level perturbations. The results were used to derive a prediction for the threshold between meandering and braiding channels as shown in Figure 2.2. Here the exponent 'b' was found to be an important factor for deriving the threshold values. They showed that wave length L_p and damping length L_D of perturbations are dependent on the ratio of the adaptation length λ_s of the sediment transport and the bed topography development and the adaptation length λ_w of the main flow. This ratio was again related to the exponent 'b' as shown in Figure 2.3. The criteria derived for different planform of the rivers are as follows:

$\lambda_s/\lambda_w < \lambda_s/\lambda_w^*$: meandering

$\lambda_s/\lambda_w^* < \lambda_s/\lambda_w < \lambda_s/\lambda_w^{**}$: transition between meandering and braiding

$\lambda_s/\lambda_w^{**} < \lambda_s/\lambda_w$: braided

where λ_s/λ_w^* and λ_s/λ_w^{**} are lower and upper limit of harmonic range.

The values of λ_s/λ_w^* and λ_s/λ_w^{**} depend on the value of the exponent 'b', according to the following relationship:

$$\frac{\lambda_s^*}{\lambda_w} = \frac{2}{b-3} \tag{2.4}$$

and

$$\frac{\lambda_s}{\lambda_w}^{**} = \left[\frac{1}{2}(b+1)-\frac{1}{2}((b+1)^2 - 2(b-3))^{0.5}\right]^{-1} \qquad (2.5)$$

It is important to mention here that Figure 2.1 was used for the transformation of θ' to exponent 'b'. The proposed criterion for planform classification merely consists of computing the values of λ_s/λ_w and 'b' comparing these with the appropriate values of λ_s/λ_w^* and λ_s/λ_w^{**}. Figure 2.2 can also be used for this purpose. In this figure, the index B and M indicates whether the channel pattern is braided or meandering. Thus it is necessary to determine the accurate value of exponent 'b' for a fair prediction of channel pattern.

Struiksma et al (1985) have also shown the importance of exponent 'b' for bed deformation. Because the exponent 'b' affects the rate of damping in such a way that a decrease of the exponent 'b' leads to a considerable increase of damping.

For a constricted or a widened river sections, the influence of the exponent 'b' on the main parameters of sediment and flow in the river can be shown easily. Consider a river with fixed banks and constant discharge Q. The question is raised to what extent the depth will increase if the width is decreased. Indicating the original values of the parameters with subscript "o" and the new ones with "1", the following basic equations describe in principle the flow and sediment transport along a flow line (using depth instead of hydraulic radius):

<u>For Discharge</u> :

Continuity equation : $Q_o = Q_1$

Motion equation : $Q = B.C.h^{3/2}.S^{1/2}$

<u>For Sediment</u>:

Continuity equation : $Q_{S1} = Q_{So}$

Motion equation : $Q_S = B.a.u^b$

In fact two equilibrium situations were compared. These are the existing and the final future situation. For a restricted reduction in the width, the assumption is $C_1 \approx C_o$, as well as $d_1 \approx d_o$. This leads to the conclusion that 'a' and 'b' are also same in the two situations. It can be shown that:

$$\frac{h_1}{h_o} = \left(\frac{B_o}{B_1}\right)^{\frac{b-1}{b}} \tag{2.6}$$

and

$$\frac{S_1}{S_o} = \left(\frac{B_1}{B_o}\right)^{1-\frac{3}{b}} \tag{2.7}$$

A graphical representation of equations (2.6) and (2.7) is shown in Figure 2.4 which indicates the effect due to the constriction of river width. As an example, for 'b' equal to 3, slope does not change but depth will change. However, for higher values of 'b' both slope and depth become influenced.

2.3 Sediment Transport Equations

The mechanism of sediment transport has been a subject of study for centuries due to its importance in river regulation as well as in design and operation of canal systems. A number of relationship have been developed indicating the magnitude of sediment discharge as a function of the various flow parameters. None of the available formulae for the calculation of sediment discharge has gained universal acceptance in confidently predicting the sediment transport rate. The calculated results from different equations often differ drastically from each other and from the observed data.

Many theories have been put forward to provide the framework for sediment transport prediction. Only the sediment transport equations which are related to the present study has been outlined in the following sections.

2.3.1 Ackers & White (1973)

Based on analysis of 925 sets of flume and field data, the following empirical formula was proposed:

$$q_t = k\, u\, d_{35} \left(\frac{u}{u_*}\right)^n \left(\frac{Y - Y_{cr}}{Y_{cr}}\right)^m \tag{2.8}$$

The particle mobility parameter, Y can be expressed as:

$$Y = \left(\frac{u_*^{\,n}}{\sqrt{(s-1)\; g\; d_{35}}}\right) \left(\frac{u}{5.66 \log\left(\frac{10h}{d_{35}}\right)}\right)^{1-n} \tag{2.9}$$

The particle parameter D_* can be defined as:

$$D_* = d_{35} \left(\frac{(s-1) g}{\nu^2}\right)^{\frac{1}{3}} \tag{2.10}$$

The coefficients k, n, m are defined as:

$$k = 10^{-3.53 + 2.86 \log(D_*) - (\log D_*)^2} \quad For\ 1 < D_* < 60 \tag{2.11}$$

$$n = 1 - 0.56 \log(D_*) \quad For\ 1 < D_* < 60 \tag{2.12}$$

$$m = \frac{9.66}{D_*} + 1.34 \quad For\ 1 < D_* < 60 \tag{2.13}$$

$$k = 0.025,\ n = 0,\ m = 1.5,\ Y_{cr} = 0.17 \quad For\ D_* \geq 60 \tag{2.14}$$

The k and m coefficients were later (HR Wallingford, 1990) revised:

$$Y_{cr} = \frac{0.23}{D_*^{\,0.5}} + 0.14 \quad for\ 1 < D_* < 60 \tag{2.16a}$$

$$k = 10^{-3.46 + 2.79\log(D_*) - 0.98(\log D_*)^2} \quad For\ 1 < D_* < 60 \tag{2.15}$$

$$m = \frac{6.83}{D_*} + 1.67 \quad For\ 1 < D_* < 60\ ;\ m = 1.78 \quad For\ D_* \geq 60 \tag{2.16}$$

The form of the Y parameter ensures that the fine sediment transport depends upon the total bed shear stress and the coarse transport rate upon the effective grain shear stress.

2.3.2 Bagnold (1966)

The method of Bagnold is based on a energy balance concept relating the suspended load to the work done by the fluid. The total load transport is the sum of the volumetric suspended load and bed load transport and can be expressed as:

$$q_t = q_s + q_b \tag{2.17}$$

$$q_t = \frac{e_s(1-e_b)\tau_b u}{(\rho_s-\rho)g\cos\beta[(\frac{w_s}{u})-\tan\beta]} + \frac{e_b\tau_b u}{(\rho_s-\rho)g\cos\beta(\tan\phi-\tan\beta)} \tag{2.18}$$

2.3.3 Engelund-Hansen (1967)

The method of Engelund-Hansen is based on a energy balance concept. The total load transport can be expressed as:

$$q_t = \frac{0.05\, u^5}{(s-1)^2 g^{0.5} d_{50} C^3} \tag{2.19}$$

2.3.4 Hossain (1985)

In deriving this approach, it was argued that sediment concentration in a stream of steady water and sediment flows is a power function of

(a) the product of Froude number and slope of energy gradient

(b) the settling velocity ratio and

(c) the discharge ratio

The functional form of the equation could be expressed as follows:

$$C_t = A\ (X^a\ Y^b\ Z^c) \tag{2.20}$$

in which:

$$A = 6.946 * 100000 \quad For\ \frac{B}{H} < 500 \tag{2.21}$$

$$A = 6.946 * 1000000 \quad For\ \frac{B}{H} > 500 \tag{2.22}$$

$$X = \frac{VS}{(gH)^{1/2}} \tag{2.23}$$

$$Y = \frac{w_r}{w} \tag{2.24}$$

$$Z = \frac{Q}{Q_c} \tag{2.25}$$

Assessed discharge can be obtained from the following equation:

$$Q_c = [(2.15+K\ \frac{B}{H})\ H(gS)^{1/5}]^{5/2} \tag{2.26}$$

The value of K is proposed to be 0.055 when Q < 15000 cumec and 0.17 when Q > 15000 cumec. Settling velocity of the sediment particles have been computed using Rubey's equation as follows:

$$w = \sqrt{\frac{36\,\mu^2}{\rho_f^{\,2} d^2} + \frac{2}{3}\,\frac{(\gamma_s - \gamma_f)\,d}{\rho_f}} - \frac{6\mu}{\rho_f d} \tag{2.27}$$

2.3.5 Van Rijn (1984)

According to Van Rijn, suspended load transport (q_s) and bed load transport (q_b) can be computed as:

$$q_s = F\,u\,h\,c_a \tag{2.28}$$

$$q_b = 0.1\,(s-1)^{0.5}\,g^{0.5}\,d_{50}^{1.5}\,D_*^{-0.3}\,T^{1.5} \quad For\ T \geq 3 \tag{2.29}$$

in which:

$$c_a = 0.015\,\frac{d_{50}}{a}\,\frac{T^{1.5}}{D_*^{0.3}} \tag{2.30}$$

$$F = \frac{(\frac{a}{h})^{z'} - (\frac{a}{h})^{1.2}}{(1 - \frac{a}{h})^{z'}(1.2 - z')} \tag{2.31}$$

$$D_* = d_{50}\,\left(\frac{(s-1)g}{\nu^2}\right)^{\frac{1}{3}} \tag{2.32}$$

$$T = \frac{\tau_b' - \tau_{b,cr}}{\tau_{b,cr}} \tag{2.33}$$

$$\tau_b' = \rho g \left(\frac{u}{C'}\right)^2 \qquad (2.34)$$

$$u_* = \frac{g^{0.5}}{C}\, u \qquad (2.35)$$

$$C' = 18 \log\left(\frac{12h}{3d_{90}}\right) \qquad (2.36)$$

$$C = 18 \log\left(\frac{12h}{k_s}\right) \qquad (2.37)$$

$$\tau_{b,cr} = (\rho_s - \rho)\; g\; d_{50}\; \theta_{cr} \qquad (2.38)$$

$$z' = z + \psi \qquad (2.39)$$

$$z = \frac{w_s}{\beta \kappa u_*} \qquad (2.40)$$

$$\psi = 2.5 \left(\frac{w_s}{u_*}\right)^{0.8} \left(\frac{c_a}{c_o}\right)^{0.4} \qquad (2.41)$$

$$\beta = 1 + 2 \left(\frac{w_s}{u_*}\right)^2 \qquad (2.42)$$

$$d_s = [1 + 0.011\,(\sigma_s - 1)\,(T - 25)]\; d_{50} \qquad (2.43)$$

2.3.6 Yang (1973)

Yang assumed that the sediment transport is related to the unit stream power, defined as uS. The total sediment concentration (c_t), defined as the ratio of the sediment and fluid discharge per unit width, ($c = q_s/q$), was expressed as:

$$\log(c_t) = \alpha_1 + \alpha_2 \log\left(\frac{u\,S - u_{cr}\,S}{w_s}\right) \tag{2.44}$$

Analysis of flume and field data resulted in:

$$\alpha_1 = 5.435 - 0.286 \log\left(\frac{w_s d_{50}}{\nu}\right) - 0.457 \log\left(\frac{u_*}{w_s}\right) \tag{2.45}$$

$$\alpha_2 = 1.799 - 0.409 \log\left(\frac{w_s d_{50}}{\nu}\right) - 0.314 \log\left(\frac{u_*}{w_s}\right) \tag{2.46}$$

Atinitiation of motion the depth-averaged flow velocity, u_{cr} can be expressed as:

$$u_{cr} = \left(\frac{2.5}{\log\left(\frac{u_* d_{50}}{\nu}\right) - 0.06} + 0.66\right) w_s \quad For \quad 1.2 < \frac{u_* d_{50}}{\nu} < 70 \tag{2.47}$$

$$u_{cr} = 2.05\, w_s \quad For \quad \frac{u_* d_{50}}{\nu} \geq 70 \tag{2.48}$$

The total load transport rate is given by

$$q_t = 10^{-3}\, c_t\, u\, h \tag{2.49}$$

CHAPTER THREE

DATA ORGANIZATION

3.1 Introduction

There are many relationships which describe various aspects of the alluvial channel phemonenon. The majority of these are adjusted using laboratory and field data. The relationship or expressions based on such particularised laboratory or field data may be found inadequate when extrapolated to other conditions. Certainly the limitations of such relationship is the better understood. In this regard field data is of particular value in verifying the worth of any derived relationship. However, to some extent laboratory data used by various investigators can be utilised for any related comparative study.

The necessity for organizing a data-bank has been well recognised in the past. Such a data-bank can be of immense use to the others in related studies. In this connection, a substantial effort has been made to organize a data-bank which will be utilised in this study.

It is to be mentioned here that the present study concentrates mainly on the data from an alluvial river in Bangladesh for the development of a schematised sediment transport formula. In recent time, organizations under various FAP studies have been collecting flow and sediment data for studying the morphological behaviour of the major rivers in Bangladesh. For instance, extensive programme for collecting such data for the river Jamuna has been undertaken by the River Survey Project. A brief characteristic features of flow and sediment data of the Jamuna river will be described. In addtion, similar data obtained from Bangladesh Water Development Board (BWDB) has also been utilised in this study and summarized in this Chapter.

3.2 River Jamuna and Its Characteristics

The Jamuna river is a braided river system with several parallel channels in each cross-section. The number of this parallel channels are variable in space and time. The river basin of the Brahmaputra/Jamuna river extends over China, Bhutan, India and Bangladesh and it measures about 560,000 km^2. The length of the alluvial reach between the Indo-Chinese border and the confluence with the Ganges river is about 1,100 km. The length of the river in Bangladesh up to the confluence with the Ganges river is about 240 km. During the monsoon period from June to October the water-level and the discharges are high, during the lean period from November to March the water-levels and the discharges are low. Some characteristic water-levels and discharges of the Jamuna river near Bahadurabad are shown in Table 3.1. The water surface slope of the river decreases in down-stream direction. The average water surface slope is approximately 7.6 cm per km in the upper reach of the Jamuna river and 6.5 cm per km down-stream of Mathurapara. The variation of this slope with different discharges is relatively small. In general the grain size of the river reduces in the down-stream direction. The bed material is fine sand with an average size varying between 0.22 mm at Chilmari and 0.165 mm at Aricha. The gradation is about 1.3 which indicates fairly uniform sediments. The bank materials consist of a slightly cohesive top layer of mostly slightly clayey to clayey, sandy silt of low plasticity. This sediment consists of about 3 to 33 % clay, about 15 % silt and more than 50 % fine sand. This top layer has a thickness of an average 5 m at the banks and 1 to 2 m on the highest chars. Below the top layer loosely to medium densely packed micaceous silty fine sand is found until a depth of about 20 m below the ground level and at larger depths medium dense to dense silty fine sand is found (FAP 1 and FAP 21/22). This slightly cohesive top layer on non-cohesive silty fine sand may have some influence on the bank erosion process. The sediment transport by the Jamuna river is quite large. Coleman (1969) already gave some figures based on suspended load measurements at Bahadurabad during the period 1958-1962. Average yearly sediment transport is about 600 million tons. This is in line with figures based on the same data provided by Latif (1969). The average coarse suspended sediment transport is approximately 200 million tons per year, and the average fine suspended sediment transport is approximately 390 million tons per year. The analysis of several surveyed cross-sections showed that the steepest slope near a bank of silty fine sand is about 1:3 during the lean period. During the monsoon period temporarily steeper slopes upto the natural angle of repose can be expected. An average shifting rate of the Jamuna river is estimated at about 50 m/year (HALCROW/DHI/EPC/DIG, 1991b). The upper reaches of the river are widening over the last decades and the lower reaches seem to have started widening also recently. The widening of the braid belt is associated with the growth of island, chars and sandbars in the river. The bank erosion by less aggressive bends seem to be the main contribution to this gradual widening at a rate of 75 to 150 m/year.

3.3 Data Sources

Data from three sources have been collected to carry out this study. These are the field data from the River Survey Project (FAP 24) and the Bangladesh Water Development Board (BWDB) and laboratory data from various literature. In the following sections, a brief description of each data would be discussed.

3.3.1 Data from the River Survey Project (FAP 24)

The River Survey Project started in 1992 as a component of the Bangladesh Flood Action Plan. The main activities of this project are the execution of different types of surveys on the main rivers of Bangladesh, the processing the survey data and to store these data in a large data base and studying the morphological characteristics of the main rivers using the above mentioned data. The overall objective of the study component of the River Survey Project (FAP 24) is to improve the understanding of the behaviour of the main rivers in Bangladesh by studying the hydrological and morphological characteristics of the main river system.

The River Survey Project is collecting flow and sediment data by using the sophisticated instruments such as Ott current meter (mechanical), S4 Inter-ocean (electromagnetic) etc. for point current measurements, ADCP, EMF and float tracking etc. for integrated current measurements, pump bottle, depth-integrated suspended sediment sampler, Mex 3 turbidity recorder etc. for suspended sediment measurements, Helley-

Smith trap sampler, sand-dune tracking by echo sounding etc. for bed load sediment measurements, Van Veen grab and US BM-54 for river bed sampling.

Test gauging data performed by the River Survey Project (FAP 24) in the Jamuna River at Bahadurabad during the period of 20-22 August 1993 have been collected and organized to make the critical comparison between simplified method and multipoint method for calculating suspended sediment discharge. During these measurements, they selected 19 sampling verticals from the ADCP's on-line suspended sediment concentration profile. The sampling verticals are generally more dense for the cross-section where the suspended sediment concentration is relatively higher and vice versa. The suspended sediment samples were carried out as point sampling. The number of measuring points in a vertical depends on the water depth of that vertical. In this measurements, six point sampling in a vertical were done for depths more than 5 m and three points for depth less than 5 m.

The transverse distribution of total suspended sediment along the cross section are shown together with the sampling verticals in Figure 3.1. The verticals are relatively dense in the section having high sediment concentration. The data used for the computation of suspended sediment discharge is given in Table 3.2. In addition to this data, the grain size of bed material and the seasonal water level slopes also collected from the River Survey Project as shown in Table 3.3 which would be used in the present study.

3.3.2 Data from the Bangladesh Water Development Board (BWDB)

BWDB has been collecting the flow and sediment data at a number of stations on a weekly basis for the major rivers. The FAO-SF hydrological survey team started sediment investigations in 1965 in a more rational footing using improved techniques. However, they limited their attention to the suspended sediment only. Samples of water with sediment in suspension are normally taken by the Binkley sampler for every alternate vertical at which velocities are measured from a number of verticals at the gauging section and from two points on each vertical. The discharge and sediment measurement station for the Jamuna river at Bahadurabad is located at a distance of 100 m up-stream of the transit line gauge and the section is marked by permanent monument and pillars which are shown in Figure 3.2. Extensive flow and suspended bed material data have been collected from Surface Water Hydrology II, (BWDB) for the Jamuna river at Bahadurabad. Field sheets on sediment measurements and discharges are collected for the periods of 1984-1987. A total of 582 sets of vertical data of 83 channels have been organized from 16 measurements campaign. A summary of the different data range is given in Table 3.4. Details of these data are presented in Table 3.5. In additon to these, all the channel data have been processed for normalised channel and presented in Table 3.6. This normalisation was done by coverting the actual cross-sections to those of equivalent rectangular channel with same flowing capacity. Particularly, this data (Table 3.6) will be used for the development of sediment transport equation based on the concept of normalised channel section as described Chapter Six of this thesis.

In oder to verify the schematised sediment transport equation to be developed, an independent set of water and sediment measurements for the year 1993 has also been collected for the Jamuna river and is presnted in Table 3.7.

3.3.3 Data from various literatute

The different ranges of test data used by many investigators for deriving sediment transport equations have been collected from various literature in order to compare with the data for the main rivers in Bangladesh. Most of these data were based on flume experiments and are presented in Table 3.8. In addition to this data, a depth range as expected in the Jamuna river and assumed Froude number in an alluvial river has also been considered in order to make the graphical relation between the exponent 'b' and the Shields parameter (θ). These data are presented in Table 3.9.

The median particle diameter of bed material for the main rivers in Bangladesh is in the order of 0.14 mm to 0.30 mm. In the derivation of Bagnold and Meyer-Peter and Mueller sediment transport formulae, larger ranges of grain sizes were used (as shown in Table 3.8) than the median grain sizes for the main rivers in Bangladesh. On the other hand Meyer-Peter and Mueller and Yang used much steeper slopes for deriving their equation than the slopes in the alluvial rivers in Bangladesh. In general the slope varies between 4-9 cm/km for the alluvial rivers in Bangladesh.

CHAPTER FOUR

COMPUTATIONAL METHODOLOGY

4.1 Introduction

This Chapter deals with the methodology adopted for various analyses to carry out the study. The overall methodology includes the procedure used for comparison of various techniques for computation of suspended sediment discharge, methods to assess the exponent 'b' of the flow velocity and the schematised sediment transport relation to produce dimensionless sediment transport equation. The related equations and methodology presented in this Chapter will be dealt with in the subsequent analysis as referred to the next Chapters.

4.2 Methods Available for Computing Suspended Sediment Discharge

Suspended sediment discharge over an entire cross-section is usually measured by dividing the cross-section into a number of sections. Sediment discharge passing through each section is obtained by taking measurements along the vertical within the portion it represents. The sediment discharge per unit width in each vertical may be determined by graphical integration of the product of the velocity and sediment concentration throughout the depth and can be represented as follows:

$$q_s = \sum_{i=1}^{n} c_{si} u_i \Delta d_i \tag{4.1}$$

The number of measuring points in a vertical can vary according to the depth of the river and the size of the sediment in suspension. Basically two methods are classified for the technique of velocity measurements in a vertical such as multipoint and simplified methods.

Straub method and Chinese standard are the example of simplified methods which differ from the multipoint methods in that samples are taken at fewer points for the interest of reducing the work involved in taking and processing the measured data. Such method should be adopted only after results obtained with them are checked against measurements with multipoint methods. In the following sections simplified and multipoint methods are described.

4.2.1 Straub method

While investigating the sediment problem of the Missouri river, Straub established a method to compute the mean concentration of suspended sediment in a vertical. In this method, samples are collected at 0.2 depth and 0.8 depth and the values are weighted by 5/8 and 3/8 respectively. The mean concentration of suspended sediment in a vertical can be calculated approximately by the following expression:

$$C_s = \frac{3}{8} C_{0.8d} + \frac{5}{8} C_{0.2d} \qquad (4.2)$$

This method is best suited having a moderate water level slope and where the vertical sediment distribution is fairly constant. If the sediment distribution is logarithmic, this method is not sound theoretically.

4.2.2 Chinese standard

In this method fractions of depth 'k' is considered as a weight to be applied to the products of the velocity and sediment concentration which can be written as

$$q_s = \frac{d}{N} \sum_{i=1}^{N} k_i C_i u_i \qquad (4.3)$$

Values of the factor 'k' as recommended in the Chinese standards (Ministry of Water Conservancy, 1975b) are given in Table 4.1. The above formula applies to the method which measures velocity and sediment concentration simultaneously at each sampling point.

4.2.3 Multipoint method

The suspended sediment transport is calculated as the depth integration of the product of velocity (u) and concentration (c) at each point in a vertical. The suspended load transport per unit width, q_s (kg/s/m) can be computed as:

$$q_s = [\frac{1}{2} (u_1 c_1 z_1) + \sum_{i=1}^{n-1} (u_i c_i + u_{i+1} c_{i+1}) (z_{i+1} - z_i)] 10^{-3} \qquad (4.4)$$

The first term of the above equation is an estimate for the sediment transport between the lowest sampling point and the reference level. This estimation is necessary because of the difficulties to take samples very close to the river bed due to the structural limitations of the samplers. Also in the measurements by multipoint methods, an unmeasured zone exists in each vertical. The gradient of sediment concentration is the largest in this unmeasured zone (Dey and Matin, 1995). In order to compute the suspended sediment transport in this zone, it is necessary to specify the reference level, above which the sediment transport is considered as suspended load transport. Estimation of the measured suspended load transport without consideration of the concentration c_a at the reference level always underestimate the actual sediment transport. The reference concentration c_a is computed from the following expression as developed by Van Rijn (Van Rijn, 1984b).

$$c_a = 0.015 \frac{d_{50}}{a} \frac{T^{1.5}}{D_*^{0.3}} \qquad (4.5)$$

where 'a' is the reference level and can be taken equal to half the bed-form height (Δ), equal to Nikuradse roughness height (k_s), equal to the zero velocity level (z_0), equal to one percent of the vertical depth (h) as a minimum value or five percent of the vertical depth (h) as a maximum value. The Nikuradse roughness height k_s can be determined by the logarithmic flow velocity profile (Von Karman and Prandtl) as follows:

$$u = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_o}\right) \qquad z_0 = 0.033 k_s \tag{4.6}$$

4.3 Assessment of the Exponent "b"

In general, the value of the exponent 'b' from the sediment transport formula can be assessed straightforward analytically from the sediment transport equation in which the exponent of the flow velocity directly exists. For example, the Engelund-Hansen prediction formula directly yields the value of the exponent 'b' equal to 5. However, there are other sediment transport prediction formula where the exponent of the flow velocity does not exist directly. In order to assess the exponent 'b' of those prediction formula, two possible ways have been identified in this study. These are as follows:

The exponent 'b' of the flow velocity can be assessed by using the following relation:

$$b = \frac{dq_s}{du} \cdot \frac{u}{q_s} \tag{4.7a}$$

Here dq_s/du is the derivative of sediment transport per unit width with respect to 'u', 'u' is the flow velocity and 'q_s' is the sediment transport per unit width. The above analytical expression can only be used when it is possible to find the differential ds/du from the sediment transport prediction formula. However, there are some complicated sediment transport equations where there is a problem to find the differential ds/du. This problem can be solved numerically by determining $\Delta s/\Delta u$ and then using the following expression:

$$b \approx \frac{\Delta q_s}{\Delta u} \cdot \frac{u}{q_s} \tag{4.7b}$$

In order to make the graphical relation between the exponent 'b' and the Shields parameter (θ), it is necessary to compute the Chezy coefficient (C) and the water surface slope (S) for a given value of water depth and the depth averaged flow velocity. Here the two variables can be computed by Engelund-Hansen roughness predictor. The following stepwise procedures are used in the computations:

(a) assume h'

(b) compute u_*' from the following expression:

$$u = 2.5\ u_*'\ \ln\left(\frac{12h'}{2.5d_{50}}\right) \tag{4.8}$$

(c) compute θ'

(d) determine θ from the following expressions:

$$\theta' = 0.06 + 0.4\ \theta^2\ \mathit{for}\ \theta \leq 0.7 \tag{4.9}$$

$$\theta' = \theta\ \mathit{for}\ 0.7 < \theta < 1 \tag{4.10}$$

$$\theta' = (0.3 + 0.7\ \theta^{-1.8})^{-0.56}\ \mathit{for}\ \theta \geq 1 \tag{4.11}$$

(e) compute h′ = (θ′/θ) h and compare with the initial value

(f) repeat until h′ = constant

(g) compute C from the following expression:

$$C = 2.5\ g^{0.5}\left(\frac{h'}{h}\right)^{0.5} \ln\left(\frac{12h'}{2.5d_{50}}\right) \tag{4.12}$$

(h) compute S from the following equation:

$$u = C\sqrt{hS} \tag{4.13}$$

4.4 Schematised Sediment Transport Relation for the Development of Dimensionless Sediment Transport Equation

The relation between the dimensionless sediment transport (ψ) to the dimensionless

Shields parameter (θ) gives better understanding of the transport processes of alluvial river. This relation considers the bed-shear stress an important variable for sediment transport and can be expressed as follows:

$$\psi = \alpha(\theta-\theta_{cr})^{\beta} \tag{4.14}$$

Since Shields parameter (θ) tends to square of the flow velocity, it can be shown that exponent 'b' equal to 2β. And also in Bangladesh, usually the Shileds parameter (θ) is very very greater than the critical Shields value (θ_{cr}). Therefore the above expression can be simplified to:

$$\psi = \alpha(\theta)^{\frac{b}{2}} \tag{4.15}$$

The above expression can also be written in another form as

$$\frac{q_s}{\sqrt{g\Delta d_{50}^{\ 3}}} = \alpha \left(\frac{u^2}{C^2\Delta d_{50}}\right)^{\frac{b}{2}} \tag{4.16}$$

Most of the existing sediment transport prediction formula can be easily transformed into the dimensionless form of sediment transport as in equation (4.16).

CHAPTER FIVE

A THEORETICAL ANALYSIS ON THE TRANSPORT PREDICTORS FOR EVOLVING THE EXPRESSION OF THE EXPONENT VALUE

5.1 Introduction

In previous Chapter, methodology used for various analyses carried out in this study had been discussed. This Chapter mainly deals with the derivation of exponent 'b' for the selected prediction formula. These formulae were selected based on the criteria such that it is suitabile for the application in the alluvial river cases and the sediment transport is described as a function of the bed-shear stress and influenced by the accelerating and decelerating flow conditions.

5.2 Basis of the Derivation

The schematised sediment transport equation can be expressed as

$$q_s = a\ u^b \qquad (5.1)$$

Differentiation of the above expression with respect to 'u' gives

$$\frac{dq_s}{du} = \frac{b}{u}\ (a\ u^b) = \frac{b}{u}\ q_s \qquad (5.2)$$

In the derivation, first attempt was made to derive the exponent 'b' from the selected prediction formula and then relate the exponent 'b' to the Shields parameter (θ). It is evident that in the Shields parameter (θ), most of the hydraulic parameters (e.g slope, velocity, grain size etc.) influencing sediment transport exist.

5.3 Derivation from Selected Total Load Formula

Six total load prediction formulae are selected for the derivation of exponent 'b'. These are Ackers and White, Bagnold, Colby, Engelund-Hansen, Hossain, Van Rijn and Yang. The criteria of selecting these equations are stated in article 5.1. In the following section, the details of the derivation for each prediction formula are made and outlined.

5.3.1 Exponent of flow velocity for Ackers and White (1973) total load formula

The total load formula for Ackers and White had been presented in Chapter Two (Eq. 2.8). In equation (2.8), substituting the bed-shear velocity 'u_*' equal to $g^{1/2}$ u/C and considering ψ equal to Y/Y_{cr} gives

$$q_t = k\, d_{35} \left(\frac{C}{\sqrt{g}}\right)^n (\psi-1)^m\, u \qquad (5.3)$$

Differentiation of equation (5.3) with respect to u gives

$$\frac{dq_t}{du} = k\, d_{35} \left(\frac{C}{\sqrt{g}}\right)^n \left[m\, (\psi-1)^{m-1} \frac{d\psi}{du}\, u + (\psi-1)^m \right] \qquad (5.4)$$

Applying the relation (Eq. 4.7a) in equation (5.4) the following expression can be obtained

$$k\, d_{35} \left(\frac{C}{\sqrt{g}}\right)^n \left[m\, (\psi-1)^{m-1} \frac{d\psi}{du}\, u + (\psi-1)^m \right] = \frac{b}{u}\, q_t \qquad (5.5)$$

$$But \quad \frac{d\psi}{du} = \frac{d}{du}\left(\frac{Y}{Y_{cr}}\right) = \frac{1}{Y_{cr}} \frac{dY}{du} \qquad (5.6)$$

The particle mobility parameter, Y had been given in Chapter Two (Eq. 2.9). Substituting bed-shear velocity 'u_*' equal to $g^{1/2}$ u/C in equation (2.9) and then simplifying yields

$$Y = \frac{1}{\sqrt{(s-1)gd_{35}}} \left(\frac{\sqrt{g}}{C}\right)^n \frac{u}{\left[5.66 \log\left(\frac{10h}{d_{35}}\right)\right]^{1-n}} \tag{5.7}$$

Differentiating equation (5.7) with respect to 'u' and substituting in equation (5.6) yields

$$\frac{d\psi}{du} = \frac{1}{Y_{cr}} \cdot \frac{1}{\sqrt{(s-1)gd_{35}}} \left(\frac{\sqrt{g}}{C}\right)^n \frac{1}{\left[5.66 \log\left(\frac{10h}{d_{35}}\right)\right]^{1-n}} \tag{5.8}$$

Now combining equations (5.3), (5.5) and (5.8) yields the exponent b as

$$b = 1 + \frac{m}{1 - \frac{Y_{cr}}{Y}} \tag{5.9}$$

in which:

$$Y = \left(\frac{\sqrt{g}}{C}\right)^{n-1} \sqrt{\frac{\theta d_{50}}{d_{35}}} \left(\frac{1}{5.66\log\left[\frac{10h}{d_{35}}\right]}\right)^{1-n} \tag{5.10}$$

and the expression for m and Y_{cr} can be obtained in equations (2.13), (2.14), (2.16) and (2.16a) respectively in Chapter Two.

