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APPLICATION AND TESTING OF A DYNAMIC FLOOD WAVE MODEL

by

Usha Chatwani

A thesis
submitted to the Faculty of Graduate Studies through the
Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degree of
Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada

1990

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**This work is dedicated to the loving memory of
my father-in-law
the late Shri Uttamchand Chatwani.**

ABSTRACT

In this thesis, an unsteady flow open channel model called MOBED has been modified and tested. Model-MOBED can be used to solve a number of practical river engineering problems. The original model was developed by Krishnappan (1981) of the Hydraulics Division of the National Water Research Institute at Burlington, Ontario. MOBED, a flexibly designed model is based on a numerical solution of St. Venant's equations and a sediment continuity equation that predicts unsteady flows in both mobile bed channels and rigid boundary channels. A four-point implicit numerical scheme developed by Priessmann (1960) and the Double Sweep Method are used to solve the flow continuity and momentum equations. The sediment continuity equation is then used to predict the change in the bed level during each time step.

The model source code has been modified with respect to input formatting. Instead of inputting flow rate or flow depth as a function of time at the upstream and downstream boundary for all the number of time steps for which the model predictions are carried out, a subroutine called HYDROG is written and incorporated into the source code.

The sensitivity and stability of the model was extensively tested to determine the importance of input variables and discretization parameters. In order to assess the predictive accuracy of the unsteady rigid bed portion of the model, the data of Treske (1980) taken from the experimental channel in Obernach, West Germany was used. The mathematical model output was compared with the measured values for u/s elevations and d/s flows and it was found that the model gave stable and

accurate results for practical engineering purposes.

The steady state mobile bed component of the model was evaluated using data from the link canals of Pakistan. In this case, the model has been tested for the accuracy of the frictional parameters. The original model uses Kishi and Kuroki's (1974) friction relations which appear to give good results for $R/D_{65} < 2000$. The model was modified to incorporate the new friction parameters to take into account the larger canals with $R/D_{65} > 2000$ as well as higher Reynold numbers. Several test runs for different cases of bed forms were made using the Kishi and Kuroki's friction relations and the modified friction parameters. It was found that after the modification the model results are in good agreement with the field data.

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CHAPTER 1

INTRODUCTION

1.0 GENERAL

The unsteady-flow problem most commonly encountered in open channels deals with translatory gravity waves which propagate along the channel reach giving rise to appreciable displacement of the water particles parallel to the flow.

Unsteady-flow can be categorized into two types: gradually varied unsteady-flow and rapidly varied unsteady-flow. The distinguishing features between the two types of flow are the type of curvature of the wave profile, the change in depth, vertical acceleration of the water particles and the effect of channel friction. In this study, gradually varied unsteady-flow hydraulics has been discussed in detail since this is the most common type of unsteady flow in natural channels.

Prediction of unsteady flows in both rigid boundary channels and mobile bed channels, requires the knowledge of numerical methods for analysis in addition to the theory behind them. Many mathematical models have been developed for the prediction of rigid boundary channel unsteady flows, since this is relatively easier to model than mobile bed flows. In order to solve a number of practical river engineering problems, involving unsteady flow, a model called MOBED which is in the operational stage has been developed by Krishnappan (1981) of the Hydraulics Division of the National Water Research Institute at Burlington, Ontario. MOBED, a dynamic flood wave model is

based on the numerical solution of St. Venant's equations and a sediment continuity equation that predicts unsteady flows in both mobile bed channels and rigid boundary channels. This model can predict both short term river problems (involving prediction of flood waves and sand wave movement) as well as long term effects (involving prediction of regime changes due to flow diversions, changes in sediment supply, development of hydraulic structures, meander cut-offs, and dredging).

All models have some error, no matter, how small, when compared to the accurate field measurements. The objective of this study is, therefore, to test the sensitivity and stability of the model and obtain an estimate of the possible errors involved in applying MOBED. To satisfy this objective, statistical tools are employed and a quantitative and comparative analyses of the errors are made.

1.1 JUSTIFICATION OF THE STUDY

Model MOBED incorporates many of the theoretical aspects of mobile bed unsteady flow and employs a numerical scheme to solve the governing equations. It, however, has not been extensively tested and compared against measured field data. The Users Manual (1981) illustrates one application of the model, which is a reach in South Saskatchewan River between Gardiner dam and Saskatoon. However, it is not a sufficient calibration of the model, e.g. the flow is relatively steady for the simulation run.

Hence, several test runs are made with varying input conditions to determine the reliability and sensitivity of the model. The input data for the test runs are obtained from reports containing both laboratory and field measurements.

1.2 METHODOLOGY

A review of unsteady flow hydraulics, as well as the application and testing of the model are presented in the following chapters.

Chapter 2 documents the literature review and gives a detailed description of the model. The governing equations which are the modification of pair of equations by Barre De St. Venant and the auxiliary relations required are outlined. Also, the numerical scheme and the solution procedure of the model is presented.

Chapter 3 describes the organization of a number of numerical experiments, and model testing methodology for both stability and sensitivity tests. It also details the methodology for testing of the model against field data for both the rigid bed data of Treske channel and mobile bed link canal data of Pakistan conducted under the Alluvial Channel Observation Project (ACOP). Chapter 3 also documents the methodology of the modifications made in the source code that are of two types. Firstly, instead of inputting flow rate as a function of time at the upstream or downstream boundary (TQ) for all number of time steps for which the model predictions are to be carried out (IL) a subroutine- HYDROG has been incorporated. Similar changes have been made for values of flow depth varying as a function of time at upstream or downstream boundary (TY). Secondly, the friction parameters for mobile bed cases for different bed forms which were set on the basis of the research of Kishi and Kuroki (1974) have been modified. New friction parameters are justifiable as they take into account larger canals with $(R/D_{65}) > 2000$ and higher Reynold Numbers. The friction factor relations of Kishi and Kuroki appear to give good results for $(R/D_{65}) < 2000$.

Chapter 4 describes the input file organization for model testing. Chapter 5 of the thesis presents and discusses all the results of the tests described in Chapter 3. Finally, in Chapter 6, conclusions are drawn from the application and testing.

Following Chapter 6 are the appendices and the list of references cited in this paper. All figures and tables appear following their reference in the paper. Wherever found appropriate, reference is also made to appendices. Also, the variables used in various equations are defined following their first occurrence. Two diskettes attached in the thesis contain all the input data files for both unsteady rigid bed and mobile bed flow cases as well as intermediate programs written as an aid in testing and error analysis.

CHAPTER 2

LITERATURE REVIEW

2.0 GENERAL

Mathematical models of river flows solve a number of practical river engineering problems by providing numerical solutions of differential equations that describe the flow conditions. Prerequisite to solving differential equations are simplifying assumptions and approximations. As models differ widely in complexity and applicability, limitations of different models should be kept in mind while applying the models to practical problems. Although there are several steady state and unsteady state flow models, only the unsteady state flow models that treat flows in rigid and mobile boundary channels are presented here.

As the basic set of governing equations for all models is similar, the accuracy of a model depends on two things: firstly the numerical technique used to solve the governing equations, and secondly, the selection of the suitable auxiliary relationships that evaluate the friction factor and the sediment transporting capacity of river flows. In order to ascertain the accuracy of the model and to make the user aware of its applications and limitations, the model should be evaluated comparatively.

The model evaluation is carried out in two stages. Stage one examines the theoretical base and assumptions of each model for unsteady river flow. Stage two consists of actually running the model with common data sets and comparing the model results with data from both laboratory and

field measurements. Stage one is presented in this chapter along with detailed background of the MOBED model. Stage two has been carried out for the MOBED model and comparisons of the predicted and measured results have been presented in Chapter 5 of the thesis.

2.1 COMPARISON OF VARIOUS UNSTEADY FLOW MODELS

In order to assess the strengths and weaknesses, each model is critically evaluated. Some of the well known rigid boundary unsteady models are DWOPER, DAMBRK, 1D, and FERNS whereas the mobile boundary unsteady models are FLUVIAL 11 and MOBED. Their governing equations are compared with a general set of governing equations and a comparative statement is made based on how well they agree with the general set of equations.

A brief description of each model listed above and the model comparison follows the basic set of governing equations.

2.1.1 Basic Form of Governing Equation

Equations governing the unsteady flows in natural channels in one dimensional form are the momentum equation, the continuity equation, and the sediment mass balance equation (Krishnappan et al 1981). They are listed below.

Momentum Equation

$$\frac{\partial Q}{\partial x} + 2\beta \frac{Q}{A} \frac{\partial Q}{\partial x} - \beta B \frac{Q^2}{A^2} \left(\frac{\partial y}{\partial x} \right) + gA \frac{\partial y}{\partial x} + \frac{Q^2}{A} \frac{\partial \beta}{\partial x} - gA [S_x - (S_{bx} + S_{bx'} + S_{bxx'} + S_{p'} + S_{kx} + S_{ex})] + q_i \left(U_e - \frac{Q}{A} \right) + \beta \frac{Q^2}{A^2} A_z^2$$

Eq. (2.1)

Continuity Equation

$$\frac{\partial Q}{\partial x} + B \frac{\partial y}{\partial x} + P \frac{\partial z}{\partial x} - q_i$$

Eq. (2.2)

Sediment Mass Balance Equation

$$\frac{\partial Q_s}{\partial x} + P_s \left(\frac{\partial z}{\partial x} \right) + BC_s \frac{\partial y}{\partial x} + A \frac{\partial C_s}{\partial x} - q_s$$

Eq. (2.3)

Where

x is the longitudinal coordinate axis measured along the length
of the stream

t is the time axis

Q is the flow rate

y is the flow depth

z is the bed elevation or the vertical distance between a fixed datum and the mean bed level within a control volume.

P is the wetted perimeter

B is the top width

A is the cross-sectional area

g is the acceleration due to gravity.

A_x^y is the rate of change of A with respect to x when y is held constant

q_l is the lateral flow input rate

U_q is the x-component of the lateral inflow velocity

S_x is the slope of the river bed at the location of the control volume

Q_s is the total bed material load

P_o is the portion of the wetted perimeter over which the sediment is in motion

C_{av} is the average volumetric concentration of the suspended bed material within a control volume

p is the volume of sediment on the bed per unit volume of bed layer

q_s is the sediment input rate entering the stream from tributaries

β is the momentum correction factor and is defined approximately as

$$\beta = \frac{\frac{Q_c^2}{A_c} + \frac{Q_f^2}{A_f}}{\frac{Q^2}{A}}$$

Eq. (2.4)

and evaluated by the following two equations

$$Q = Q_c + Q_f$$

Eq. (2.5)

and

$$\frac{Q_f}{Q_c} = \frac{\frac{A_f R_{sf}^{0.5} [\ln(\frac{y_f}{K_{sf}}) + B_{sf}]}{\kappa}}{\frac{A_c R_{sc}^{0.5} [\ln(\frac{y_c}{K_{sc}}) + B_{sc}]}{\kappa}}$$

Eq. (2.6)

where

Q_c is the flow rate in the main channel

Q_f is the flow rate in the flood plains

A_c is the cross-sectional area of the main channel

A_f is the cross-sectional area of the flood plains

K_{sf} is the equivalent sand grain roughness of flood plains

K_{sc} is the equivalent sand grain roughness of the main channel bed

B_{sf} is the additive constant of the logarithmic velocity distribution corresponding to the flood plain flow

B_{sc} is the additive constant of the logarithmic velocity distribution corresponding to the main channel flow

y_f is the flow depth corresponding to the flood plain flow

y_c is the flow depth corresponding to the main channel flow

R_f is the hydraulic radius of the flood plain

R_c is the hydraulic radius of the main channel

κ is the von-Karman constant

S_{ks} , S_{fd} , S_{bend} , S_{fp} , S_{ice} and S_{ec} are defined below and a set of general relationships for them is listed as follows:

S_{ks} is the energy loss per unit weight of fluid and unit river length due to skin friction

$$S_{ks} = \phi_k \left(\frac{VD_{65}}{v}, \frac{D_{65}}{y} \right)$$

Eq. (2.7)

S_{fd} is the energy loss per unit weight of fluid and unit river length due to form drag caused by sand waves

$$S_{fd} = \phi_{fd} \left(\frac{\Delta_d}{\lambda_d}; \frac{\Delta_d}{y} \right)$$

Eq. (2.8)

S_{bend} is the energy loss per unit weight of fluid and unit river length due to meander bends

$$S_{bend} = \phi_{bend} \left(\frac{\lambda_m}{H}; \frac{H}{B}; etc. \right)$$

Eq. (2.9)

S_{fp} is the energy loss per unit weight of fluid and unit river length due to interaction of main channel flow and floodplain flow

$$S_{fp} = \phi_{fp} \left(\frac{B_f}{B_c}; \frac{y_{fp}}{y_c}; etc. \right)$$

Eq. (2.10)

S_{ice} is the energy loss per unit weight of fluid and unit river length due to ice-cover

$$S_{ice} = \phi_{ice} \left(\frac{V_* K_{s,ice}}{\nu} ; \frac{K_{s,ice}}{y} ; etc. \right)$$

Eq. (2.11)

S_{ec} is the energy loss per unit weight of fluid and unit river length because of sudden expansion or contraction

$$S_{ec} = \phi_{ec} \frac{\Delta \left(\frac{Q}{A} \right)^2}{2g\Delta x}$$

Eq. (2.12)

where V_* is the shear velocity

D_{65} is the sediment size for which 65% of the material by weight is finer

ν is the kinematic viscosity of fluid

Δ_d is the sand wave height

Λ_d is the sand wave length

Λ_m is the meander wavelength

H is the meander amplitude,

B_f is the width of the floodplain

B_c is the width of the main channel

y_{fp} is the flow depth of the flood plain

y_c is the flow depth of the main channel

$K_{s,ice}$ is the equivalent sand size roughness height of the ice cover

ϕ_{ec} is an empirical constant varying between 0 and ± 1 (+ for contraction and - for expansion)

Δ is an operator which signifies a change between adjacent nodes

Of the five functions, (ϕ_{ks} , ϕ_{fd} , ϕ_{bend} , ϕ_{fp} , and ϕ_{ice}), ϕ_{ks} can be established with the help of Moody's diagram. Many researchers have worked to evaluate ϕ_{fp} and ϕ_{fd} . The evaluation of ϕ_{bend} and ϕ_{ice} requires more research to understand them (CSCE Task Committee, 1987).

In order to evaluate Q_s , one of the ten unknowns ($Q, y, z, Q_s, \beta, S_{ks}, S_{fd}, S_{bend}, S_{fp}$, and S_{ice}) in the system of equations mentioned previously, a sediment transport relationship equation is required. The following sediment transport equations are most often used (CSCE Task Committee, 1987).

(1) Meyer Peter and Mueller equation (1949)

(2) Einstein's bed load function (1950)

(3) Yalin's equation (1963)

(4) Bagnold's equation (1966)

(5) Ackers and White equation (1973)

(6) Yang's stream power equation (1973)

For a given application, selection of a particular relationship depends on the sediment transport mechanism and the range of parameters for which the relationship was developed.

Initial conditions for Q and y have to be specified all along the river to solve Equations (2.1) and (2.2), whereas Q_s and C_{av} are computed from the results of Equations (2.1) and (2.2). Initial conditions to the model could be any one of the following types:

- (a) the known steady-state solution for y and Q for all nodes**
- (b) the computed steady-state solution from known flows and downstream depth**
- (c) the known unsteady flow conditions from a previous model run**

Boundary condition specification is required at both upstream (u/s) and downstream (d/s) sections of a given river reach. The u/s boundary condition can either be a stage hydrograph or flow hydrograph whereas the d/s boundary condition for a model can be any one of the following types:

- (a) Stage hydrograph,
- (b) Flow hydrograph,
- (c) Single value rating curve,
- (d) Looped rating curve, or
- (e) Stage-discharge power function relationship.

All nine possible combinations of boundary conditions have been summarized in Table 2.1, for both the Q and y variables. Also, it should be remembered that for non-equilibrium problems, values of Q_s at the upstream boundary should be specified.

2.1.2 Unsteady Flow Models

Most of the model capabilities have been described in Table 2.2; however, a brief description of theoretical base and numerical technique for each model is presented in this section. First, the description of four rigid bed unsteady flow models is presented, followed by mobile boundary flow models.

TABLE 2.1 Nine Possible Combinations of Boundary Conditions

		Upstream Boundary Type		
		$y(t)$	$Q(t)$	$Q(y)$
Downstream Boundary Type	$y(t)$	$y(t)$ u/s	$Q(t)$ u/s	$Q(y)$ u/s
		$y(t)$ d/s	$y(t)$ d/s	$y(t)$ d/s
	$Q(t)$	$y(t)$ u/s	$Q(t)$ u/s	$Q(y)$ u/s
		$Q(t)$ d/s	$Q(t)$ d/s	$Q(t)$ d/s
	$Q(y)$	$y(t)$ u/s	$Q(t)$ u/s	$Q(y)$ u/s
		$Q(y)$ d/s	$Q(y)$ d/s	$Q(y)$ d/s

Reference: Krishnappan 1981

TABLE 2.2 Capabilities of Unsteady Flow Models (CSCE Task Committee, 1987)

Type of Model	Governing Equations				Specification of Channel Geometry				Energy Loss Components						Solution Procedure					Special Features																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
	Steady State - Rigid Boundary	Steady State - Mobile Boundary	Unsteady State - Rigid Boundary	Unsteady State - Mobile Boundary	Energy Equation + Sediment Mass Balance Eqn.	Complete Sc. Venant Equation	Complete Sc. Venant Equation + Sediment Mass Balance Eqn.	C.S. definition by a series of space-elevation coordinates	C.S. Definition by power function	C.S. Definition by a stage vs top width table	C.S. Definition by length, n, space increment, table of hydraulic parameters	Friction Slope - S_{fo}	Bed Form Drag - S_{bnd}	Bed Energy Loss - S_{bnd}	Floodplain - Main Channel Interaction - S_{fp}	Energy Loss Due to Ice Cover - S_{ice}	Energy Loss Due to Sudden Expansion and Contraction S_{ec}	Finite Element Techniques	Finite Difference Method	Non-linear Algebraic Equations	Linear Algebraic Equations	Stability Criterion Investigated	Momentum Correction for Overbank Flow	Off-Channel Storage	Tributary Inflow of Water	Tributary Inflow of Sediment	Channel Network	Ice-Cover Effects	Bridge, Weir and Spillways	Armouring	Generalized Energy Equation	Automatic Calibration	Documentation	Channel Width Adjustment + Lateral Migration of Beds																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
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2.1.2.1 FERNS (Finite Element River Network Simulator model developed by Water Planning and Management, Ontario region model)

This implicit model solves Eqs. (2.1) and (2.2) by a predictor-corrector method. The double sweep technique is used for solving single reach river system. However, for a looped network, the above technique does not work and hence, is solved by forming a matrix which is solved using Gauss elimination. The model uses Manning's equation to calculate the friction slope.

2.1.2.2 1D (One Dimensional Unsteady Flow model developed at MIT)

The 1D model is very similar to FERNS except that it considers a full or partial ice-cover and its growth and decay. The computation of the friction slope is carried out either using Manning's or Chezy's equation. The numerical scheme to solve the governing equations has been developed by Gunaratnam and Perkins (1970). For the convergence of the scheme, following criteria were proposed.

$$100 \geq \frac{\lambda}{\Delta x}$$

Eq. (2.13)

$$\Delta t = \frac{5.5 \Delta x}{V + c}$$

Eq. (2.14)

where

λ is the wavelength of the flood wave

V is the average flow velocity

c is the celerity of the flood wave

2.1.2.3 DWOPER (Dynamic Wave Operational model developed by NWS, U.S.A)

This model like many other models evaluates the friction slope by Manning's equation. The governing Eqs. (2.1) and (2.2) are solved using the four-point implicit finite difference scheme presented by Fread (1974), and the non-linearized algebraic system of resulting equations is solved by the Newton-Raphson method. This model makes the assumption of a wide channel, i.e. channel width approximates the wetted perimeter.

2.1.2.4 DAMBRK (Dam break, NWS, U.S.A)

The DAMBRK model routes the flow downstream by using the breach generated flow hydrograph as the upstream boundary condition. It is also capable of handling supercritical flows. Thus, the breach formation and the resulting reservoir-outflow hydrograph is calculated before solving the governing Eqs. (2.1) and (2.2). The mathematical formulations for the flood wave

propagation is the same as DWOPER.

The total outflow resulting from a dam breach is the sum of the broad-crested weir flow through the breach and the flow through the spillway outlets. Thus,

$$Q = Q_b + Q_s$$

Eq. (2.15)

where Q_b , breach flow (breach forming at the top) is given by the following equation.

$$Q_b = C_1(h - h_b)^{1.5} + C_2(h - h_b)^{2.5}$$

Eq. (2.16)

where C_1 is the factor accounting for the flow through the

rectangular portion of the breach

C_2 is the factor accounting for flow through triangular

ends

h is the water surface elevation behind the reservoir

h_b is the elevation of breach bottom

Q_s is the flow over spillways and turbines

2.1.2.5 FLUVIAL 11 (San Diego State University model)

This is an unsteady, mobile boundary flow model that involves a sediment transport equation along with two complete St. Venant's equations. The set of three governing equations is discretized

using the four-point implicit, finite difference scheme developed by Fread (1974) and Amien and Chu (1975).

Simulation of channel width variation is handled by the model using the concept of minimum stream power at each time step. It also takes into account the lateral migration of channel bends and calculates its effects on channel bed profile and changes in the cross sectional profile. FLUVIAL 11 is also capable of updating the bed load composition at each time step.

2.1.2.6 MOBED (Developed by National Water Research Institute)

This model also solves the three governing equations and simplifies them by making following assumptions:

- (1) $\beta = 1$,
- (2) S_{bend} , S_{fp} , S_{ice} and S_{ec} are negligible, thus reducing the number of unknowns,
- (3) it combines the energy loss terms S_{ks} and S_{fd} into a single term S_f expressed as given below:

$$S_f = Const \left(\frac{R}{D_{65}} \right)^m \left(\frac{Q^2}{gRA^2} \right)^n$$

Eq. (2.17)

The values of $Const$, m , and n depend on the geometry of the bed forms, as well as the sediment and flow characteristics. The model uses the friction factor relations of Kishi and Kuroki (1974) and the sediment transport formulae of Ackers and White (1973). A four point implicit finite difference scheme developed by Priessmann (1960) is used to solve the governing equations.

The above paragraph highlighted some important aspects of the MOBED model in order to give a basis for comparison with other models. The detailed description of the numerical technique employed by MOBED model is given in Section 2.2.

2.2 BACKGROUND

Moins (1988) has discussed in detail, theoretical developments behind various numerical techniques in the domain of unsteady flow. Instead of repeating these theoretical aspects and practical applications, this section of the chapter highlights only the following points:

- (a) the finite-difference and the finite element techniques related to solving discontinuity introduced in the flow domain.
- (b) the underlying theory, the numerical technique used by MOBED, and the program structure of MOBED.

As has been discussed in the previous section, all the models for solving the open channel flow problems employ some form of the St. Venant's equations. Based on the nature of the flow, there are rapidly varied and gradually varied flow solutions.

In the gradually varied flow, the curvature of the wave profile is mild and the change in depth

is gradual. The vertical component of the acceleration of the water particles is negligible in gradually varied flow, whereas in rapidly varied flow, the vertical acceleration is very important. Because of the dynamic effect of the flow in rapidly varied flows, the channel friction effect is negligible, whereas the effect of channel friction is appreciable in gradually varied flows and should be considered.

Examples of rapidly varied unsteady flow are surges of various kinds caused by the rapid operation of controlling structures or the flood waves resulting from the sudden failure of a dam. Examples of gradually varied unsteady flow are flood waves or waves resulting from the slow operation of controlling structures. Several methods are available for studying rapidly varied and gradually varied flows and can be categorized into two types:

- (a) the hydraulic or dynamic flood routing method, and
- (b) the hydrologic method.

The hydraulic method of flood routing is distinguished from the hydrologic method by the fact that the former is based on the solution of the open channel unsteady flow differential equations, whereas the latter method makes no direct use of the equations, but approximates in some sense to their solutions, e.g. by using empirical equations. The hydrologic method is in general simpler but it fails to give entirely satisfactory results in problems other than those of determining the progress of a flood down a long river.

Literature reviews in this topic have been provided by many investigators including Moins (1988), Fread (1982), Linsley, Kohler, and Paulhus (1982), Miller (1971), and Wurbs (1985). Both finite difference and finite element methods for the open channel flow equations applied to the gradually varied unsteady flow in natural streams have been considered in this paper.

2.2.1.1 Finite Difference Methods

The three approaches in discretizing the solution domain [(x,t) plane] are implicit, explicit and characteristic methods. Strelkoff et al (1970) developed the characteristic method, a computational scheme which is based on four equations:

$$\frac{dV}{dt} \pm \frac{gdy}{Cd} - g(S_0 - S_f) \mp VC \frac{A'}{A} = 0$$

Eq. (2.18)

and

$$\frac{dx}{dt} = V \pm C$$

Eq. (2.19)

where

$$C = \sqrt{gy}$$

Eq. (2.20)

Newton Raphson method is used to solve the resulting four equations for the unknowns V and y as well as x and t. "This technique emanates from the very nature of hyperbolic equations, that any disturbance introduced at the upstream boundary moves along the characteristics" (Moins 1988). For the prismatic channel, the solution is accurate whereas for non-prismatic channel, due to

different top- widths at adjacent nodes and characteristics, unreliable results have been obtained.

Several of methods belonging to the general category of "method of characteristics", have been proposed and developed. Lai in 1965 gave the complete derivation of the governing equations and their solution by the characteristic method. Outstanding contributions to the development of such methods have been made by Amein (1966) and Wylie (1970) for implicit models; Liggitt and Woolhiser (1967), Stoker and Wylie (1967), and Ellis (1970) for explicit characteristic models.

Stoker (1953) is considered as the pioneer for his work in explicit models. Others that made significant contributions in the field of explicit based models are Martin and DeFazio (1969), Dronkers (1969), Balloffett (1969), Kamphius (1970), and Liggett and Cunge (1975).

The model adopted by the U.S Corps of Engineers, developed by Garrison et al (1969), has been used for several flood routing studies including the case study of the Tennessee Valley and its associated reservoir system.

However, the size of the time step in explicit models was a major limitation. This has been overcome by solving the flow equations by implicit methods. Isaacson, Stoker, and Troesch (1956) presented the concept of the implicit method. Some of the contributors to the research and development of implicit based models are Lai (1965), Baltzer and Lai (1968), Abbott and Ionescu (1967), Dronkers (1969), Kamphius (1970), Amein and Fang (1970), Contractor and Wiggert (1972), Quinn and Wylie (1972), Fread (1973), Chaudhry and Contractor (1973), Moin (1974), Greco and Panattoni (1975), Amein and Chu (1975), Chen and Simons (1975), Bennett (1975), and Fread (1974).

Implicit methods can be further classified into linear and non-linear, characteristic form,

divergent and non-divergent based momentum equations, six-point and four-point discretization, and velocity or flow, depth or stage as dependent variables.

The six-point scheme, proposed by Vasileiv (1965), Abbott and Ionescu (1967), Moin (1974) requires uniform nodal spacing.

Priessmann (1961), was amongst the earlier contributors to the implicit method, proposed a four-point numerical scheme to solve the flow continuity and momentum equations simultaneously. According to this numerical scheme, any variable 'f', and its spatial and temporal derivatives are represented by the following equations.

$$f(x,t) = 0.5\theta(f_i^{t+1} + f_{i+1}^{t+1}) + 0.5(1-\theta)[f_i^t + f_{i+1}^t]$$

Eq. (2.21a)

$$\frac{\partial f}{\partial x} = \theta \left[\frac{f_{i+1}^{t+1} - f_i^{t+1}}{\Delta x} \right] + (1-\theta) \left[\frac{f_{i+1}^t - f_i^t}{\Delta x} \right]$$

Eq. (2.21b)

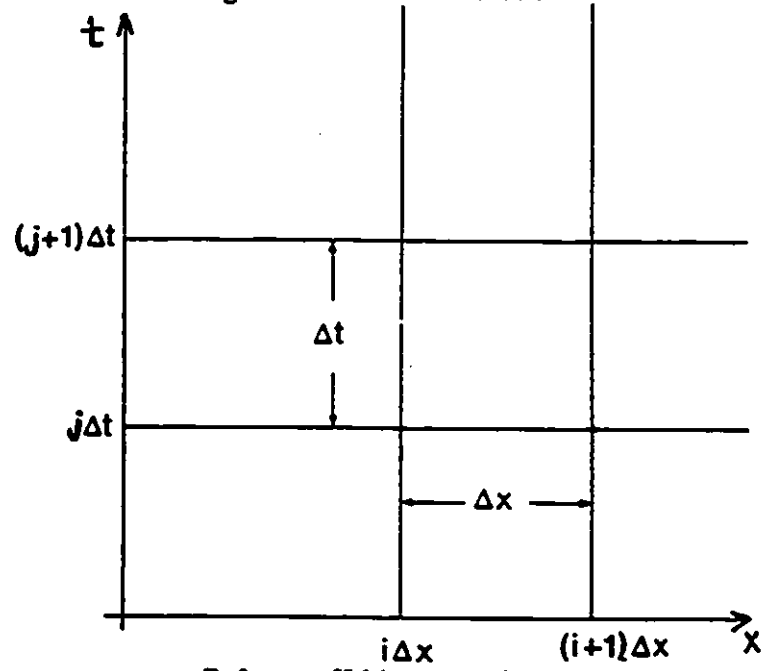
$$\frac{\partial f}{\partial x} = 0.5 \left[\frac{f_{i+1}^{n+1} - f_{i+1}^n}{\Delta x} \right] + 0.5 \left[\frac{f_i^{n+1} - f_i^n}{\Delta x} \right]$$

Eq. (2.21c)

where i, j, x and t are as shown in Fig 2.1; i denotes the nodes along the x axis and j along the time axis, Δx and Δt are space and time steps, and Θ is a weighting coefficient having values ranging from 0 to 1. Cunge (1975) studied this scheme for stability and accuracy and showed that for values of Θ between 0.5 and 1.0, the scheme results in a smooth and stable solution. Further studies by Cunge, suggested a practical range for Θ between 0.6 to 1.0. Value of $\Theta = 0.5$ results in a fully explicit solution and for $\Theta = 1.0$, the scheme is fully implicit.

Several models employed a four-point implicit scheme with significant variations for discretizing it. Krishnappan (1981) used departures (changes) of dependent variables in the weighted four-point scheme model called MOBED, whereas in the DWOPER model, a four-point scheme developed by Fread (1978,1982) is used.

Fig. 2.1 Finite Difference Grid



Reference: Krishnappan 1981

2.2.1.2 Finite Element Method

Applications of the finite element method in open channel flow solutions is not as advanced as the finite difference methods.

Gunaratnam and Perkins (1970), studied finite element applications in open channel hydraulics. Cooley and Moins (1976), Smith (1979), and Moins (1979) made noteworthy contributions to the development of finite element method for unsteady open channel flow. Other contributors towards the research of the finite element method are King (1976), Keuning (1976), and Katopodes (1984).

2.2.2 Detailed Description of Model MOBED

The numerical scheme for this mathematical model is centered around five equations; a set of three governing equations and two auxiliary equations namely the Ackers and White sediment transport relations and the Kishi and Kuroki's (1974) friction factor relations. The governing equations are listed here.

$$\frac{\partial Q_s}{\partial x} + P\left(\frac{\partial z}{\partial x}\right)p + BC_{sw}\left(\frac{\partial V}{\partial x}\right) + A\left(\frac{\partial C_{sw}}{\partial x}\right) - q_s$$

Eq. (2.22a)

$$\frac{\partial Q}{\partial x} + B\left(\frac{\partial y}{\partial x}\right) + P\left(\frac{\partial z}{\partial x}\right) - q_i$$

Eq. (2.22b)

$$\frac{\partial Q}{\partial x} + 2\frac{Q}{A}\left(\frac{\partial Q}{\partial x}\right) - B\frac{Q^2}{A^2}\left(\frac{\partial y}{\partial x}\right) + gA\left(\frac{\partial y}{\partial x}\right) -$$

$$gA(S_x - S_f) + q_i\left(U_f - \frac{Q}{A}\right) + \frac{Q^2}{A^2}A_x'$$

Eq. (2.22c)

One reasonable assumption made here is that $\partial z/\partial t \ll \partial y/\partial t$ which uncouples the flow continuity and momentum equations from the sediment continuity equation.

As has been previously mentioned, the numerical scheme employed by the model MOBED is an implicit four-point method developed by Priessmann. Equations (2.21a) to (2.21c) define the variable 'f' and its derivatives according to this scheme.

The value of f at $(j+1)^{th}$ time interval is a sum of a value at j^{th} time interval and a difference Δf , that is,

$$f^{i+1} = f^i + \Delta f$$

Eq. (2.23)

Substituting the Eq. (2.23) in Eqs. (2.22a) to (2.22c), one obtains the following expressions:

$$f(x,t) = 0.5[\theta(\Delta f_{i+1} + \Delta f_i) + (f_{i+1} + f_i)]$$

Eq. (2.24a)

$$\frac{\partial f}{\partial x} = \frac{1}{\Delta x} [\theta(\Delta f_{i+1} - \Delta f_i) + (f_{i+1} - f_i)]$$

Eq. (2.24b)

$$\frac{\partial f}{\partial t} = \frac{1}{2\Delta t} [\Delta f_{i+1} + \Delta f_i]$$

Eq. (2.24c)

Substitution of the Eqs. (2.24a), (2.24b), and (2.24c) in the continuity equation, results in:

$$\frac{1}{\Delta x} [\theta(\Delta Q_{i+1} - \Delta Q_i) + (Q_{i+1} - Q_i)] + [0.5[\theta(\Delta B_{i+1} + \Delta B_i) + (B_{i+1} + B_i)]] \frac{1}{2\Delta t}$$

$$[\Delta y_{i+1} + \Delta y_i] - 0.5[\theta(\Delta q_{i+1} + \Delta q_i) + (q_{i+1} + q_i)]^* = 0$$

Eq. (2.25)

* means that the subscript 1 for q will be dropped henceforth and q without subscript will stand for lateral inflow of water and sediment mixture.

Linearization of Eq.(2.25) by neglecting second and higher order terms gives following expression.

$$a_i \Delta y_{i+1} + b_i \Delta Q_{i+1} = c_i \Delta y_i + d_i \Delta Q_i + e_i$$

Eq. (2.26)

where a_i , b_i , c_i , d_i , and e_i are as defined in Appendix A.

Similarly, substitution of Eqs. (2.24) in the momentum equation and linearizing of the resulting equation gives,

$$a_i' \Delta y_{i+1} + b_i' \Delta Q_{i+1} = c_i' \Delta y_i + d_i' \Delta Q_i + e_i'$$

Eq. (2.27)

where a_i' , b_i' , c_i' , d_i' , and e_i' are defined in Appendix A.

Also, Appendix A, gives the assumptions and expressions that were used in deriving the above equations. Equations (2.26) and (2.27) form the basis for the solution procedure for the model. Knowing the initial and boundary conditions, Eqs. (2.26) and (2.27) are solved to obtain the flow conditions at the end of the first time step. To solve a system of linear algebraic equations, the Double Sweep Method (Krishnappan 1981) is used by the model.

Double Sweep Method is outlined in section 2.2.2.1, with a complete derivation in Appendix B.

2.2.2.1 Double Sweep Method

The Double sweep method works in two steps: Forward sweep and Backward sweep.

Step 1: Forward Sweep

The upstream boundary condition ($i = 1$) can be expressed as

$$\Delta Q_i = E_i \Delta y_i + F_i$$

Eq. (2.28)

where i is any point for a particular time step j .

It can also be shown that for the next point $i+1$ and the same time step, the above relation holds good (Appendix B.).

Thus,

$$\Delta Q_{i+1} = E_{i+1} \Delta y_{i+1} + F_{i+1}$$

Eq. (2.29)

where $E_i, F_i, E_{i+1}, F_{i+1}$ are defined in Appendix B.

Forward Sweep thus works from u/s to d/s and evaluates $E_2,$

$F_2, \dots, E_n, F_n.$

Step 2: Backward Sweep

For backward sweep to proceed, the d/s boundary condition is used to evaluate $\Delta y_n.$

Thus, knowing $\Delta y_n, E_n, F_n, \Delta Q_n$ can be solved from Eq.(2.29). From Eq.(B.2), listed in Appendix B, Δy_{n-1} can be evaluated once ΔQ_n , and Δy_n are known. Thus, the backward sweep method works from d/s to u/s and evaluates $\Delta y_{n-2}, \Delta Q_{n-2}; \Delta y_{n-3}, \Delta Q_{n-3};$ and so on to $\Delta y_1, \Delta Q_1.$

The flow depth and flow rate can be easily computed since the initial condition provides the values of flow rates and flow depths at all grid locations along the river reach.

The Double sweep method requires the use and complete understanding of the boundary conditions. The different types of boundary conditions are:

- (1) the flow depth as a function of time
- (2) the flow rate as a function of time

(3) the flow rate as a function of flow stage or depth.

The User's Manual (Krishnappan 1981) considers each of the boundary conditions in evaluating E_I , F_I , and Δy_H . However, for continuity and for the convenience of the reader, this has been included in Appendix C.

As far as the rigid bed unsteady case is concerned, this is the underlying numerical scheme used in the model. However, the mobile bed unsteady flow conditions requires the sediment continuity equation to predict the change in the bed level Δz .

Rearranging the sediment continuity equation:

$$\frac{\partial z}{\partial t} = \frac{1}{P} \left[q_s - \frac{\partial Q_s}{\partial x} - \frac{\partial (AC_w)}{\partial t} \right]$$

Eq. (2.30)

Change in bed level at grid 'i' during one time step Δt is given by the following equation.

$$\Delta z_i = 0.5 [\Delta z_{i-0.5} + \Delta z_{i+0.5}]$$

Eq. (2.31)

where $\Delta z_{i-0.5}$ and $\Delta z_{i+0.5}$ results from discretization of Eq.(D.1 & D.2) and are defined in Appendix D.

Thus, Δz_i 's are computed for all grid points; the revised flow depth is used to solve flow depth for the next time step.