5.3.2 Exponent of flow velocity for Bagnold (1966) total load formula

The total load formula for Bagnold had been presented in Chapter Two (Eq. 2.18). In equation (2.18), the bed slope, $\tan\beta$ ($= S_b$) is very very less than the value of the dynamic friction coefficient, $\tan\phi$ ($= 0.6$) and again the bed slope, $\tan\beta$ ($= S_b$) is very very less than the ratio of the fall velocity to the bed-shear velocity (i.e w_s/u_*). Therefore neglecting the parameter $\tan\beta$ and substituting bed-shear stress, τ_b equal to ρghS in equation (2.18) yields

$$q_t = \frac{u^3}{C^2 \Delta \cos\beta} \left[\frac{e_s (1 - e_b)}{w_s} + \frac{e_b}{\tan\phi}\right] \qquad (5.11)$$

$$\text{Now considering} \quad \psi = \frac{e_s (1 - e_b) u}{w_s} + \frac{e_b}{\tan\phi} \qquad (5.12)$$

Then equation (5.11) yields

$$q_t = \frac{u^3}{C^2 \Delta \cos\beta} \psi \qquad (5.13)$$

Now differentiation of equation (5.13) with respect to 'u' gives

$$\frac{dq_t}{du} = \frac{1}{C^2 \Delta \cos\beta} \left[3u^2 \psi + u^3 \frac{e_s (1-e_b)}{w_s}\right] \qquad (5.14)$$

Again applying the relation (Eq. 4.7a) in equation (5.14) yields

$$\frac{1}{C^2 \Delta \cos\beta} \left[3u^2 \psi + u^3 \frac{e_s (1-e_b)}{w_s}\right] = \frac{b}{u} q_t \qquad (5.15)$$

Combining equations (5.13), (5.15) and with 'u' equal to $C(\Delta d_{50}\, \theta)^{1/2}$, it is possible to obtain the exponent 'b' as

$$b = 3 + \frac{1}{1 + \dfrac{e_b}{e_s (1 - e_b) \tan\phi} \cdot \dfrac{w_s}{C \sqrt{\Delta d_{50} \theta}}} \qquad (5.16)$$

5.3.3 Exponent of flow velocity for Colby (1957) total load formula

Colby studied the variation of unmeasured sediment load of several streams in U.S.A. He has found that the unmeasured sediment load, q_s (kN/day/m) increases with the mean velocity of flow, U (m/s). The relationship obtained between these two parameters can be expressed as follows:

$$q_s = 353.6\ U^{3.1} \tag{5.17}$$

The exponent of the flow velocity, 'b' can be obtained straightforward analytically from the above equation and found to be 3.1.

5.3.4 Exponent of flow velocity for Engelund-Hansen (1967) total load formula

The total load formula for Engelund-Hansen had been presented in Chapter Two (Eq. 2.19). The exponent of the flow velocity, 'b' can be obtained straightforward analytically from equation (2.19) and found to be 5.

5.3.5 Exponent of flow velocity for Van Rijn (1984) total load formula, original form

The total load transport (q_t) for Van Rijn formula can be expressed as

$$q_t = F\ u\ h\ c_a + 0.1\ (s-1)^{0.5} g^{0.5} d_{50}{}^{1.5} \frac{T^{1.5}}{D_*{}^{0.3}} \tag{5.17a}$$

The reference concentration c_a was presented in Chapter Two (Eq. 2.30). Substituting the value of c_a in equation (5.17a) and then simplifying gives

$$q_t = A\ T^{1.5}\ u^3 \tag{5.18}$$

In which A is considered constant for the simplification of derivation and is given in the following expression

$$A = \frac{1}{C^2 s}\ [0.015\, F\ \frac{d_{50}}{a}\ \frac{1}{D_*{}^{0.3}} + 0.10 \frac{d_{50}}{D_*{}^{0.3}} \frac{1}{Ch} \sqrt{\frac{g}{\theta}}\ ] \tag{5.19}$$

The transport stage parameter T was presented in Chapter Two (Eq. 2.33), Substituting T in equation (5.18) and considering ψ equal to $\tau_b'/\tau_{b,cr}$ yields

$$q_t = A\ (\psi-1)^{1.5}\ u^3 \tag{5.20}$$

Differentiation of equation (5.20) with respect to 'u', it is possible to obtain the following expression

$$\frac{dq_t}{du} = A\left[\frac{3\rho g}{C'^2 \tau_{b,cr}} (\psi-1)^{0.5} u^4 + 3 (\psi-1)^{1.5} u^2\right] \tag{5.21}$$

Now applying the relation (Eq. 4.7a) in equation (5.21) gives

$$A\left[\frac{3\rho g}{C'^2 \tau_{b,cr}} (\psi-1)^{0.5} u^4 + 3 (\psi-1)^{1.5} u^2\right] = \frac{b}{u} q_t \tag{5.22}$$

Combining equations (5.20) and (5.22), it is possible to obtain the expression for exponent 'b' as

$$b = 3 + \frac{3}{1-\frac{\theta_{cr}}{\theta}\left(\frac{C'}{C}\right)^2} \tag{5.23}$$

5.3.6 Exponent of flow velocity for Van Rijn (1984) total load formula, simplified form

The simplified form of Van Rijn formula for total load transport can be expressed as

$$q_t = \left(\frac{u-u_{cr}}{\sqrt{(s-1) g d_{50}}}\right)^{2.4} \left[0.012\, uh \frac{d_{50}}{h} \left(\frac{1}{D_*}\right)^{0.6} + 0.005\, uh \left(\frac{d_{50}}{h}\right)^{1.2}\right] \tag{5.24}$$

The above expression can also be simplified in the following form

$$q_t = A \left(1-\frac{u_{cr}}{u}\right)^{2.4} u^3 \tag{5.25}$$

In which A is considered constant for the simplification of derivation and is given in the following expression

$$A = \frac{1}{C^2 S} \left(C \sqrt{\frac{\theta}{g}}\right)^{2.4} \left[0.012 \frac{d_{50}}{h} \left(\frac{1}{D_*}\right)^{0.6} + 0.005 \left(\frac{d_{50}}{h}\right)^{1.2}\right] \qquad (5.26)$$

Now considering ψ equal to $(1-u_{cr}/u)$, equation (5.25) gives

$$q_t = A\, \psi^{2.4}\, u^3 \qquad (5.27)$$

Differentiation of equation (5.27) with respect to 'u', it is possible to obtain

$$\frac{dq_t}{du} = A\ (2.4\, u_{cr}\, \psi^{1.4}\, u + 3\, \psi^{2.4}\, u^2] \qquad (5.28)$$

Now applying the relation (Eq. 4.7a) in equation (5.28) yields

$$A\ (2.4\, u_{cr}\, \psi^{1.4}\, u + 3\, \psi^{2.4}\, u^2] = \frac{b}{u} q_t \qquad (5.29)$$

Combining equations (5.27),(5.29) and with 'u' equal to $(\Delta d_{50}\theta)^{1/2}$, the exponent 'b' yields as

$$b = 3 + \frac{2.4}{C \frac{\sqrt{\Delta d_{50}\theta}}{\bar{u}_{cr}} - 1} \qquad (5.30)$$

In which the critical velocity, u_{cr} according to Shields can be obtained by the following expressions

$$u_{cr} = 8.50\ (d_{50})^{0.6} \log\left(\frac{12h}{3d_{90}}\right) \quad for\ 0.0005 \le d_{50} \le 0.002 \qquad (5.31)$$

$$u_{cr} = 0.19\ (d_{50})^{0.1} \log\left(\frac{12h}{3d_{90}}\right) \quad for\ 0.0001 \le d_{50} \le 0.0005 \qquad (5.32)$$

5.3.7 Exponent of flow velocity for Yang (1973) total load formula

The total sediment concentration, c_t had been presented in Chapter Two (Eq. 2.44) and can be rewritten as

$$c_t = 10^{\alpha_1} . \left(\frac{uS-u_{cr}S}{w_s}\right)^{\alpha_2} \tag{5.33}$$

The total load transport, q_t was presented in Chapter Two (Eq. 2.49). Substituting the value of c_t in equation (2.49) and with 'S' equal to u^2/C^2h gives

$$q_t = 10^{\alpha_1-3}\ h\ \left[\frac{1}{C^2 . h . w_s}\right]^{\alpha_2} (u-u_{cr})^{\alpha_2}\ u^{2\alpha_2+1} \tag{5.34}$$

In practical cases the critical depth averaged velocity, u_{cr} is very very less than depth averaged velocity 'u'. Therefore neglecting the term $u_{cr,}$ the above expression can be rewritten as

$$q_t = 10^{\alpha_1-3}\ h\ \left[\frac{1}{C^2 . h . w_s}\right]^{\alpha_2} u^{3\alpha_2+1} \tag{5.35}$$

Differentiating equation (5.35) with respect to 'u' and applying the relation (Eq. 4.7a) yields

$$(3\alpha_2+1)\ 10^{\alpha_1-3}\ h\ \left[\frac{1}{C^2 . h . w_s}\right]^{\alpha_2} u^{3\alpha_2} = \frac{b}{u}\ q_t \tag{5.36}$$

Combining equation (5.35) and (5.36) gives the exponent 'b' as

$$b = 3\alpha_2+1 \tag{5.37}$$

Substituting the parameter α_2 from equation (2.46) and with the bed-shear velocity u_* equal to $(g\Delta d_{50}\theta)^{1/2}$ yields the above expression as

$$b = 6.397 - 1.227 \log \left(\frac{w_s d_{50}}{\nu}\right) - 0.942 \log \left(\frac{\sqrt{g \Delta d_{50} \theta}}{w_s}\right) \tag{5.38}$$

5.3.8 Exponent of flow velocity for Hossain (1985) total load formula

The total average sediment concentration, C_t (in ppm) had been presented in Chapter Two (Eq. 2.20). Substituting the value of X, Y and Z presented in Chapter Two in equation (2.20) and then simplifying yields the following expression

$$C_t = M \left[\frac{uS}{\sqrt{gH}}\right]^{0.745} \left[\frac{u}{H.\sqrt{g}.\sqrt{HS}}\right]^{0.5} \tag{5.39}$$

In which M is considered constant for the simplification of derivation and is given by the following expression:

$$M = A \left[\frac{w_r}{w}\right]^{0.633} \left[\frac{B}{(2.15 + KB/H)^{5/2}}\right]^{0.5} \tag{5.40}$$

The total load transport, q_t can be expressed as

$$q_t = 10^{-3} C_t V H \tag{5.41}$$

Substituting the expression C_t in equation (5.41) and then simplifying, it is possible to obtain the following expression

$$q_t = M \frac{u^{3.25}}{(\sqrt{g})^{1.25} C H^{0.625}} \tag{5.42}$$

Therefore the exponent of the flow velocity is obtained straightforward analytically from the above expression and the value 'b' is found to be 3.25.

5.4 Derivation from Selected Bed Load Formula

Three bed load prediction formulae are selected for the derivation of exponent 'b'. These are Meyer-Peter and Mueller, two form of Van Rijn formula and Parker & Klingeman formula. The details of the derivation for each bed load prediction formula are made and outlined in the following sections.

5.4.1 Exponent of flow velocity for Meyer-Peter and Mueller (1948) bed load formula

The bed load transport formula in dimensionless form can be expressed as:

$$\Phi_b = 8\ (\mu\ \Theta - 0.047)^{1.5} \qquad (5.43)$$

Substituting ϕ_b equal to $q_b/(\Delta g d_{50}^3)^{1/2}$ and considering ψ equal to $\mu\theta$, the above expression yields

$$q_b = 8\ \sqrt{\Delta g d_{50}^3}\ (\psi - 0.047)^{1.5} \qquad (5.44)$$

Differentiation of equation (5.44) with respect to 'u' gives

$$\frac{dq_b}{du} = 24\ \frac{\mu\ \sqrt{\Delta g d_{50}{}^3}}{C^2 \Delta d_{50}}\ (\psi - 0.047)^{0.5}\ u \qquad (5.45)$$

Applying the relation (Eq. 4.7a) in equation (5.45) yields

$$24\ \frac{\mu\ \sqrt{\Delta g d_{50}{}^3}}{C^2 \Delta d_{50}}\ (\psi - 0.047)^{0.5}\ u = \frac{b}{u}\ q_b \qquad (5.46)$$

Combining equation (5.44) and (5.46) yields the exponent 'b' as

$$b = \frac{3}{1 - \frac{0.047}{\mu\Theta}} \qquad (5.47)$$

It is worthwhile to mention here that the above expression is similar to the expression (except the parameter μ) derived by de Vries (1987).

5.4.2 Exponent of flow velocity for Van Rijn (1984) bed load formula, original form

The bed load transport formula for Van Rijn had been presented in Chapter Two (Eq. 2.29) and can be rewritten as:

$$q_b = 0.10\, d_{50}\, g^{0.5} \sqrt{\Delta d_{50}}\, \frac{T^{1.5}}{D_*^{0.3}} \tag{5.48}$$

Substituting $(\Delta d_{50}\theta)^{1/2}$ equal to $u/C\theta^{1/2}$ and T equal to $(\tau_b'/\tau_{b,cr}-1)$, the above expression yields

$$q_b = A \left(\frac{\tau_b'}{\tau_{b,cr}} - 1\right)^{1.5} u \tag{5.49}$$

In which A is considered constant for the simplification of derivation and is given by the following expression:

$$A = 0.10 \sqrt{\frac{g}{\theta}}\, \frac{d_{50}}{C\, D_*^{0.3}} \tag{5.50}$$

Considering ψ equal to $\tau_b'/\tau_{b,cr}$ and differentiating equation (5.49) with respect to 'u' gives

$$\frac{dq_b}{du} = A \left[\frac{3\rho g}{\tau_{b,cr}\, C'^2} (\psi-1)^{0.5}\, u^2 + (\psi-1)^{1.5}\right] \tag{5.51}$$

Applying the relation (Eq. 4.7a) in equation (5.51) yields

$$A \left[\frac{3\rho g}{\tau_{b,cr}\, C'^2} (\psi-1)^{0.5}\, u^2 + (\psi-1)^{1.5}\right] = \frac{b}{u}\, q_b \tag{5.52}$$

Combining equation (5.49) and (5.52), it is possible to obtain the exponent 'b' as

$$b = 1 + \frac{3}{1 - \frac{\theta_{cr}}{\theta} \left(\frac{C'}{C}\right)^2} \tag{5.53}$$

5.4.3 Exponent of flow velocity for Van Rijn (1984) bed load formula, simplified form

The bed load transport formula for Van Rijn equation in simplified form can be expressed as:

$$q_b = 0.005\, u\, h \left(\frac{u - u_{cr}}{\sqrt{(s-1)\, g\, d_{50}}}\right)^{2.4} \left(\frac{d_{50}}{h}\right)^{1.2} \tag{5.54}$$

Substituting 'h' equal to u^2/C^2S and considering ψ equal to $(1-u_{cr}/u)$, the above expression gives

$$q_b = A\, \psi^{2.4}\, u^{0.6} \tag{5.55}$$

In which A is assumed constant for the simplification of derivation and is given by the following expression:

$$A = 0.005\, d_{50}^{1.2} \frac{(C^2 S)^{0.2}}{\left(\sqrt{\frac{g}{C^2 \theta}}\right)^{2.4}} \tag{5.56}$$

Now differentiation of equation (5.55) with respect to 'u' gives

$$\frac{dq_b}{du} = A \left[0.6 \frac{\psi^{2.4}}{u^{0.4}} + 2.4\, \psi^{1.4} \frac{u_{cr}}{u^{1.4}}\right] \tag{5.57}$$

Applying the relation (Eq. 4.7a) in equation (5.57) yields

$$A \left[0.6 \frac{\psi^{2.4}}{u^{0.4}} + 2.4\, \psi^{1.4} \frac{u_{cr}}{u^{1.4}}\right] = \frac{b}{u}\, q_b \tag{5.58}$$

Now combining equation (5.55) and (5.58) and with 'u' equal to $C(\Delta d_{50}\theta)^{1/2}$, it is possible to obtain the exponent 'b' as

$$b = 0.6 + \frac{2.4}{C\,\dfrac{\sqrt{\Delta d_{50}\theta}}{u_{cr}} - 1} \qquad (5.59)$$

5.4.4 Exponent of flow velocity for Parker and Klingeman (1982) bed load formula

The bed load transport formula for gravel bed river can be expressed as

$$q_b = \frac{W^*}{\Delta}\, g^{1/2}\, (hS)^{3/2} \qquad (5.60)$$

The expression for the parameter w^* is given as follows

$$w^* = \alpha_2\, \left(1 - \frac{0.822}{\Phi_{50}}\right)^{4.5} \quad for\ \Phi_{50}\ )\ 1.65 \qquad (5.61)$$

Substituting the expression w^* in equation (5.60) and then simplifying yields

$$q_b = A\, \left(1 - \frac{0.822}{\Phi_{50}}\right)^{4.5} u^3 \qquad (5.62)$$

In which A is considered constant for the simplification of derivation and is given by the following expression:

$$A = \frac{\alpha_2 g^{1/2}}{\Delta C^3} \qquad (5.63)$$

Now differentiating equation (5.62) with respect to 'u' gives

$$\frac{dq_b}{du} = A\, \left[7.398\, \frac{u^2}{\Phi_{50}}\, \left(1 - \frac{0.822}{\Phi_{50}}\right)^{3.5} + 3u^2\, \left(1 - \frac{0.822}{\Phi_{50}}\right)^{4.5}\right] \qquad (5.64)$$

Applying the relation (Eq. 4.7a) in equation (5.64) yields

$$A\left[7.398\frac{u^2}{\Phi_{50}}\left(1-\frac{0.822}{\Phi_{50}}\right)^{3.5}+3u^2\left(1-\frac{0.822}{\Phi_{50}}\right)^{4.5}\right]=\frac{b}{u}q_b \qquad (5.65)$$

Combining equation (5.62) and (5.65), it is possible to obtain the exponent 'b' as

$$b = 3\left[\frac{\Phi_{50}+1.644}{\Phi_{50}-0.822}\right] \qquad (5.66)$$

In which Φ_{50} equal to $\tau_{50}^*/0.0876$ and τ_{50}^* equal to $hS/\Delta d_{50}$. The value of α_2 equal to 11.2 according to Parker and Klingeman.

The exponent 'b' of the flow velocity have already been derived for the total and bed load transport formulae. In the following tables the expressions of exponent 'b' for each total load and bed load formula are given.

Total load formula	Expression of exponent b
Ackers & White (1973)	$b = 1 + \frac{m}{1-\frac{Y_{cr}}{Y}}$
Bagnold (1966)	$b = 3 + \frac{1}{1+\frac{e_b}{e_s(1-e_b)\tan\phi}\cdot\frac{w_s}{C\sqrt{\Delta d_{50}\theta}}}$
Colby (1957)	$b = 3.1$
Engelund-Hansen (1967)	$b = 5$
Hossain (1985)	$b = 3.25$
Van Rijn (1984), original	$b = 3 + \frac{3}{1-\frac{\theta_{cr}}{\theta}\left(\frac{C'}{C}\right)^2}$
Van Rijn (1984), simplified	$b = 3 + \frac{2.4}{C\frac{\sqrt{\Delta d_{50}\theta}}{\bar{u}_{cr}}-1}$
Yang (1973)	$b = 6.397 - 1.227\log\left(\frac{w_s d_{50}}{\nu}\right) - 0.942\log\left(\frac{\sqrt{g\Delta d_{50}\theta}}{w_s}\right)$

Bed load formula	Expression for exponent b
Meyer-Peter & Mueller (1948)	$b = \frac{3}{1 - \frac{0.047}{\mu\theta}}$
Van Rijn (1984), original	$b = 1 + \frac{3}{1 - \frac{\theta_{cr}}{\theta} (\frac{C'}{C})^2}$
Van Rijn (1984), simplified	$b = 0.6 + \frac{2.4}{C \frac{\sqrt{\Delta d_{50} \theta}}{u_{cr}} - 1}$
Parker & Klingeman (1982)	$b = 3 [\frac{\Phi_{50} + 1.644}{\Phi_{50} - 0.822}]$

CHAPTER SIX

ANALYSIS, RESULTS AND DISCUSSIONS

6.1 Introduction

In this Chapter, various analyses carried out for the present study and the results obtained have been discussed. These analyses include the performance of the simplified methods over multipoint methods for assessing suspended sediment discharge computation, the ranges of exponent 'b' of the flow velocity for the selected prediction formula and the schematised sediment transport equation in dimensionless form developed for the Jamuna river. It is to be mentioned here that the relevant computational methodology of the present analyses and related equations used for various computations have already been discussed in Chapter Four.

6.2 Performance of the Simplified Methods

The computation of suspended sediment discharge based on simplified methods such as Straub method, Chinese standard and measured multipoint methods have been compared utilising the data given in Table 3.2.

For computing suspended sediment discharge by Straub method, mean sediment concentration for each vertical was determined by equation (4.2). The sediment discharge is then computed by multiplying the depth averaged flow velocity, mean sediment concentration and the vertical depth. On the other hand, in sediment discharge computed by Chinese standard, equation (4.3) was utilised. It is to be noted here that in Chinese standard, two different weighting factors were used as shown in Table 4.1 for the consideration of two (i.e 0.2d and 0.8d) and three (i.e 0.2d, 0.6d and 0.8d) measuring points in a vertical. Again, considering multipoint in a vertical the measured sediment discharge was computed by using equation (4.4). In this computation, reference concentration c_a were calculated using equation (4.5) in which the reference level 'a' was considered equal to the Nikuradse roughness height, k_s. This roughness height was determined from the logarithmic flow velocity profiles as defined in equation (4.6).

The results obtained using various techniques for the computation of sediment discharge are summarized in Table 6.1. The sediment discharge computed by Straub method shows good correlation (r^2=0.99) with the measured sediment discharge considering multipoint in a vertical. Results are shown in Figure 6.1. The total sediment discharge computed by this method is 21,642 kg/s which is 4.2 % less compared to the measured sediment discharge. Again the results obtained by Chinese standard considering two and three points in a vertical were also plotted in Figure 6.2 and Figure 6.3 where the coefficient of correlation are found to be 0.96 and 0.98 respectively. The sediment discharge considering two and three points give 22,449 kg/s and 22,402 kg/s which is 0.6 % and 0.8 % less than the measured sediment discharge.

6.2.1 Comments on results

The analysis shows that simplified methods for assessing suspended sediment discharge seems to be satisfactory. The present analysis also indicates that the two point Straub method comparatively underestimates the sediment discharge than the two point Chinese standard. The later method gives approximately closer to the discharge measured by multipoint methods. In summary, it is apparent that two and three point Chinese standard are found consistent compared to Straub method. However two point Chinese standard gives relatively better result.

6.3 Ranges of Exponent "b"

The derivation of exponent 'b' of the flow velocity have already been made in Chapter Five for different transport formulae. The ranges of exponent 'b' for the selected prediction formulae were compared utilising the data shown in Table 3.9.

In the computation of exponent 'b', the Chezy roughness coefficient (C) and the water surface slope (S) were calculated using equation (4.12) and (4.13). The median particle size (d_{50}) for the Jamuna river was taken 0. 22 mm.

The results of exponent 'b' obtained from each total load prediction formula were plotted with the Shields parameter (θ) shown in Figure 6.4. In this figure, it is seen that most of the sediment transport prediction formula show an increase of exponent 'b' with a decrease of Shields parameter (θ). But the exceptions are seen for the Bagnold formula in which the exponent 'b' is decreasing with the decrease of Shields parameter (θ). For the Colby, Engelund-Hansen and the Hossain formula, the exponent 'b' is found to be constant. This is because a term related to initiation of motion were not included with their formulae. It is also evident from Figure (6.4) that at higher values of θ, variation of exponent 'b' is almost constant, however at smaller values, this variation is significant. The ranges of exponent 'b' for each total load prediction formula are shown in Table 6.2.

For the selected bed load prediction formula, the results of exponent 'b' were also plotted with the Shields parameter (θ) as shown in Figure 6.5. This figure indicates that the exponent 'b' computed by the simplified form of Van Rijn formula gives extremely higher range of exponent 'b' compared to the Van Rijn original form. The reason could be that the simplified form of Van Rijn formula was based on computer computations and regression analysis (Van Rijn 1992). The range of exponent 'b' for Parker and Klingeman (Parker and Klingeman, 1982) formula is approximately similar to the original formula of Van Rijn whereas Meyer-Peter and Mueller formula gives smaller values than the original formula of Van Rijn. The ranges of exponent 'b' for each bed load prediction formula are shown in Table 6.3.

6.3.1 Sensitivity analysis

The sensitivity of the exponent 'b' for the selected prediction formulae was compared utilising the data shown in Table 3.9. This sensitivity analysis was based on two parameters such as variation of grain size (d_{50}) and with variation of water surface slope (S).

The results of the exponent 'b' with variation of grain size for each total load prediction formula were plotted with the Shields parameter (θ) shown in Figures 6.6 to

6.9. From these figures, it is seen that the exponent 'b' obtained from Ackers and White and Van Rijn formula are very sensitive than other formulae used. Finer bed material show higher range of exponent 'b' whereas coarser bed material show lower range of exponent 'b'.

On the other hand, results of the exponent 'b' obtained with varying water surface slopes (S), based on the average condition of the Jamuna river were also plotted with the Shields parameter (θ) shown in Figure 6.10. In this figure, it is observed that the influence of slope on the exponent 'b' is sensitive for Van Rijn formula at lower value of Shields parameter, but less sensitive for other formula used in this study.

6.3.2 Comments on results

The exponent of the flow velocity 'b' varies between 3.1 to 8.5 for the total load transport and 3.3 to 10.5 for bed load transport. It is evident that most of the sediment transport prediction formulae show an increase of the exponent 'b' with a decrease of Shields parameter (θ). It is also observed that at higher depth, the variation of exponent 'b' is negligible. Little influence of slope on the exponent 'b' was found at low values of the Shields parameter (θ). However, the influence of the grain sizes on the exponent 'b' is found to be significant for the cases of Ackers & White and Van Rijn formula.

6.4 Schematised Sediment Transport Predictors

The developed dimensionless sediment transport equation has been compared with the selected sediment transport prediction formula based on two considerations. In the first consideration, the dimensionless sediment transport equation has been made utilising the data summarizing in Table 3.4 which was based on the data from each vertical of the cross sections. The details of this data are also shown in Table 3.5. In the second consideration, the same transport equation has also been made utilising the data given in Table 3.6 which was processed for normalized channel section. In the following sections, these analyses and results are discussed.

6.4.1 Analysis against the data from each vertical

The measured suspended sediment transport per unit width (q_s) is calculated from the measured sediment concentration, depth averaged flow velocity and vertical depth. The suspended sediment transport per unit width for the selected prediction formulas were also computed. Table 3.3 shows the grain size and water level slopes used for this computation. The suspended sediment transport from the measured data and with the prediction formulae was then transformed into the dimensionless sediment transport (ψ) and the Shields parameter (θ) was computed from the measured data using equation (4.16).

A linear regression analysis has been made for the measured data with the dimensionless Shields parameter (θ) as an independent variable and the dimensionless sediment transport (ψ) as a dependent variable in which a coefficient of correlation is found to be 0.80. Power type equation has been developed relating ψ and θ by employing regression technique. The relationship obtained is shown in Figure 6.11 and can be expressed as:

$$\psi = \alpha\ \theta^{b/2} \qquad (6.1)$$

Here the coefficient α is found to be 10.96 and the power b/2 equal to 1.83 which is the exponent of the Shields parameter (θ) and 'b' equal to 3.66.

The value of the coefficient α can again be related to the roughness parameter (Chezy C) of alluvial river. Therefore an attempt has been made to incorporate the roughness parameter in equation (6.1). Considering the dimensionless term $C/g^{0.5}$ is a third variable and the other two dimensionless terms ψ and θ can be correlated and the following relationship is obtained:

$$\psi = 0.16\ \left(\frac{C}{\sqrt{g}}\right)^{1.45} \theta^{1.83} \qquad (6.2)$$

Equation (6.2) is the Suggested schematised sediment transport equation (non dimensional form) developed based on the data from each vertical of the Jamuna river cross sections. In order to show the degree of performance of the Suggested equation (Eq.

6.2), lines are generated for various Chezy's C value as shown in Figure 6.12.

6.4.2 Analysis against the data from normalized channel section

Similarly data in Table 3.6 is utilised to develop the relationship between ψ and θ based on normalised channel data. The relationship obtained is shown in Figure 6.13, which can be expressed as:

$$\psi = 1.09\ \theta^{1.61} \tag{6.3}$$

Here the exponent 'b' is found to be 3.22. Again, similar to Eq. (6.2), the expression of dimensionless sediment transport parameter (ψ) is as follows:

$$\psi = 0.18\ \left(\frac{C}{\sqrt{g}}\right)^{1.51} \theta^{1.61} \tag{6.4}$$

Thus Eq. (6.4) is the Suggested dimensionless schematised sediment transport equation developed based on the data from normalised channel section of the river Jamuna.

6.4.3 Comments on results

The exponent 'b' of the Suggested equation are found to be 3.66 and 3.22 based on the data from each vertical and on the normalised channel section respectively. These values lie within the range of exponent 'b' derived from the theoretical analysis.

6.4.4 Verification of the Suggested equation

The dimensionless sediment transport equation (Eq. 6.2) for the Jamuna river had been derived based on the measured data of the Jamuna from 1984-1987. In order to verify this equation, an independent set of data was utilised shown in Table 3.7. The result obtained with this new set of data is plotted against the line of perfect agreement shown in Figure 6.14 which indicates that the Suggested equation slighty overpredicts the sediment transport rate. This discrepancy in prediction is not surprising for the case of a dynamic braided river like the Jamuna. The changes in morphology of the Jamuna river system might be the reason of this slight overprediction. However a correction factor can be used to adjust this variation which is found to be 0.75. The predicted versus measured transport rates using Suggested equation in corrected form is shown in Figure 6.15. Table 6.4 shows the percentage of data falls within 0.75 to 1.25 and 0.50 to 1.50 ranges of discrepancy ratio band are 49% and 81 % respectively.

6.5 Comparison with the Prediction Formula

The schematised sediment transport equation as developed in this study has been compared with the selected prediction formula as its schematised form. As mentioned earlier, these comparisons were based on the data from two considerations. The results of these comparison are discussed in the following section.

6.5.1 Comparison based on data from each vertical

The results obtained from the Suggested equation and the other selected six sediment transport equations were compared against the measured sediment transport data. The criteria selected for this comparison are the percentage of data coverage within the selected discrepancy ratio (the predicted variable to that of observed variable) band and the distribution of the predicted values against the line of perfect agreement. The percentage of data coverage within the selected discrepancy ratio band is shown in Table 6.5. From this table, it is observed that the number of data falling within the closest discrepancy ratio band 0.75 to 1.25 are found to be 57 %, 35%, 32 % and 30 % for Suggested (1995), Hossain (1985), Bagnold (1966) and Engelund-Hansen (1967) respectively. The distribution of the predicted transport rate against the observed data is also shown graphically in Figures 6.16 to 6.22 for each of the prediction formula used in this study. From these figures, it is observed that the Suggested, Hossain, Bagnold and Engelund-Hansen equations comply better against the measured data. Relatively closer agreement are achieved for the Suggested and the Hossain equation. It is to be mentioned here that the estimation by the Hossain equation significantly overpredicts the whole range of data, although shows a similar trend of the measured distribution. Therefore a correction factor is used to adjust the Hossain equation which is found to be 0.095.

In order to use the data for each vertical in computation of sediment transport by the Hossain equation, a little modification has been made. The pocket area in a vertical is assumed to represent a channel, the pocket width in a vertical is assumed to represent the normalised average width, while the vertical depth in a pocket to represent the normalised depth in a channel.

6.5.2 Comparison based on normalised channel data

Similar comparison has also been made from the results obtained for the Suggested and the other selected six prediction formulae against the measured sediment transport data. The percentage of data coverage within the selected discrepancy ratio band is shown in Table 6.6. From this table, it is seen that 64 %, 45%, 45% and 32 % of the data fall within 0.75 to 1.25 range of discrepancy ratio for the Suggested, Hossain, Engelund-Hansen and Van Rijn equations respectively. These comparisons are also shown in Figure 6.23 to 6.29. It is evident from these figures that the Suggested and the Hossain equations show comparatively better results.

6.5.3 Comments on results

Comparison of the Suggested and the selected prediction formulae shows that the Suggested and the Hossain formula are found to comply satisfactorily against the measured data. However relatively better performance is achieved from the Suggested equation against the data used in this study.

CHAPTER SEVEN

APPLICATION OF THE DEVELOPED SEDIMENT TRANSPORT EQUATION IN ID MORPHOLOGICAL MODEL FOR BED LEVEL COMPUTATION

7.1 Introduction

An application of one dimensional morphological model has been demonstrated in this Chapter. The purpose of this application is to focus the influence of schematised transport equation developed in this study for the computation of bed level changes of alluvial rivers due to any man made interferences. In this regard, a case study for the Jamuna river has been attempted to show the influence of exponent of the flow velocity due to constriction of the Jamuna river width for bridge construction. In the following section the description of the morphological model such as the basic equations, limitations of the governing equations, numerical solution scheme, boundary conditions and the results obtained by a morphological model are described.

7.2. Basic Equations

Four basic equations are required to describe the one dimensional morphological processes of an alluvial river. These are the momentum and continuity equation of water, sediment transport equation and the sediment continuity equation and can be defined as follows:

Momentum equation of water

$$[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x}] + [g\frac{\partial h}{\partial x} + g\frac{\partial z}{\partial x}] = -[g\frac{u|u|}{C^2 h}] \tag{7.1}$$

The first term of the above equation is referred to as the inertia term, the second is the gravity term and the third is the friction term expressing the production of momentum by bottom and wall stress.

Continuity equation of water

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + h \frac{\partial u}{\partial x} = 0 \qquad (7.2)$$

Here ∂h/∂t expresses the rate of change of water surface elevation caused by storage in the control volume and the combination of second and third term describes the change of inflow to the control volume with respect to x-direction of flow.

Sediment transport equation

$$q_s = f\ (u,\ \Delta,\ d_{50},\ C\ ) \qquad (7.3)$$

where 'u' is the f'low velocity, Δ is the bulk density of sediment, d_{50} is the median particle diameter and C is the Chezy roughness coefficient.

Sediment continuity equation

$$\frac{\partial z}{\partial t} + \frac{\partial q_s}{\partial x} = 0 \qquad (7.4)$$

7.2.1 Limitations of the governing equations

The following limitations should be taken into consideration before applying the basic equations in one dimensional morphological model.

(a) Equation (7.1) to (7.4) are valid for a wide river of constant width, B. The width B (x,t) may also be considered as a dependent variable in cases of erodible banks. However these considerations will require an additional equation.

(b) Above equations are valid for small sediment concentration e.g. q_s/q is very very less than 1.

(c) For the calculation of q_s basically any suitable transport formula can be used. However for preliminary analysis all variables except 'u' are supposed to be constant e.g not varying with space and time.

(d) As expressed in equation (7.3), the sediment transport is a function of local hydraulic and sediment conditions. Therefore the model developed based on equation (7.3) is not applicable for change in suspended load over a short distance and

(e) Equation (7.1) contains Chezy's C in the friction term. Although, C varies with time and space under given hydraulic condition, for preliminary analysis it is assimed that C(x,t) = C = constant.

7.2.2 Computation for rivers with mobile bed

The assumption and limitation of the basic equations which were already explained in the previous section can again be summarized as

(i) The equation for water and sediment movement can be decoupled and led to a quasi-steady flow sitution

(ii) Computations for mobile bed are applicable for non-tidal rivers with subcritical flow ($Fr < 0.6 - 0.8$)

(iii) The local sediment transport is governed by the local hydraulic conditions e.g. q_s is a function of 'u' and

(iv) The alluvial roughness should be known or can be predicted using a sub-model.

By combining the momentum and continuity equations described above, the following equations can be written for the computation of mobile bed.

$$[u - \frac{gq}{u^2}] \frac{\partial u}{\partial x} + g \frac{\partial z}{\partial x} = -g \frac{u^2}{C^2 h} = -g \frac{u^3}{C^2 q} \qquad (7.5)$$

$$\frac{\partial z}{\partial t} + \frac{d}{du} f(u) \cdot \frac{du}{dx} = 0 \qquad (7.6)$$

Here $f(u) = q_s = a\, u^b$

7.2.3 Numerical solution scheme

In order to solve the basic morphological equations, a number of schemes are available in the literature (Vreugdenhil, 1989). The morphological model considered in this study is decoupled and valid for subcritical flow. A complete numerical solution of equations (7.5) and (7.6) can be obtained by two alternative steps:

Step I : for a given value of 'z', solve equation (7.5) to compute 'u' and 'h'.

Step II: for known value of 'u' and 'h', solve equation (7.6) to obtain a new bed level 'z'. Here Step I which comprises the computation of a flow profile, can be achieved by using any suitable method. However in Step II, the differential equation (7.6) can be replaced by a first order explicit finite difference scheme which can be expressed as:

$$z_k^{n+1} = z_k^n - \frac{\Delta t}{2\Delta x} \left(f_{k+1}^n - f_{k-1}^n + \frac{1}{2} \alpha . (z_{k+1}^n - 2 z_k^n + z_{k-1}^n\right) \qquad (7.7)$$

or according to Vreugdenhil (1982), equation (7.7) can be written as

$$z_k^{n+1} = z_k^n - \frac{\Delta t}{2\Delta x} (f_{k+1}^n - f_{k-1}^n) + \frac{1}{4} [(\alpha_{k+1}^n + \alpha_k^n) \quad (z_{k+1}^n - z_k^n) - (\alpha_k^n + \alpha_{k-1}^n) \quad (z_k^n - z_{k-1}^n)] \qquad (7.8)$$

in which $z_k^n = z\,(k\Delta x,\, n\Delta t)$ and $f = f(u) = q_s = a\, u^b$

7.2.4 Boundary conditions

In order to solve the equations (7.5) and (7.6), proper boundary conditions have to be known. These boundary conditions are explained as follows:

Initial condition : As an initial condition, the bed level at t= 0, e.g z (x,0) should be known for initial computation of a flow profile by using equation (7.5).

Upstream boundary : At x = 0, the discharge q (t) has to be known. For known bed levels z (x,t), it is then possible to solve equation (7.5) with the help of h (x,t). Also equation (7.6) requires information at x = 0 for the sediment transport rate, q_s (0,t). If the relation q_s as a function of 'u' is assumed then a known value q_s (0,t) can be translated into u (0,t). In some cases, instead of using the transport rate q_s (0,t), the bed level z (0,t) can be specified. As the water level h (0,t) is governed by the downstream reach, a known value of z (0,t) leads to a known value of h (0,t). Then the value u (0,t) can be obtained from the continuity condition, 'q' equal to 'uh'. However the boundary condition q_s (0,t) or z (0,t) sometimes leads to an erroneous computation. Such error can be minimized by extending the upstream boundary to a length l greater than equal to c_3t from the point of interest. The propagation of error can be analyzed from the x-t diagram.

Dowmstream boundary: The downstream water level should be known at 'x' equal to L. This can be obtained from the stage discharge relation. If the bed level at 'x' equal to L changes, then the Q-h relationship is not valid anymore. Then the boundary should be selected as far as downstream so that no bed level changes take place during the simulation. In addition to the above boundary condition, an internal boundary condition for changing in river width is required. A sudden change in width of a channel can be incorporated in the basic equation as:

$$B \frac{\partial z}{\partial t} + \frac{\partial Q_s}{\partial x} = 0 \qquad (7.9)$$

Here two branches are required with B = B_1 and B = B_1-ΔB. In which ΔB is the change in width.

Based on the above numerical description, a one dimensional morphological model

(ODIRMO) (Vermeer and Nieuwkamer, 1985) was developed. This model has been applied in the present case study.

7.3 Application of the Schematised Sediment Transport Equation

In order to demonstrate the application of the suggested schematised transport equation developed in this study, the constriction of the Jamuna river due to Jamuna bridge is considered. Considering the Jamuna river reach from Sirajganj to Porabari, the influence of exponent 'b' on the bed level changes due to bridge constriction is computed using one dimensional morphological model as described earlier. This river reach comprises a length of 25.5 km. Data used for the computation of bed level changes are summarized in the following:

River reach (km)		Original width, B (km)	Constricted width, B_1 (km)	Discharge (m^3/s)	Chezy C ($m^{1/2}/s$)	Slope, S (-)
from	to					
Sirajganj	Porabari					
0.00	25.5	9	4.8	30,000	70	0.00007

In the model run, the following consideration were made:

(a) upstream boundary : constant bankfull discharge (Q)

(b) bed level at the upstream boundary : 0 level plus slope

(c) downstream boundary : water level

(d) original river width : mainstream width e.g no flood plain is included

(e) external source of sediment is not taken into account

The model has been run for three different exponent values (3, 3.66 and 5) to show the influence of exponent 'b' on the propagation of bed level changes. Also three different grain sizes such as 0.15 mm, 0.20 mm and 0.25 mm were used to show the bed level changes due to the variation of grain sizes. It is to be noted here that the results obtained from this model is presented here as a qualitative scenario. Due to large morphological time scale, no attempt has been made to run the model for the attainment of a new equilibrium situation. Only for demonstration, the model run time is considered as one year. With this small time scale, the model results can be influenced by the associated minor numerical errors to a certain extent.

7.4 Results and Discussions

With the variation of exponent value, results obtained for the water and bed level changes were plotted shown in Figure 7.1 and 7.2. From this figure, it is observed that the influence of the exponent value for the propagation of bed level changes is significant. The higher the exponent, the faster the rate of propagation of bed level changes in the downstream direction and the erosion is higher for high value of exponent. The water level rise upstream of the constriction is more for less value of exponent 'b'. The results obtained with the variation of grain sizes are shown in Figures 7.3 and 7.4. From this figures, it is evident that the variation of grain sizes does not have significant influence on the propagation of bed level changes. Also no significant changes in water level is observed at the upstream of constriction.

CHAPTER EIGHT

CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDY

8.1 Conclusions

Summarizing the present study, the following conclusions can be drawn:

1) The sediment discharge computation techniques have been evaluated in this study. It is found that the Simplified methods of discharge computation (gives only 4 % less than multipoint method) can be used satisfactorily compared to that of multipoint method.

2) Theoretical analysis on the exponent of the flow velocity of the selected transport equations reveals that the value of the exponent 'b' for the alluvial rivers ranges between 3.1 to 8.5. The value of exponent 'b' is thus considered a dominant parameter of sediment transport in alluvial rivers.

3) From the graphical relation between the exponent of the flow velocity, 'b' and the Shields parameter (θ), it is evident that most of the sediment transport formulae show an increase of the exponent 'b' with the decrease of the Shields parameter (θ) which implies that near the initiation of motion, the exponent 'b' is expected to be high.

4) The value of the exponent 'b' of the selected prediction formulae are found to be more sensitive with the variation of grain size specially for the cases of Ackers and White and Van Rijn formula. However, the other formulae selected in this study shows less sensitive e.g more or less constant.

5) Schematised sediment transport equations have been developed based on the data collected from each vertical of cross sections of the river Jamuna (Eq. 6.2). This developed equation has also been verified with independent sets of data and found to be

satisfactory with the observed data. A seperate equation has also been suggested for the application in normalised channel section (Eq. 6.4). These equations are useful for the application of two dimensional modelling, as it incorporates the roughness parameter.

6) With the same set of data, the predictive capacity of the Suggested and the selected prediction formulae has been compared in this study. From this comparison, it is observed that the Suggested equation in its schematised form performs relatively in closer agreement with the observed data. Other selected formulae such as Bagnold, Hossain and Engelund-Hansen are also found to be suitable for the application in the Jamuna as assessed within this limited data used in this study. Also comparision has been made with the normalised channel data and found that Hossain, Engelund-Hansen and Van Rijn formulae are suitable for the application in the Jamuna.

7) The application of the Suggested schematised transport equation in terms of its exponent of the flow velocity has been demonstrated in this study. A one dimensional morphological model has been applied to focus the usage of flow velocity exponent for the cases of Jamuna bridge constriction. This study shows that the variation of exponent 'b' has however more influence than the variation of grain sizes on the propagation of bed level changes.

8.2 Suggestions for Future Study

1) Though the simplified methods for assessing sediment discharge computation show reasonably satisfactory but needs further confirmation with more data analysis.

2) The schematised transport relation technique can be applied utilising more data for other alluvial rivers in Bangladesh.

3) The Suggested equation incorporates the roughness parameter (Chezy C) which is a dependent variable for the prediction of sediment transport capacity in a vertical or in a

cross section. Therefore proper investigation on the appraisal of the resistance of flow in a large alluvial rivers can be studied further.

4) In this study, an attempt was made to generalize the coefficient (a) of the schematised sediment transport equation as a function of non dimensional resistance parameter (e.g. $C/g^{0.5}$). Similarly attempt should be made to generalize the exponent 'b' with suitable non dimensional terms.

5) River responses due to various man-made interventions such as withdrawal of water and sediment from a river section, widening of river sections, loop cutting etc. can be studied utilising the ranges of exponent 'b' obtained from this study by a one dimensional morphological model.

6) One dimensional morphological model was applied considering steady state equlibrium case. Similarly this application can be done with time dependent flow and sediment of the river.

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TABLES

Table 3.1 : Characteristics water-levels and discharge along the Jamuna river (Source: RRI/L&P/CNR/DELFT HYDRAULICS, 1993)

Location along the Jamuna river	Return Period (years)	Discharge (m^3/s)	Water level (m+pwd)
maximum Bahadurabad	2 100	67,000 100,500	19.76 20.59
average d/s Bahadurabad	-	20,200	15.70
minimum Bahadurabad	-	2,400	13.00

Table 3.2 : Flow and sediment data for the Jamuna river, left channel at Bahadurabad, August 1993, used for the comparison of Simplified and Multipoint methods for assessing suspended sediment discharge (Source: River Survry Project)

vertical number	depth (m)	distance from left bank (m)	point depth (m)	point velocity (m/s)	point concentration (mg/l)
1	6.8	160	0.50	1.72	964.71
			1.29	1.55	1128.81
			2.82	1.52	1185.03
			4.15	1.38	1717.72
			5.67	1.19	1094.81
			6.38	1.01	1889.83
2	9.0	324	0.50	2.18	575.71
			1.86	2.28	729.34
			3.56	2.26	858.33
			5.45	2.10	966.15
			7.16	2.01	1004.08
			8.46	1.66	2076.71
3	8.5	468	0.50	2.56	824.82
			1.57	2.37	851.01
			3.22	2.42	734.33
			5.12	2.33	736.84
			6.65	2.17	1093.23
			8.08	1.69	1238.17
4	7.8	568	0.50	2.73	1206.78
			1.56	2.48	723.19
			3.02	2.61	631.27
			4.60	2.40	687.84
			6.24	2.29	751.89
			7.37	1.97	936.00
5	7.9	676	0.50	2.68	988.73
			1.55	2.55	1059.82
			3.22	2.50	669.27
			4.99	2.36	759.17
			6.36	2.24	815.70
			7.48	1.71	1162.20

Table 3.2 : Flow and sediment data for the Jamuna river, left channel at Bahadurabad, August 1993, used for the comparison of Simplified and Multipoint methods for assessing suspended sediment discharge (Source: River Survry Project) (Contd.)

vertical number	depth (m)	distance from left bank (m)	point depth (m)	point velocity (m/s)	point concentration (mg/l)
6	6.0	885	0.50	2.88	1092.00
			1.24	2.59	962.69
			2.35	2.61	1027.14
			3.52	2.51	675.38
			4.79	2.29	638.50
			5.50	1.90	1140.43
7	8.7	1005	0.50	2.27	787.00
			1.85	2.17	788.74
			3.54	2.09	792.82
			5.43	1.96	805.38
			7.36	1.72	875.89
			8.36	1.49	1509.20
8	9.6	1030	0.50	2.20	540.66
			1.75	2.00	623.17
			3.68	1.93	713.89
			5.60	1.66	767.16
			7.52	1.54	929.08
			8.98	1.23	882.86
9	13.2	1161	0.50	1.33	1591.72
			2.48	1.15	640.58
			5.08	0.99	803.75
			7.62	0.91	861.11
			10.11	0.83	840.00
			12.37	0.57	1354.84
10	11.1	1255	0.47	1.15	465.89
			2.19	1.12	388.89
			4.44	1.08	571.43
			6.64	0.95	593.65
			9.03	0.80	654.44
			10.53	0.60	736.30
11	8.0	1354	0.49	0.98	419.05
			1.63	0.98	477.05
			3.22	0.95	506.78
			4.82	0.84	531.85
			6.43	0.68	673.53
			7.10	0.56	752.63
12	5.4	1525	0.53	0.93	529.75
			1.11	0.93	467.95
			2.19	0.87	533.33
			3.33	0.79	519.31
			4.38	0.64	576.12
			4.97	0.55	602.92
13	7.0	1634	0.47	0.91	313.79
			1.44	0.97	386.55
			2.76	0.97	485.55
			4.21	0.88	630.51
			5.62	0.73	676.80
			6.44	0.62	698.58

Table 3.2 : Flow and sediment data for the Jamuna river, left channel at Bahadurabad, August 1993, used for the comparison of Simplified and Multipoint methods for assessing suspended sediment discharge (Source: River Survry Project) (Contd.)

vertical number	depth (m)	distance from left bank (m)	point depth (m)	point velocity (m/s)	point concentration (mg/l)
14	7.2	1901	0.51	1.09	429.00
			1.41	1.12	403.00
			2.76	0.99	479.00
			4.14	0.83	492.00
			5.51	0.87	468.00
			6.42	0.66	557.20
15	5.3	2047	0.50	1.00	572.31
			1.00	1.09	597.62
			2.10	1.04	591.61
			3.20	0.94	623.10
			4.20	0.77	618.21
			4.80	0.50	675.38
16	4.2	2219	0.82	0.98	719.95
			2.49	0.87	681.69
			3.49	0.68	739.20
17	4.7	2438	0.95	0.95	538.75
			2.81	0.81	654.65
			3.82	0.69	669.01
18	2.0	2748	0.40	0.88	693.53
			1.00	0.82	693.53
			1.20	0.78	693.53
			1.60	0.68	693.53
19	6.9	2908	0.50	0.64	347.14
			1.38	0.72	359.76
			2.76	0.74	389.97
			4.40	0.76	392.07
			5.50	0.73	385.29
			6.40	0.62	406.06

Table 3.3 : Water-level slopes and sediment grain sizes used for sediment transport predictors (Source : River Survey Project)

River	Gauging station	Collection period	Water-level slopes (cm/km)			Grain size of bed material				
			Jul	Aug	Nov	No. of samples	d16 (mm)	d35 (mm)	d50 (mm)	d90 (mm)
Jamuna	Bahadurabad	1993-94	9.13	7.57	6.89	56	0.13	0.16	0.22	0.34
				6.21						

Table 3.4 : Summary of flow and sediment data used for the sediment transport predictors of the Jamuna river at Bahadurabad

Date	vertical no.		Depth range (m)		Velocity range (m/s)		Concentration range (mg/l)		water disch. range, (m^3/s)		sed. disch. range, (kg/s)	
	from	to	from	to	from	to	from	to	from	to	from	to
04/06/84	4	77	1.20	11.2	0.45	1.56	8	132	25	2097	1.03	188.50
25-26/06/84	4	87	1.20	13.35	0.38	2.24	42	123	93	2767	4.19	337.57
09-10/07/84	2	86	0.90	16.25	0.32	2.32	33	176	42	2731	2.44	456.08
23-24/07/84	4	92	0.50	13.92	0.17	2.03	31	189	81	5437	2.60	815.55
06-07/08/84	6	85	1.00	17.10	0.23	2.18	41	189	105	4775	6.72	708.50
13-14/08/84	6	75	0.90	11.60	0.14	1.91	36	139	53	3493	2.81	485.53
03-04/06/85	4	90	1.50	10.35	0.43	1.72	75	146	79	1739	5.93	201.72
10-11/06/85	6	95	1.75	11.00	0.66	1.59	75	168	79	1348	4.52	214.33
08-09/07/85	2	86	0.90	13.20	0.37	2.56	38	199	103	2062	3.91	2883.23
22-23/07/85	6	88	1.00	13.75	0.39	2.74	55	204	111	2375	6.44	381.18
05-06/08/85	7	103	1.40	12.50	0.38	2.23	62	186	86	8750	5.50	262.96
13-14/08/85	2	98	1.10	11.40	0.25	1.83	10	164	22	1594	1.49	173.75
02-03/06/86	6	75	1.40	8.60	0.21	1.23	11	83	61	600	0.94	49.20
08-09/08/87	4	74	1.40	9.90	0.58	1.62	59	120	239	1070	19.63	101.65
12-13/11/84	2	56	0.70	11.20	0.16	1.53	18	130	24	1740	0.43	226.20
10-11/11/86	2	80	2.15	8.65	0.37	1.07	9	91	87	450	0.78	36.90

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
04-06-84	4	583	7.20	1.21	792	73
	6	671	8.05	1.08	762	70
	8	757	6.80	0.98	702	58
	10	893	5.15	0.94	867	70
	12	1178	3.10	0.74	1030	79
	14	1717	1.70	0.49	352	20
	17	2149	3.95	0.62	278	23
	19	2377	3.60	1.01	657	52
	21	2521	4.50	1.32	589	48
	23	2636	6.50	1.49	976	86
	25	2759	4.70	1.56	1024	84
	35	97	1.20	0.45	25	1
	37	150	2.85	0.68	88	4
	39	190	5.30	0.83	159	13
	41	230	5.10	0.76	124	9
	44	3419	2.95	0.76	144	9
	46	3567	2.70	0.67	279	15
	50	5274	3.10	0.81	323	20
	52	5488	5.50	1.15	1135	78
	54	5662	3.75	1.10	907	67
	56	5811	7.10	1.25	1043	90
	58	5949	7.10	1.32	1885	189
	60	6167	8.45	1.21	2097	178
	62	6541	2.55	0.98	1270	57
	65	7470	2.00	0.53	204	2
	67	7761	4.45	1.12	903	75
	69	7914	3.85	1.21	662	60
	71	8064	7.90	1.48	1256	122
	73	8165	11.10	1.39	1429	163
	75	8247	11.20	1.16	985	130
	77	8319	7.80	1.08	543	62
25-06-84 26-06-84	4	586	8.80	1.61	1243	150
	6	682	9.80	1.45	1711	210
	8	835	8.00	0.91	1066	117
	10	1032	2.80	0.41	412	34
	12	1198	1.70	0.44	244	15
	14	1850	1.40	0.38	189	8
	17	2070	3.10	1.21	471	21
	21	2465	6.60	2.08	1623	144
	23	2566	3.45	1.52	811	68
	25	2702	4.40	2.24	1036	99
	27	2806	5.25	1.76	1036	111
	29	2914	7.10	1.22	893	101
	31	3002	5.55	1.30	787	83
	35	1435	3.25	0.78	334	23
	37	1665	3.50	0.68	477	29
	39	1794	1.20	0.41	93	4
	42	2690	2.70	0.67	110	7
	44	2762	2.95	0.75	103	6
	47	3345	1.55	0.47	101	4
	49	3444	2.65	0.42	195	12
	51	3617	3.10	0.83	390	25

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
25-06-84	53	3742	2.50	0.92	381	24
26-06-84	57	5146	4.30	0.89	957	78
	59	5422	6.40	1.01	1388	125
	61	5557	7.80	1.08	903	88
	63	5678	7.70	1.15	1333	144
	65	5829	9.90	1.44	2128	243
	67	6024	5.50	1.21	1878	190
	69	6396	2.80	1.30	1407	132
	71	6919	3.30	1.68	2171	163
	73	7295	1.50	0.55	528	28
	75	7671	2.75	1.25	772	63
	77	7792	5.70	1.39	1068	88
	79	7932	8.35	1.47	1315	150
	81	8030	7.90	1.49	1194	137
	83	8160	13.35	1.41	2767	338
	85	8284	12.40	1.43	1872	223
	87	8377	8.00	1.19	510	60
9-10.07.84	2	13156	5.50	1.03	457	53
	4	12966	2.00	1.31	397	31
	6	12744	3.40	2.12	1477	95
	8	12544	3.50	2.32	1680	139
	10	12301	2.40	2.12	1428	113
	12	11926	2.20	1.72	1832	159
	14	11487	2.10	1.47	1128	95
	16	11317	6.30	1.17	1398	148
	18	11130	12.30	1.24	2104	217
	20	11019	12.60	1.44	2702	276
	22	10816	9.60	1.38	2355	221
	24	10685	5.10	1.10	980	96
	26	10471	2.65	0.32	505	43
	30	7691	3.80	0.90	487	40
	32	7496	4.30	0.54	468	38
	34	7354	1.10	0.51	42	2
	37	6450	3.05	0.68	112	8
	39	6384	3.10	0.82	122	9
	42	5773	6.95	0.51	278	23
	44	5527	3.75	0.85	758	57
	46	5289	2.95	0.98	461	31
	50	4768	1.35	0.73	271	20
	52	4402	1.50	0.67	195	17
	54	4132	0.90	0.36	275	9
	56	3915	7.30	1.39	1380	112
	58	3713	6.60	0.86	1502	210
	60	3527	8.90	1.01	1428	220
	62	3401	11.50	1.26	2120	373
	64	3221	6.40	1.27	1695	288
	66	3007	5.10	1.17	1607	257
	68	2717	4.50	1.33	1983	29
	70	2376	5.40	1.01	1742	277
	72	1894	2.50	0.73	580	71
	74	1654	4.70	0.99	917	120
	76	1440	4.60	1.50	1595	225

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
9-10.07.84	78	1283	5.70	1.93	1272	187
	80	1172	6.70	1.97	1517	246
	82	951	8.60	1.99	2731	456
	84	830	16.25	1.73	2048	303
	86	752	11.00	1.18	889	118
23-07-84 24-07-84	4	13088	1.70	0.86	168	15
	6	12966	2.66	1.01	210	17
	8	12854	3.00	0.59	365	31
	10	12685	4.40	1.39	1425	137
	12	12462	8.00	1.52	2440	295
	14	12037	3.90	0.82	2804	331
	16	11552	3.45	0.72	1095	124
	18	11317	4.20	1.41	1321	159
	20	11166	9.80	1.82	2674	369
	22	11058	10.60	1.80	1402	205
	24	10976	9.30	2.03	1519	287
	26	10888	8.05	1.65	1539	211
	28	10755	6.90	1.57	1678	215
	30	10425	3.30	0.49	801	100
	34	7702	4.00	0.98	490	44
	36	7506	2.00	0.69	407	34
	38	7354	3.80	0.83	194	16
	41	6463	2.10	0.41	81	6
	43	6369	2.40	0.74	171	11
	48	5400	3.60	0.62	311	21
	50	5289	5.60	1.01	419	32
	52	5070	0.80	0.17	274	11
	54	4819	0.50	0.32	84	3
	56	4394	1.25	0.42	215	12
	58	3982	3.80	0.91	360	22
	60	3801	4.60	1.28	893	85
	62	3614	4.30	1.35	1248	142
	64	3465	9.80	0.86	1375	187
	66	3259	6.00	1.17	1977	283
	68	2968	5.50	1.17	1904	253
	70	2687	9.00	1.60	2315	326
	72	2253	5.60	1.28	5437	816
	74	1936	0.60	0.21	853	113
	76	1668	3.80	0.41	153	10
	78	1517	5.00	1.01	407	33
	80	1388	7.40	1.34	915	108
	82	1265	10.80	1.77	1687	223
	84	1155	8.40	1.79	1834	266
	86	1045	9.00	1.43	1867	304
	88	949	12.20	1.45	1464	208
	92	762	13.92	1.20	1961	245
06-08-84 07-08-84	6	12842	2.90	0.88	584	36
	8	12646	6.60	1.02	1111	86
	10	12467	6.90	1.58	2184	225
	12	12214	7.80	1.53	3573	429
	14	11736	2.60	1.30	1768	196
	16	11405	3.20	1.38	1226	124

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
06-08-84	18	11233	5.20	1.87	1395	158
07-08-84	20	11151	8.05	2.02	1122	145
	22	11075	7.65	1.92	1387	171
	24	10981	7.30	2.18	1237	151
	26	10914	6.60	2.04	1162	142
	28	10785	4.00	2.07	1236	151
	30	10560	2.70	1.29	969	96
	35	7732	3.60	0.91	242	17
	37	7563	4.10	0.83	794	69
	39	7377	3.10	0.63	147	11
	42	6450	2.30	0.79	169	11
	44	6310	1.75	0.68	154	11
	47	5815	1.90	0.45	105	7
	49	5568	2.30	0.29	252	19
	51	5324	4.60	0.47	306	24
	53	5205	5.40	1.16	720	71
	55	4625	1.00	0.24	201	10
	57	4111	1.00	0.23	190	8
	59	3892	5.70	1.67	1380	120
	63	3417	6.60	1.36	2056	191
	65	3112	3.70	1.60	2506	205
	67	2804	9.60	1.57	4755	708
	69	1055	12.80	1.33	3879	473
	71	939	17.10	1.08	890	75
	77	2635	9.60	1.64	1905	316
	79	2294	5.40	1.65	1965	344
	81	1936	1.10	0.47	2024	383
	83	1462	2.60	1.22	1628	296
	85	1317	6.15	2.16	1102	192
13-08-84	6	12678	4.80	0.58	539	39
14-08-84	8	12492	5.90	0.98	1179	105
	10	12295	7.05	1.15	2676	268
	12	11830	3.90	0.59	1422	129
	14	11415	3.70	0.47	615	62
	16	11199	3.50	1.72	1214	129
	18	11041	5.70	1.66	1474	167
	20	10899	5.10	1.91	908	97
	22	10729	3.80	1.12	1201	115
	28	10086	2.25	0.88	256	16
	30	9931	2.80	0.58	374	27
	34	6445	1.60	0.68	381	30
	36	6349	1.30	0.43	53	4
	39	5786	3.30	0.32	94	4
	41	5427	1.05	0.14	78	3
	47	3993	2.90	0.77	489	36
	49	3655	1.60	1.04	606	44
	51	3433	8.10	1.13	1109	140
	53	3061	1.70	0.54	462	36
	57	2635	8.50	1.26	3493	486
	63	1619	0.90	0.50	255	10
	65	1398	6.10	1.18	1278	152
	67	1247	8.10	1.43	1445	184

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
13-08-84	69	1095	9.30	1.23	2188	304
14-08-84	73	850	11.60	1.89	1169	161
	75	760	11.20	0.94	682	81
03-06-85	4	12254	5.30	0.82	944	122
04-06-85	6	12074	5.30	1.36	1469	182
	8	11879	6.50	1.41	1739	202
	10	11709	5.65	1.47	1554	182
	12	11536	4.90	1.72	1489	164
	14	11344	3.65	1.56	1142	119
	16	11135	4.70	1.46	1366	127
	18	10893	3.30	1.04	985	92
	20	10435	2.10	0.62	811	71
	24	7726	2.65	0.43	126	10
	26	7625	4.00	1.26	467	46
	28	7529	2.70	1.08	438	41
	32	6453	1.60	0.74	92	7
	34	6370	1.60	0.88	79	6
	37	5427	2.95	0.66	304	25
	39	5250	3.40	1.05	485	38
	43	3933	2.80	0.90	232	24
	45	3739	1.90	0.74	449	41
	47	3495	2.10	0.99	462	37
	51	2858	1.50	1.11	246	20
	53	2732	4.30	1.31	566	51
	55	2565	5.20	1.54	982	88
	57	2463	7.20	1.58	1120	120
	59	2374	7.75	1.50	959	115
	61	2300	8.15	1.45	769	98
	63	2233	8.70	1.51	893	130
	65	2162	9.50	1.46	994	144
	67	2101	10.30	1.20	606	79
	72	1583	3.20	1.33	479	45
	74	1462	6.40	1.22	854	96
	76	1368	8.10	1.40	907	103
	78	1289	8.90	1.47	1069	108
	80	1206	10.35	1.43	1217	151
	82	1119	6.90	1.60	965	109
	84	1045	7.60	1.45	757	86
	86	970	7.50	1.23	689	79
	88	903	7.10	1.17	607	69
	90	814	3.10	0.82	251	25
10-06-85	6	12184	5.00	0.94	907	102
11-06-85	8	12015	6.00	1.10	1072	119
	10	11828	4.10	1.48	1270	147
	12	11609	4.70	1.41	1209	131
	14	11452	5.10	1.54	1165	134
	16	11286	5.00	1.45	1042	135
	18	11127	4.10	1.52	921	122
	20	10994	3.50	1.48	770	85
	22	10840	3.20	1.38	727	79
	24	10703	3.80	1.16	760	88
	26	10334	2.15	0.66	349	25

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
10-06-85	29	7732	2.50	0.82	278	29
11-06-85	31	7583	4.70	1.28	460	50
	33	7389	2.05	0.72	291	23
	36	6453	1.75	0.71	79	6
	38	6367	1.85	0.88	105	8
	41	5439	2.30	0.88	186	14
	43	5285	3.60	0.87	422	37
	47	4023	1.75	0.84	295	25
	49	3743	2.50	0.67	560	54
	51	3477	2.90	0.78	552	49
	55	2880	2.35	0.85	330	32
	57	2747	5.00	1.29	541	57
	59	2651	7.75	1.41	1046	129
	61	2547	10.00	1.42	1348	214
	63	2454	9.75	1.47	1222	205
	65	2384	11.00	1.52	938	140
	67	2310	7.15	1.50	861	119
	69	2244	9.00	1.51	903	5
	71	2174	10.30	1.28	901	105
	73	2101	6.50	1.36	720	82
	77	1606	5.20	1.04	712	80
	79	1472	8.00	1.59	1178	123
	81	1398	9.00	1.41	933	92
	83	1320	9.70	1.49	1078	103
	85	1247	9.50	1.53	932	86
	87	1175	8.00	1.46	868	89
	89	1095	7.45	1.25	715	69
	91	1016	6.50	0.89	564	63
	93	916	5.15	0.82	408	44
	95	824	3.10	0.77	193	18
8-9.07.85	2	13025	1.90	0.37	157	14
	4	12678	2.50	0.56	635	59
	6	12298	3.80	0.97	998	103
	8	12052	4.65	1.41	1438	157
	10	11793	7.20	1.68	1890	270
	12	11650	8.60	1.89	1970	305
	14	11557	11.00	2.13	1702	296
	16	11491	9.60	2.56	1696	2883
	18	11422	9.80	2.51	1701	304
	20	11347	8.85	2.25	1488	269
	22	11272	7.30	2.22	1717	203
	24	11156	6.30	2.14	1816	238
	26	11016	5.25	1.91	1280	145
	28	10896	4.50	1.45	856	85
	30	10667	3.30	1.15	1226	113
	32	10284	3.00	0.90	610	52
	35	7726	3.90	0.68	411	35
	37	7578	4.30	1.13	552	51
	39	7451	3.30	0.99	489	43
	43	6445	3.00	0.85	139	10
	45	6361	2.05	0.79	112	6
	48	5576	0.90	0.64	103	4