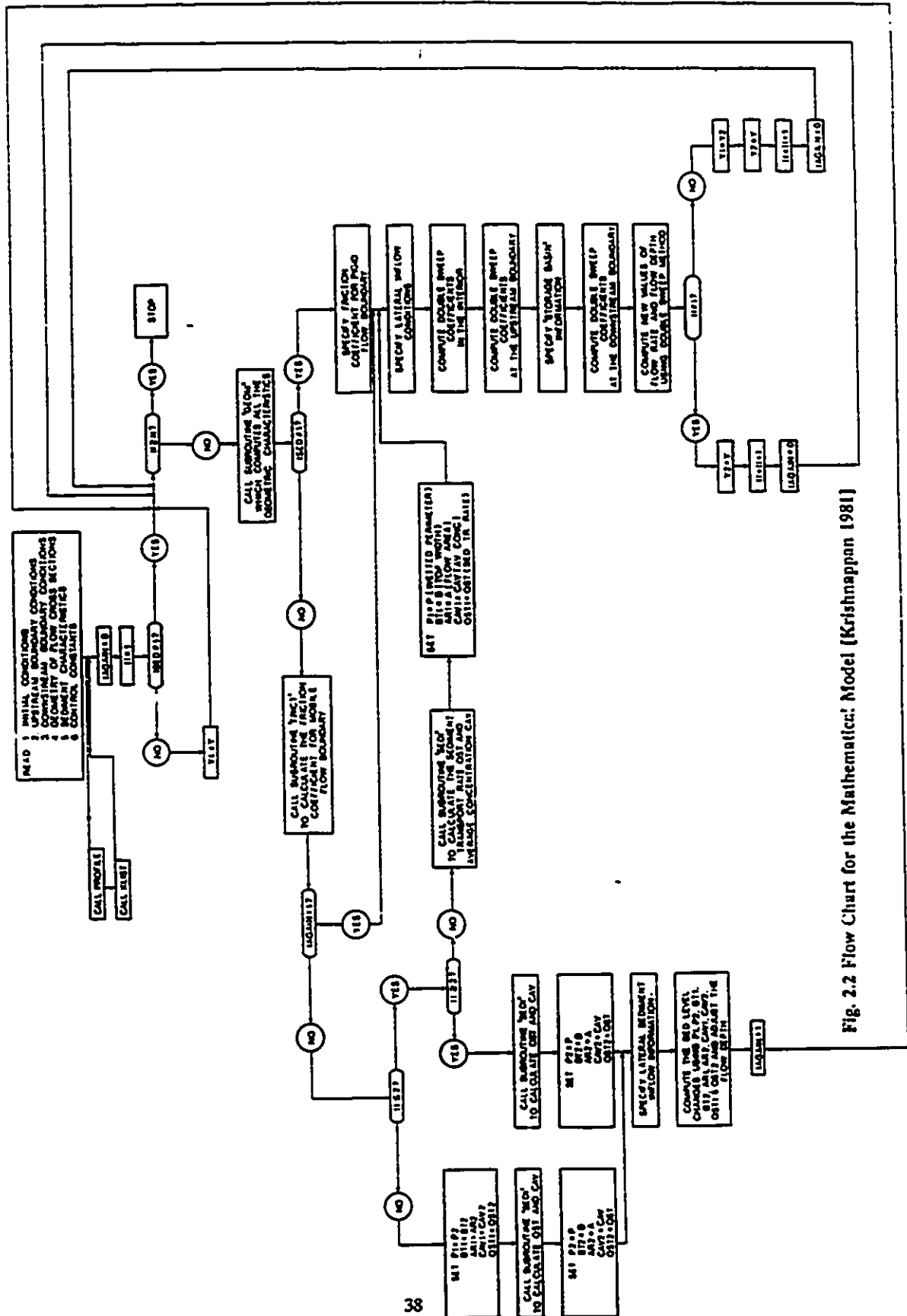
$$\text{Corrected flow depth} = y_i^{j+1} - y_i^{j+1} - \Delta z_i$$

Eq. (2.32)

The flow rate is assumed to be unaffected.

MOBED also takes into consideration the effect of a possible storage basin in a river reach, by modifying the Double Sweep constants. The User's Manual (1981) describes the derivation and the modified constants.

Various subroutines are set in the computer program to carry out the complete solution of the unsteady flow problem. Coding of the program is done in Fortran language. Step by step sequence of the operation has been presented in the form of the flow chart in Fig. 2.2.



The description of the input formatting and the modifications to the model code in input formatting has been presented in Chapter 3.

CHAPTER 3

MODEL TESTING METHODOLOGY

3.0 GENERAL

In order to prove that the model developed is not a futile work in numerical analysis, it is necessary that the model be tested and compared against real life measured data, since there are no universal standards to test unsteady flow models. Hence, results of the numerical model have been compared against observations collected both in the field and experiments conducted in a laboratory by setting up of appropriate physical models.

This chapter describes the methodology involved in model testing and evaluation. The sensitivity and stability analyses of the data for unsteady rigid bed case and mobile bed case have been also discussed. Methodology for error estimation and analysis of the results for both these cases is presented. Since the above discussion requires the knowledge of model code with respect to input formatting, the modifications made to the model code in input formatting has been presented before describing the sensitivity and stability analyses.

3.1 MODIFICATIONS TO THE MODEL CODE

For a model to be practical, it is desirable to have minimum of input values, to obtain a meaningful output. The various subroutines that are built into the structure of the model code, performing different functions, are described in Appendix. E. A sample of the old format of flow file is given in the Users Manual of MOBED (Krishnappan 1981), but a brief description of various input

parameters is presented in the Appendix E.

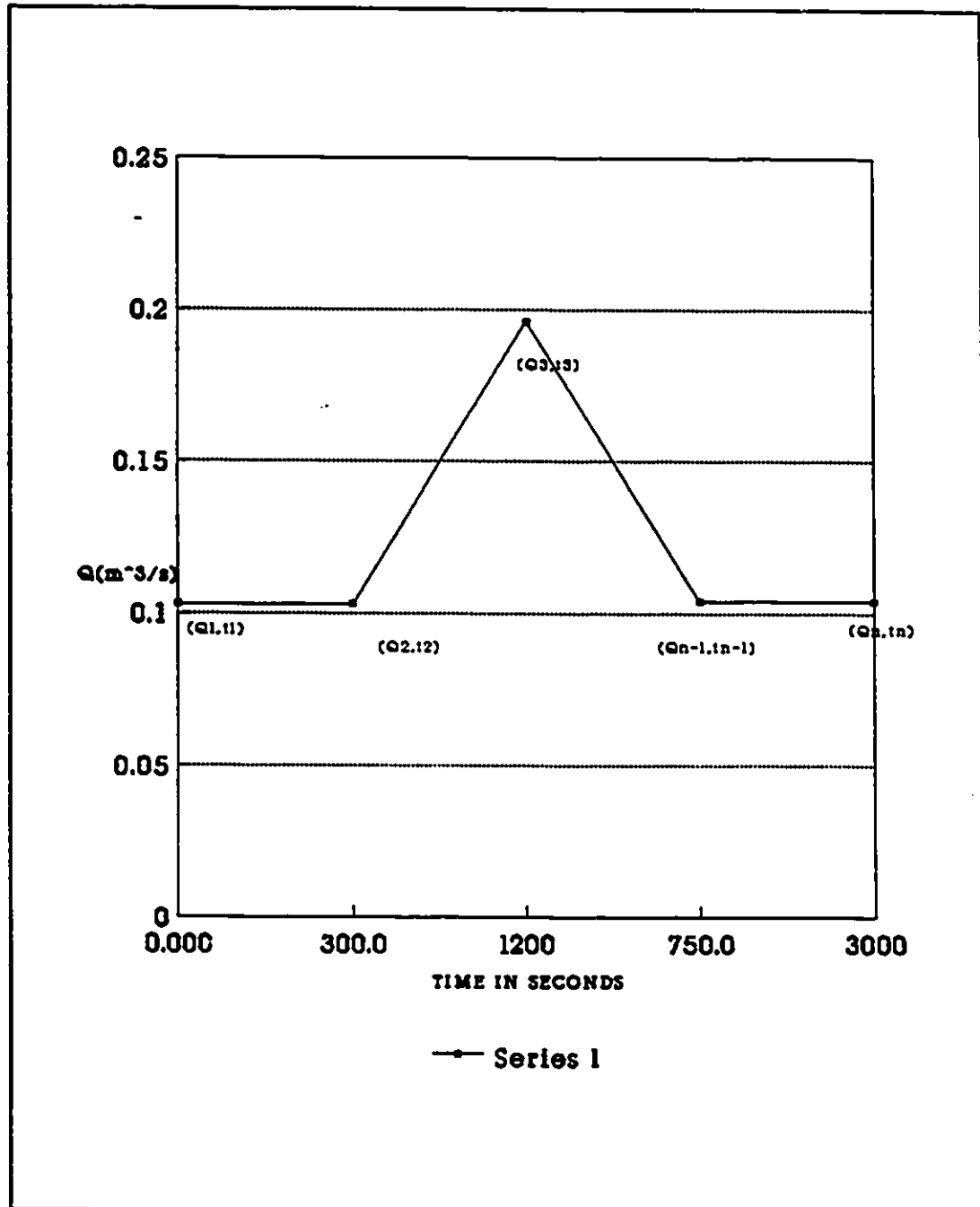
Model code has been modified with the help of a subroutine called "HYDROG.FOR", the function of which is described as follows.

The MOBED input expects upstream flow values Q at interval Δt for $I=1$ to IL as the upstream boundary condition. This may result in an excessively large input file. For example, for a 3000s simulation time, and Δt equal to 2s, 1500 values of flow ' Q ' are required to be given as input. However, the values of flow ' Q ' are usually not random. They can be described by a hydrograph consisting of small finite number of linear sub-sections as shown in Fig. 3.1. We need only specify the number of points(n), and the values of (Q_1, t_1) , (Q_2, t_2) , (Q_n, t_n) , and the subroutine HYDROG calculates the intermediate values of Q at every Δt interval. A sample of modified input format is given in Appendix E. Appendix E also gives a sample of output to give an idea to the reader, as to how the output looks.

3.2 UNSTEADY RIGID BED CASE

The experiment adopted for the unsteady rigid bed case is the test carried out in the experimental channel in Obernach, West Germany. The data for this channel has been collected from a series of experiments which have been well documented and analyzed in the reports of the hydraulic research station of the Technical University of Munich (Treske 1980).

Figure 3.1 INLET HYDROGRAPH



3.2.1 TRESKE DATA

The experiment is defined by the following particulars:

Physical Description:

The channel is prismatic and rectangular in cross-section. It is 1.25m wide and 210m long with the bottom slope of 0.019% or 0.00019. The bed of the downstream cross-section is at elevation 0.052 meters (Krishnappan 1990; and Fig. 3.1A). The channel roughness is described by the Strickler coefficient of roughness $K_s = 87$. However, the straight forward computation of Manning's formulae gives $n = 0.012$ (Krishnappan) and has been considered as the typical value.

Initial and Boundary conditions:

The initial conditions in the channel consisted of a channel depth of 0.2250 m with $0.103 \text{ m}^3/\text{s}$ flow. Boundary condition at inflow or u/s end is defined by hydrograph and is given here:

Inflow or u/s end:

$$\begin{array}{ll} 103.0 & 0 < t < 300\text{s} \\ 41.375 + 0.2055t & 300 < t \leq 750\text{s} \\ Q(0,t) \text{ in l/s} = 347.975 - 0.2033t & 750 < t \leq 1200\text{s} \\ 104.0 & 1200 < t \leq 3000\text{s} \end{array}$$

Eq. (3.1)

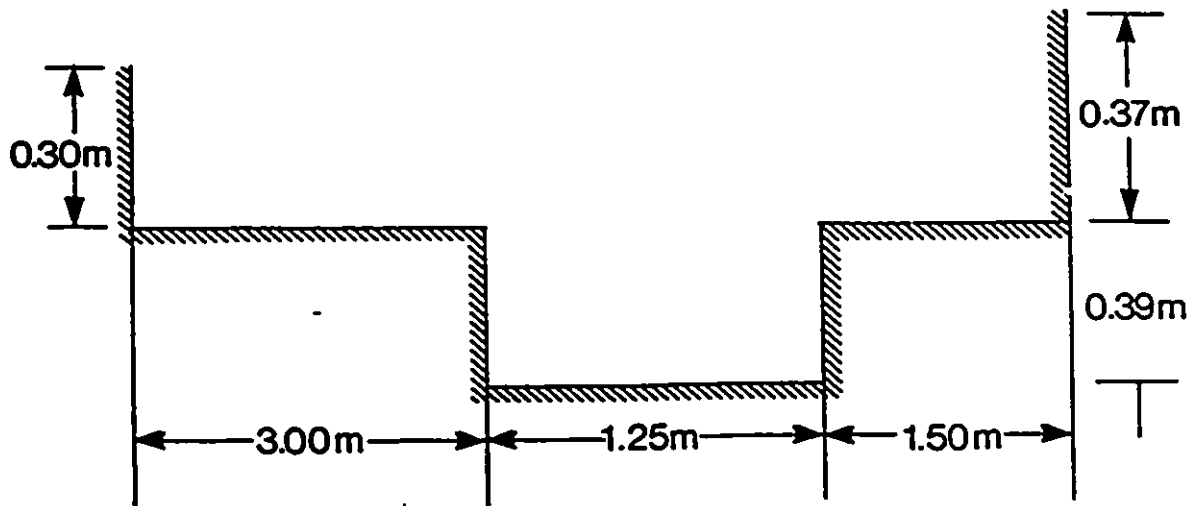


Fig 31A. Cross-section of Treske's prismatic channel

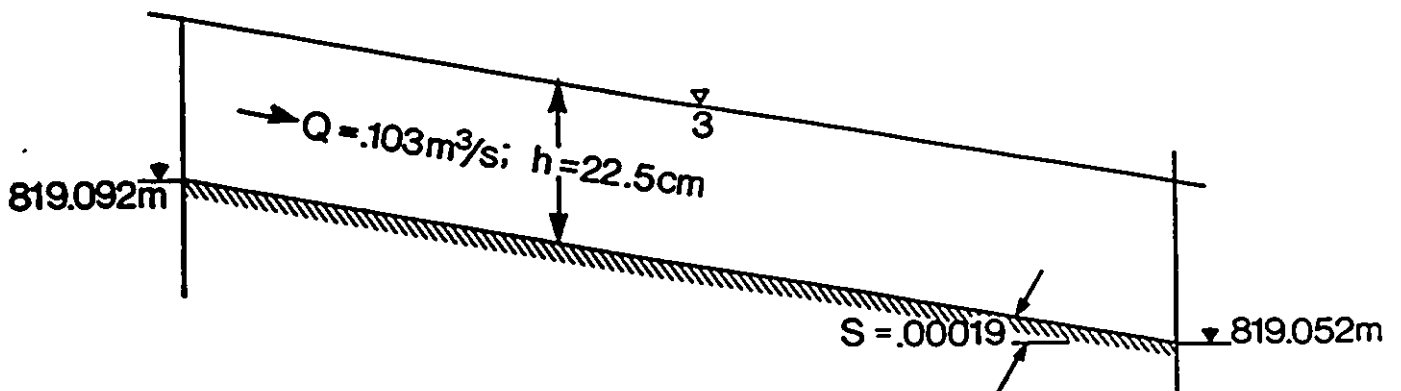


Fig 31B. Profile under uniform flow conditions

Reference: Krishnappan 1990

The downstream stage discharge equation as the d/s boundary condition has been selected to be as follows (Krishnappan):

$$H(L) \text{ in m} = (1.344) Q(L) + 0.08656$$

Eq. (3.2)

where Q is in m^3/s .

3.2.2 SENSITIVITY ANALYSIS

The next step involved in model testing is the sensitivity analysis. Sensitivity analysis is done to highlight those variables which most significantly influence the model output.

Several test runs are made for the Treske channel to check the sensitivity of the model to various factors. The sensitivity of the model has been studied with respect to the following parameters:

- (1) Manning's coefficient of roughness " n "
- (2) The bed slope " S_o "

A typical test run was carried out for the following conditions:

- (1) $\Delta x = 30\text{m}$
- (2) Manning's coefficient of roughness = 0.012
- (3) Bed slope = 0.00019
- (4) Total simulation time being constant at 3000s although Δt was varied
- (5) Rectangular cross-sectional geometry.

Manning's Coefficient of Roughness " n ":

Several test runs are made by varying the value of Manning's " n " from 0.010 to 0.016. For each

value of "n", 7 test runs are made by varying the values of Δt from 2s to 14s in steps of 2s. The results are listed and discussed in Chapter 5, along with the figures and tables.

Bed Slope "So":

Two values of bed slope i.e., 0.00015 and 0.00022 were selected for the test runs, one being lower and other being higher than the typical bed slope value. The results are presented and discussed in Chapter 5.

3.2.3 STABILITY ANALYSIS

To study the convergence and stability of the mathematical model, several runs were made using various space increments ' Δx ' and time increments ' Δt ', as the element length is related to the time step. Δt has been established based on the following equation.

$$\Delta t \leq \frac{\Delta x}{V + \sqrt{gy}}$$

Eq. (3.3)

For the channel in Obernach, time step has been varied by intervals of 2s, and ranged from 2s to 14s. To achieve convergence and stability requirements, space increment was 15m and its value ranged from 15m to 45m. Results are presented in Chapter 5, with the aid of figures.

3.2.4 ERROR ESTIMATE

The laboratory measured values of flow ' Q ' and elevation ' y ' are available at one minute intervals for both u/s and d/s boundary sections. For the specified Δt , MOBED generates the values of ' Q ' and ' y ' at all grid locations at time = 0s. It then repeats the operation for the next time interval and prints

the output. The value of flow 'Q' at a particular grid location, for example, at u/s boundary section is extracted from this output file to result in values of 'Q' at each Δt . Now, from this series of values, only those boundary values which correspond to the one minute interval are selected. If the value of Δt is such that, no value of 'Q' was generated at the one minute interval, then the value is interpolated by selecting the two nearest values. Thus, we have the values of Q calculated by the model at one minute intervals for the u/s section. The same process is repeated for 'Q' at the d/s section as well as the elevation at u/s and d/s sections.

Now, the error can be computed by comparing the calculated value with the measured value. The standard error is defined as follows:

$$\text{Standard Error in Flow} = \sqrt{\frac{\sum_i^n (\text{predicted flow}_i - \text{measured flow})^2}{n-1}}$$

Eq. (3.4)

where n = number of observations,

Standard_e = standard error

Similarly,

$$\text{Standards in Elev.} = \sqrt{\frac{\sum_i^n (\text{predicted elev.}_i - \text{measured elev.})^2}{n-1}}$$

Eq. (3.5)

Standard error in flow and elevation has been calculated both at u/s and d/s boundary sections.

The error is also reported in terms of percent error, which is defined mathematically as follows:

$$\text{Percentage Standards} = \frac{\text{Standards}}{\text{maximum measured}} * 100$$

Eq. (3.6)

Percentage error in flow and elevation has been found and is given for both the u/s and the d/s boundary sections.

The bias errors in peak d/s flow and u/s elevation has also been found and is defined as follows:

$$Bias = \frac{(peak\ predicted - Peak\ measured)}{peak\ measured} * 100$$

Eq. (3.7)

For Treske's channel the bias error is estimated in predicting peak flow at the d/s section $Q(d/s)$ and the peak stage at the u/s section $y(u/s)$. The phase shift between the predicted and measured peak values is also noted.

A program called "EXTRACTR.RIG" is written to carry out the above computations efficiently. The program is coded in Basic and the mathematical flow chart is given in Fig. 3.2, to explain the step by step procedure. Appendix F gives the listing of the program "EXTRACTOR.RIG".

3.3 MOBILE BED CASE

The equilibrium state experiments adopted for mobile bed case are the link canals of Pakistan. Field experiments were conducted under ACOP (Alluvial Cuannel Observation Project) to obtain hydraulic, sedimentation, and morphologic data (bed form characteristics) of these channels. Field measurements were made under equilibrium conditions for the channel reaches. The complete data comprising numerous equilibrium runs made on fifteen different canals has been well documented in ten volumes of report 'ACOP CANALS EQUILIBRIUM DATA'(Khalid Mahmood, et al, 1981, 1982). Each equilibrium experiment was preceded by two days of steady, uniform flow conditions to allow

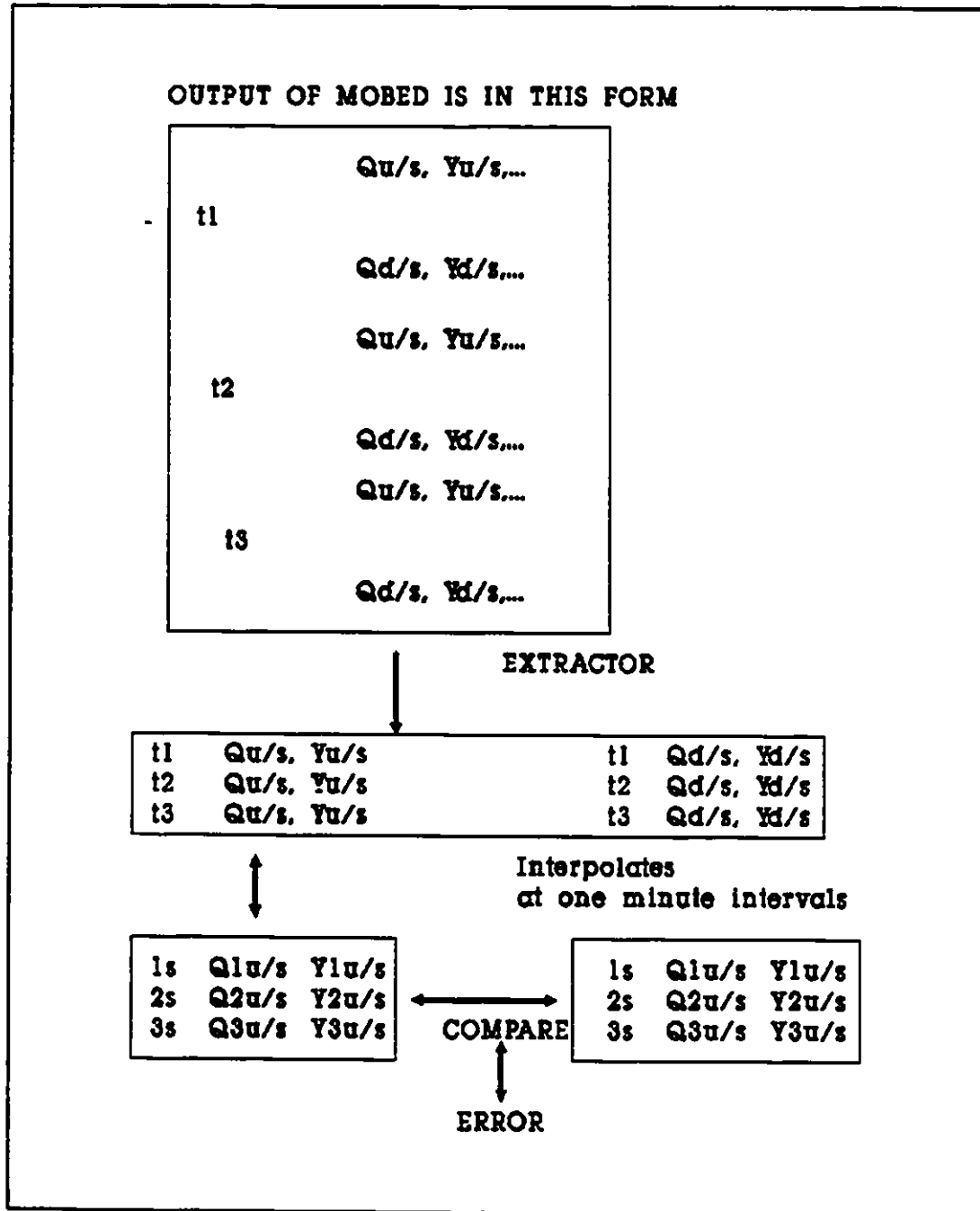
the bedforms to adjust and stabilize to the flow. The link canals that were selected for the equilibrium studies are as follows:

1. Qadirabad-Balloki link
2. Balloki-sulemanki links I & II
3. Taunsa-Panjnad link
4. Chasma Jhelum link
5. Jamrao canal

Their location has been shown in the map of Indus Basin of Pakistan in Fig. (3.3).

The data for various input files to the model were obtained from the above reports, and about 200 test runs were made for different bed forms and for varying conditions of flow.

Figure 3.2 Flow Chart for the Extractor



3.3.1 LINK CANALS

In this section, a brief description of the link canals is presented followed by the discussion on the bed configuration and roughness of alluvial streams.

3.3.1.1 Description of Link Canals

1. Qadirabad-Balloki link Canal

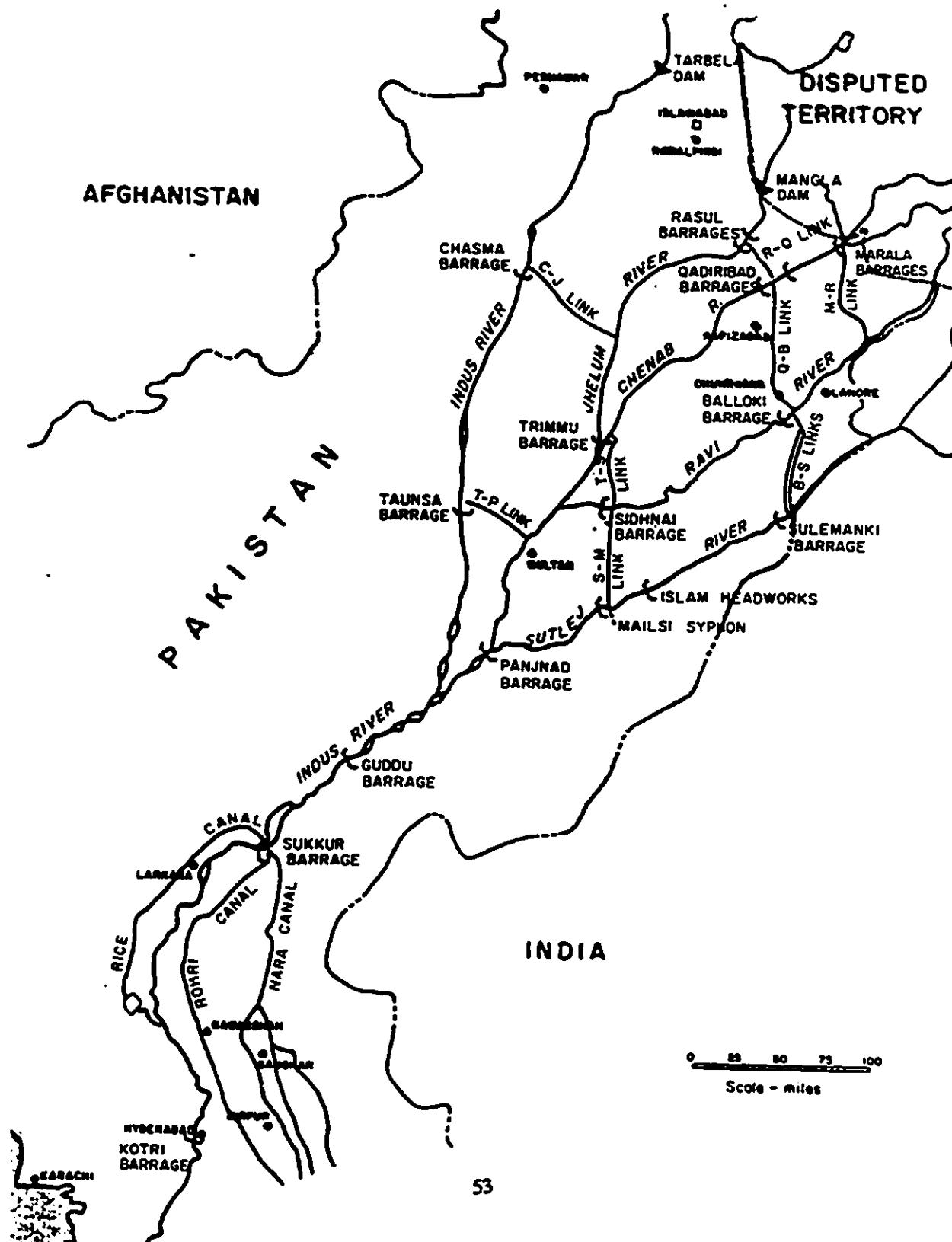
As seen on the map in Fig. 3.3, Qadirabad Balloki link canal is the second segment of the Rasul-Qadirabad-Balloki-Sulemanki link system. This unlined earth link canal has a capacity of 18,600 cusecs (ft^3/s), bottom width of 335 feet and the normal depth of 13 feet from its headworks to Sagar. From Sagar up to the point of outfall, its discharging capacity changes to 14,500 cusecs with a bottom width of 300 feet and a normal depth of 12 feet. The bed slope varies between 0.000125 to 0.000130 and the side slope ranges between 2:1 to 3:1 (H:V).

2. Balloki-Sulemanki link Canal

Balloki Sulemanki link Canal I, mainly a lined canal offtakes from the left bank of Ravi River at Balloki extending for a distance of 53 miles and then outfalls ten miles (approx.) above the Sulemanki Barrage. The upper 14 miles of the link which is unlined has a capacity of 18,500 cfs. It has a bed width of 325 feet and a full supply width of 14.0 feet. This canal has a bed slope of 0.0001.

Balloki Sulemanki link Canal II, extending to a distance of 39 miles is an unlined earth canal and has a design discharge capacity of 6,500 cusecs. It has a bottom width of 190 feet and a normal depth of 10.0 feet. The vertical side slope and the bed slope of this link canal is the same as that of Qadirabad Balloki link canal.

Fig. 3.3 INDUS BASIN OF PAKISTAN



3. Taunsa Panjnad Link Canal

This 38 mile long, unlined earth link canal has been designed to carry a discharge of 12,000 cusecs. It has a bottom width of 266 feet and bed slope varying from 0.0002 to 0.00011. Average normal depth is 12 feet for this link canal.

4. Chashma Jhelum Link

Chashma Jhelum Link extending to a distance of 67 miles, is the biggest unlined earth channel in Pakistan. It has a design discharge capacity of 21,700 cusecs, a bottom width of 380 feet and a normal depth varying from 11.8 to 14 feet. It has an average bed slope of 0.000118.

5. Jamrao Canal

Jamrao canal is basically, an irrigation canal located in the lower Indus Plain. It is the smallest and has a finer bed material size than the other canals mentioned above. This unlined canal carries a design discharge capacity of 3,400 cusecs and maintains a full supply depth of 8.6 feet. Bed width of this canal is 148 feet.

3.3.1.2 Bed Configuration and Roughness of Alluvial Streams

One of the significant parameters required for model evaluation in cases of mobile bed flows is the success of bed form prediction. Based on the characteristics of bed material and hydraulic conditions acting at the interface of flowing water and sediment flow, various types of sand waves are formed on the erodible river bed. Ashida and Kishi(1973), have classified these bed configurations on the basis of scale of disturbance in stream as follows:

1. RIPPLES, the smallest of all bed forms is controlled by the properties of sand grains and appears below the Grain Reynold's number of 20.

2. DUNE , are most stable and larger bed forms than ripples; their dimensions are of the same order as the flow depth. They are out of phase with the water surface.

3. TRANSITION, is the state of bed in transition, and consists of portions of ripples, dunes, and flat beds.

4. FLAT BED, is the state of river bed, relatively flat, and does not have any significant wavy bed forms such as ripples, dunes or antidunes.

5. ANTIDUNES, unlike dunes are in phase with surface waves and depending on the properties of bed load and flowing water, these sand waves may move upstream, downstream or remain stationary. The height of these bed forms is similar to the depth of flow.

The above bed forms are also classified under micro-scale bed configuration. Kishi and Kuroki gave a general description of the criteria for the bed configurations as shown by the following expression:

$$f(\phi_0, \tau_*, \frac{R}{d}, \kappa) = 0$$

Eq. (3.8)

where

ϕ_0 is the velocity factor

τ_* is the bed friction stress

R/d is the ratio of hydraulic radius and depth

κ is Von- Karman constant

Based on the studies by Engelund (1967) and Garde-Raju (1963) on flow resistance and bed configurations, Kishi and Kuroki (1974) varied $\tau_* - \tau_{*c}$ relationship (Resistance law) with R/d . Results of Kishi and Kuroki are summarized in Fig. 3.4 and their equations are as follows:

$$1. \text{ Dunes I, } \phi_0 = (8/1)^{1/2} = 2.4(R/d)^{1/6} \tau_*^{-1/3}$$

Eq. (3.9)

$$2. \text{ Dunes II, } \phi_0 = 8.9$$

Eq. (3.10)

$$3. \text{ Transition I, } \phi_0 = 1.1 \cdot 10^6 (R/d)^{-3/2} \tau_*^3$$

Eq. (3.11)

4. As a boundary between dunes and transition beds

$$1/s = 0.02(R/d)^{-1/2}$$

$$\tau_* = 0.02(R/d)^{1/2}$$

$$\phi_0 = 8.9, \text{ on the boundary curve}$$

Eq. (3.12)

$$5. \text{ Flat bed, } \phi_o = (8/f)^{1/2} = 6.9(\kappa_o/\kappa)^{1/2} (R/d)^{1/6}$$

Eq. (3.13)

$$6. \text{ Antidunes, } \phi_o = 2.8(R/d)^{3/10} \tau_o^{-1/3}$$

Eq. (3.14)

7. Criteria between dunesII, flat bed and antidunes

$$I/s = 0.07(R/d)^{3/5}$$

$$\tau_o = 0.07(R/d)^{2/5}$$

Eq. (3.15)

where

f is the friction factor

I is the slope

s is the submerged specific gravity

$$s = \frac{(\rho_s - \rho_o)}{\rho_o}$$

Eq. (3.16)

where

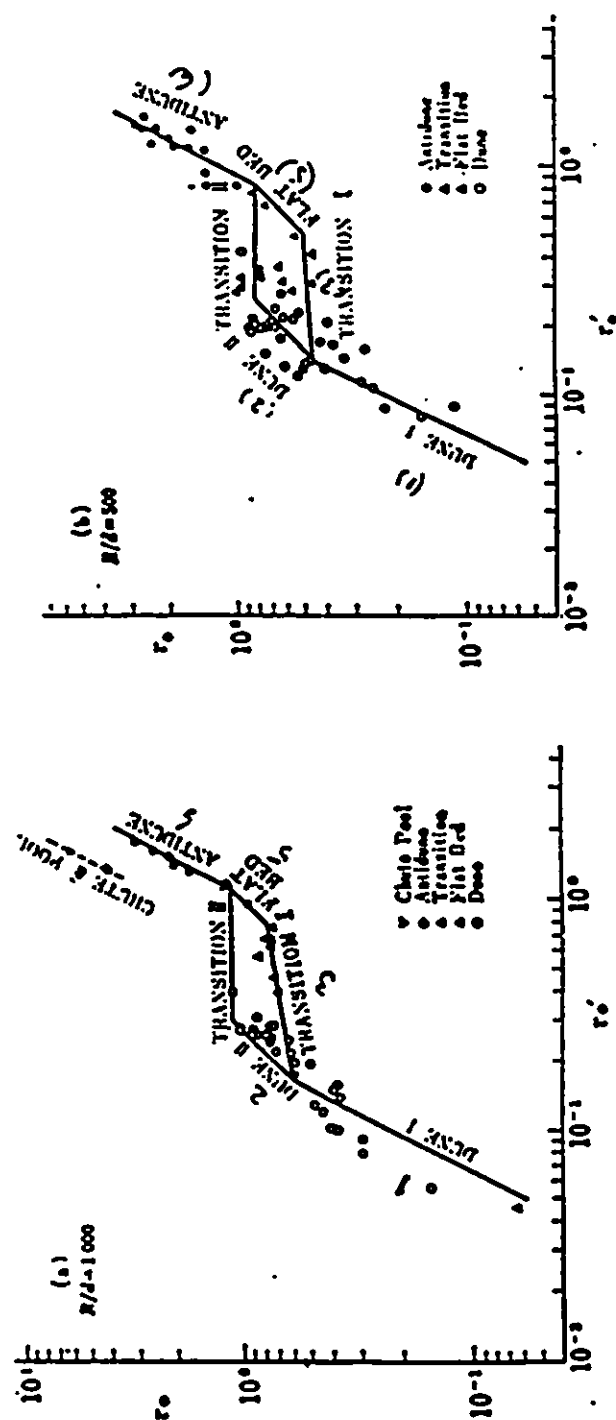
ρ_s is the density of sediment

ρ_o is the density of liquid.

κ_o is the variation in Von-Karman constant

τ_o is the grain friction stress

Fig. 3.4 MODIFIED $\tau_0 - \tau_e'$ DIAGRAM [Kishi and Kuroki 1974]



3.3.2 ERROR ESTIMATE

The error can be computed by comparing the calculated values with the field measured values. Error is found in the same way as defined for the unsteady rigid bed case. For mobile bed steady flow cases, the model is evaluated by the percentage of success rate in predicting bed form, in addition to the percentage error in flow and depth for both upstream and downstream sections.

Of "n" number of total test cases of a particular bed form, say "x" number of test cases that predicted the correct bed form, then the percentage of success rate for bed form prediction is defined as follows:

$$\text{Percentage of success rate} = (x/n) * 100$$

Eq. (3.17)

Error analysis has been carried out for all the test cases with IL=100 followed by IL=400. Selection of longer simulation time was necessary for link canals to adjust and stabilize to the adjusting flow. This is illustrated by the figures presented in Chapter 5.

The overall average percentage error has been found in flow and depth for u/s and d/s sections. The results of error analysis and estimation are listed in Chapter 5. Also, for the link canals, the bias error has been calculated at the IL=400th value for d/s flow and u/s depth.

The program "EXTRACTR.RIG" has also been modified to predict the bed form and is attached in Appendix F as "EXTRACTR.MOB".

3.3.3 MODIFICATIONS TO THE MODEL CODE- VALUE OF FRICTION CONSTANTS

The MOBED model uses Kishi and Kuroki's (1974) friction equations as the default equations for the various bed forms. Values of the parameters const , m , and n for Kishi's friction relations are given in User's Manual No.2 (Krishnappan 1983), and are built-in to the source code. However, the model gives the user the choice of using different friction parameters given in Manual No. 2, and are to be given as the input values.

Modifications made are discussed in Chapter 5 and the error analysis with and without the modification are also presented in the same Chapter.

Portions of the source code of MOBED with all modifications highlighted is attached in Appendix G.