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
8-9.07.85	50	5452	6.00	1.00	405	24
	52	5329	2.45	1.03	444	55
	56	3944	3.80	0.88	747	87
	58	3477	3.00	0.73	1021	87
	60	3037	2.70	1.10	1780	150
	62	2786	9.90	1.63	1878	203
	64	2676	10.90	1.60	1850	270
	66	2574	12.00	1.57	1272	347
	68	2463	13.20	1.38	2062	40
	70	2310	4.40	1.36	1637	16
	72	2020	2.95	0.88	940	52
	74	1748	5.60	1.29	1658	132
	76	1594	9.00	1.72	146	219
	78	1529	12.00	1.82	1333	45
	80	1462	11.40	1.79	1059	186
	82	1378	10.50	1.21	1484	295
	84	1255	6.70	1.35	1243	235
	86	1116	8.15	1.08	1370	44
22-07-85 23-07-85	6	12164	4.30	0.65	875	95
	8	11879	2.50	1.27	858	90
	10	11620	2.40	1.48	1109	109
	12	11513	9.50	2.31	1630	274
	14	11445	9.15	2.61	1700	304
	16	11386	8.70	2.64	1147	205
	18	11323	8.50	2.66	1762	296
	20	11245	9.30	2.72	2006	357
	22	11162	9.50	2.74	1975	381
	24	11089	10.00	2.44	1707	304
	26	11012	8.00	2.07	1491	253
	28	10916	6.45	2.21	1540	223
	30	10803	5.70	2.05	1518	194
	32	10584	1.75	0.67	755	72
	36	7744	3.90	0.87	337	28
	38	7593	4.20	1.03	717	65
	40	7435	3.30	0.86	410	33
	44	6445	2.70	0.89	142	9
	46	6349	1.50	0.72	111	6
	49	5699	1.00	0.47	111	7
	51	5493	3.45	0.39	398	27
	53	5324	2.85	0.77	685	43
	58	3906	3.40	0.92	415	26
	60	3646	2.45	0.46	408	22
	62	3320	3.95	1.16	943	81
	64	2999	2.40	1.22	1262	133
	66	2834	10.00	1.97	1972	294
	68	2747	12.60	1.89	2233	380
	70	2651	13.75	1.85	2375	347
	72	2547	6.00	2.30	1709	200
	74	2404	5.50	1.65	1796	199
	76	2138	3.90	1.57	2078	214
	78	1837	5.80	1.63	1828	197
	80	1645	7.20	1.65	2270	322

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB), (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
22-07-85	82	1514	11.85	1.64	2040	363
23-07-85	84	1378	9.30	1.50	1856	379
	86	1186	7.30	1.07	1552	239
	88	931	7.30	1.61	1976	358
05-08-85	7	12613	1.65	0.81	263	22
06-08-85	9	12374	3.50	0.88	859	93
	15	11457	6.20	1.96	1290	183
	17	11361	7.40	2.23	1387	218
	19	11285	9.00	1.93	1263	216
	21	11204	8.00	1.69	1034	168
	23	11133	7.50	1.73	1216	192
	25	10996	7.60	1.61	1730	263
	27	10860	8.00	1.59	1520	216
	29	10749	6.20	1.65	1402	177
	31	10607	4.85	1.75	1098	111
	33	10453	3.90	1.90	1254	117
	37	7775	2.50	0.46	172	13
	39	7641	4.30	0.80	369	31
	41	7553	4.50	0.82	329	31
	43	7426	2.45	0.77	200	15
	46	6442	2.65	0.81	130	9
	48	6349	1.40	0.69	86	6
	51	5526	2.70	0.58	154	10
	53	5401	2.40	0.51	198	14
	55	5298	3.40	0.59	232	19
	57	5169	3.10	1.37	513	49
	61	3883	3.80	0.38	408	34
	63	3379	2.00	0.49	709	38
	65	2921	6.05	1.18	1111	142
	67	2851	10.70	1.47	781	127
	69	2793	12.10	1.16	1008	187
	71	2732	11.00	2.02	1369	235
	73	2676	12.50	1.89	1093	172
	75	2626	8.70	1.43	591	83
	77	2574	7.30	1.46	575	74
	79	2498	6.10	1.62	1260	151
	81	2322	3.20	1.78	1203	131
	83	2128	5.20	1.31	1606	161
	85	1974	7.20	1.15	941	106
	87	1848	8.50	1.39	1533	210
	89	1709	7.20	0.94	1027	126
	91	1549	7.40	0.95	932	109
	93	1440	6.75	0.93	643	72
	95	1320	4.80	0.61	421	44
	97	1155	3.80	0.72	439	38
	99	1047	6.50	1.04	8750	71
	101	931	6.70	1.02	827	88
	103	786	7.00	1.21	886	105
13-08-85	2	13168	1.30	0.89	22	2
14-08-85	5	12601	1.50	0.66	411	25
	9	11491	2.85	0.89	917	76
	11	11181	5.00	1.17	1423	161

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.).

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
13-08-85	13	11006	7.00	1.39	935	117
14-08-85	15	10936	8.00	1.41	695	99
	17	10866	7.05	1.28	619	87
	19	10804	6.50	1.57	632	86
	21	10743	7.30	1.38	613	94
	23	10683	7.85	1.38	601	97
	25	10623	6.70	1.40	732	108
	27	10548	5.30	1.63	672	82
	29	10485	6.30	1.72	606	84
	31	10427	6.10	1.54	576	74
	33	10347	3.50	1.34	688	66
	35	10222	3.50	1.01	397	34
	38	7726	2.50	0.54	149	1
	40	7604	3.45	0.81	305	27
	42	7492	2.15	0.60	230	18
	46	6437	1.90	0.66	74	5
	48	6351	1.10	0.59	51	3
	53	5141	2.80	1.10	779	49
	57	4015	2.70	0.51	309	18
	59	3719	1.25	0.25	140	7
	62	3305	3.30	0.68	495	35
	64	2989	5.35	0.90	648	56
	66	2900	8.70	1.12	664	74
	68	2837	10.60	1.63	818	118
	70	2793	10.75	1.53	746	116
	72	2747	11.40	1.53	813	133
	74	2700	11.00	1.83	902	143
	76	2651	7.30	1.69	989	145
	78	2463	3.00	1.78	1594	174
	80	2192	2.45	1.56	1274	130
	82	2007	6.90	1.40	1130	129
	84	1890	7.00	1.30	1172	170
	86	1764	8.15	1.08	989	116
	88	1666	5.10	0.92	683	67
	90	1538	7.10	0.77	645	63
	92	1405	5.80	0.53	479	42
	94	1217	3.55	0.70	389	30
	96	1064	6.00	0.98	593	58
	98	961	7.05	1.05	897	98
02-06-86	6	11173	4.85	0.63	325	17
03-06-86	8	11089	6.40	0.74	407	28
	10	11010	8.15	0.93	579	46
	12	10933	8.05	0.94	579	41
	14	10855	6.35	0.89	450	30
	16	10772	4.50	0.70	285	17
	18	10676	3.85	0.58	233	15
	20	10566	4.40	0.55	271	19
	22	10456	4.85	0.60	303	24
	24	10369	6.55	0.75	361	28
	26	10276	4.40	0.60	268	18
	28	10183	3.20	0.49	111	5
	31	3024	1.40	0.21	85	1

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
02-06-86	33	2851	5.50	0.77	392	13
03-06-86	35	2770	7.55	1.02	541	43
	37	2696	7.30	1.06	558	39
	39	2626	7.45	1.07	553	42
	41	2561	8.30	1.23	600	49
	43	2501	8.60	1.08	510	42
	45	2449	7.90	1.04	487	37
	47	2384	7.30	0.96	447	30
	49	2321	5.15	0.96	385	22
	51	2221	2.90	0.66	264	7
	57	1132	3.95	0.31	61	2
	59	1076	3.20	0.56	105	5
	61	1024	3.80	0.52	97	6
	63	978	4.85	0.63	135	9
	65	935	5.80	0.76	166	11
	67	899	6.50	0.69	150	11
	69	869	6.90	0.69	148	12
	71	836	6.00	0.66	139	11
	73	803	5.40	0.78	151	11
	75	769	5.50	0.82	181	13
08-06-87	4	10999	4.65	0.81	581	35
09-06-87	6	10836	6.00	0.96	881	65
	8	10705	6.30	1.38	832	66
	10	10634	6.65	1.51	657	54
	12	10569	6.80	1.62	667	61
	14	10509	7.25	1.57	681	61
	16	10450	7.90	1.57	1070	102
	18	10362	7.80	1.41	649	66
	20	10304	7.70	1.26	555	53
	22	10246	7.20	0.95	386	33
	24	10187	6.50	0.66	274	21
	28	2895	1.85	1.12	348	21
	30	2810	7.40	1.25	514	38
	32	2753	7.30	1.12	493	42
	34	2698	7.20	1.11	460	36
	36	2629	5.75	0.88	394	28
	38	2537	3.90	0.85	346	21
	40	2444	4.10	0.80	293	20
	42	2343	4.45	0.58	279	23
	44	2241	5.20	0.84	384	30
	46	2157	6.80	1.05	523	44
	48	2084	6.65	0.96	448	38
	50	2008	5.35	0.72	388	31
	52	1883	1.40	0.80	467	30
	56	1523	6.30	0.93	239	21
	58	1467	6.40	1.04	337	31
	60	1415	7.10	0.93	361	30
	62	1365	8.20	0.85	354	34
	64	1316	9.80	0.76	387	41
	66	1266	9.90	0.96	474	49
	68	1213	9.00	1.03	507	48
	70	1153	8.20	1.08	565	68

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
08-06-87	72	1087	6.40	1.11	468	56
09-06-87	74	1022	5.15	1.02	394	43
12-13.11.84	2	12615	1.30	0.50	180	12
	4	12288	0.80	0.57	420	16
	6	11812	3.00	0.98	410	30
	8	11683	5.00	0.91	690	70
	10	11505	4.75	0.72	665	79
	12	11334	3.90	0.60	396	44
	14	11110	3.15	0.16	187	15
	16	10829	2.85	0.23	223	17
	19	7668	1.00	0.57	60	3
	23	5324	0.70	0.18	24	0
	25	5205	1.15	0.61	61	1
	29	3900	1.00	0.38	57	3
	33	2804	1.10	0.73	193	11
	35	2580	2.40	0.78	413	31
	37	2376	9.00	1.02	1050	135
	39	2267	11.20	1.23	1740	226
	41	2118	3.30	0.68	458	52
	44	1521	2.20	0.66	150	11
	46	1426	5.60	1.13	485	45
	48	1317	4.70	1.53	847	93
	50	1194	5.00	1.53	864	103
	52	1106	3.90	1.24	494	63
	54	972	5.70	0.83	521	64
	56	814	2.60	0.31	147	14
10-11.11.86	2	11155	2.15	0.39	87	1
	4	11067	4.25	0.46	169	4
	6	10988	5.15	0.54	205	10
	8	10913	5.35	0.62	249	15
	10	10833	5.65	0.64	270	19
	12	10756	5.70	0.67	278	19
	14	10691	6.40	0.75	299	21
	16	10627	6.25	0.78	312	24
	18	10566	6.40	0.80	318	24
	20	10505	6.50	0.82	320	23
	22	10446	6.70	0.86	330	24
	24	10388	6.10	0.74	281	19
	26	10333	5.85	0.83	271	21
	28	10272	6.10	0.80	340	28
	30	10181	5.45	0.69	289	20
	39	2399	5.50	0.37	155	3
	41	2329	8.00	0.53	252	13
	43	2271	8.00	0.82	359	22
	45	2219	8.40	1.00	431	33
	47	2167	8.65	0.94	450	37
	49	2113	7.90	0.99	428	33
	51	2056	7.30	1.00	428	30
	53	1984	4.35	0.75	274	16
	55	1901	2.50	0.57	101	5
	58	1371	4.70	0.79	220	17
	60	1295	5.80	1.07	399	33

Table 3.5 : Verticalwise flow and sediment data of the Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical no.	Dist. from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/sec
10-11.11.86	62	1227	5.70	1.03	402	30
	64	1156	4.70	0.66	237	14
	66	1068	3.70	0.48	227	13
	68	978	5.70	0.80	311	19
	70	909	5.70	0.77	305	22
	72	849	7.20	0.88	354	30
	74	792	7.60	0.91	376	34
	76	736	6.30	0.97	353	31
	78	678	6.90	0.89	353	29
	80	626	7.60	0.94	431	33

Table 3.6 : Flow and sediment data of normalised channel section, Jamuna river at Bahadurabad

Date	Channel	Area (A) m2	Width (B) m	Water Discharge (Qw) m3/s	Sediment Discharge (Qs) gm/s
04/06/84	Ful ch 1	5483	1562	4809	400581
	Ful ch 2	4239	1067	5209	406249
	Ba ch 1	617	241	396	27624
	Ba ch 2	766	397	432	23715
	Ba ch 3	7781	1719	8660	679052
	Ba ch 4	5086	1116	5982	258655
25/6/84	Ful ch 1	5669	1646	5725	597668
	Ful ch 2	5222	1094	8431	732574
	Ba ch 1	1281	435	904	56185
	Ba ch 2	334	148	213	12271
	Ba ch 3	1798	729	1077	66362
	Ba ch 4	18498	3551	22282	2248082
9/7/84	Ful ch 1	13277	3051	18444	1686392
	Ba ch 1	1391	480	997	80765
	Ba ch 2	346	150	234	17112
	Ba ch 3	2338	765	1497	111272
	Ba ch 4	20505	4225	25748	3800792
23/7/84	Ful ch 1	15681	3079	19403	2519398
	Ba ch 1	1385	480	1091	93299
	Ba ch 2	342	150	249	16605
	Ba ch 3	25700	5174	30202	4017535
6/8/84	Ful ch 1	13611	3079	19306	2133894
	Ba ch 1	1520	518	1183	97432
	Ba ch 2	436	209	323	22118
	Ba ch 3	23399	5191	29867	3844062
13/8/84	Ful ch 1	12732	3021	11823	1154913
	Ba ch 1	925	502	630	43686
	Ba ch 2	688	200	434	34455
	Ba ch 3	1457	684	779	55019
	Ba ch 4	10107	2104	9454	1202604
	Ba ch 5	8184	1104	8682	1140239

Table 3.6 : Flow and sediment data of normalised channel section, Jamuna river at Bahadurabad (Contd.)

Date	Channel	Area (A) m2	Width (B) m	Water Discharge (Qw) m3/s	Sediment Discharge (Qs) gm/s
3/6/85	Ful ch 1	10682	3134	12091	1331083
	Ba ch 1	5883	919	7795	869772
	Ba ch 2	5338	989	7475	876983
	Ba ch 3	1537	644	1143	101715
	Ba ch 4	1013	418	789	63062
	Ba ch 5	226	176	171	13377
	Ba ch 6	1117	493	1031	97737
10/6/85	Ful ch 1	10309	3134	11139	1260406
	Ba ch 1	6035	933	7581	767035
	Ba ch 2	6520	1072	8820	1087333
	Ba ch 3	2011	976	1407	127116
	Ba ch 4	801	418	618	50664
	Ba ch 5	254	176	187	13800
	Ba ch 6	1093	493	1029	102150
8/7/85	Ful ch 1	13184	3111	20880	2896377
	Ba ch 1	19673	3374	25394	2462249
	Ba ch 2	1163	705	952	51785
	Ba ch 3	376	201	251	15863
	Ba ch 4	1665	541	1452	128262
22/7/85	Ful ch 1	12959	3113	21039	3251527
	Ba ch 1	18902	3423	26712	3753896
	Ba ch 2	1758	740	1194	77166
	Ba ch 3	372	216	253	15668
	Ba ch 4	1773	562	1464	126018
5/8/85	Ful ch 1	91	165	49	3724
	Ful ch 2	10457	2901	16413	2190437
	Ba ch 1	17935	3427	20213	2536723
	Ba ch 2	1607	668	1095	91433
	Ba ch 3	350	211	216	14994
	Ba ch 4	1542	558	1070	90698

Table 3.6 : Flow and sediment data of normalised channel section, Jamuna river at Bahadurabad (Contd.)

Date	Channel	Area (A) m2	Width (B) m	Water Discharge (Qw) m3/s	Sediment Discharge (Qs) gm/s
13/8/85	Ful ch 1	48	73	22	1540
	Ful ch 2	9104	2877	11297	1309883
	Ba ch 1	14427	2743	16552	1980560
	Ba ch 2	1171	664	449	24811
	Ba ch 3	1022	586	904	68202
	Ba ch 4	242	196	125	8092
	Ba ch 5	1110	533	684	55888
2/6/86	Ful ch 1	6312	1492	4414	291041
	Ba ch 1	2009	451	1333	324514
	Ba ch 2	5650	1631	4949	91469
8/6/87	Ful ch 1	6749	1376	7473	627690
	Ba ch 1	4295	617	4086	420630
	Ba ch 2	5936	1339	5337	400291
12/11/84	Ful ch 1	5626	2313	3171	281413
	Ba ch 1	154	226	60	3180
	Ba ch 2	230	347	85	1713
	Ba ch 3	157	210	57	2907
	Ba ch 4	3823	937	3814	455380
	Ba ch 5	3376	905	3508	393327
10/11/86	Ful ch 1	5897	1184	4018	269501
	Ba ch 1	4746	867	3968	303868
	Ba ch 2	6023	1035	3349	193417

Table 3.7: Vericalwise flow and sediment data used for the verification analysis, Jamuna river at Bahadurabad (Source : BWDB)

Date	Vertical No.	Dist from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/s
07-06-93	2	1915	3.35	0.80	272	9
08-06-93	4	2086	1.80	0.79	229	7
	6	2262	1.80	0.65	194	7
	8	2423	3.35	0.62	336	12
	10	2557	4.85	0.76	586	23
	12	2684	4.10	0.96	583	24
	14	2806	4.85	0.68	530	23
	16	2920	6.10	0.65	473	22
	18	3031	3.00	0.68	344	15
	20	3185	2.30	0.82	330	13
	22	3346	1.20	0.74	144	5
	25	3649	3.35	0.42	135	5
	27	3770	3.35	0.57	284	11
	29	3887	5.50	1.03	551	22
	31	3982	7.00	0.79	613	28
	33	4085	7.15	0.54	559	27
	35	4181	6.40	0.73	536	26
	37	4273	6.30	0.72	332	15
	40	7971	6.40	0.93	500	17
	42	8074	8.85	0.94	939	37
	44	8168	10.65	1.01	1240	57
	46	8262	10.20	1.18	1217	58
	48	8357	9.15	1.02	1027	51
	50	8458	6.40	1.03	755	39
	52	8583	5.20	0.50	396	19
	54	8750	3.80	0.43	498	23
	56	8914	5.20	0.62	362	16
	58	9020	3.20	0.36	159	6
	61	10378	4.85	0.50	442	16
	63	10570	3.95	0.41	331	13
	65	10791	3.05	0.49	475	17
	67	10980	2.75	0.72	369	13
	69	11067	4.10	0.55	309	11
	71	11190	4.40	0.90	735	29
	75	11422	3.05	0.81	279	11
	77	11525	3.15	0.65	432	17
	79	11676	6.20	0.78	330	14
	82	12224	7.30	1.08	553	25
	84	12291	7.60	1.46	637	31
	86	12362	6.35	1.18	637	31
	88	12450	6.40	1.18	880	46
	90	12553	6.90	1.04	719	40
	92	12655	4.55	0.87	397	21
	94	12745	3.85	0.58	327	17
	96	12835	5.20	0.56	331	17
	98	13013	4.55	0.21	406	21
21-06-93	2	279	1.05	0.29	9	0
22-06-93	4	332	0.90	0.29	11	0
	7	1915	4.65	1.33	696	27
	9	2086	7.55	0.86	1189	52
	11	2262	8.90	1.06	1609	76
	13	2423	6.45	0.69	846	43

Table 3.7: Verticalwise flow and sediment data used for the verification analysis, Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical No.	Dist from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/s
07-06-93 08-06-93	2	1915	3.35	0.80	272	9
	4	2086	1.80	0.79	229	7
	6	2262	1.80	0.65	194	7
	8	2423	3.35	0.62	336	12
	10	2557	4.85	0.76	586	23
	12	2684	4.10	0.96	583	24
	14	2806	4.85	0.68	530	23
	16	2920	6.10	0.65	473	22
	18	3031	3.00	0.68	344	15
	20	3185	2.30	0.82	330	13
	22	3346	1.20	0.74	144	5
	25	3649	3.35	0.42	135	5
	27	3770	3.35	0.57	284	11
	29	3887	5.50	1.03	551	22
	31	3982	7.00	0.79	613	28
	33	4085	7.15	0.54	559	27
	35	4181	6.40	0.73	536	26
	37	4273	6.30	0.72	332	15
	40	7971	6.40	0.93	500	17
	42	8074	8.85	0.94	939	37
	44	8168	10.65	1.01	1240	57
	46	8262	10.20	1.18	1217	58
	48	8357	9.15	1.02	1027	51
	50	8458	6.40	1.03	755	39
	52	8583	5.20	0.50	396	19
	54	8750	3.80	0.43	498	23
	56	8914	5.20	0.62	362	16
	58	9020	3.20	0.36	159	6
	61	10378	4.85	0.50	442	16
	63	10570	3.95	0.41	331	13
	65	10791	3.05	0.49	475	17
	67	10980	2.75	0.72	369	13
	69	11067	4.10	0.55	309	11
	71	11190	4.40	0.90	735	29
	75	11422	3.05	0.81	279	11
	77	11525	3.15	0.65	432	17
	79	11676	6.20	0.78	330	14
	82	12224	7.30	1.08	553	25
	84	12291	7.60	1.46	637	31
	86	12362	6.35	1.18	637	31
	88	12450	6.40	1.18	880	46
	90	12553	6.90	1.04	719	40
	92	12655	4.55	0.87	397	21
	94	12745	3.85	0.58	327	17
	96	12835	5.20	0.56	331	17
	98	13013	4.55	0.21	406	21
21-06-93 22-06-93	2	279	1.05	0.29	9	0
	4	332	0.90	0.29	11	0
	7	1915	4.65	1.15	696	27
	9	2086	7.55	0.86	1189	52
	11	2262	8.90	1.06	1609	76
	13	2423	6.45	0.69	846	43

Table 3.7: Verticalwise flow and sediment data used for the verification analysis, Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical No.	Dist from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/s
06-07-93	2	258	1.60	0.31	22	1
07-07-93	4	299	1.70	0.41	34	1
	8	1830	5.10	1.40	923	42
	10	2003	9.70	1.38	2260	120
	12	2173	8.00	1.23	1844	103
	14	2347	7.00	1.05	1220	72
	16	2491	6.60	0.83	880	55
	18	2621	6.80	0.86	922	61
	20	2745	7.90	1.07	1208	82
	22	2866	8.10	1.02	1123	79
	24	2973	7.75	1.01	892	66
	26	3098	5.20	0.95	870	63
	28	3286	4.00	1.22	918	64
	32	3534	5.60	1.22	1121	84
	34	3649	9.00	1.75	1364	106
	36	3759	10.85	1.26	2021	170
	38	3887	7.20	1.30	1159	100
	40	3982	5.60	1.08	643	53
	42	4085	4.30	0.88	496	40
	44	4181	7.40	0.68	583	47
	46	4273	7.85	0.76	637	49
	50	5436	7.15	0.90	254	21
	52	5552	2.10	0.54	232	11
	54	5711	1.90	0.32	100	3
	57	6990	3.15	0.53	37	1
	59	7021	1.85	0.48	38	1
	63	7903	6.85	0.86	818	38
	65	8022	8.30	1.09	1117	59
	67	8120	10.50	1.11	1267	75
	69	8216	12.25	1.22	1649	102
	71	8308	11.00	1.50	1682	104
	73	8402	8.80	1.09	1128	72
	75	8520	6.70	0.98	846	52
	77	8646	5.85	0.64	694	38
	79	8862	4.40	0.59	574	29
	81	8980	3.45	0.87	347	16
	83	9124	2.50	0.76	504	23
	85	9349	1.80	0.68	353	14
	87	9628	1.65	0.7	447	17
	89	10009	1.65	0.83	325	11
	91	10358	5.95	0.94	1099	38
	93	10565	3.35	0.87	956	34
	95	10760	3.25	0.83	461	16
	97	10934	2.00	0.95	272	8
	99	11049	1.40	1.05	275	9
	101	11186	2.40	1.18	337	12
	103	11299	4.30	1.10	864	34
	105	11438	6.60	1.43	983	48
	107	11555	8.60	1.97	1576	88
	109	11652	7.10	2.31	2789	165
	111	11809	4.80	2.42	1356	84
	113	11925	3.75	2.10	876	58

Table 3.7: Verticalwise flow and sediment data used for the verification analysis, Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical No.	Dist from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/s
06-07-93	115	12082	3.60	1.57	1174	77
07-07-93	117	12195	4.90	1.54	1344	93
	119	12333	4.80	1.58	864	63
	121	12445	5.80	1.57	1502	116
	125	12704	10.00	1.09	1596	140
	127	12805	9.65	1.05	1597	137
	129	12947	6.90	0.87	1285	95
	131	13114	6.00	0.36	810	52
12-07-93	2	258	1.75	0.38	25	1
13-07-93	4	299	1.75	0.29	30	1
	8	1830	5.65	1.57	986	45
	10	2003	8.65	1.33	2057	103
	12	2173	7.80	1.24	1658	88
	14	2347	6.65	0.67	973	55
	16	2491	5.85	0.67	696	41
	18	2621	6.35	0.57	527	33
	20	2745	7.65	0.55	722	45
	22	2866	7.90	1.05	1155	76
	26	3098	5.00	1.10	1085	65
	28	3286	4.20	1.26	1010	54
	30	3407	4.30	1.50	972	54
	32	3534	5.20	1.34	1116	66
	34	3649	7.60	1.46	999	66
	36	3759	9.00	1.71	1895	131
	38	3887	7.15	1.49	1074	76
	40	3982	5.10	0.97	633	46
	42	4085	4.00	0.70	388	28
	44	4181	7.15	0.62	551	42
	46	4273	7.8	0.55	584	46
	50	5436	7.50	0.80	264	22
	52	5552	2.00	0.82	258	12
	54	5711	1.20	0.49	115	2
	57	6990	3.00	0.39	26	1
	59	7029	1.50	0.39	22	1
	62	7903	6.95	0.91	882	43
	64	8022	8.00	0.94	1135	64
	66	8120	10.00	1.25	1450	88
	68	8216	11.00	1.30	1503	99
	70	8308	7.60	1.12	1082	71
	72	8402	8.70	1.06	1046	69
	74	8520	5.70	0.82	667	39
	76	8646	3.80	0.57	497	21
	78	8862	3.80	0.54	566	23
	80	8980	2.80	0.77	282	10
	82	9124	2.10	0.58	369	8
	84	9349	1.30	0.43	173	4
	86	9628	1.40	0.43	244	6
	88	10009	1.85	1.09	397	10
	90	10358	5.00	0.53	555	26
	92	10565	3.10	0.75	959	31
	94	10760	3.75	0.82	562	17
	96	10934	1.80	0.83	260	7

Table 3.7: Verticalwise flow and sediment data used for the verification analysis, Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical No.	Dist from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/s
12-07-93 13-07-93	98	11049	1.85	0.97	290	8
	100	11186	2.00	1.04	289	9
	102	11299	3.70	0.94	833	32
	104	11438	6.00	1.43	854	42
	106	11555	8.70	1.19	1191	68
	108	11652	7.00	1.81	2130	130
	110	11809	4.00	2.00	979	58
	112	11925	3.80	1.80	724	42
	114	12082	3.50	1.55	1057	63
	116	12195	4.10	1.92	1359	82
	118	12333	3.80	2.24	921	56
	120	12445	7.00	2.00	1900	137
	122	12574	8.25	1.83	1869	138
	124	12704	8.90	1.16	2002	156
	126	12805	10.70	1.26	1878	154
	128	12947	6.20	1.05	1277	86
	130	13114	6.00	0.60	584	36
	132	13206	6.70	0.70	241	14
02-08-93 03-08-93	2	258	1.50	0.38	23	1
	4	299	1.45	0.32	27	1
	8	1830	10.80	1.48	1539	89
	10	2003	9.60	1.05	1920	119
	12	2173	7.50	1.05	1721	112
	14	2347	7.45	1.15	1449	96
	16	2491	7.15	0.59	619	41
	18	2621	5.00	0.67	451	27
	20	2745	3.70	0.73	346	19
	22	2866	2.80	0.96	375	18
	24	2973	3.70	1.30	592	30
	26	3098	3.95	1.21	843	39
	28	3286	1.95	1.30	547	22
	30	3407	1.35	1.16	361	14
	32	3534	7.30	1.25	1077	57
	34	3649	8.80	1.43	1093	64
	36	3759	6.15	1.34	1345	87
	38	3887	5.90	1.43	917	61
	42	4085	5.90	1.06	704	47
	46	4273	5.00	0.66	414	25
	50	5436	6.05	0.74	190	12
	52	5552	1.20	0.52	108	4
	54	5711	0.95	0.42	35	0
	57	6990	3.10	0.38	27	1
	59	7029	1.50	0.32	22	1
	62	7830	5.60	0.82	592	30
	64	7971	7.90	0.87	970	56
	66	8074	10.45	0.83	1050	68
	68	8168	11.10	0.85	1110	75
	70	8262	9.40	0.87	890	60
	72	8357	7.20	0.82	671	44
	74	8458	4.85	0.73	494	31
	76	8583	4.00	0.88	574	31
	78	8750	5.30	0.96	1215	60

Table 3.7: Verticalwise flow and sediment data used for the verification analysis, Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical No.	Dist from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/s
02-08-93	80	8914	2.90	0.99	390	15
03-08-93	82	9059	1.10	0.55	132	3
	85	9867	1.05	0.58	214	4
	87	10153	1.80	0.64	537	16
	89	10445	1.60	0.62	369	13
	91	10681	5.70	0.66	866	34
	93	10848	4.45	0.59	550	20
	95	10997	0.75	0.60	90	1
	97	11131	0.90	0.93	161	3
	99	11231	5.35	0.84	648	27
	101	11386	9.00	0.92	1303	61
	103	11481	8.05	0.89	1032	53
	105	11574	2.80	1.08	431	24
	107	11738	2.70	1.74	846	47
	109	11863	4.20	1.85	993	63
	111	11969	6.25	1.81	2083	148
	115	12281	7.20	2.03	2297	170
	117	12384	5.15	1.70	1044	77
	119	12522	2.95	1.37	587	41
	121	12635	4.20	0.67	564	42
	123	12739	9.45	0.81	900	72
	125	12867	8.00	0.80	1229	101
	127	13023	5.85	0.79	1032	84
	129	13179	5.80	0.53	340	26
09-08-93	2	258	1.30	0.26	17	1
10-08-93	4	299	1.75	0.64	49	2
	8	1830	11.55	1.55	1828	112
	10	2003	10.00	1.28	2428	160
	12	2173	8.35	1.12	1862	121
	14	2347	7.40	0.74	1075	68
	16	2491	6.65	0.36	416	27
	18	2631	4.90	0.78	525	36
	20	2806	3.00	1.01	797	50
	22	3031	4.90	1.12	1643	108
	24	3286	5.00	1.23	1657	109
	26	3505	2.45	0.87	532	34
	28	3621	11.40	1.10	1126	77
	30	3720	10.10	0.88	1176	82
	32	3837	10.25	0.93	1645	120
	34	3969	10.40	1.24	2089	159
	36	4121	8.20	0.90	1450	103
	38	4296	1.45	1.20	379	10
	41	5436	6.05	0.87	225	15
	43	5552	1.85	0.72	210	9
	45	5711	1.55	0.37	81	2
	48	6990	2.00	0.45	20	1
	50	7024	1.20	0.29	18	0
	53	7830	4.35	1.35	921	46
	55	7971	8.80	1.07	1223	75
	57	8087	10.80	1.24	1650	104
	59	8192	11.00	0.99	1439	98
	61	8300	9.60	0.97	1152	83

Table 3.7: Verticalwise flow and sediment data used for the verification analysis, Jamuna river at Bahadurabad (Source : BWDB) (Contd.)