CHAPTER 4

FILE ORGANIZATION FOR MODEL TESTING

4.0 GENERAL

This chapter presents the naming characteristics of the input files. The input files used for rigid bed unsteady case and mobile bed unsteady case are given in two diskettes attached at the end of Appendix. This chapter gives the names of the files and the corresponding conditions for which the tests are made.

4.1 UNSTEADY RIGID BED CASE

Table 4.1 lists the test conditions defined in flow and geometric files for unsteady rigid bed case.

TABLE 4.1 CHARACTERISTICS OF UNSTEADY RIGID BED FILES

FLOW FILE	GEOMETRIC FILE	Δx IN M.	Δt IN SEC.	BED SLOPE "So"	MANNI- NG'S "n"
F1	TAPE01.DAT	30	2	0.00019	0.012
F2	TAPE01.DAT	30	4	0.00019	0.012
F3	TAPE01.DAT	30	6	0.00019	0.012
F4	TAPE01.DAT	30	8	0.00019	0.012
F5	TAPE01.DAT	30	10	0.00019	0.012
F6	TAPE01.DAT	30	12	0.00019	0.012
F7	TAPE01.DAT	30	14	0.00019	0.012
F11	TAPE01.DAT	15	2	0.00019	0.012
F12	TAPE01.DAT	15	4	0.00019	0.012
F13	TAPE01.DAT	15	6	0.00019	0.012
F14	TAPE01.DAT	15	8	0.00019	0.012
F15	TAPE01.DAT	15	10	0.00019	0.012
F16	TAPE01.DAT	15	12	0.00019	0.012
F17	TAPE01.DAT	15	14	0.00019	0.012

F21	TAPE01.DAT	45	2	0.00019	0.012
F22	TAPE01.DAT	45	4	0.00019	0.012
F23	TAPE01.DAT	45	6	0.00019	0.012
F24	TAPE01.DAT	45	8	0.00019	0.012
F25	TAPE01.DAT	45	10	0.00019	0.012
F26	TAPE01.DAT	45	12	0.00019	0.012
F27	TAPE01.DAT	45	14	0.00019	0.012

H1	G01.DAT	30	2	0.00019	0.010
H2	G01.DAT	30	4	0.00019	0.010
H3	G01.DAT	30	6	0.00019	0.010
H4	G01.DAT	30	8	0.00019	0.010
H5	G01.DAT	30	10	0.00019	0.010
H6	G01.DAT	30	12	0.00019	0.010
H7	G01.DAT	30	14	0.00019	0.010
K1	G01.DAT	30	2	0.00019	0.016
K2	G01.DAT	30	4	0.00019	0.016
K3	G01.DAT	30	6	0.00019	0.016
K4	G01.DAT	30	8	0.00019	0.016
K5	G01.DAT	30	10	0.00019	0.016
K6	G01.DAT	30	12	0.00019	0.016
K7	G01.DAT	30	14	0.00019	0.016

M1	M01.DAT	30	2	0.00022	0.012
M2	M01.DAT	30	4	0.00022	0.012
M3	M01.DAT	30	6	0.00022	0.012
M4	M01.DAT	30	8	0.00022	0.012
M5	M01.DAT	30	10	0.00022	0.012
M6	M01.DAT	30	12	0.00022	0.012
M7	M01.DAT	30	14	0.00022	0.012
P1	P01.DAT	30	2	0.00015	0.012
P2	P01.DAT	30	4	0.00015	0.012
P3	P01.DAT	30	6	0.00015	0.012
P4	P01.DAT	30	8	0.00015	0.012
P5	P01.DAT	30	10	0.00015	0.012
P6	P01.DAT	30	12	0.00015	0.012
P7	P01.DAT	30	14	0.00015	0.012

4.2 UNSTEADY MOBILE BED CASE

The naming of the link canals of Pakistan follow the general pattern of ABMN.XYZ; where AB is the name of the link canal.

= qb = Qadirabad-Balloki canal

= cj = Chasma- Jhelum canal

M stands for the number of test case

= 1 to 16 for transition bed form

= 1 to 15 for the bed covered with dunes

= 1 to 12 for plane bed

= 1 to 10 for ripples

N designates the type of input file

= 8 for flow file

= 1 for geometric file

XYZ stands for the type of bed form

= trn for transition

= dun for dunes

= pln for plane bed

= rpl for ripples

Δt , initial flow and initial depth for each of the test case has been in the results in Chapter 5. The detailed parameters of the input files can be verified from the reports of "ACOP CANALS EQUILIBRIUM DATA" (Khalid Mahmood et al, 1981, 1982).

CHAPTER 5

MODEL RESULTS AND EVALUATION

5.0 GENERAL

This chapter presents and describes the results of unsteady rigid bed and mobile bed flows. The results of the several test runs under varying conditions have been presented in figures and tables showing errors in depth and flow for both upstream and downstream boundary sections. For unsteady rigid bed case, the error has been reported in terms of u/s and d/s elevations instead of flow depth, since the Treske report gives the measured values for elevations.

5.1 UNSTEADY RIGID BED CASE

The results of the sensitivity and stability analyses are presented in this section. The basis of comparison is the case described in section 3.2.2.

5.1.1 SENSITIVITY ANALYSIS - RESULTS AND ERROR ESTIMATE

Manning's coefficient of roughness "n":

Figures 5.1 to 5.3 show the effect of varying Manning's "n" on u/s flow, u/s elevation, and d/s flow respectively. The value of "n" was varied from 0.010 to 0.016 with all other input values fixed.

Fig. 5.1 shows the verification of the u/s boundary condition. The overall error in u/s flow throughout the simulation period is +1.4 percent.

Fig. 5.2 plots the predicted u/s elevation in meters for all the values of Manning's "n" with simulation time. The predicted u/s elevation results are significantly affected by changing bed roughness. The model underpredicts the u/s elevation throughout the simulation period for the values of Manning's "n" lower than the basis of comparison ($n = 0.012$) and vice-versa. This behavior is expected since the increase in channel roughness causes a steeper gradient to discharge the same flow thus leading to higher elevations at u/s sections, with increasing roughness of channel bed.

As seen in Fig. 5.3, the predicted d/s flow values are quite close to the measured values throughout the simulation time for all the values of "n". For the initial 7 minutes of the run, the model predicted a transient in the downstream flow; this transient occurred when $n = 0.012$ and is caused by the fact that under these conditions the initial flow does not satisfy the momentum equation.

The standard errors, percentage errors, and bias errors for various bed roughnesses are shown in tabular form in Table Nos. 5.1 to 5.2. Each table deals with the errors for a particular value of bed roughness and shows in different columns standard errors and percentage errors for u/s flow and elevation, d/s flow and elevation considering the complete simulation period. The percentage errors in the peak u/s depth and peak d/s flows, are important in assessing the model. Tables 5.1 and 5.2 also show the bias errors in d/s flow and u/s elevation. The negative sign shown on the bias error, means that the model underpredicts, and the positive sign refers to overprediction in predicted values compared to measured values.

Figures 5.4 and 5.5 show the non-dimensional plot summarizing the effect of Manning's "n" on u/s depth and d/s flow respectively. The x-axis show the values of bed roughness selected for unsteady rigid bed case. The y-axis show the ratio of peak value for any value of "n" to the peak value

for " n " = 0.012.

Bed slope " S_o ":

Figures 5.6 to 5.7 present the effect of sloping bed on u/s elevation and d/s flow.

The value of bed slope varied from 0.00015 to 0.00022 with all other parameters fixed.

The results of the predicted u/s elevation are compared with the measured u/s elevations in Figure 5.6. It can be seen that increasing the bed slope underpredicts the stage. The calculated u/s elevation increased with the decreasing bed slope. The time to peak the u/s elevation is not significantly affected by varying the bed slope.

Fig. 5.7 shows that the model results of d/s flow for different values of bed slope are in good agreement with the measured values. The peak values of predicted d/s flow are slightly higher than the peak measured value while there is no significant change in the time to peak flow. The error analysis is given in Tables 5.3, and 5.4.

Figures 5.8 and 5.9 summarize the u/s depth and d/s flow results for various bed slopes.

5.1.2 STABILITY ANALYSIS- RESULTS AND ERROR ESTIMATE

Effect of Δt on flow and elevation for both u/s and d/s sections has been studied and presented in Figures 5.10 to 5.17.

For a particular value of Δx ($\Delta x = 30\text{m}$) and different values of Δt ($\Delta t = 2\text{s}, 6\text{s}, 10\text{s}, \text{ and } 12\text{s}$) Figures 5.10 to 5.17 plot the predicted and measured u/s elevations, or d/s flows with respect to

time. The basis for selecting Δt is given by Eq. (3.3) in section 3.2.3 and Δx ranged from 15m to 45m in intervals of 15m. It can be seen from the figures that the predicted peak u/s elevation for all the cases of Δt does not change significantly. There is no difference in the time to peak flow as the Δt is changed.

A similar behavior was found for d/s flows. The error analysis for stability analysis is given in Table 5.5. Tables 5.6 and 5.7 confirm that the stability is invariant for $\Delta x = 15\text{m}$ and $\Delta x = 45\text{m}$. Tables 5.5, 5.6, and 5.7 also give the bias errors for $\Delta x = 30\text{m}$; $\Delta x = 15\text{m}$; and $\Delta x = 45\text{m}$ respectively.

5.2 MOBILE BED CASE

The model results for the 55 equilibrium experiments of the link canals of Pakistan include the several test cases made for each of the bed form. The model results are presented in Figures 5.18 to 5.33 and Tables 5.8 to 5.15. Figures 5.18 to 5.33 plot the measured versus predicted u/s depth or d/s flows at equilibrium (at number of time steps = $IL = 400$) for all bed forms (transition, dunes, plane bed, and ripples). The model results are shown for the original friction factor parameters (Kishi and Kuroki, 1974) and for the modified friction factor parameters.

In order to simulate the steady conditions for the equilibrium experiments of the link canals the total simulation time was increased from $IL=100$ to $IL=400$. Figures 5.34 to 5.47 show that both the depth and the flow are unsteady for $IL=100$ but at $IL=400$ both flow and depth reach fairly steady conditions. Thus, all the results pertaining to the mobile bed cases were run with $IL=400$.

5.2.1 UNCALIBRATED CASE

The errors found described under the uncalibrated cases refers to the errors found using Kishi

and Kuroki (1974) friction factor relationships.

The predicted versus measured u/s depth and d/s flow at $IL=400$ in Figures 5.18, 5.19 (for transition), Figures 5.22, 5.23 (for dunes), Figures 5.26, 5.27 (for plane bed), Figures 5.30, 5.31 (for ripples) show that the predicted values are scattered around to the perfect fit line.

For 16 test runs of transitional regime, the percentage bias errors in the u/s depth at $IL=400$ varies from -24.08 to +4.58, and the percentage bias errors in the d/s flow vary from -17.1 to +5.37. The average error at $IL=400$ for u/s depth is -3.33% and for d/s flow -1.97%. Table 5.8 lists Δt , number of grid locations made for that test run, the percentage errors in u/s depths, and the d/s flows calculated for the overall simulation period. The positive sign for the bias error shows that the model overpredicts and the negative sign shows that the model underpredicts. The bed form predicted by the model for each of the runs is also listed in the same table. The percentage success rate for predicting the bed form for transition is found to be 66%.

For the case of dunes, the percentage bias errors in the u/s depth for $IL=400$ falls in the range of -19.11 to +1.99 and whereas the d/s flow errors falls within +9.03%. The average error is -4.89% for the u/s depth and 2.74% for the d/s flow. The error results and bed form predictions for each test run is listed in Table 5.9. The percentage success rate for predicting dunes is found to be 50%.

For plane bed form, 12 test runs were made. As is seen in the Table 5.10, the percentage bias error at $IL=400$ for the u/s depth varies from the lowest value of -27.69 to the highest value of +19.06. The d/s flow percentage errors are in the range of -10.03 to +8.69. The average errors at $IL=400$ are found as -1.33% for the u/s depth and +1.21% for the d/s flow. The overall average errors

are listed in Table 5.10. The model did not correctly predict the plane bed form in any of the computer runs.

For the case of ripples, the bias errors are in the range of -17.28% to +3.97% giving an average of -3.6% for the u/s depth. For the d/s flow, the percentage bias errors lie in the range of -1.49 to +5.72 giving an average of 1.33%. The percentage success rate in predicting this bed form is 10% only. Table 5.11 lists the error results in flow and depth for the u/s and the d/s boundary sections.

5.2.2 MODIFICATIONS TO THE MODEL CODE - VALUE OF FRICTION CONSTANTS

Kishi and Kuroki's relations were developed for $R/D_{65} < 2000$, i.e., for smaller channels. This may account for some of the significant errors of link canals where $R/D_{65} > 2000$. It is, therefore, proposed to modify the model code for larger channels. The modification is to be made in the value of const (Eq. 2.17) and is calculated as follows:

$$\text{Const(modified)} = \text{Const} \cdot C^* \quad \text{Eq. (5.1)}$$

where $C^* = \text{constant} = S_{fo}/(S_{fo} + \Delta S_f)$

and S_{fo} = observed friction slope

ΔS_f = change in friction slope predicted using Kishi and Kuroki's (1984) relations and is calculated as follows:

$$\Delta S_f = \frac{\text{Avg. percent error in u/s depth}}{100} \cdot \frac{\text{Avg. initial depth}}{\text{length of canal}} \quad \text{Eq. (5.2)}$$

The value of C^* thus obtained = 1.122 for the transition regime;
= 1.30 for dunes and ripples regime;
= 1.125 for plane bed.

Because of the lack of field data on antidunes, the model could not be evaluated for this bed form. However, the error analysis with and without the modified Const. for other bed forms and for all the test cases has been completed. The results before modification were discussed in Section 5.2.1. The results after the modification are presented in Section 5.2.3.

5.2.3 CALIBRATED CASE

For the transition bed form, the percentage bias errors at $IL=400$ for the u/s depth fall within the range of -19.75 to +8.57 giving a very low average error of -0.58%. There is also a significant improvement in bed form prediction. The percentage success rate in predicting the bed form is 87%. Table no. 5.12 documents the overall percentage errors along with the bed forms predicted by model. Figures 5.20 and 5.21 plot the predicted versus measured u/s depth and d/s flow at equilibrium.

The average errors at equilibrium for the bed covered with dunes improved from -4.89% to -3.28% for the u/s depth. The percentage success rate for the bed form prediction did not change much and was found to be 43% after the modification. The overall percentage errors for flow and depth at the u/s and the d/s sections are listed in Table 5.13. Figure 5.24 and 5.25 show the predicted and measured u/s depth and d/s flow at equilibrium respectively.

The percentage bias errors at $IL=400$ for the plane bed regime after the modification ranged

from -27.56 to +29.32 in the u/s depth giving an average of 0.02%. The modification did not have any effect on the bed form prediction. Figures 5.28 and 5.29 plot the predicted versus the measured u/s depth and d/s flow at IL=400 for the case of a plane bed. The results are listed in Table 5.14.

As can be seen from Table 5.15, for ripples the average bias error at IL=400 for the u/s depth is only -0.755%. The percent error for the d/s flow dropped from 1.33% to 0.01%. There is no change in the percentage success rate in the bed form prediction. Figures 5.32 to 5.33 are the plots of the predicted versus the measured u/s depth and d/s flow at IL=400 for the bed covered with ripples.

5.3 ACCURACY AND RELIABILITY OF THE MODEL

The difference in the predicted value and the measured value need not only be due to errors in the model. Even if, the model were 100% accurate, there may be a difference in the predicted and the measured values. This difference can therefore be attributed to human errors in the measured values themselves which we shall refer to as observational errors. Thus, in evaluating the mathematical model for accuracy and reliability, the overall average error for flow and depth should be compared to the observational field errors with good control.

For the Treske channel, the observational error in elevation is approximately 0.5mm for each reading. For most of the cases, the predicted results are not within the limits of the observational error of the depths but the percentage error in the depth is generally less than 3% which is considered acceptable for practical engineering applications. The average error in flow is in good agreement with the observational error in measured flow values which falls within the range of 1% to 2%.

Similarly, the field errors for the link canals are ± 6 inches in the depth due to undulations of the bed form and approximately 5% error in the flow. The difference in the predicted and the measured u/s depths at IL=400, for most of the test runs lies within the ± 6 inches. The average flow errors predicted by the model at IL=400 lies well within the range of 5%.

The general predictive accuracy of the model for mobile bed flows as far as the errors in flow and depth are concerned is quite good. However, the error in the prediction of the bedform especially for plane bed and ripples is only fair.

Figure 5.1 INLET HYDROGRAPH

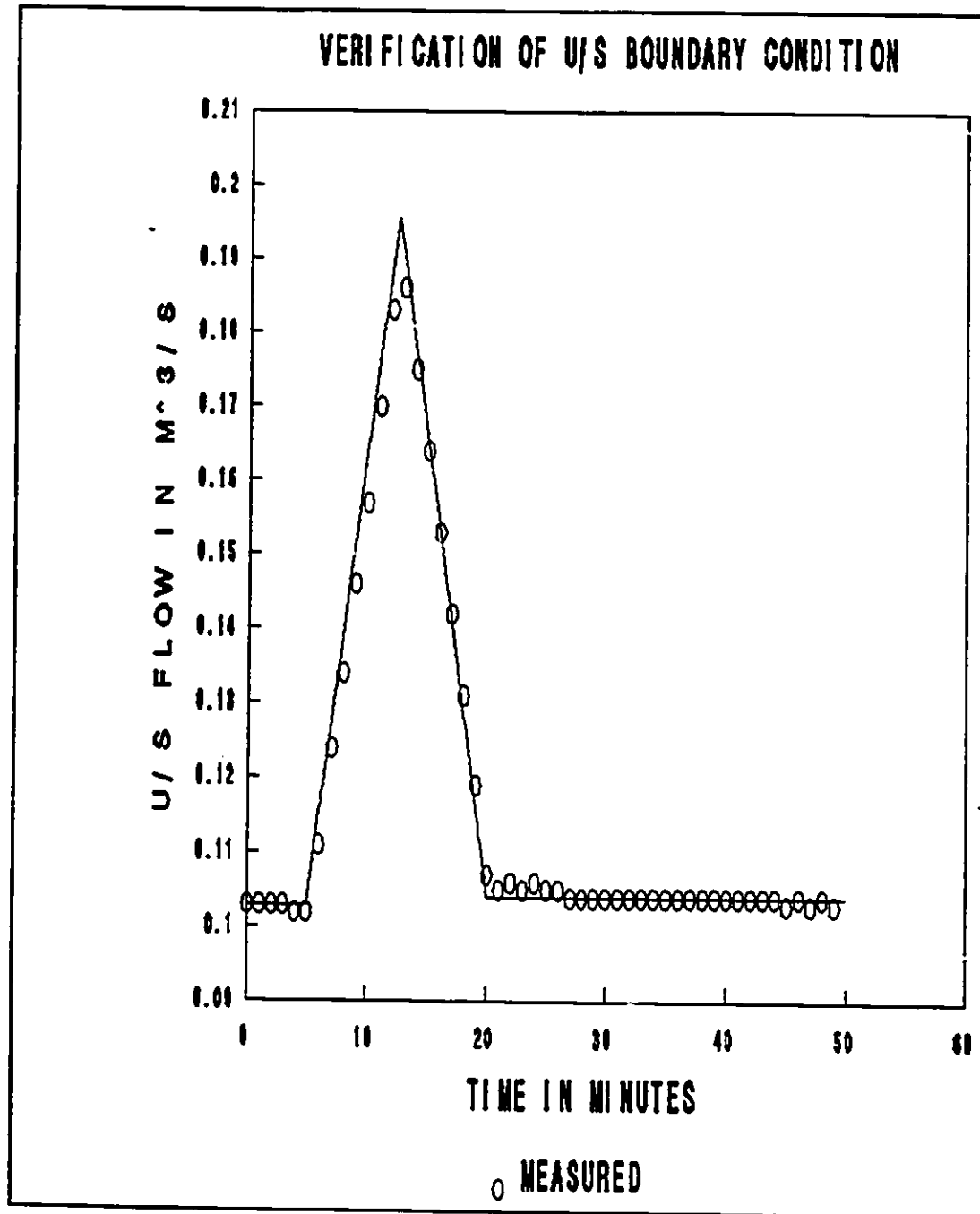


Figure 5.2 SENSITIVITY ANALYSIS-RIGID BED CASE

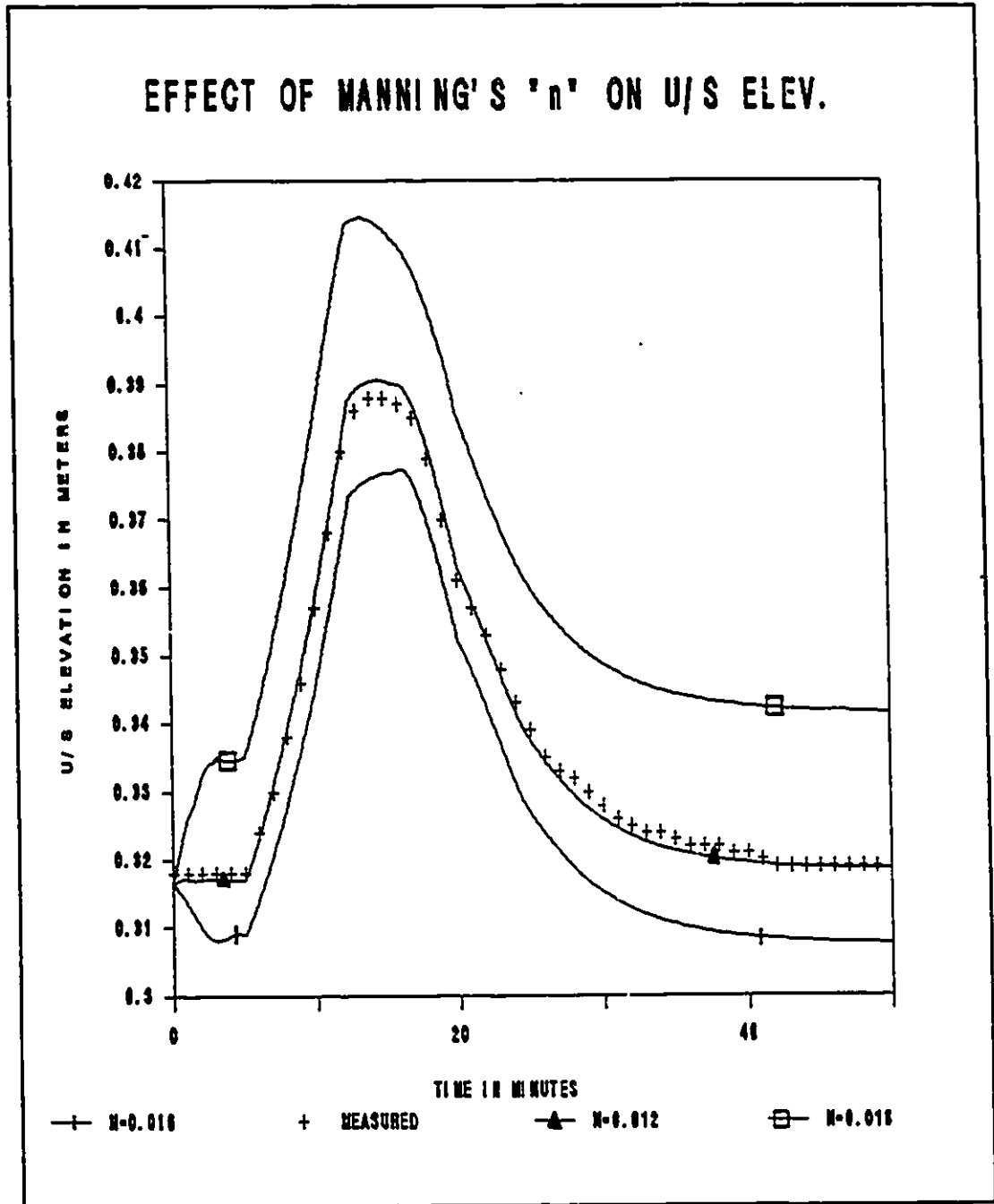


Figure 5.3 SENSITIVITY ANALYSIS-RIGID BED CASE

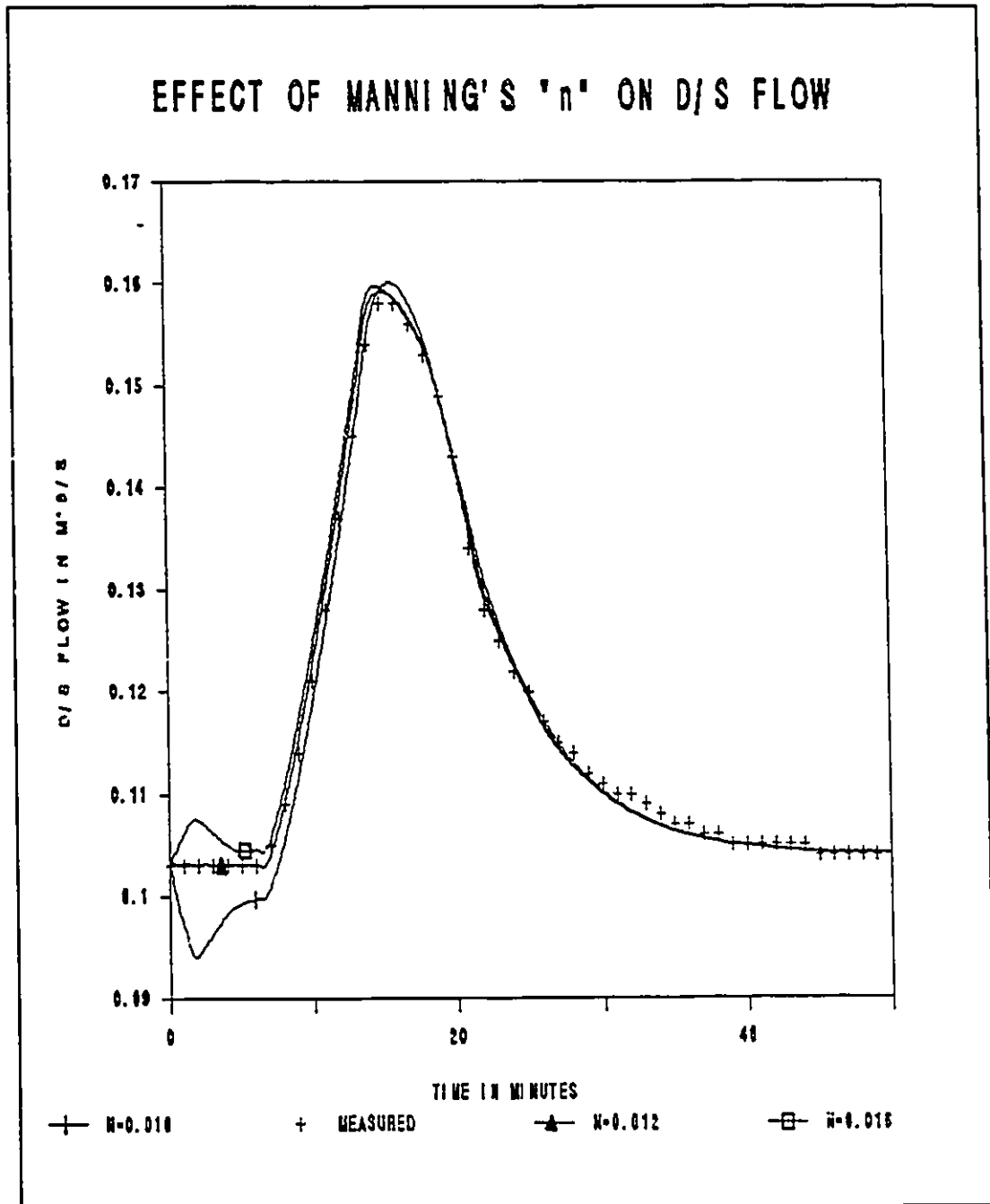


Figure 5.4 SENSITIVITY ANALYSIS-RIGID BED CASE

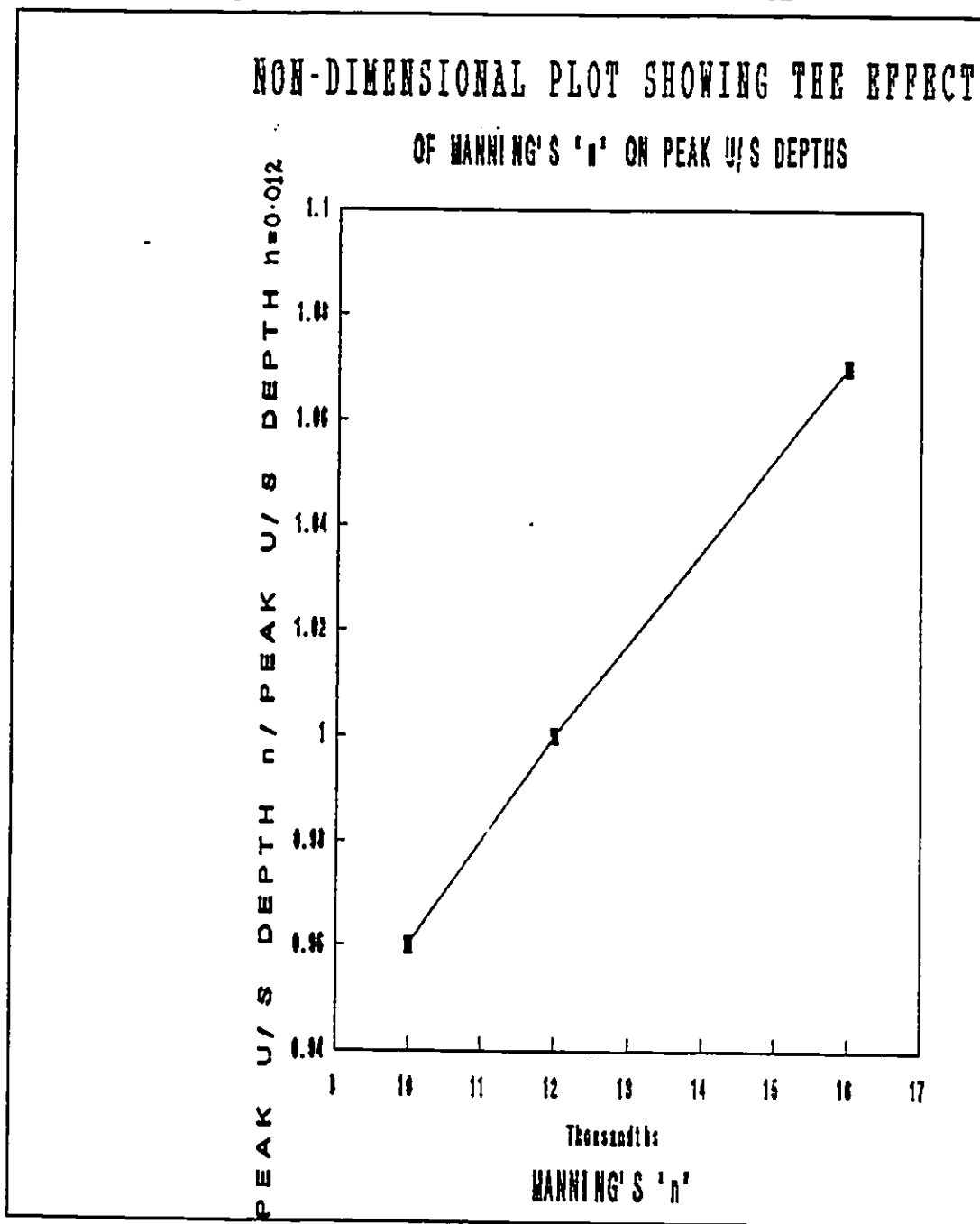


Figure 5.5 SENSITIVITY ANALYSIS-RIGID BED CASE

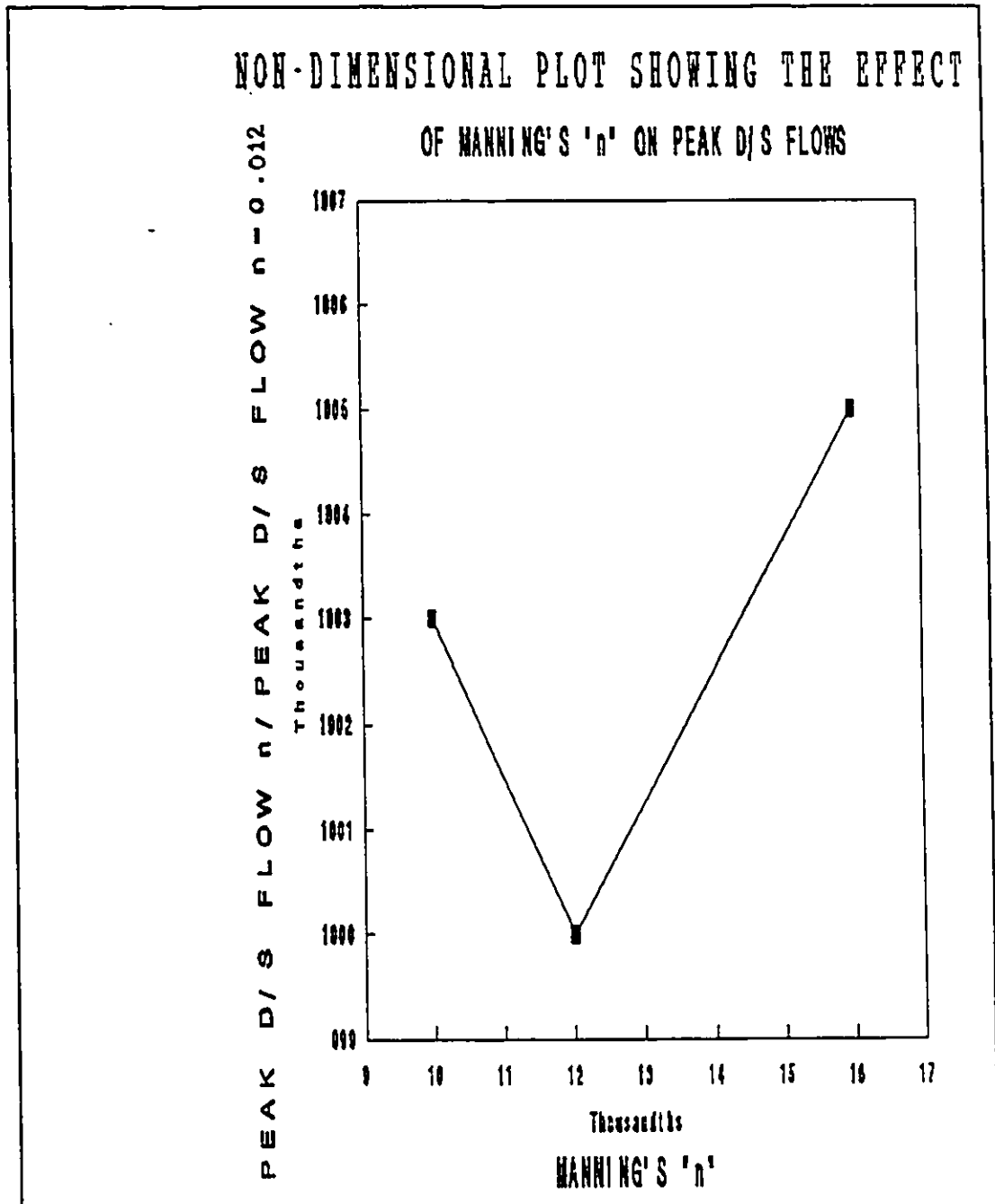


Figure 5.6 SENSITIVITY ANALYSIS-RIGID BED CASE

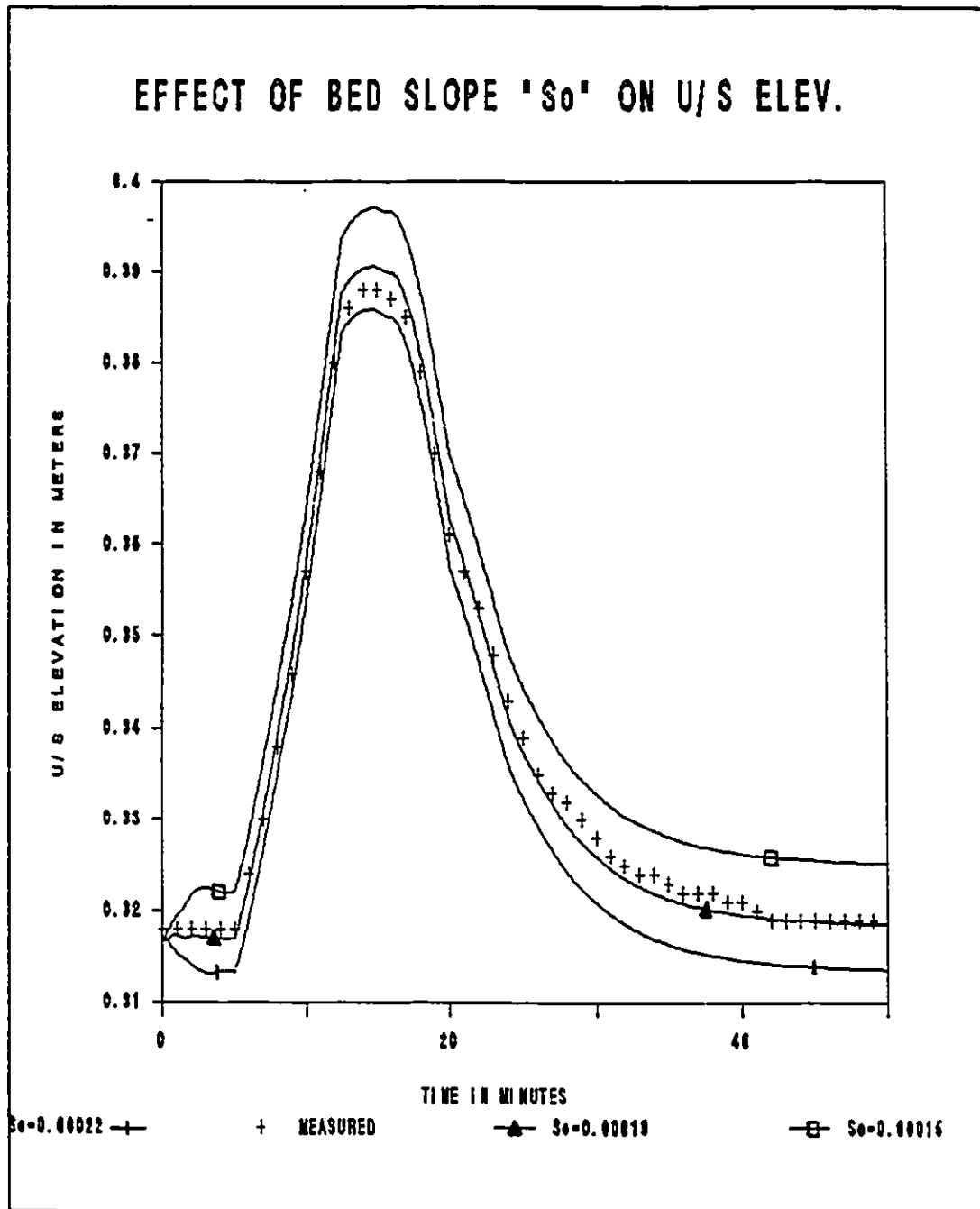