Date	Vertical No.	Dist from init. pt (m)	Depth m	Corrected Vel.(m/s)	Q m3/s	Qs kg/s
09-08-93	63	8419	6.30	0.70	634	45
10-08-93	65	8558	4.00	0.32	348	23
	67	8717	4.85	0.33	449	30
	69	8903	3.90	0.50	428	27
	71	9121	0.50	0.73	222	4
	73	9460	1.45	0.46	365	14
	75	9867	1.75	0.63	741	30
	77	10232	3.50	0.47	1165	57
	79	10565	2.60	0.52	689	32
	81	10793	1.75	0.62	364	17
	83	11018	1.40	0.85	626	26
	85	11211	2.65	0.79	567	27
	87	11333	7.30	0.77	673	36
	89	11438	7.50	1.01	778	46
	91	11560	5.10	1.09	1071	73
	93	11738	6.45	1.44	1935	137
	95	11907	9.95	1.82	3111	230
	103	12389	11.30	0.80	1644	146
	105	12548	5.55	0.98	1181	105
	107	12713	8.25	1.22	1573	140
	109	12853	11.35	0.96	1828	168
	111	12996	7.10	0.74	1096	93
	113	13142	6.20	0.38	345	26

Table 3.8 : Summary of flow and sediment data used for the development of different prediction formula (Source : DVWK, 1990)

Method	Water depth (m)		velocity (m/s)		Slopes (-)		grain dia. d_{50} (mm)	
	min	max	min	max	min	max	min	max
Ackers and White	-	-	-	-	-	-	0.04	0.40
Bagnold	-	-	-	-	-	-	0.79	30.00
Engelund-Hansen	0.09	0.33	0.25	1.60	-	-	0.19	0.93
Van Rijn	1.00	20.00	0.50	2.50	-	-	0.10	2.00
Yang	0.01	15.20	0.23	1.97	0.0043	0.0279	0.14	1.71
Meyer-Peter and Mueller	0.01	1.20	-	-	0.0004	0.0200	0.40	30.00

Table 3.9 : Data used for the sensitivity analysis of the exponent b

Type of sediment transport formula	Depth range, h (m)	Froude number range, Fr (-)	Sensitivity analysis	
			slope range, S (cm/km)	Grain dia range, d_{50} (mm)
Total load	0.50-20.00	0.20-0.40	5-10	0.12-0.35
Bed load	2.00-20.00	0.088	-	-

Table 4.1 : Values depth factor used for weighted concentration according to Chinese standard (Source : WMO, 1989)

Number of measuring points in a vertical	N	Measuring at relative depth										
		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
5	10	1		3				3		2		1
3	4			2				1		1		
	3			1				1		1		
2	2			1						1		
1							1 or	1				

Table 6.1 : Results of the comparison between Measured and Simplified methods of sediment discharge computation

Vertical No.	Total Depth m	Measured Velocity m/s	Water Disch. m^3/s	Measured Sed.disch. kg/s	Computed Sediment discharge		
					Straub 2-point kg/s	Chinese 2-point kg/s	Chinese 3-point kg/s
1	6.80	1.386	2281	2831	2630	2634	3002
2	9.70	1.993	2662	3182	3041	3467	3117
3	8.50	2.228	2345	2080	2208	2274	2100
4	7.80	2.377	1978	1597	1452	1426	1412
5	7.90	2.320	2721	2752	2634	2837	2820
6	6.00	2.393	2809	2530	2363	1951	2005
7	8.65	1.957	1163	1045	948	1013	1023
8	9.60	1.712	1366	978	1012	997	974
9	13.20	0.932	1237	1266	940	1124	1126
10	11.10	0.947	994	546	484	516	527
11	8.00	0.807	885	452	487	501	497
12	5.40	0.772	697	289	355	306	314
13	7.00	0.832	1040	550	515	573	592
14	7.20	0.882	1215	587	531	657	648
15	5.30	0.876	766	425	464	473	497
16	4.20	0.801	720	410	521	501	516
17	4.70	0.766	789	507	464	607	627
18	2.00	0.738	677	212	241	219	227
19	6.90	0.687	948	349	350	373	378
Total			27294	22589	21642	22449	22402
Difference %					4.19	0.62	0.82

Table 6.2 : Ranges of exponent 'b' of selected total load formula as obtained from theoretical analysis

Predictors	Type of formula	Ranges of exponent b
Ackers and White (1973)	Total load	4.4-6.8
Bagnold (1966)	Total load	3.4-3.9
Engelund-Hansen (1967)	Total load	5.00
Hossain (1985)	Total load	3.25
Van Rijn (1984), Original form	Total load	3.2-8.5
Yang (1973)	Total load	4.3-5.2

Table 6.3 : Ranges of exponent 'b' of selected bed load formula as obtained from theoretical analysis

Predictors	Type of formula	Ranges of exponent b
Mymer-Peter and Mueller (1948)	bed load	3.3-8.6
Parker and Klingeman (1983)	bed load	3.7-10.4
Van Rijn (1984), Original form	bed load	4.3-10.5
Van Rijn (1984), Simplified form	bed load	4.3-29

Table 6.4 : The percentage of data coverage in selected bands of discrepancy ratio for the verification of Suggested equation (Eq. 6.2) based on data from each vertical

Sediment transport predictor	mean	Discrepancy Ratio				Standard Deviation	No. of data used
		Percent of data in range					
		0.75-1.25	0.50-1.50	0.25-1.75	0.10-1.90		
Suggested equation (Eq. 6.2)	1.17	49	81	93	96	0.51	334

Table 6.5 : The percentage of data coverage in selected bands of discrepancy ratio for comparison of Suggested and selected sediment transport prediction formula against the data from each vertical

Sediment transport predictors	Discrepancy ratio					Standard deviation	No. of data sets
	mean	Percent of data in range					
		0.75-1.25	0.50-1.50	0.25-1.75	0.10-1.90		
Suggested (Eq.6.2)	0.88	57	94	98	98	0.44	582
Ackers and White	1.98	18	34	47	54	1.56	582
Bagnold	0.68	32	75	97	99	0.30	582
Engelund-Hansen	1.44	30	53	68	76	0.72	582
Hossain (adjusted)	1.42	35	63	77	82	1.49	582
Van Rijn	1.31	24	43	65	75	0.92	582
Yang	0.41	7	32	75	95	0.24	582

Table 6.6 : The percentage of data coverage in selected bands of discrepancy ratio for comparison of Suggested and selected sediment transport prediction formula against the data from normalised channel

Sediment transport predictors	Discrepancy ratio					Standard deviation	No. of data sets
	mean	Percent of data in range					
		0.75-1.25	0.50-1.50	0.25-1.75	0.10-1.90		
Suggested (Eq.6.4)	1.14	64	88	97	97	0.34	83
Ackers and White	1.96	10	13	26	42	2.72	83
Bagnold	0.58	13	63	99	100	0.21	83
Engelund-Hansen	1.00	45	69	87	93	0.54	83
Hossain (adjusted)	12.75	45	76	85	88	7.78	83
Van Rijn	0.95	32	53	81	89	0.61	83
Yang	0.30	1	15	56	89	0.18	83

FIGURES

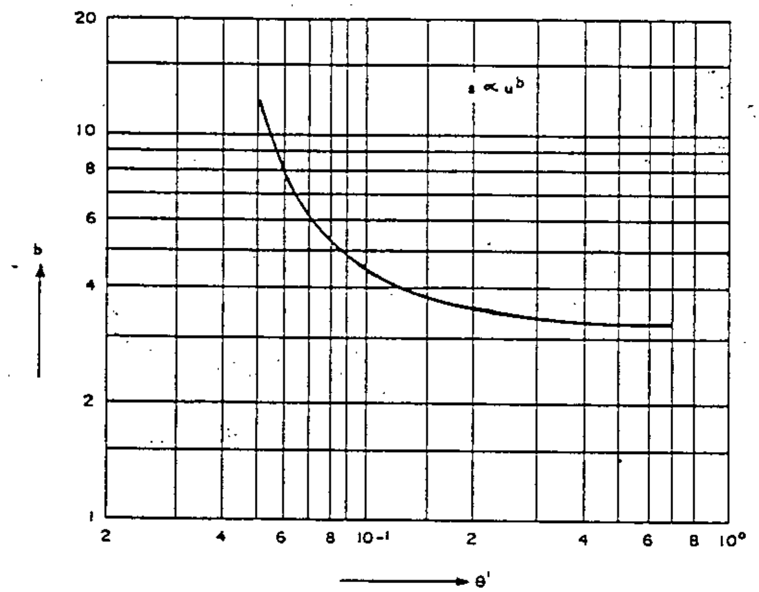


Fig. 2.1 : Approximate relationship between b and θ'

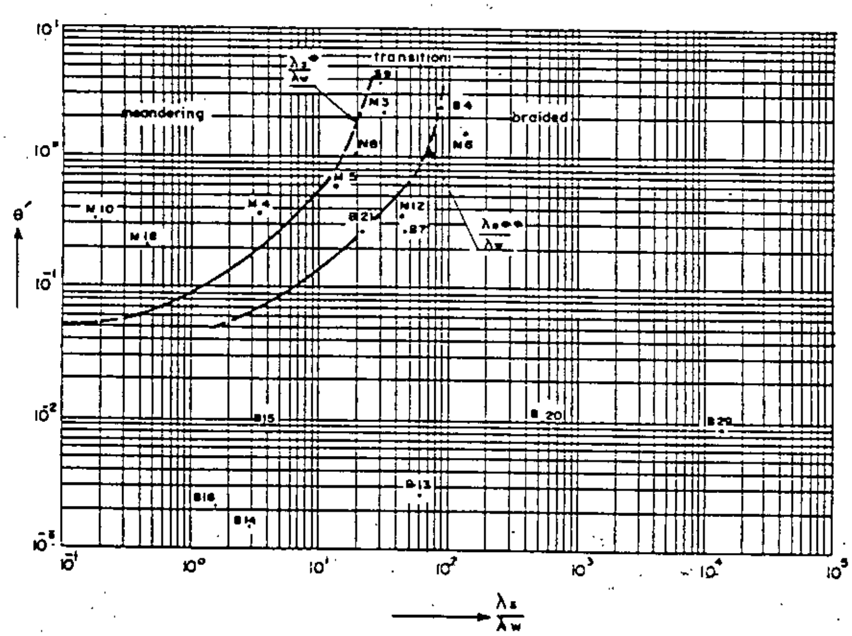


Fig. 2.2 : Classification diagram based on θ' and λ_s/λ_w

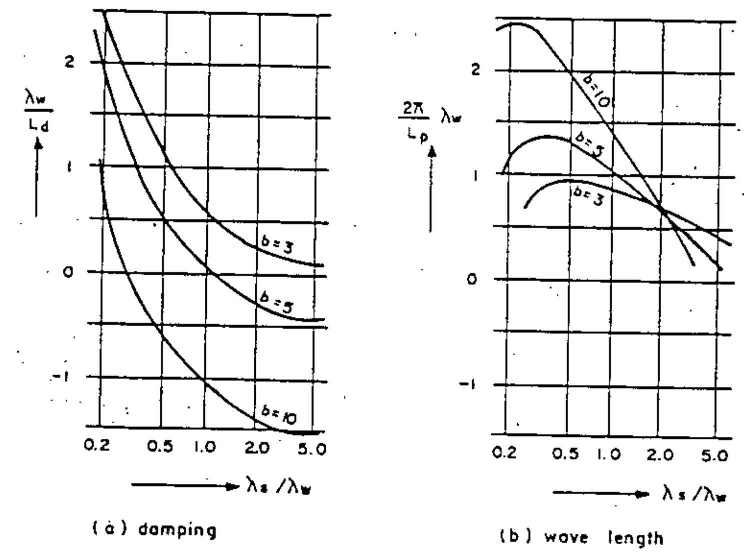
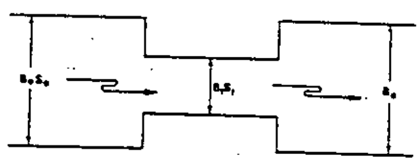


Fig. 2.3 : Damping and wave length of perturbations in the linear analysis versus λ_s/λ_w



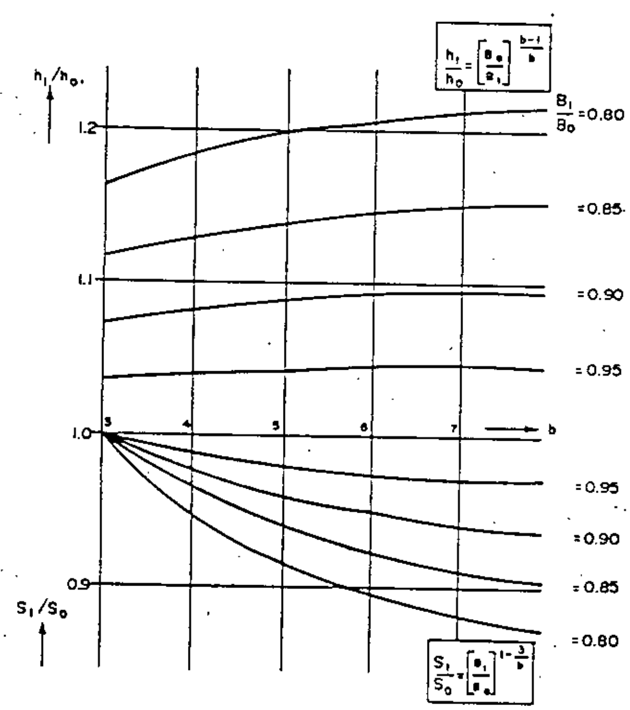
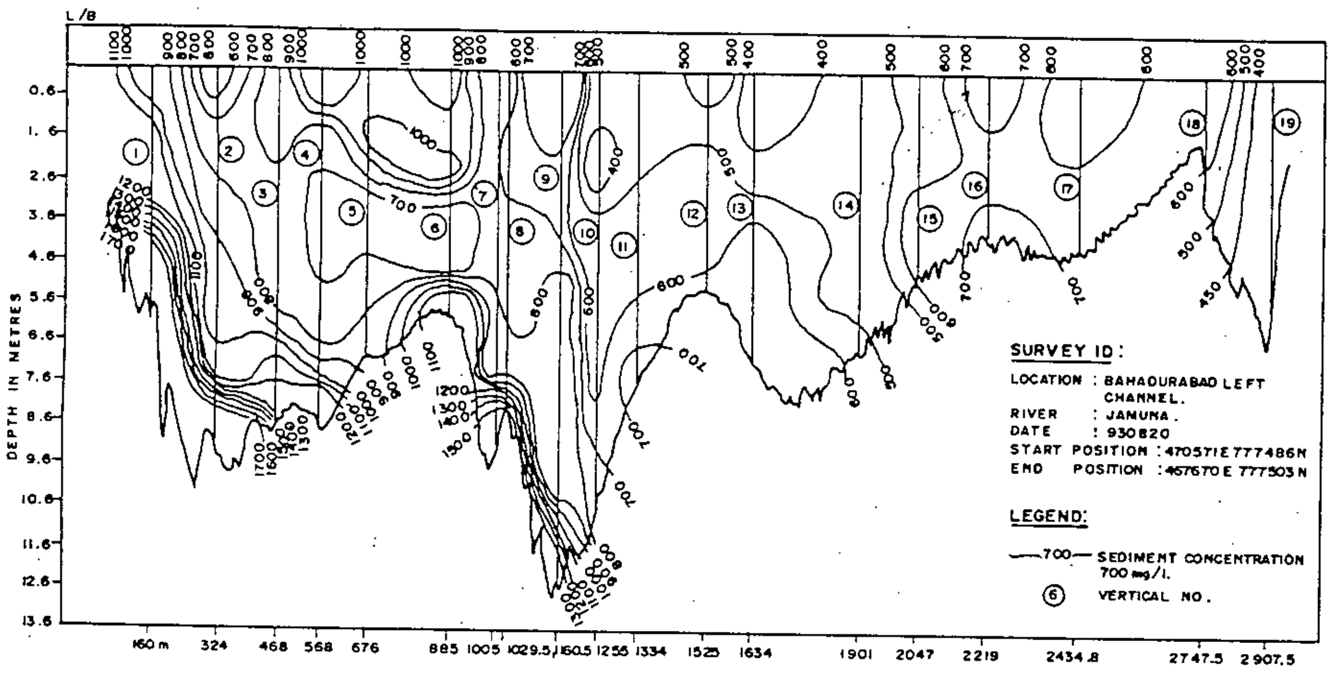
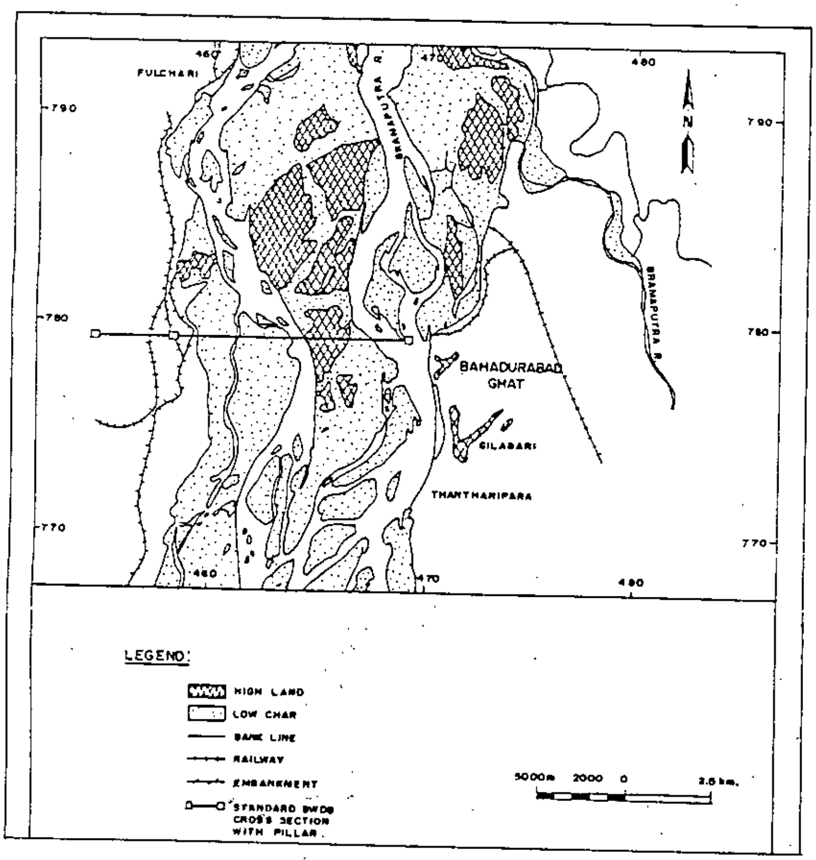


Fig. 2.4 : Consequences of constriction of river width



3.1 Transverse suspended sediment distribution



3.2 Location map for the Bahadurabad discharge gauging cross- section

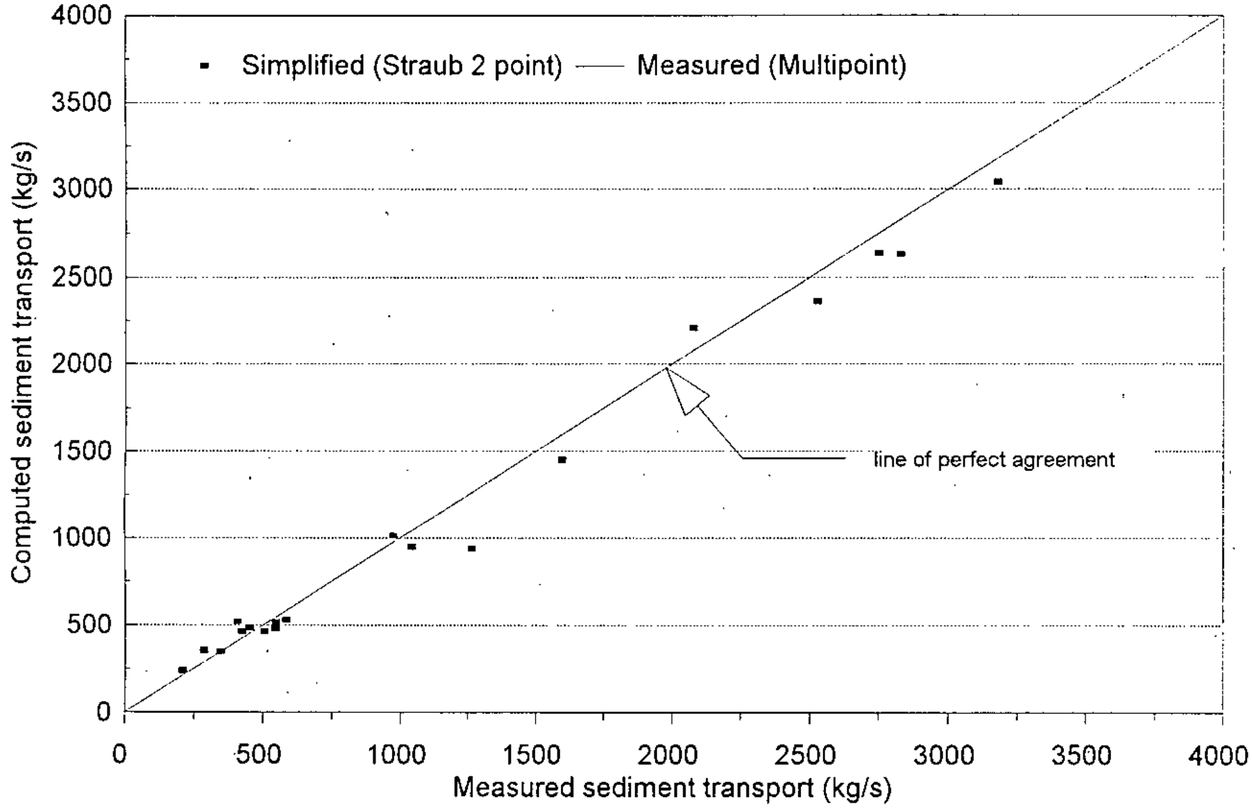


Figure 6.1 : Comparison between Measured (Multipoint) and Simplified (Straub 2 point) methods

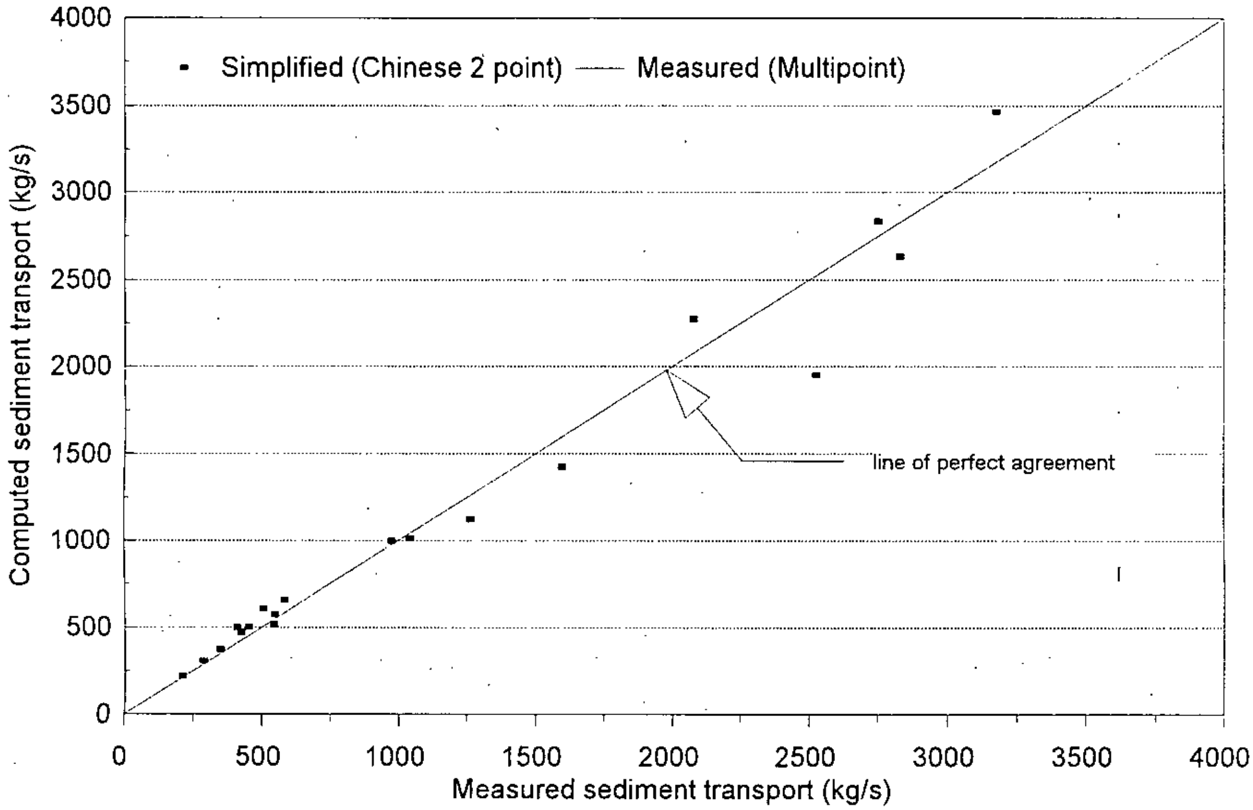


Figure 6.2 : Comparison between Measured (Multipoint) and Simplified (Chinese 2 point) methods

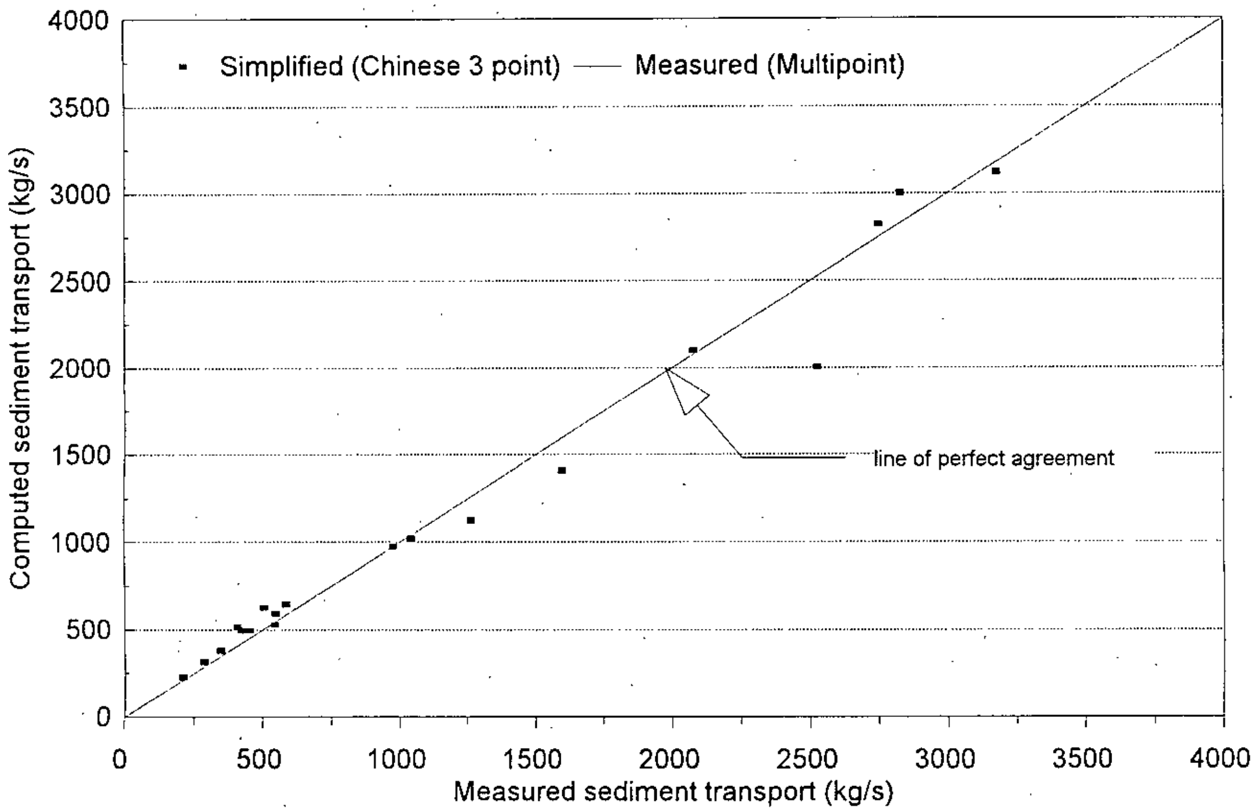


Figure 6.3 : Comparison between Measured (Multipoint) and Simplified (Chinese 3 point) methods

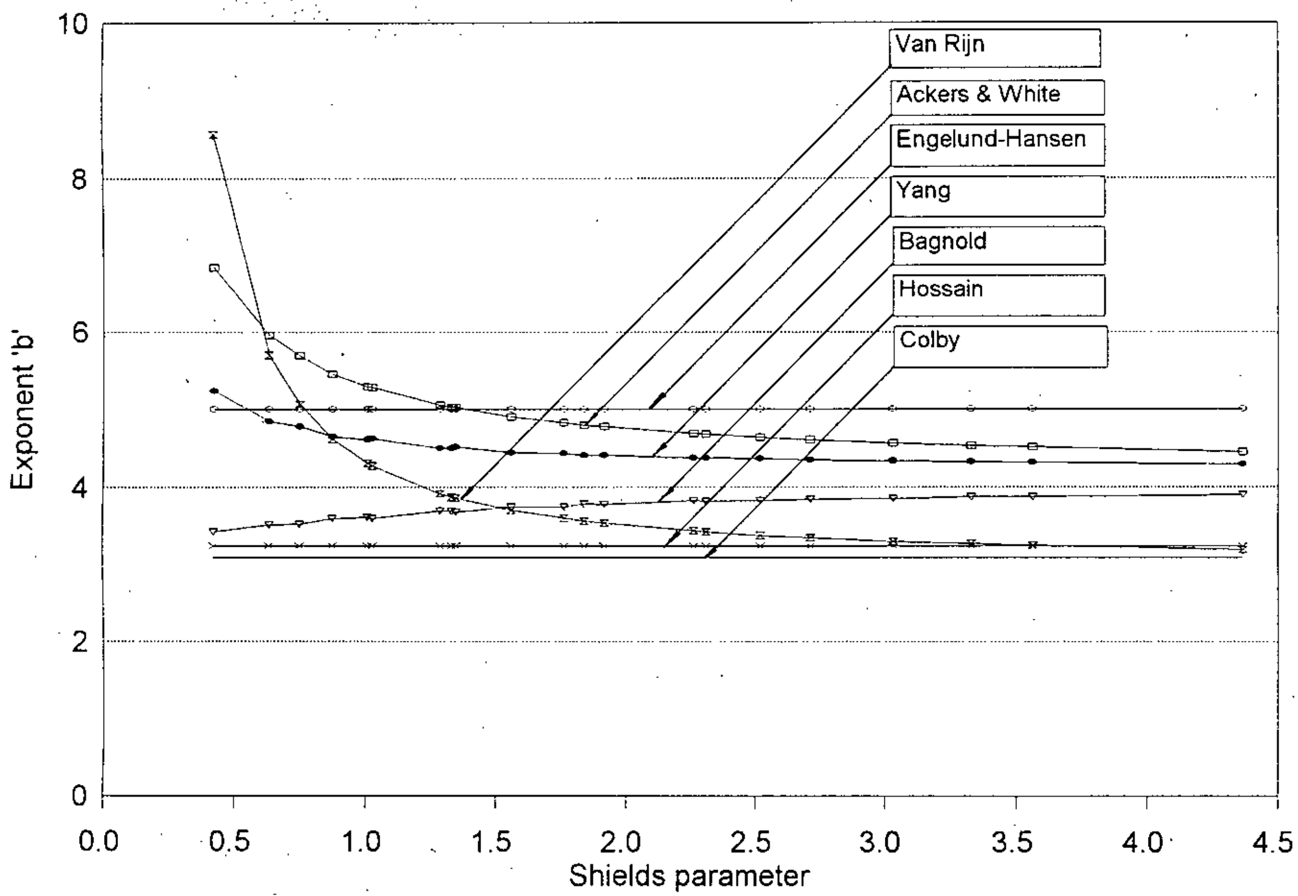


Figure 6.4 : Variation of exponent 'b' with Shields parameter for total load formula