Figure 5.7 SENSITIVITY ANALYSIS-RIGID BED CASE

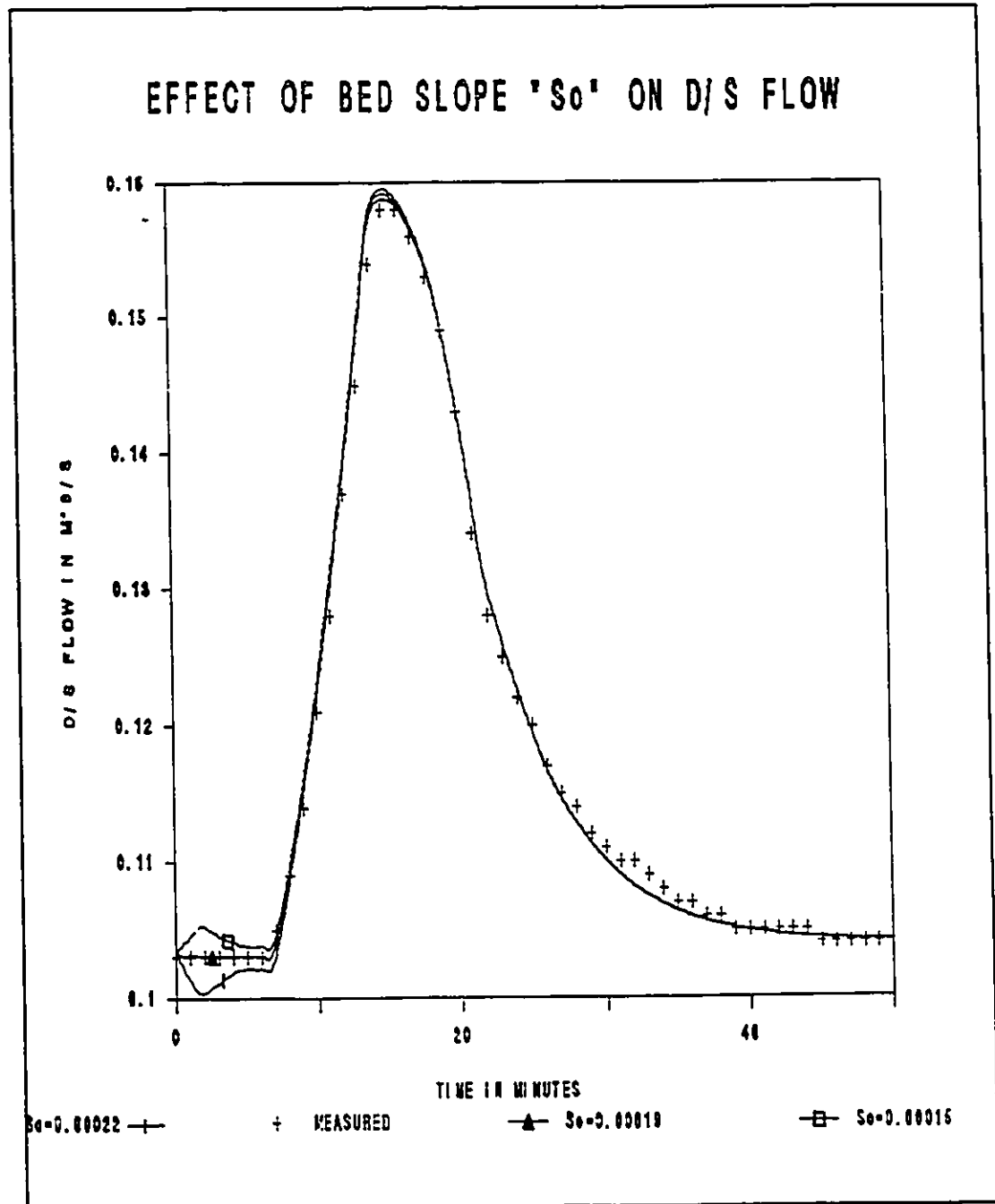


Figure 5.8 SENSITIVITY ANALYSIS-RIGID BED CASE

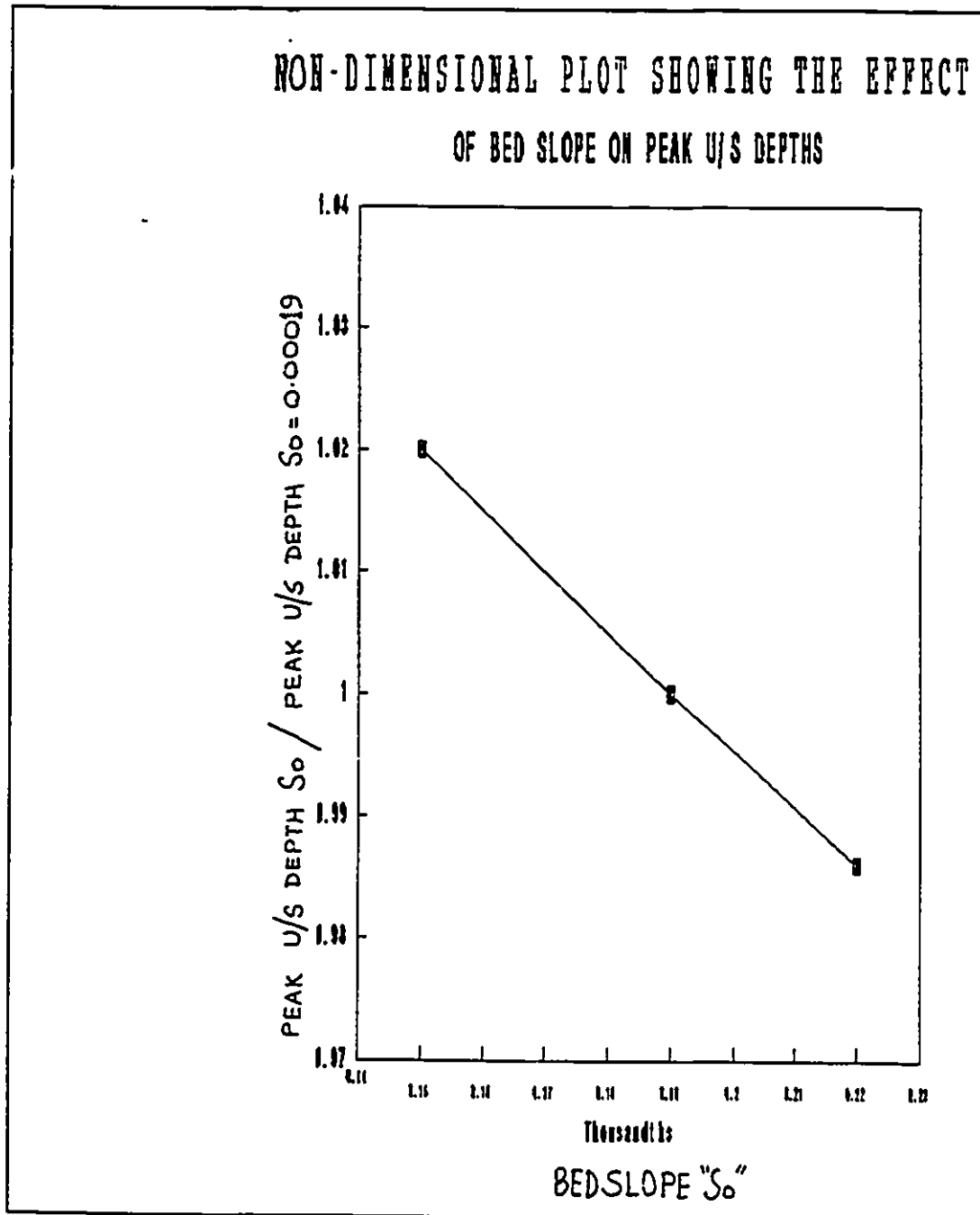


Figure 5.9 SENSITIVITY ANALYSIS-RIGID BED CASE

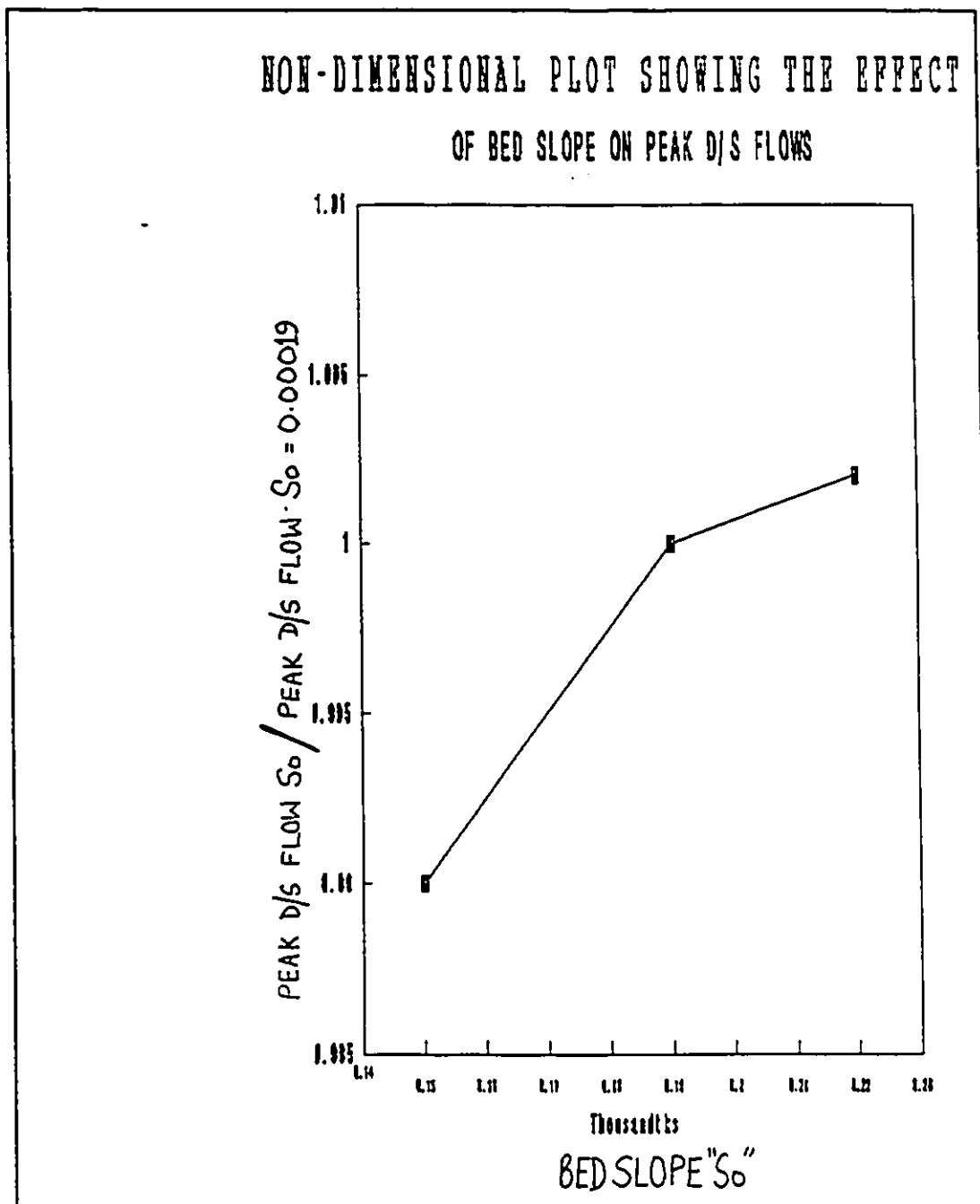


Figure 5.10 STABILITY ANALYSIS-RIGID BED CASE

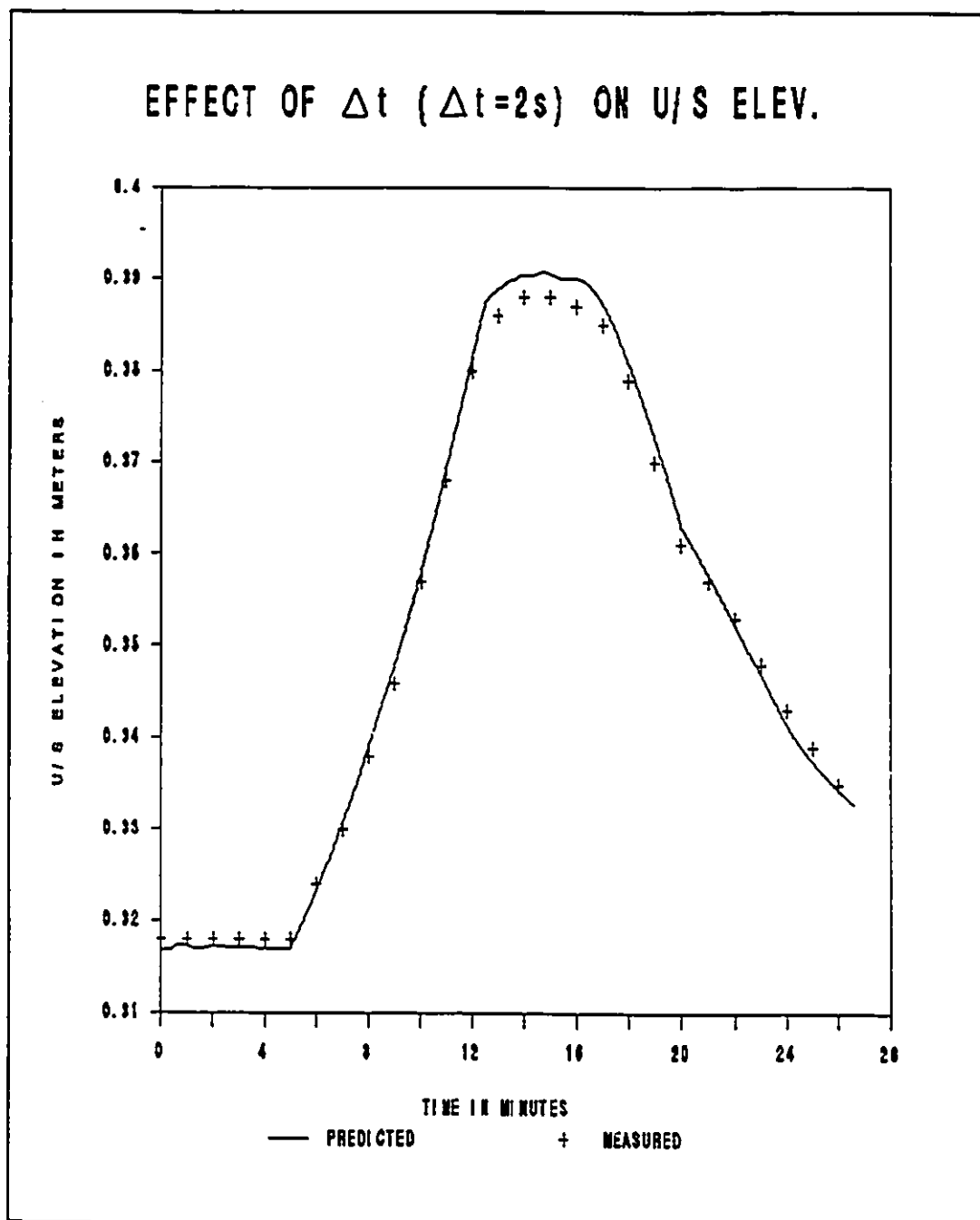


Figure 5.11 STABILITY ANALYSIS-RIGID BED CASE

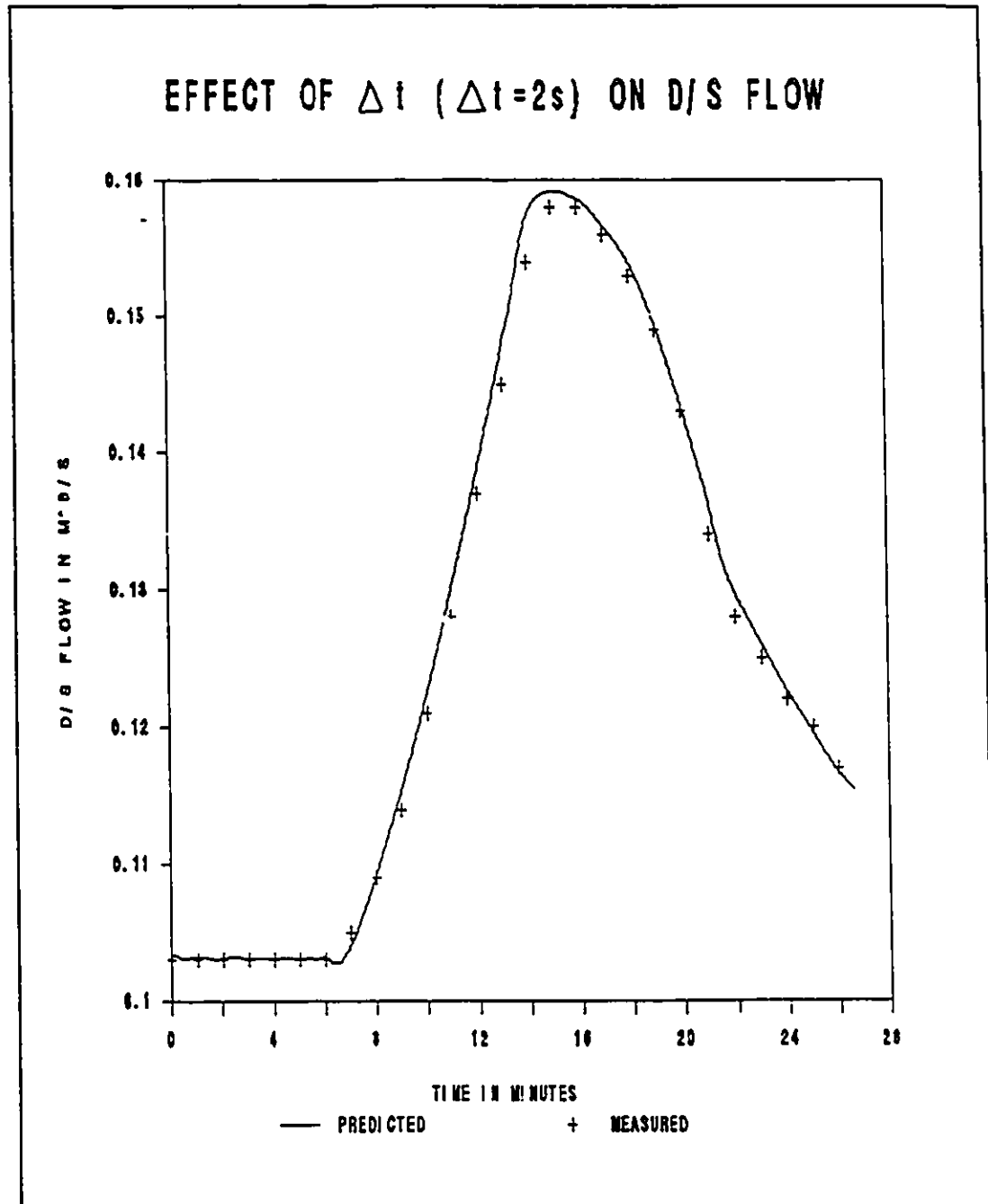


Figure 5.12 STABILITY ANALYSIS-RIGID BED CASE

EFFECT OF Δt ($\Delta t=6s$) ON U/S ELEV.