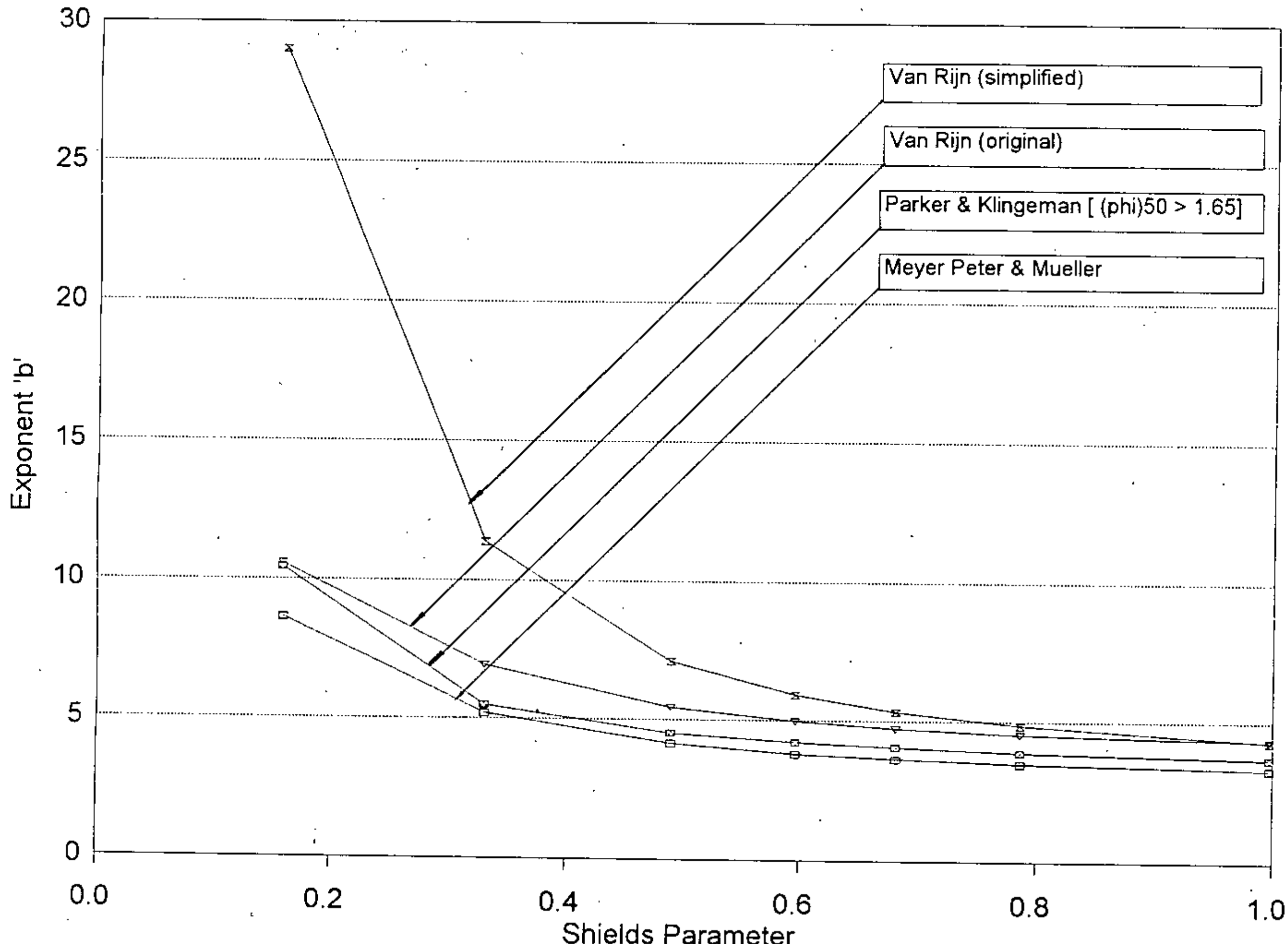


Figure 6.5 : Variation of exponent 'b' with Shields Parameter for bed load formula

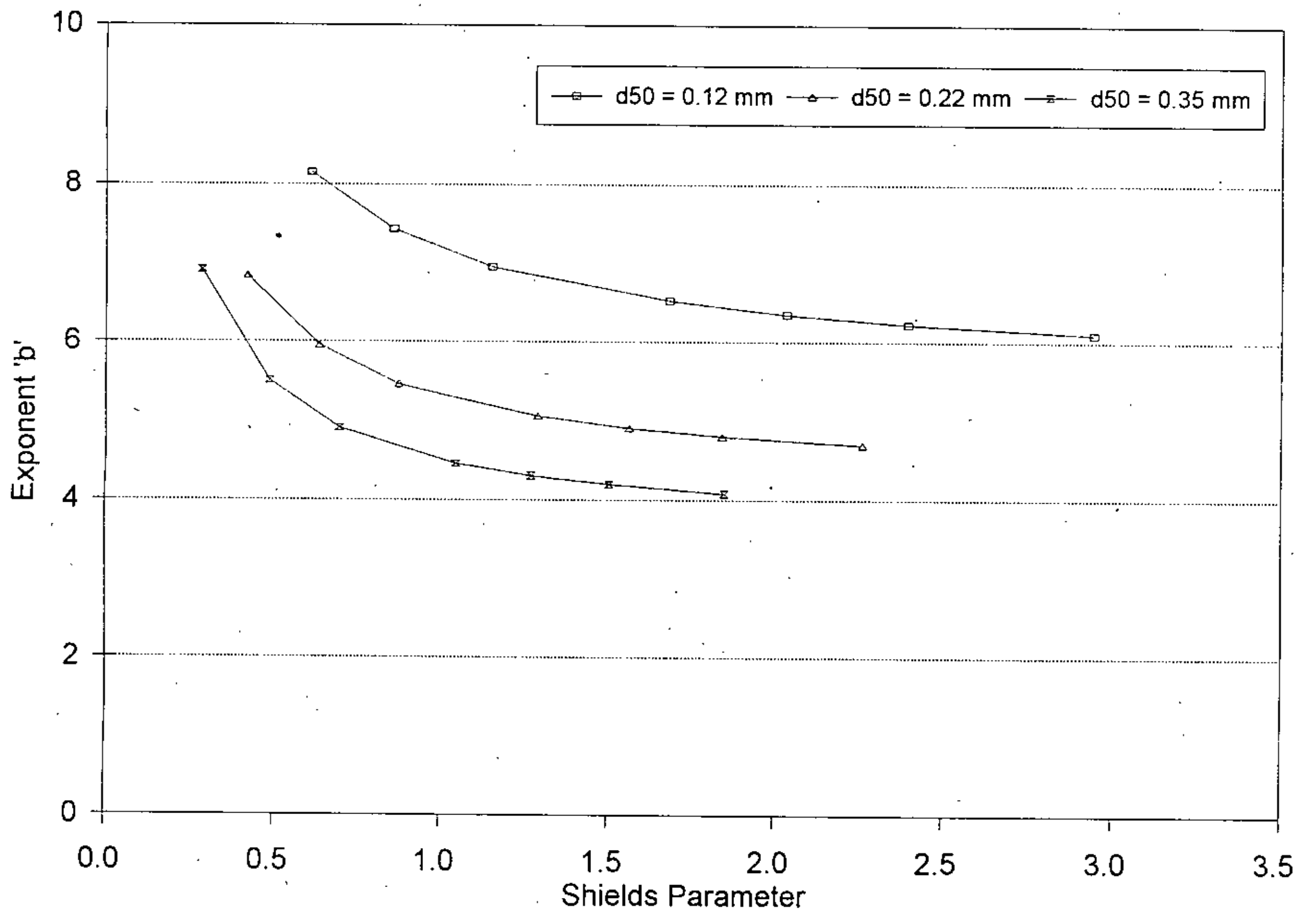


Figure 6.6 : Sensitivity of exponent 'b' with various grain sizes , Ackers & White formula

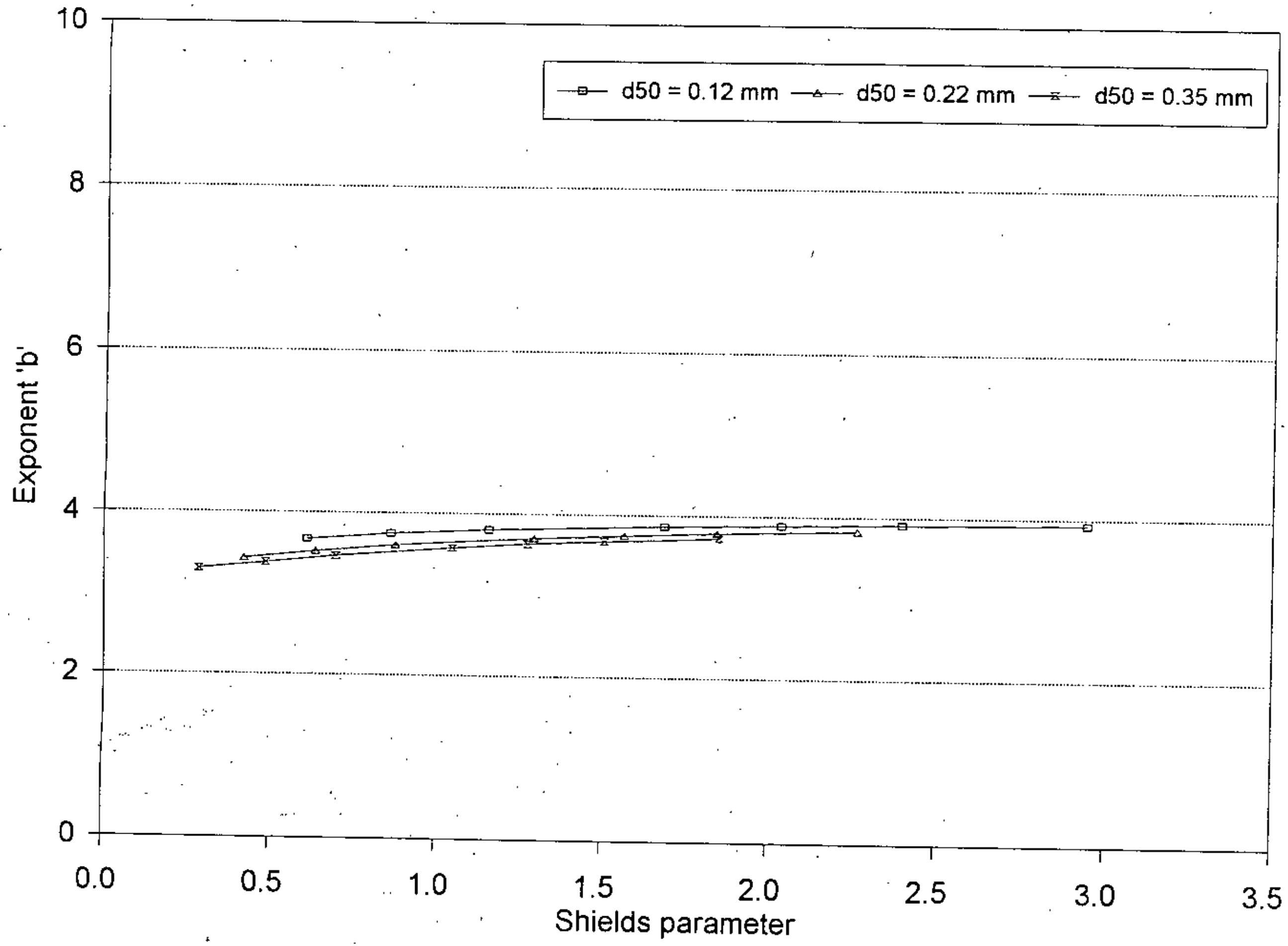


Figure 6.7 : Sensitivity of exponent 'b' with various grain sizes, Bagnold formula

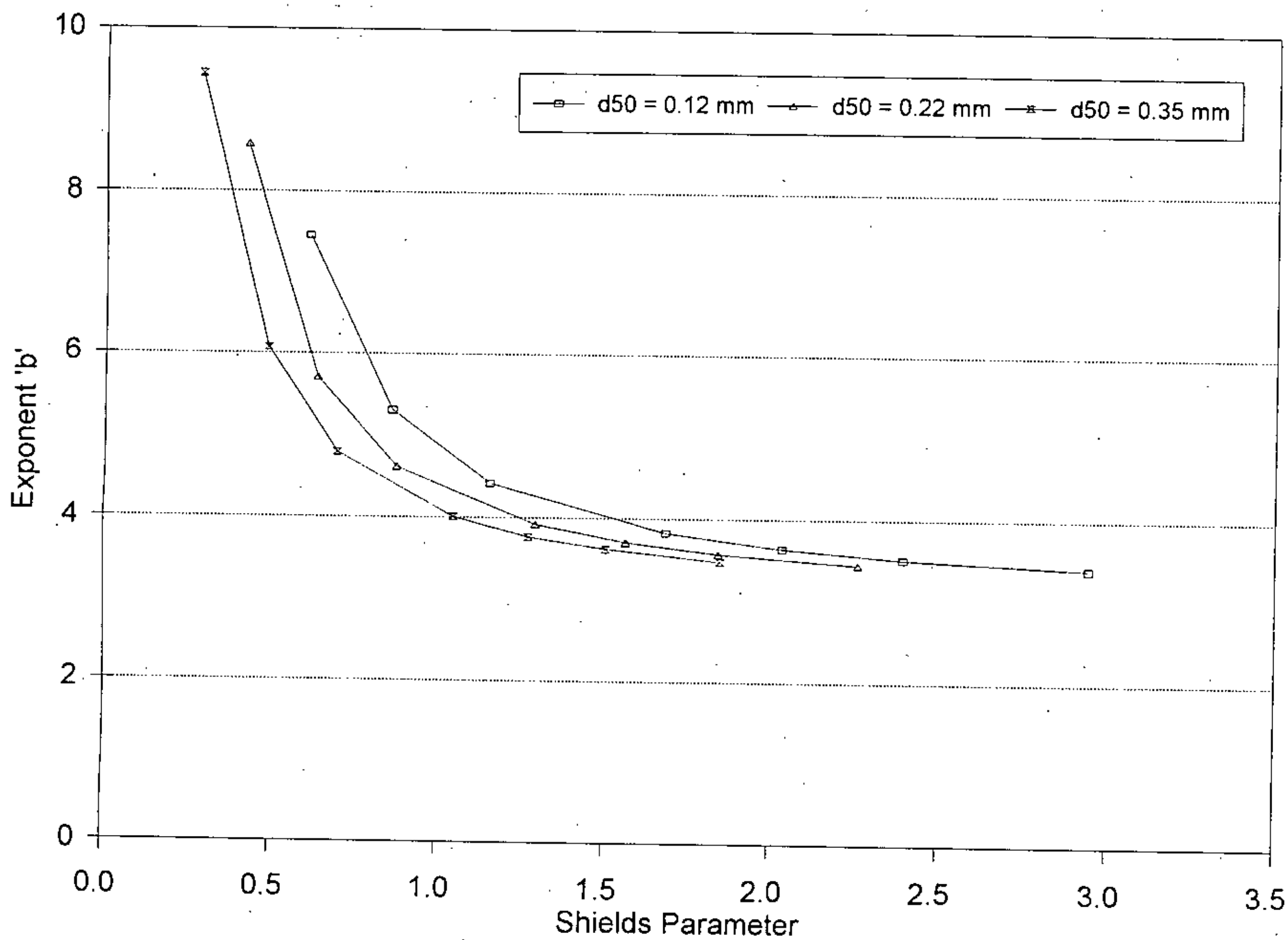


Figure 6.8 : Sensitivity of exponent 'b' with various grain sizes, Van Rijn formula

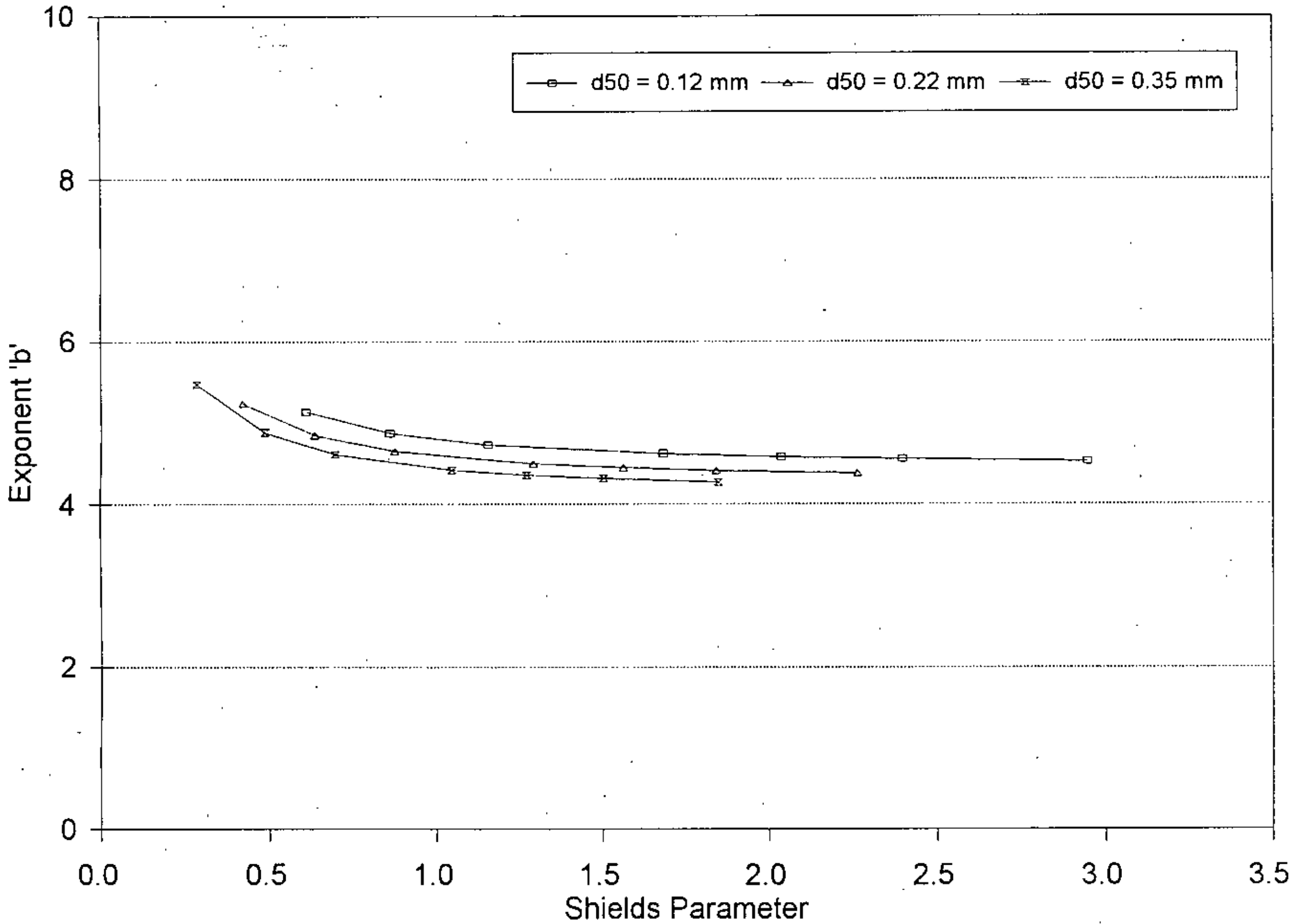


Figure 6.9 : Sensitivity of exponent 'b' with various grain sizes, Yang formula

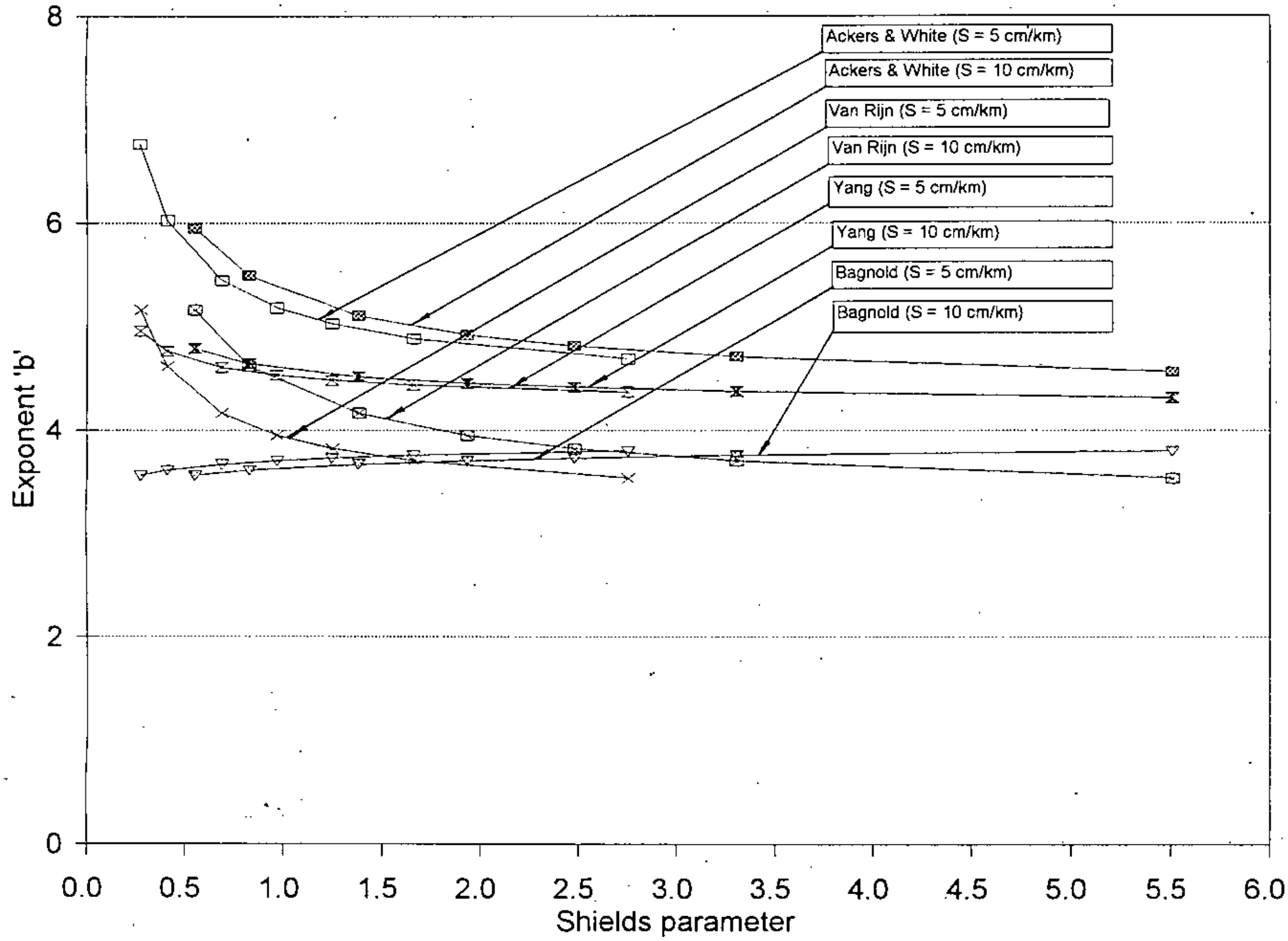


Figure 6.10 : Sensitivity of exponent 'b' for variation of longitudinal slopes, Total load formula

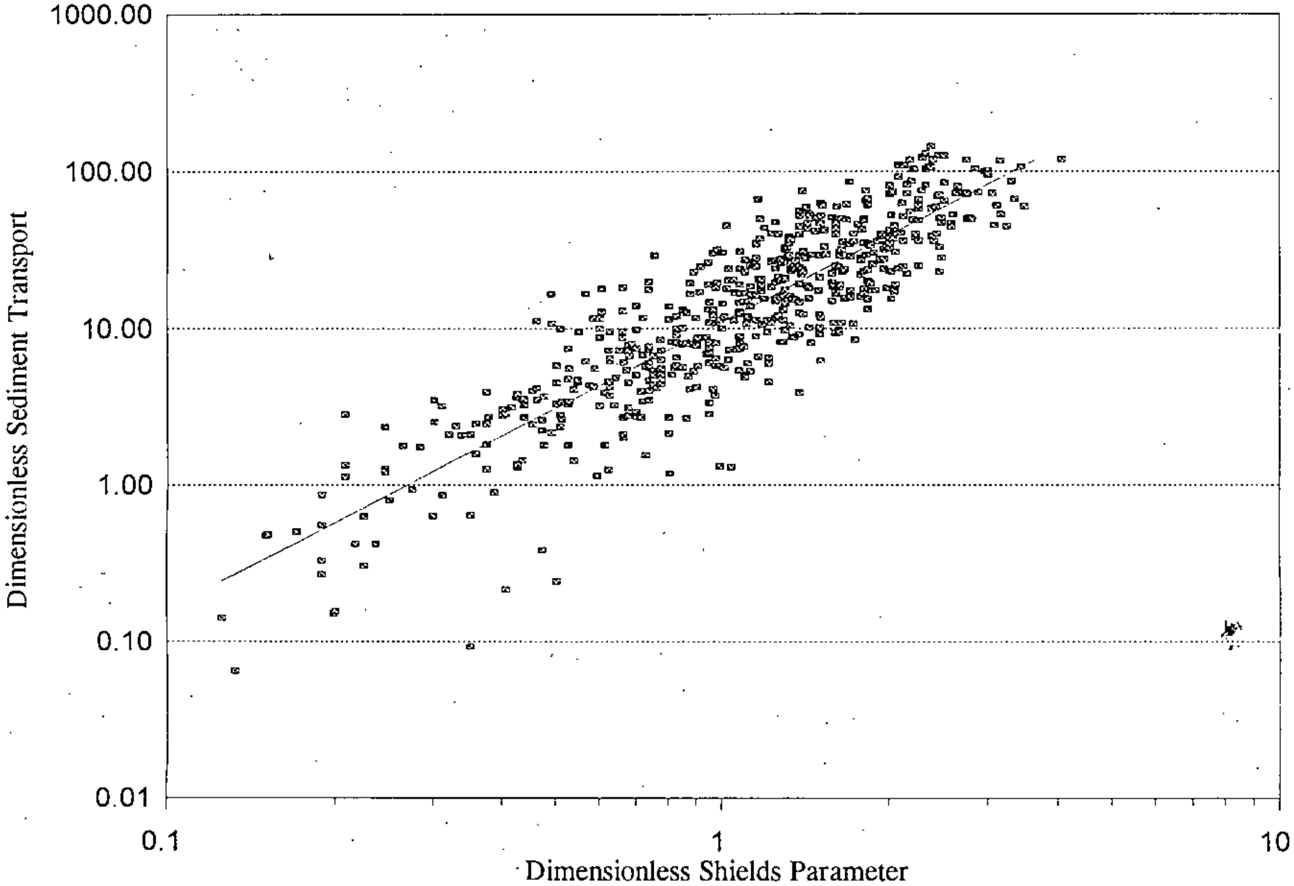


Figure 6.11 : Relationship between dimensionless Shields parameter and dimensionless sediment transport based on data from each vertical

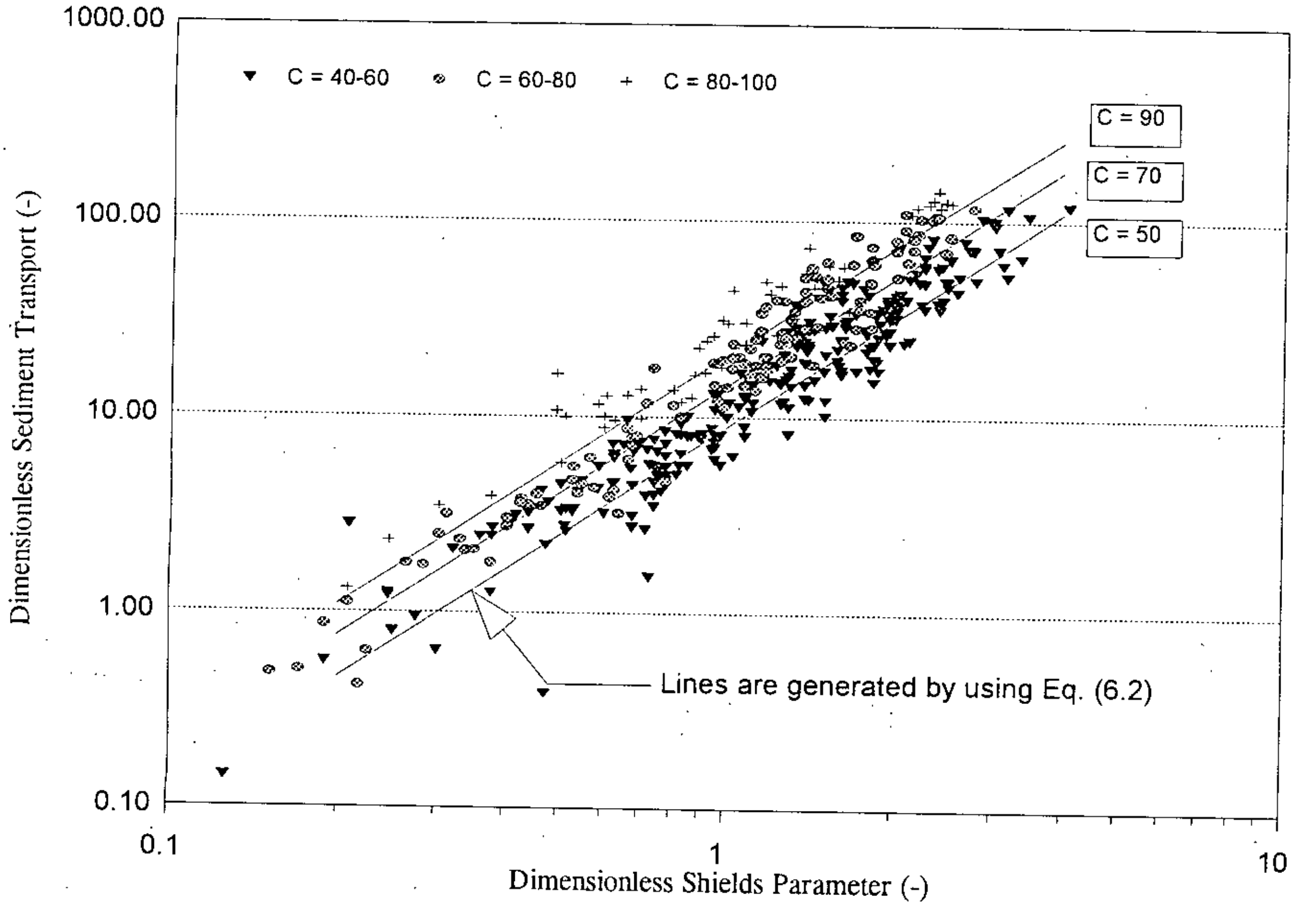


Figure 6.12 : Correlation between dimensionless Shields parameter and dimensionless sediment transport

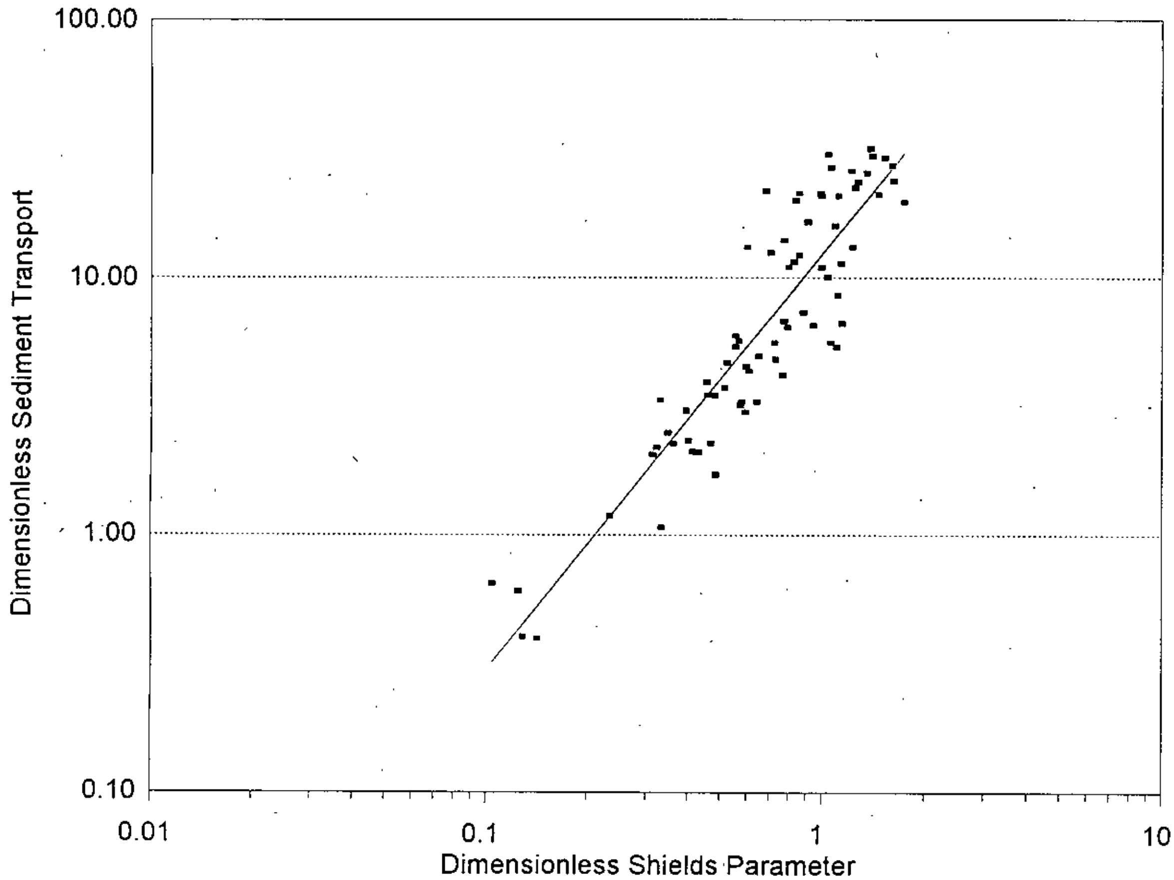


Fig 6.13 : Relationship between dimensionless Shields parameter and dimensionless sediment transport based on normalised channel data

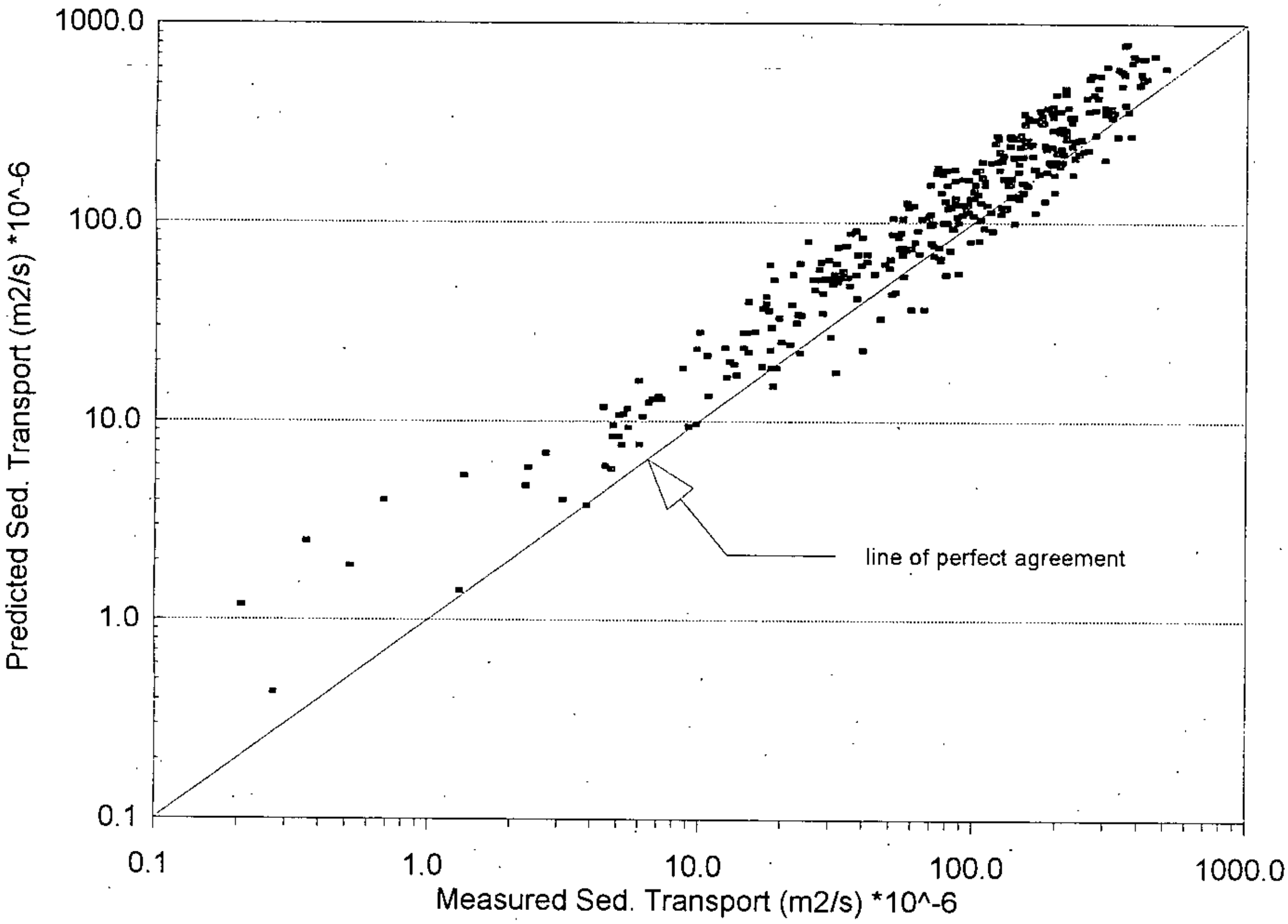


Fig. 6.14 : Verification of Suggested equation (Eq. 6.2) with measured 1993 data

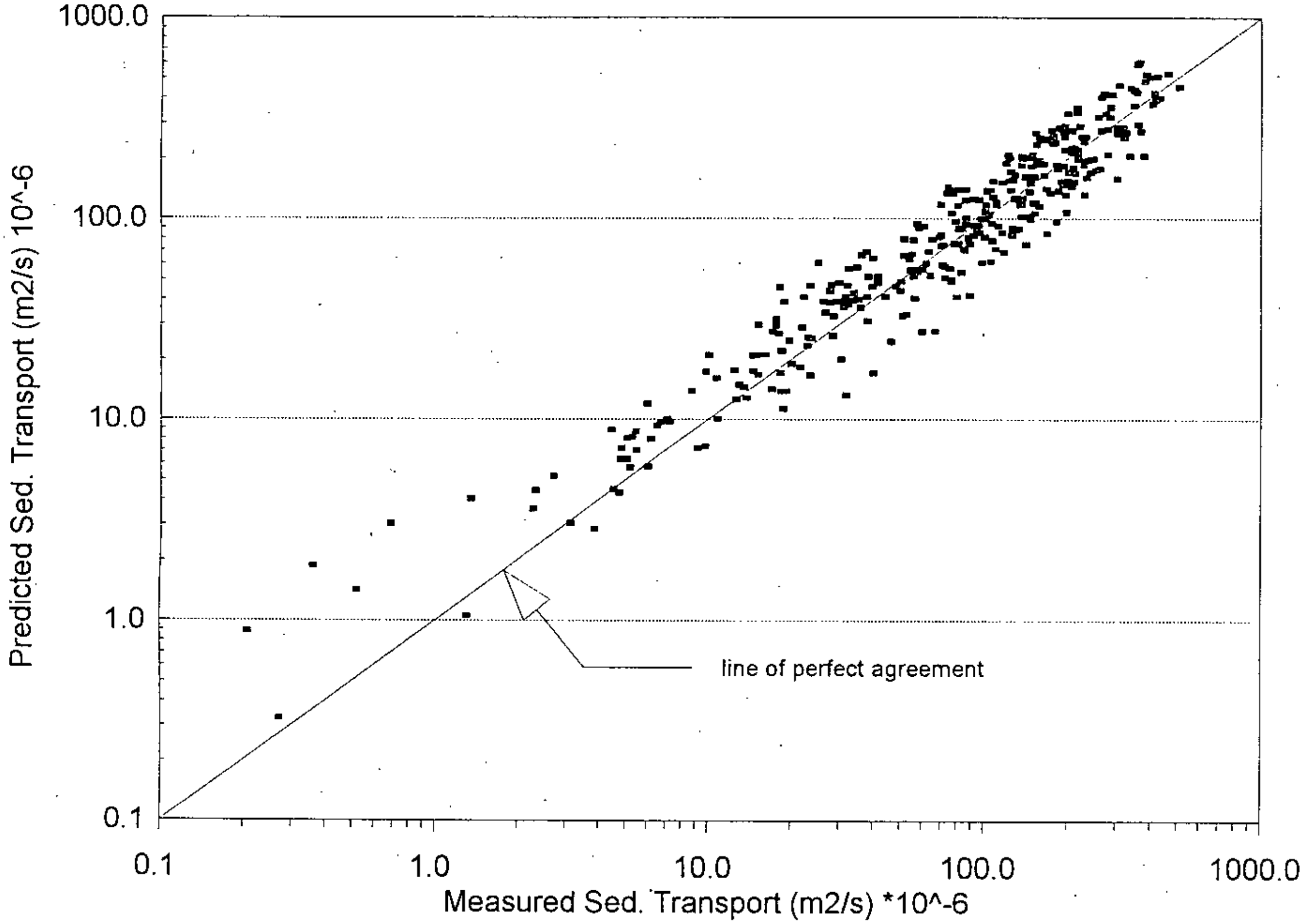


Fig. 6.15 : Verification of Suggested equation (Eq. 6.2) with measured 1993 data, corrected form

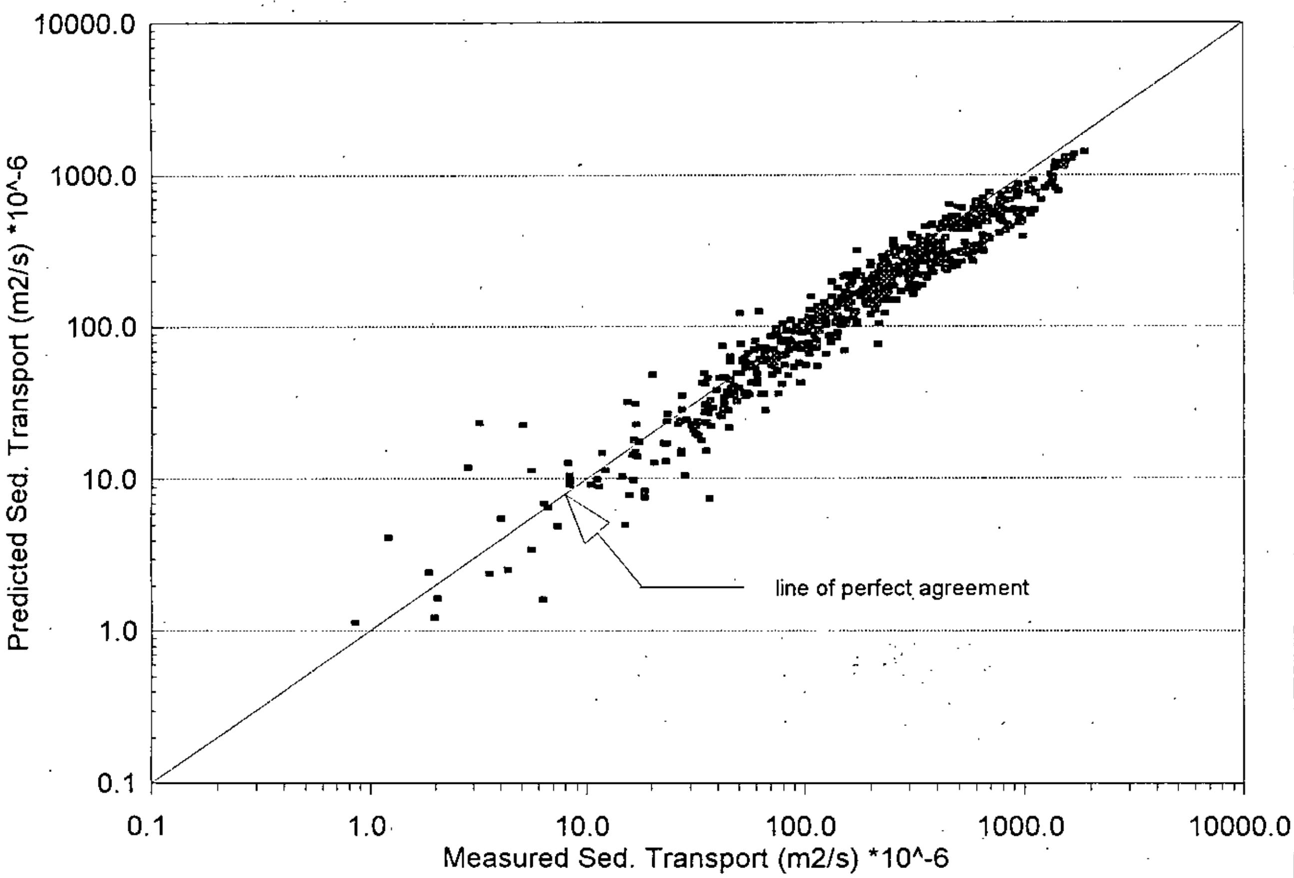


Fig. 6.16 : Predicted versus measured sediment transport (verticalwise data) for Suggested equation (Eq. 6.2)

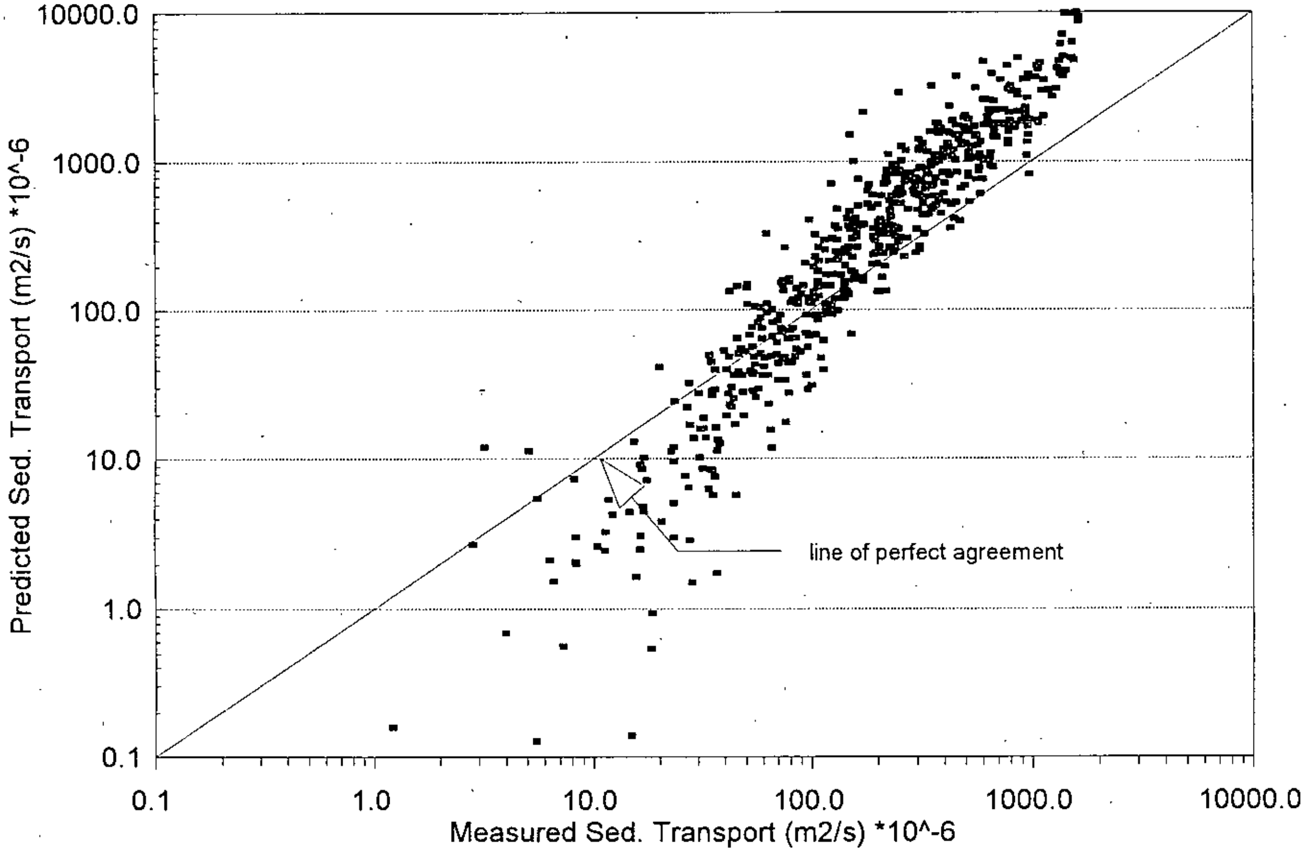


Fig. 6.17 : Predicted versus measured sediment transport (verticalwise data) for Ackers and White equation

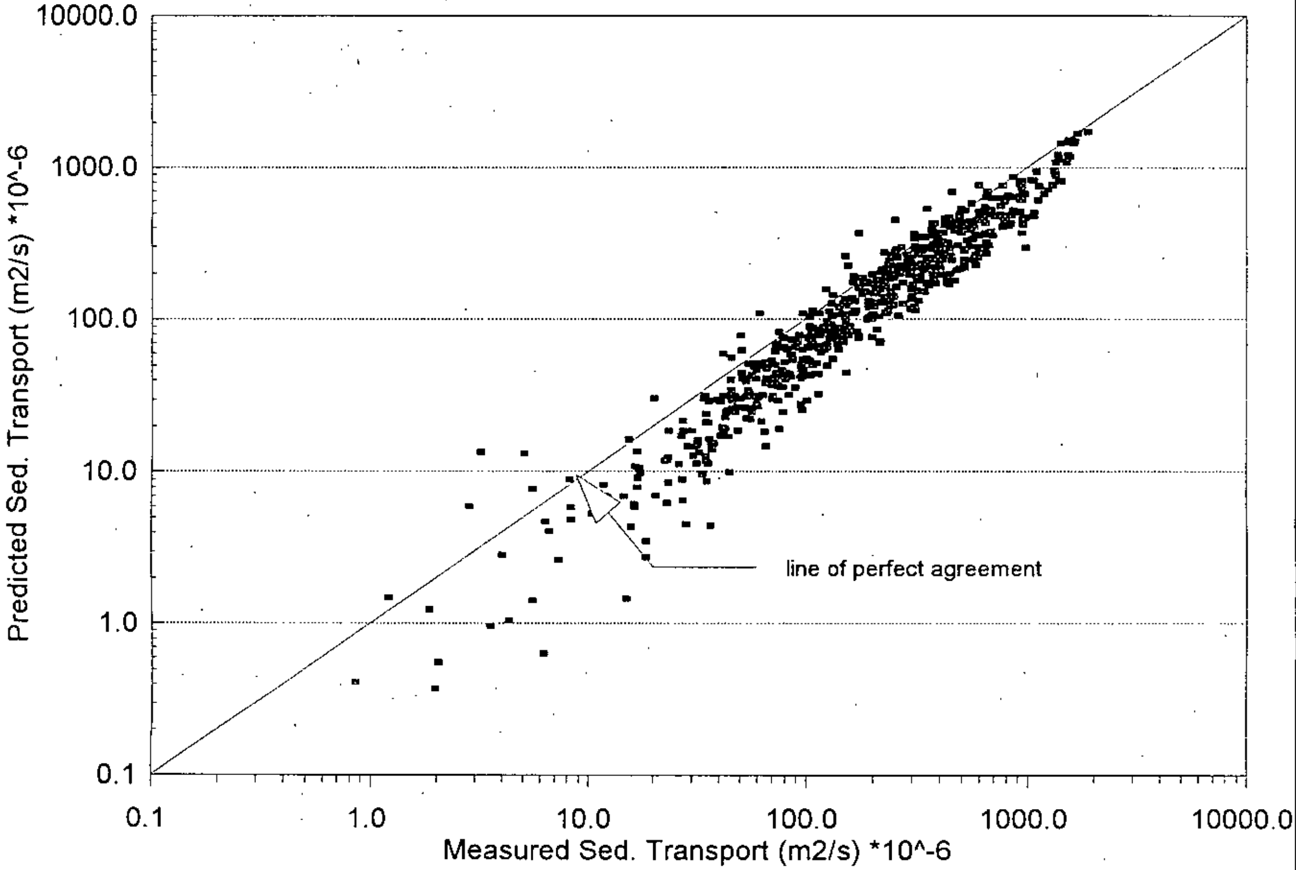


Fig. 6.18 : Predicted versus measured sediment transport (verticalwise data) for Bagnold equation

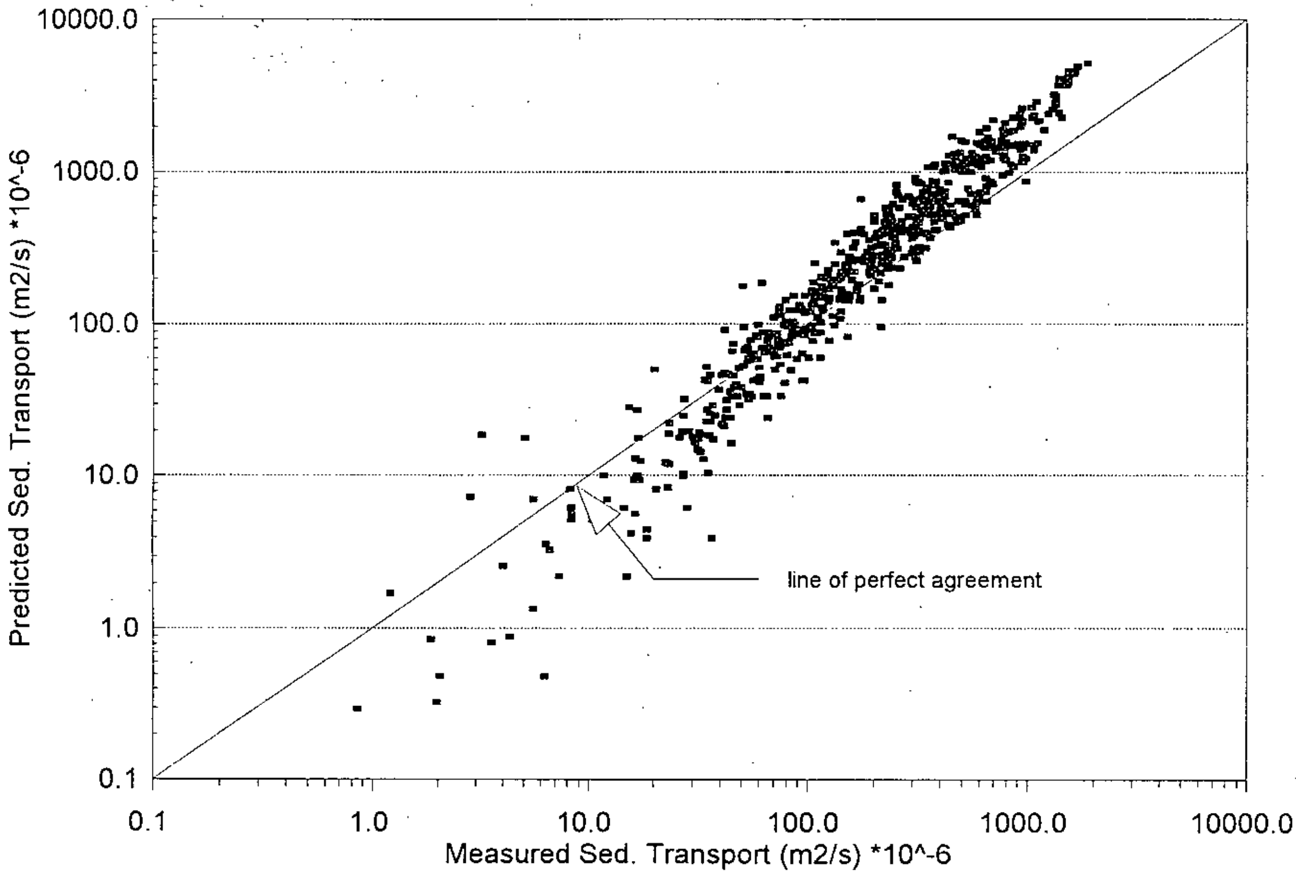


Fig. 6.19 : Predicted versus measured sediment transport (verticalwise data) for Engelund-Hansen equation

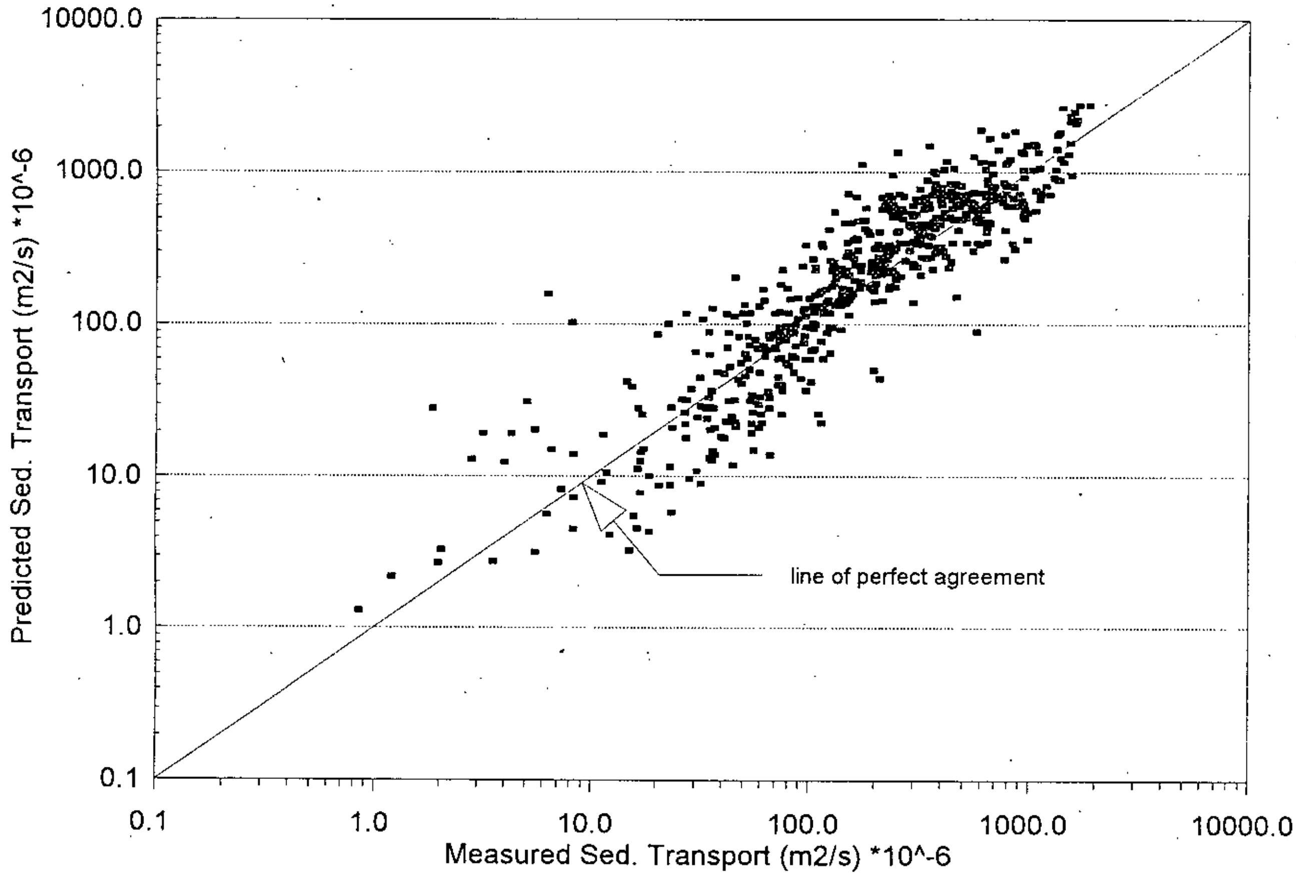


Fig. 6.20 : Predicted versus measured sediment transport (verticalwise data) for Hossain equation

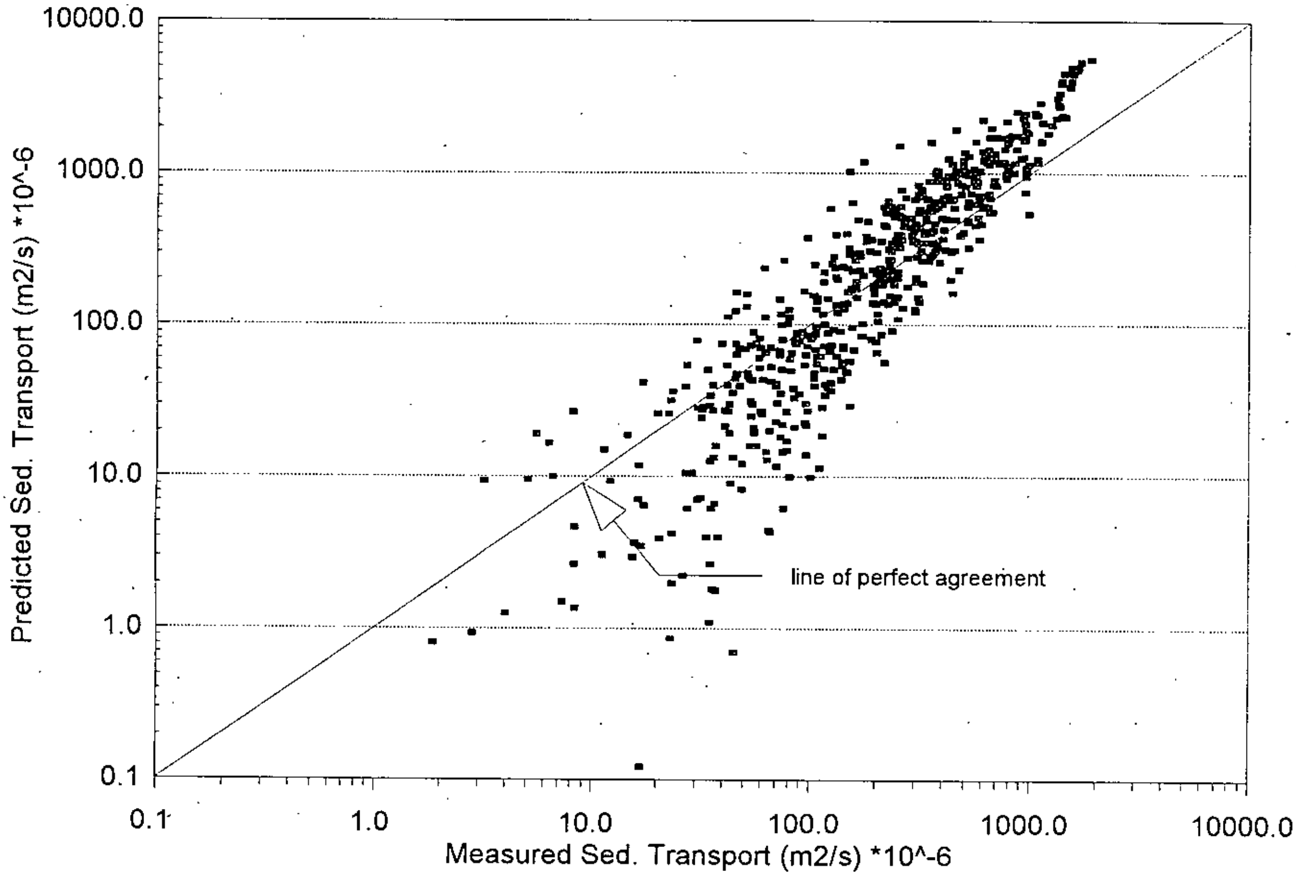


Fig. 6.21 : Predicted versus measured sediment transport (verticalwise data) for Van Rijn equation

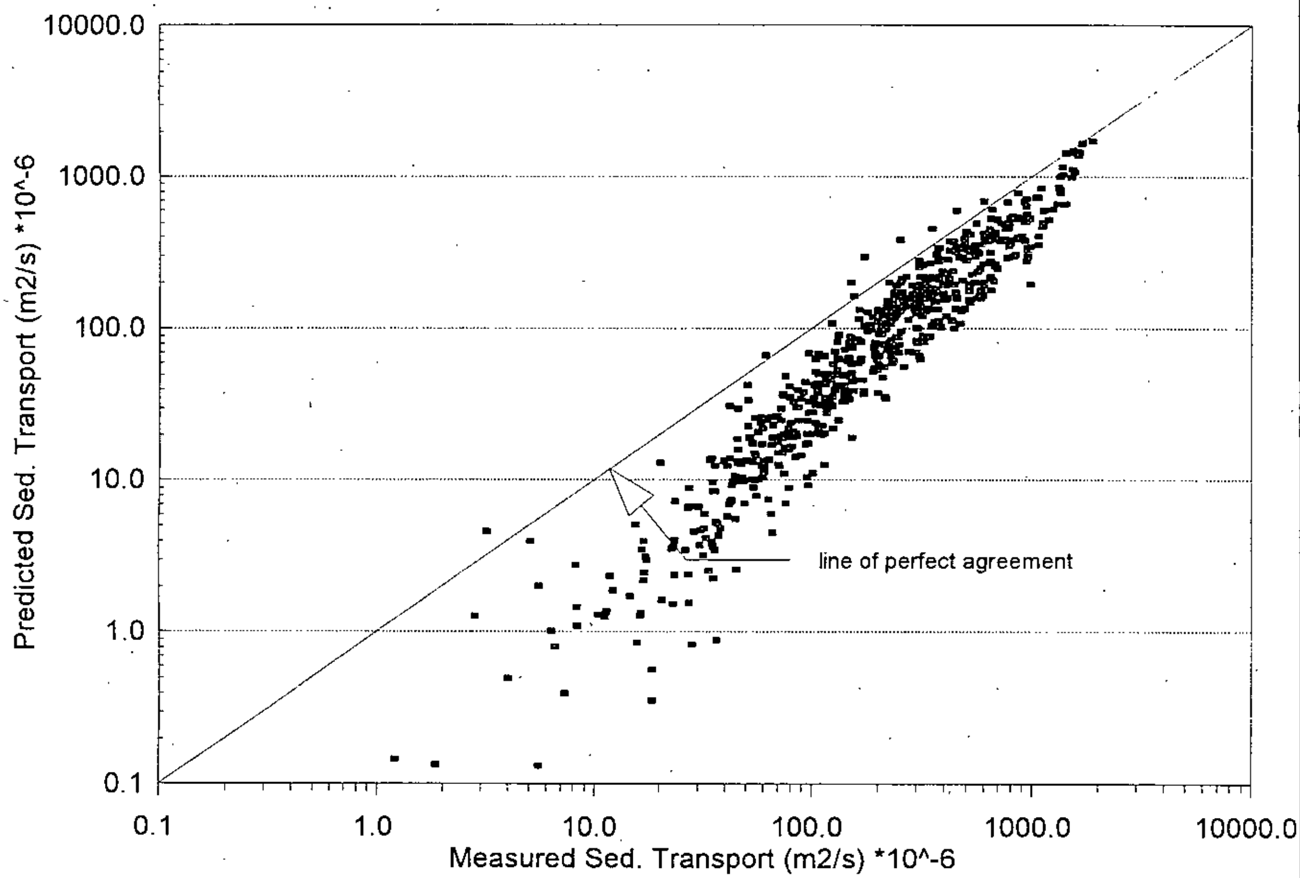


Fig. 6.22 : Predicted versus measured sediment transport (verticalwise data) for Yang equation

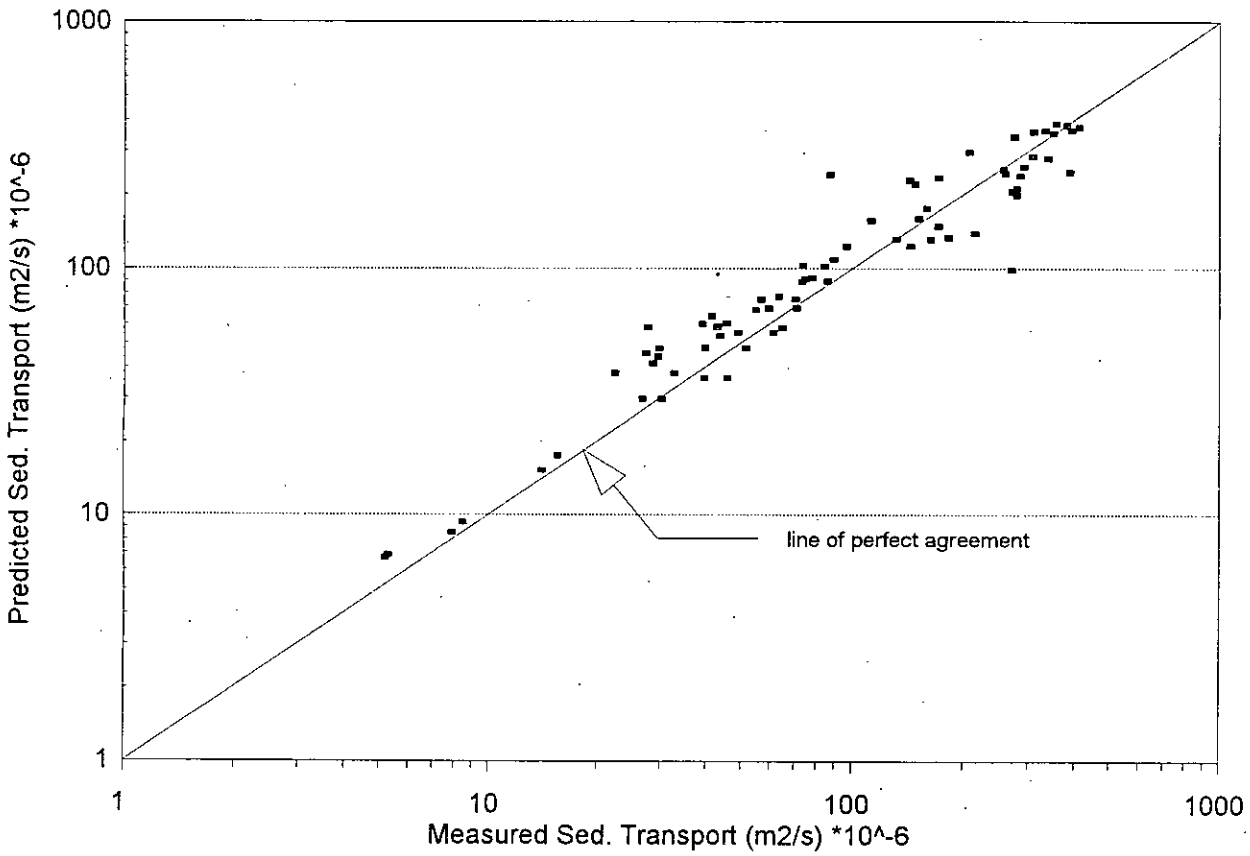


Fig.6.23 : Predicted versus measured sediment transport (normalised channel data) for Suggested equation (Eq. 6.4)

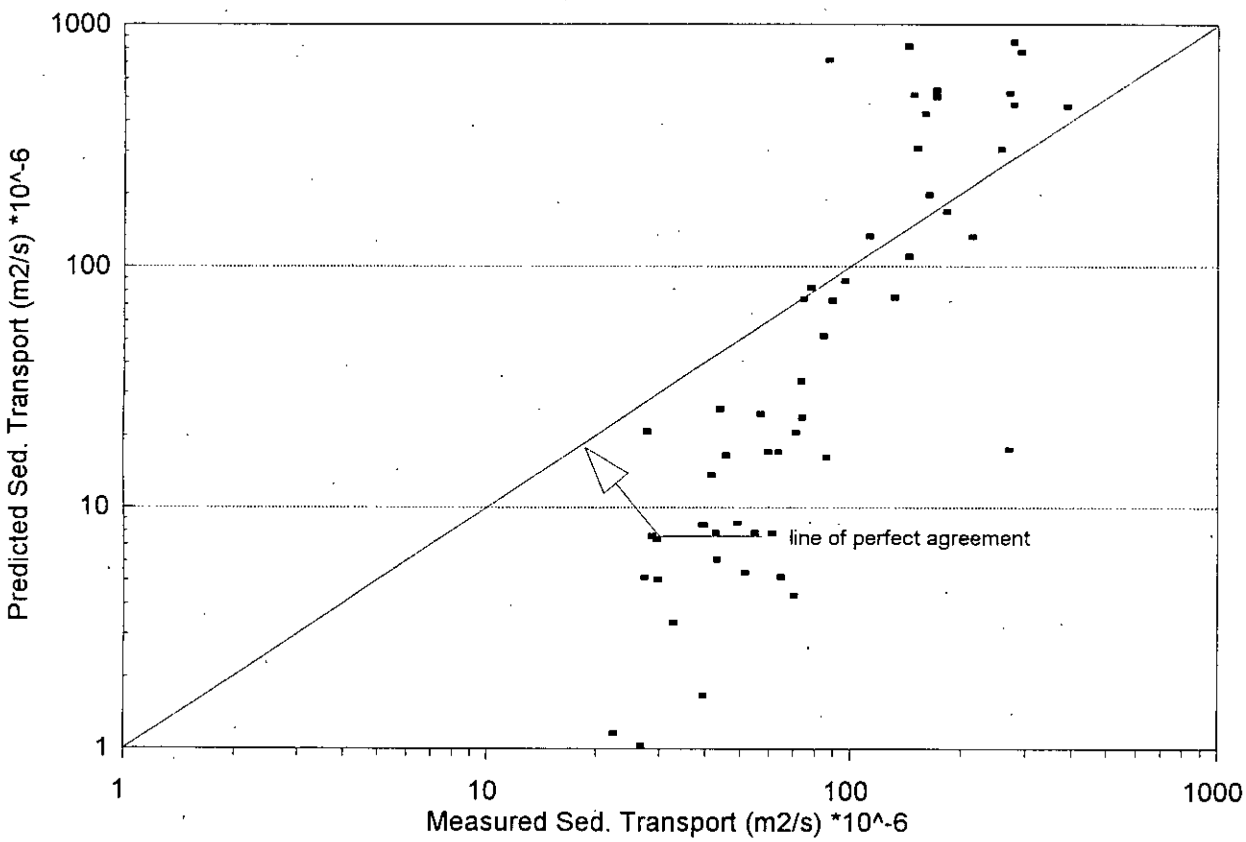


Fig.6.24 : Predicted versus measured sediment transport (normalised channel data) for Ackers and White equation

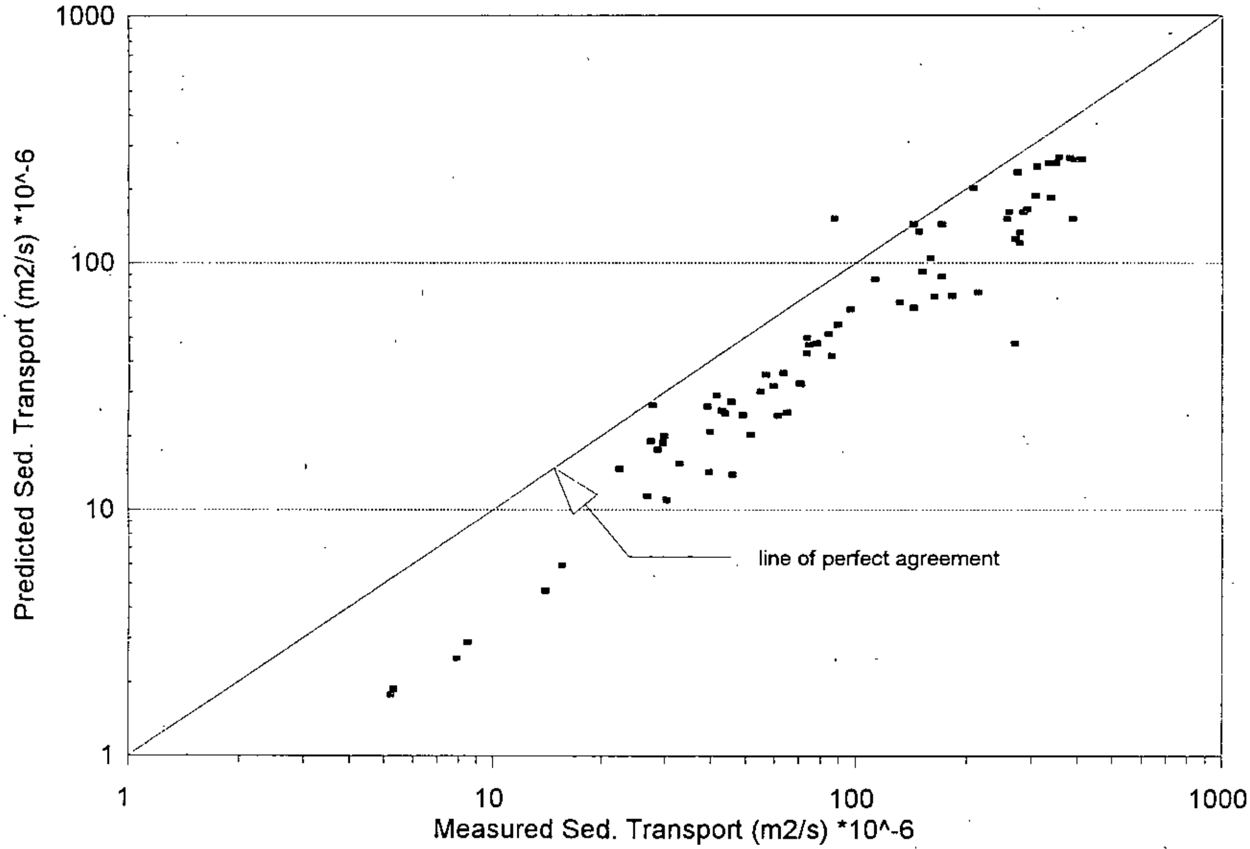


Fig.6.25 : Predicted versus measured sediment transport (normalised channel data) for Bagnold equation

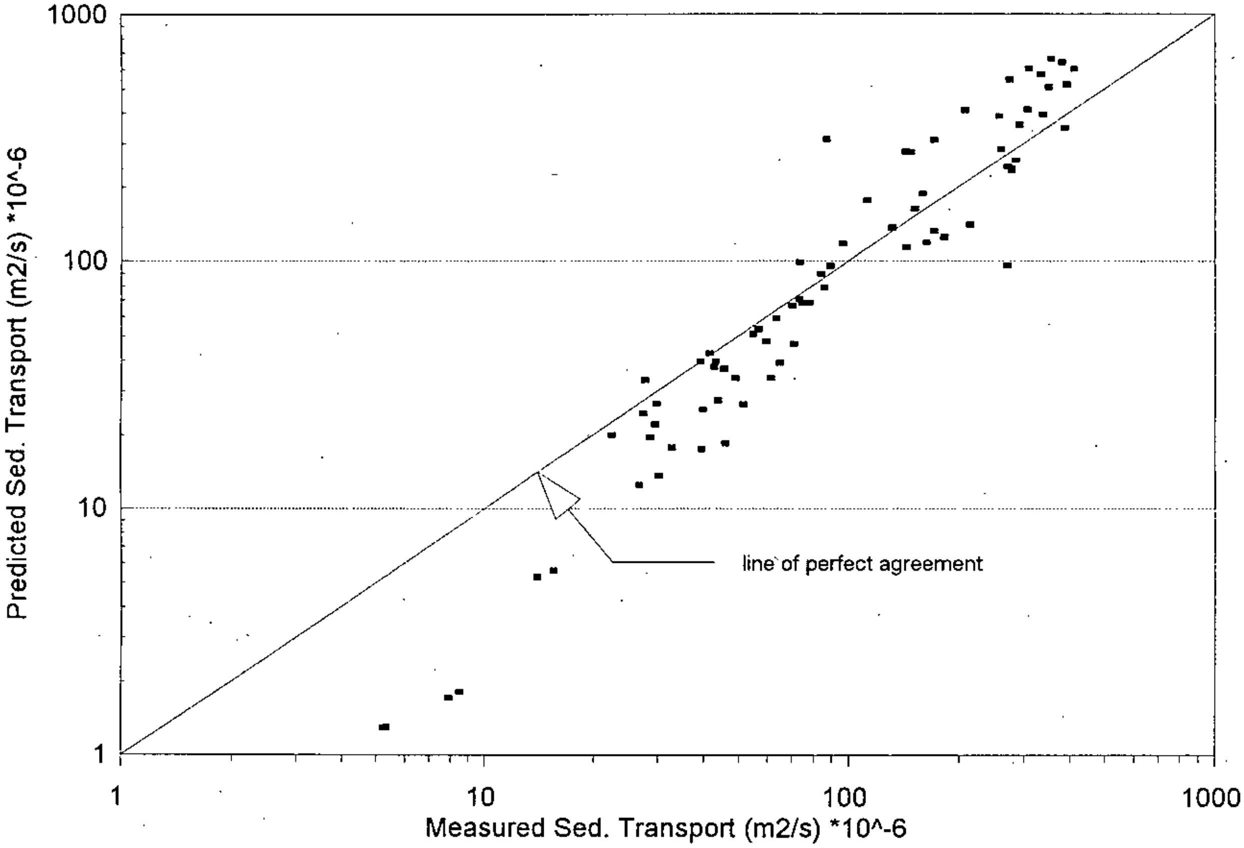


Fig.6.26 : Predicted versus measured sediment transport (normalised channel data) for Engelund-Hansen equation

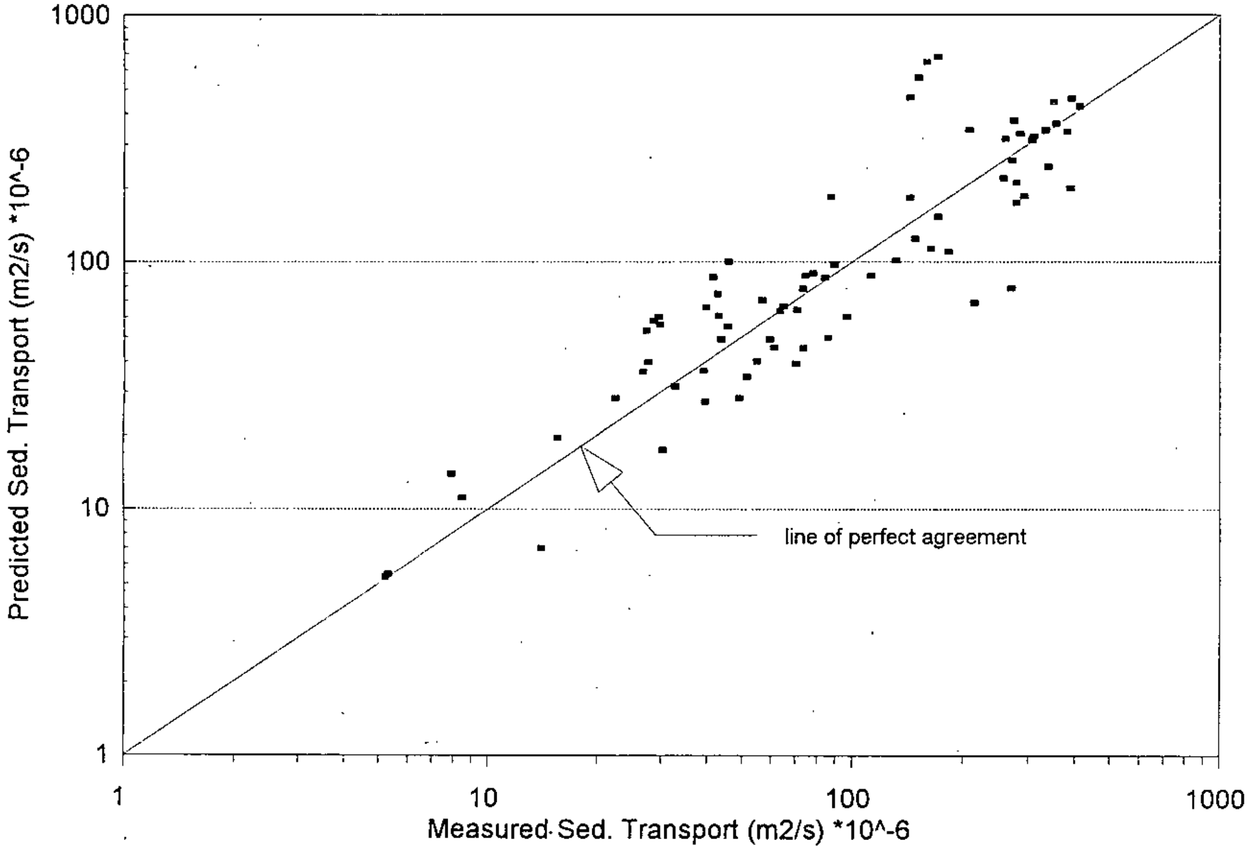


Fig.6.27 : Predicted versus measured sediment transport (normalised channel data) for Hossain equation

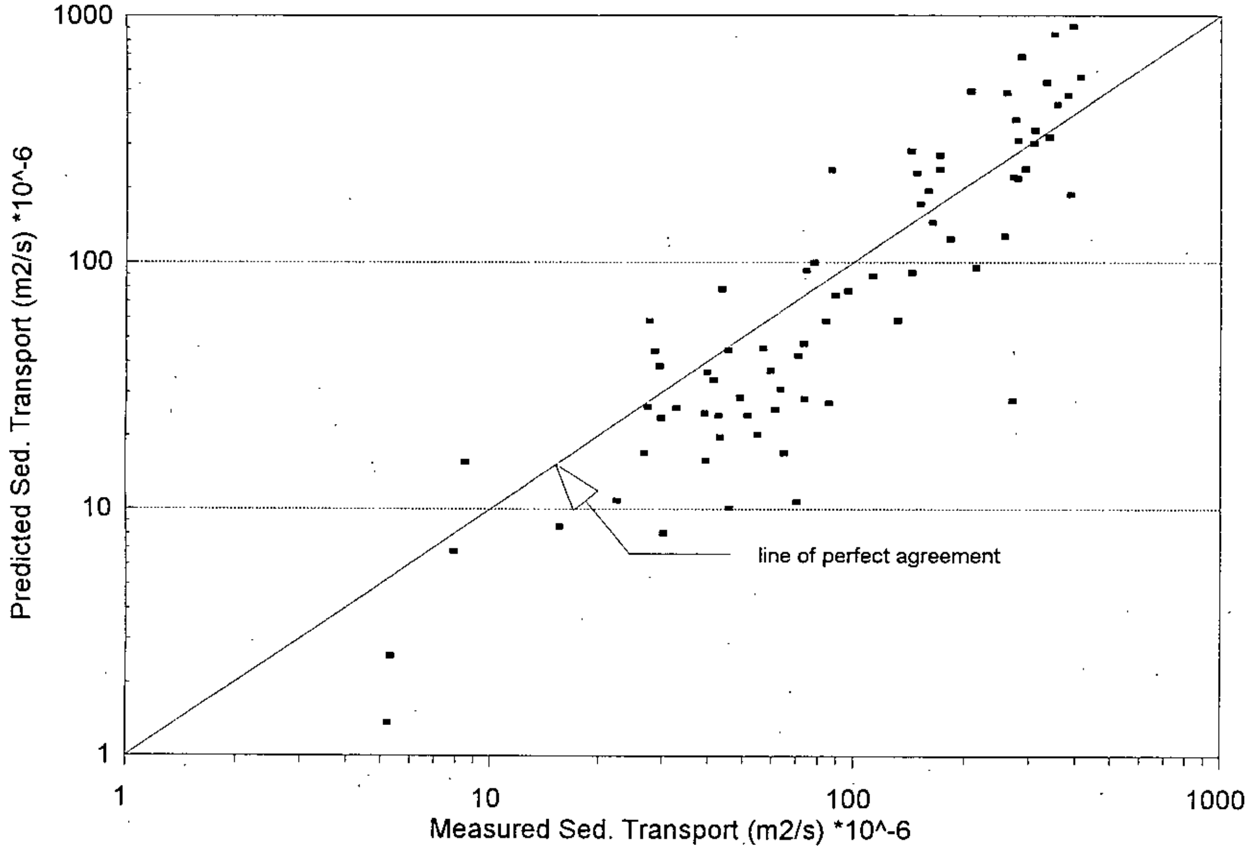


Fig.6.28 : Predicted versus measured sediment transport (normalised channel data) for Van Rijn equation

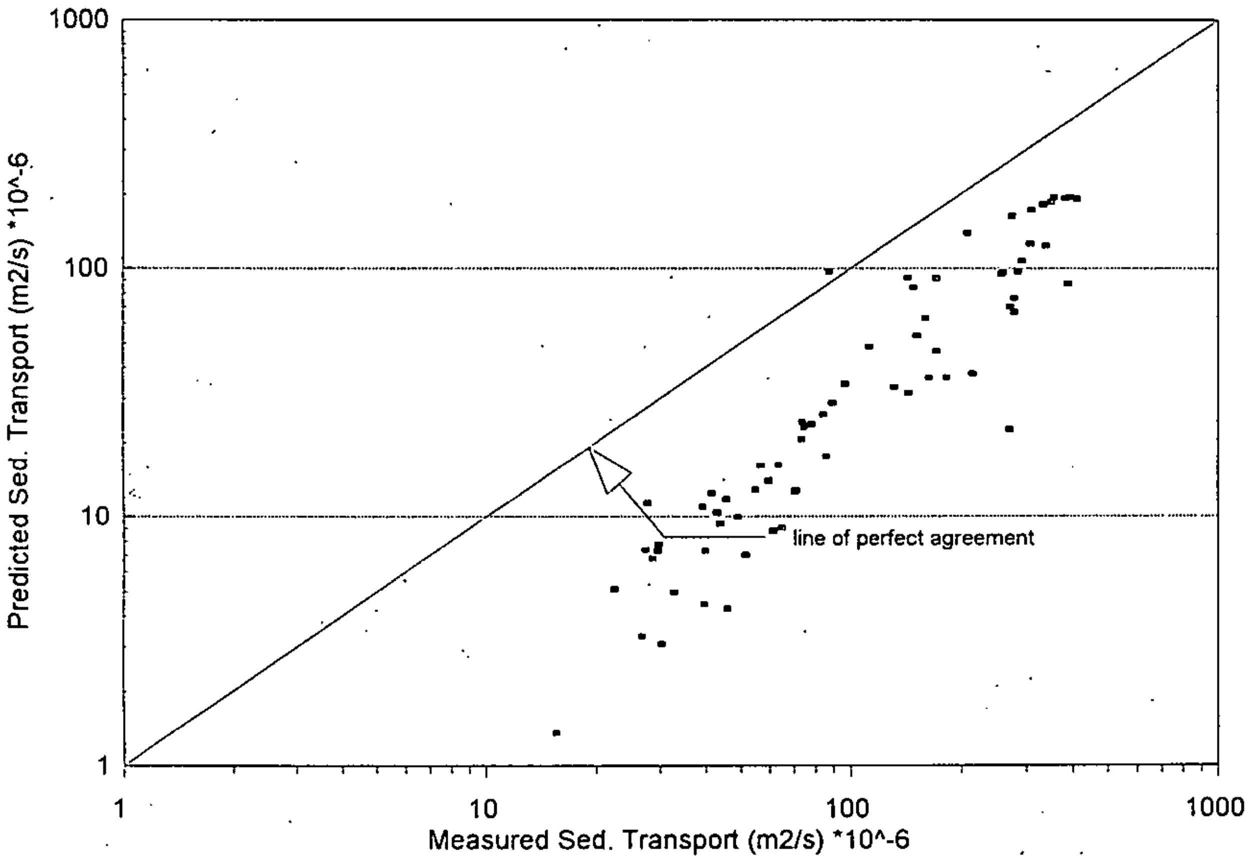


Fig.6.29 : Predicted versus measured sediment transport (normalised channel data) for Yang equation

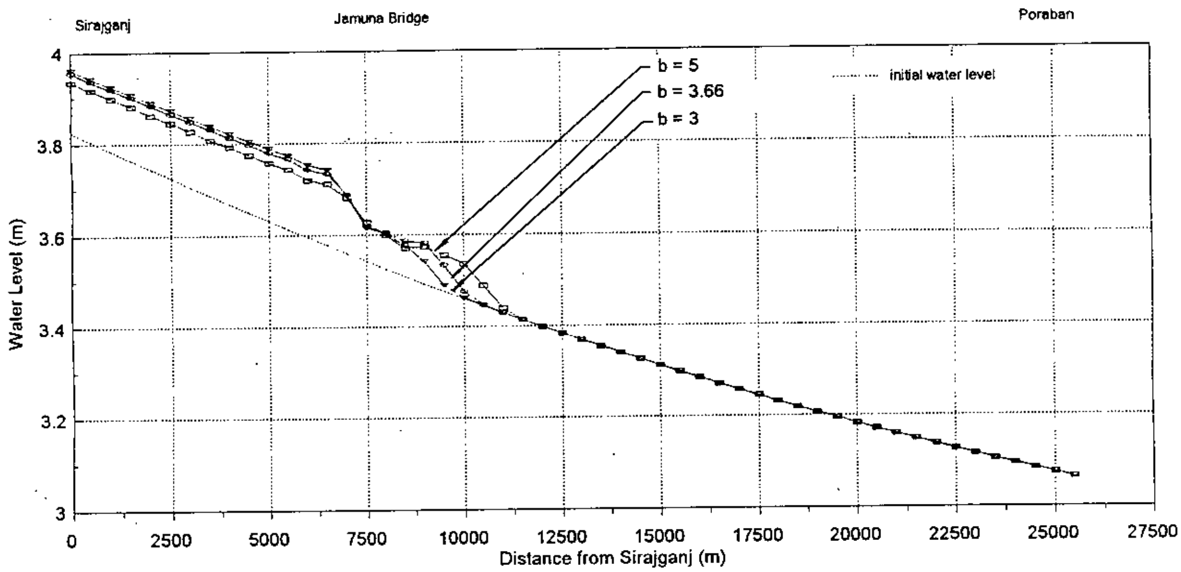


Fig. 7.1 : Influence of exponent 'b' on the water level changes

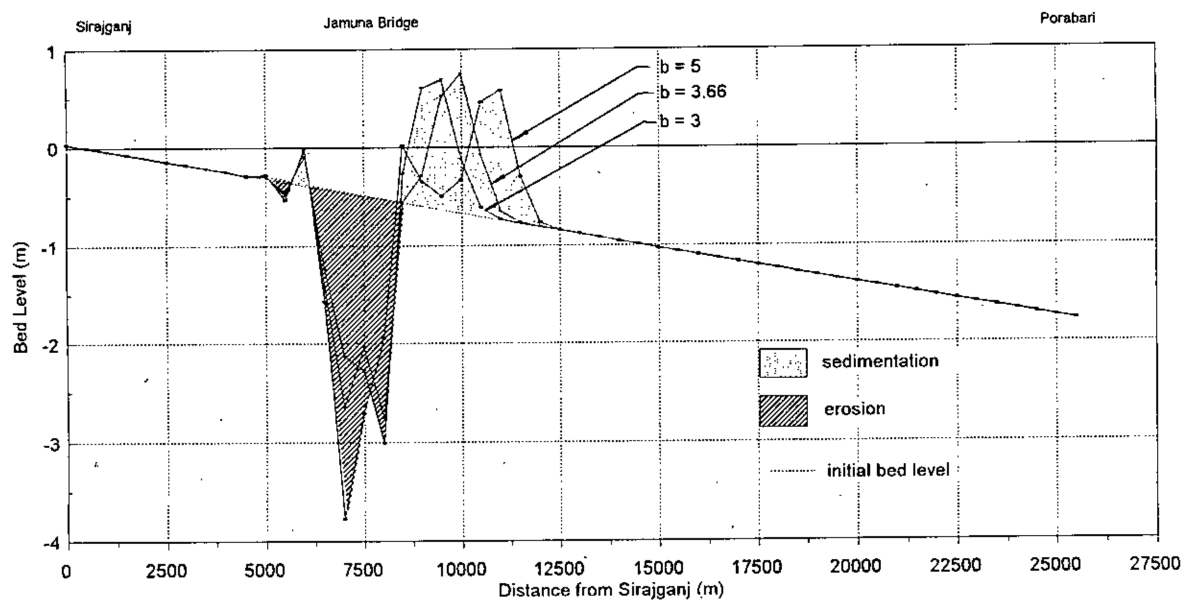


Fig. 7.2 : Influence of exponent 'b' on the propagation of bed level changes

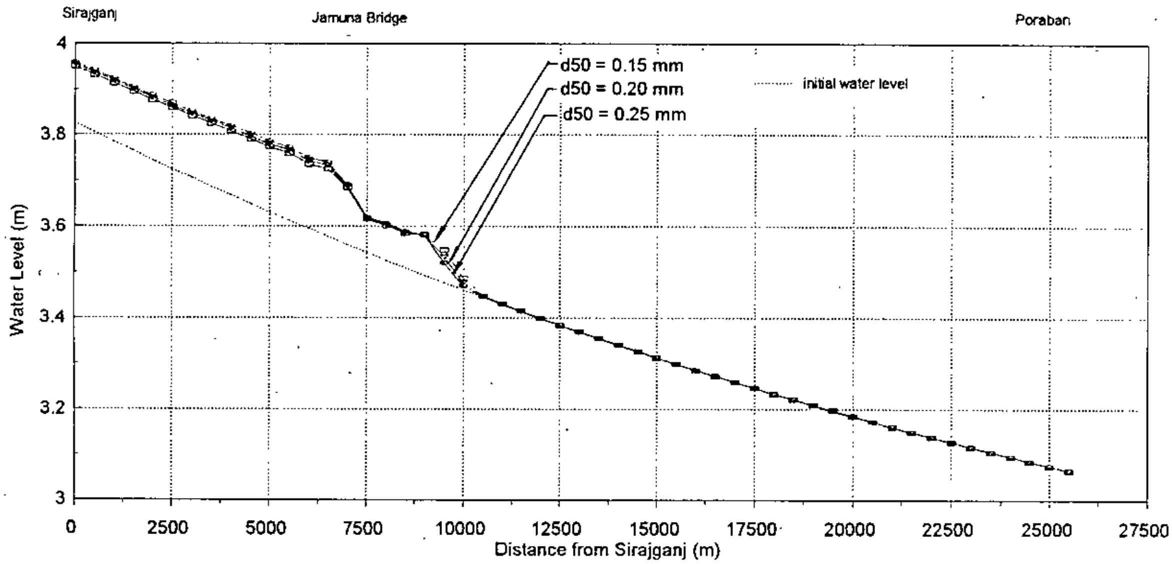


Fig. 7.3 : Influence of grain sizes on the water level changes

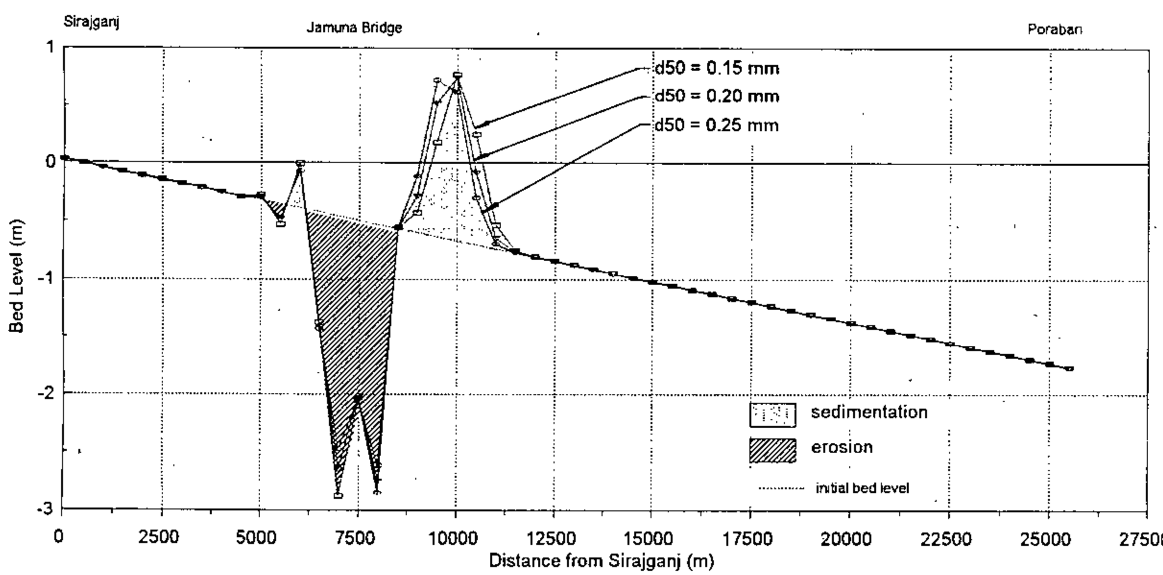


Fig. 7.4 : Influence of grain sizes on the propagation of bed level changes