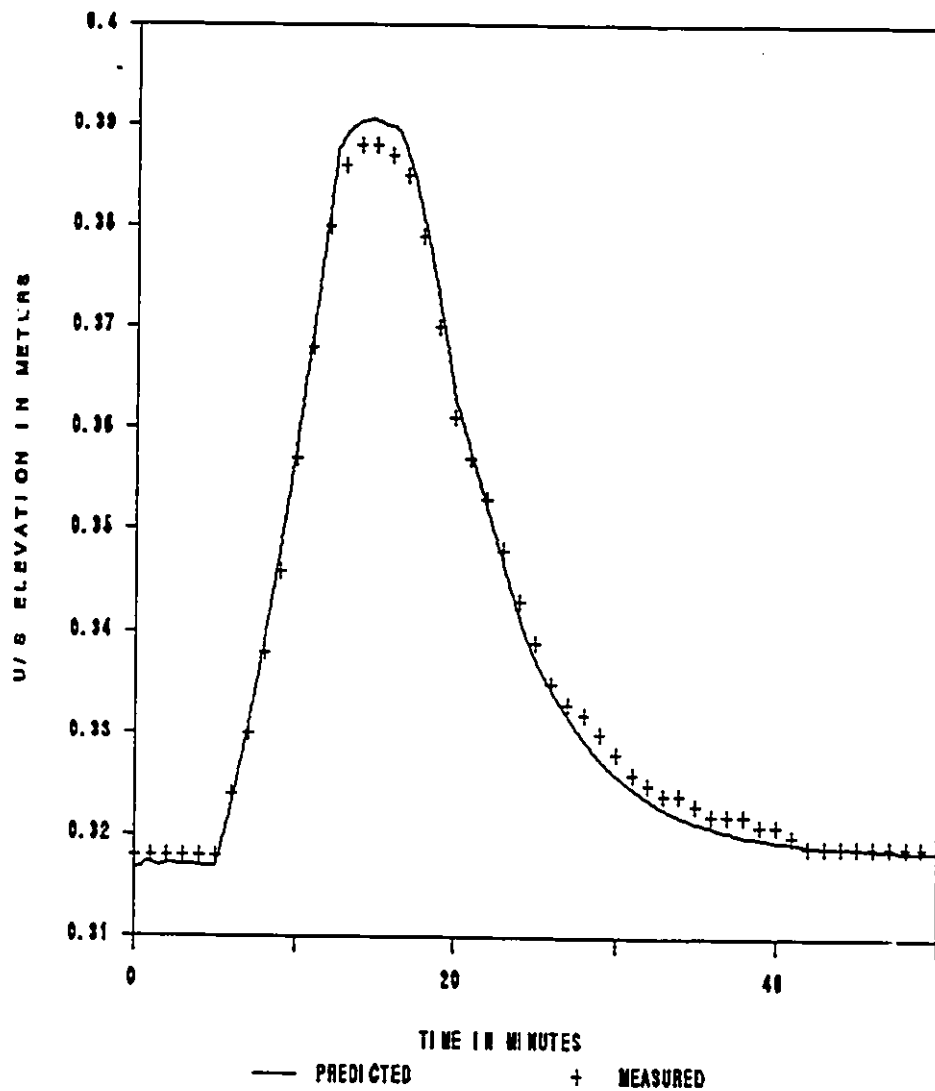


Figure 5.13 STABILITY ANALYSIS-RIGID BED CASE

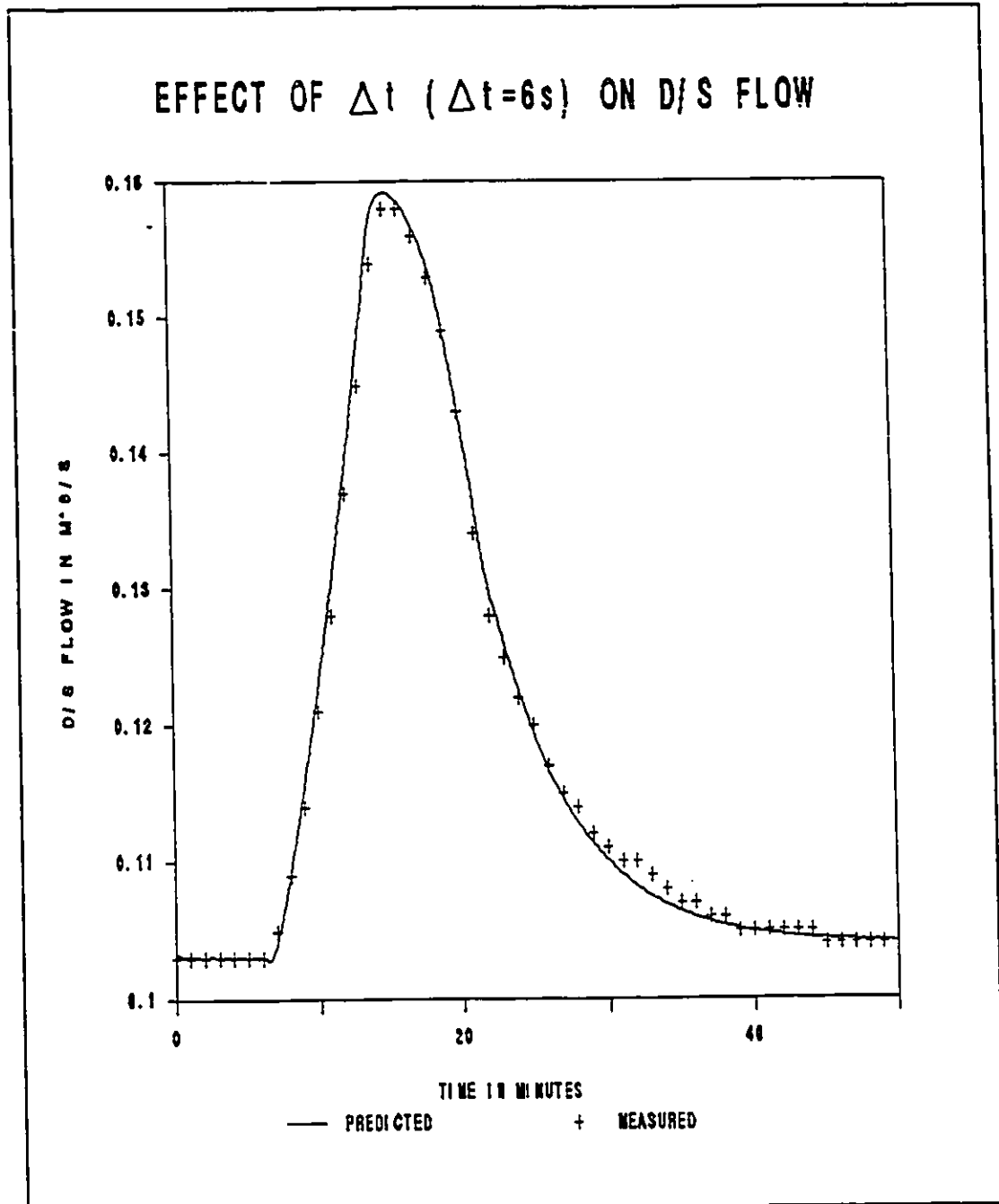


Figure 5.14 STABILITY ANALYSIS-RIGID BED CASE

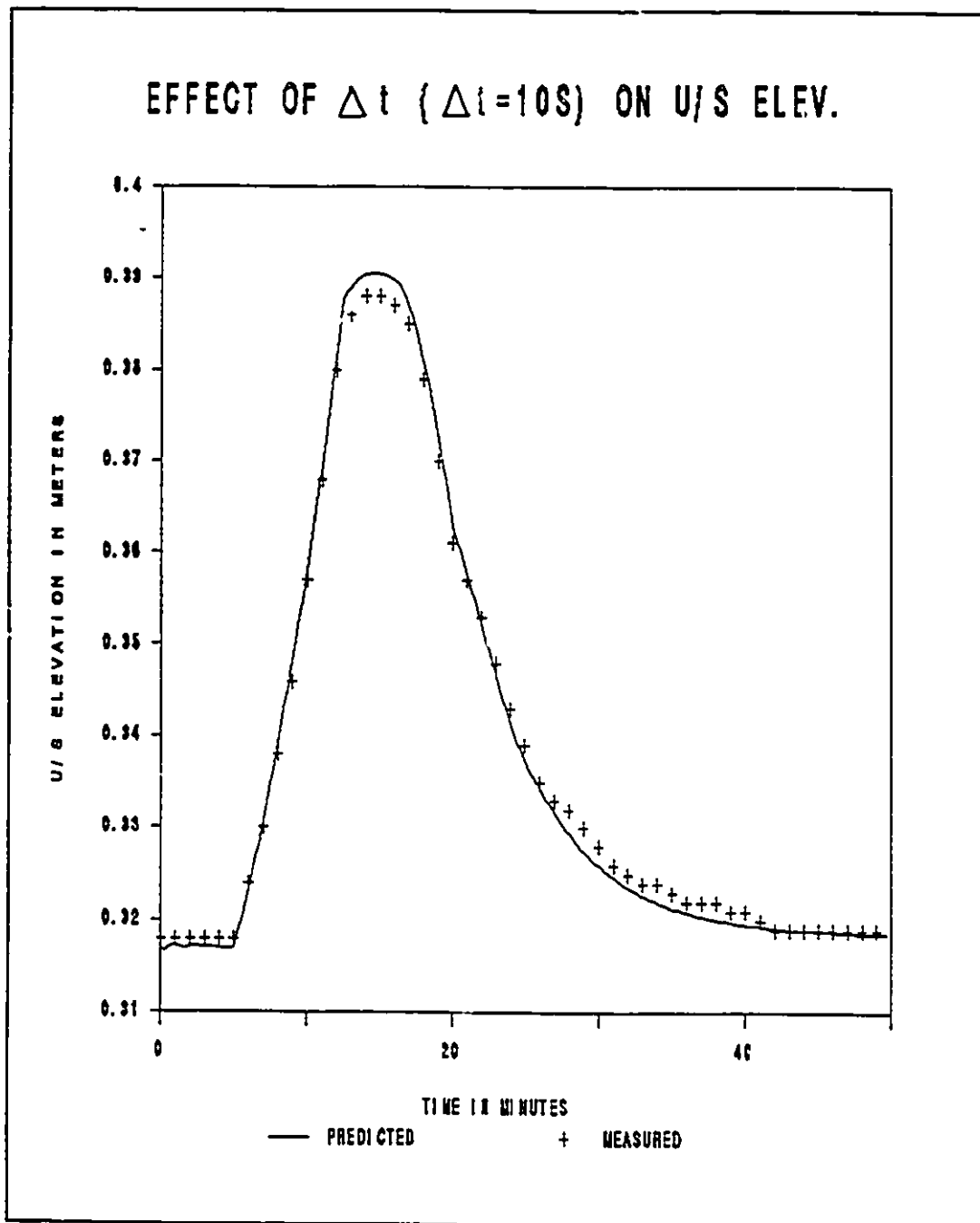


Figure 5.15 STABILITY ANALYSIS-RIGID BED CASE

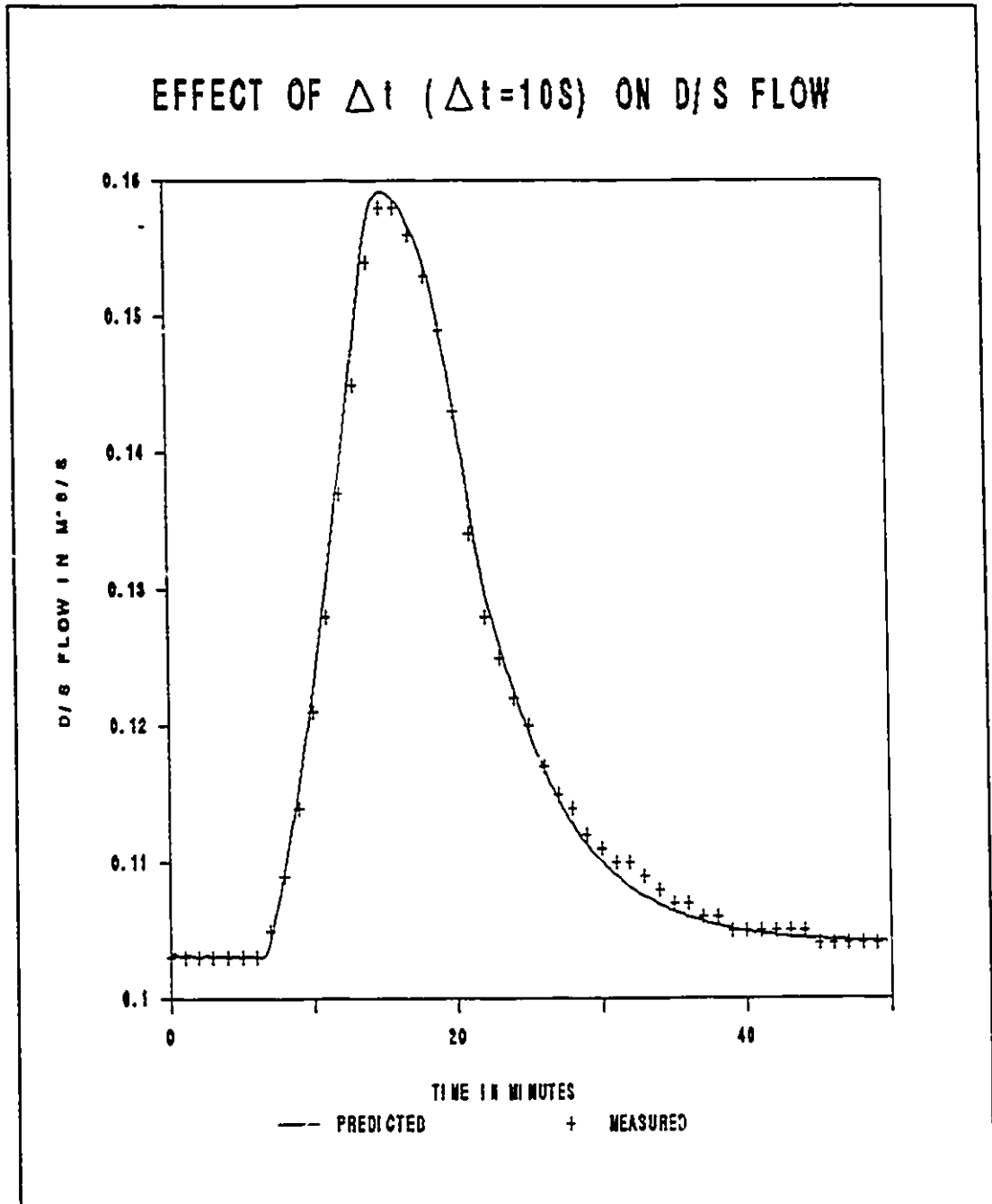


Figure 5.16 STABILITY ANALYSIS-RIGID BED CASE

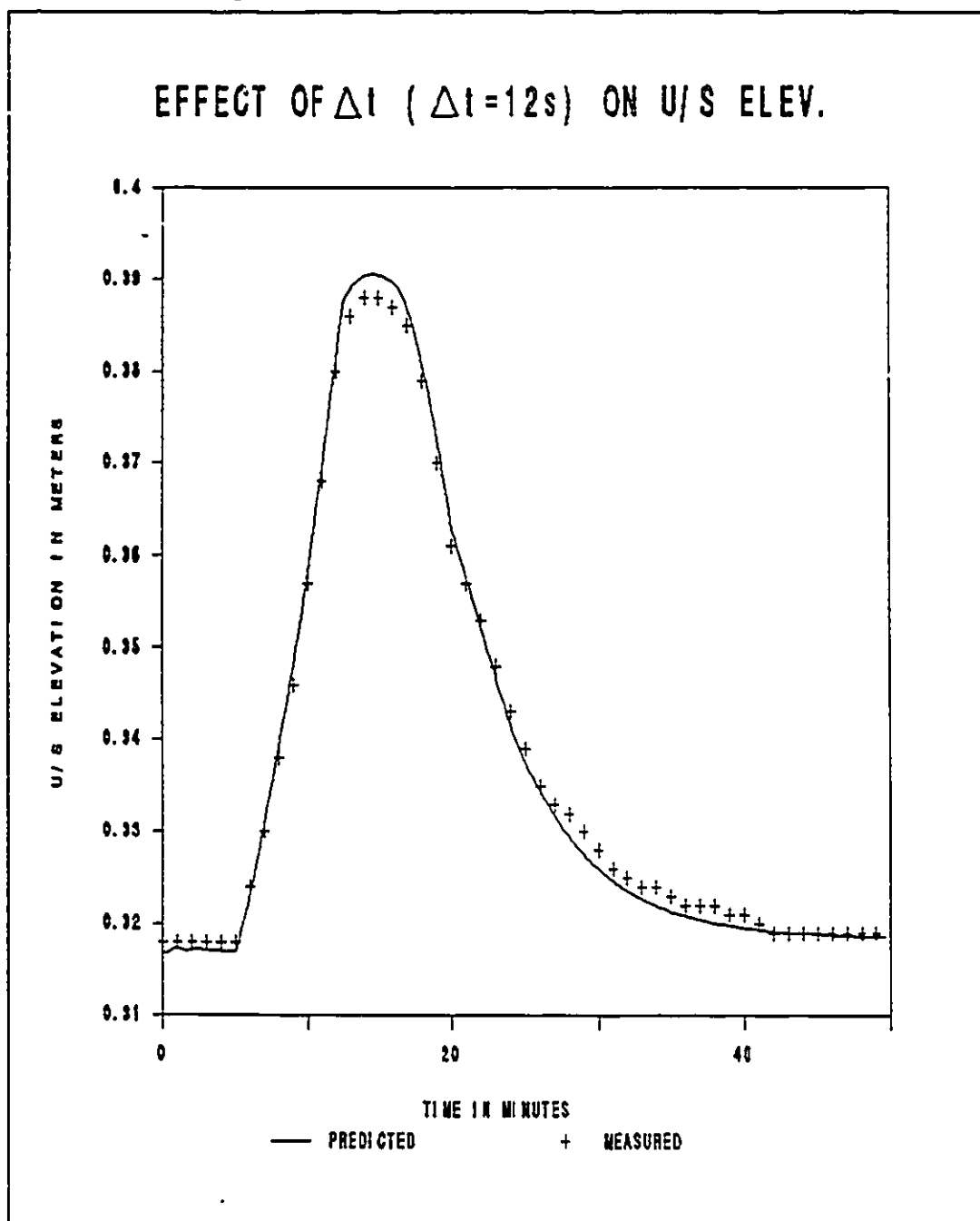


Figure 5.17 STABILITY ANALYSIS-RIGID BED CASE

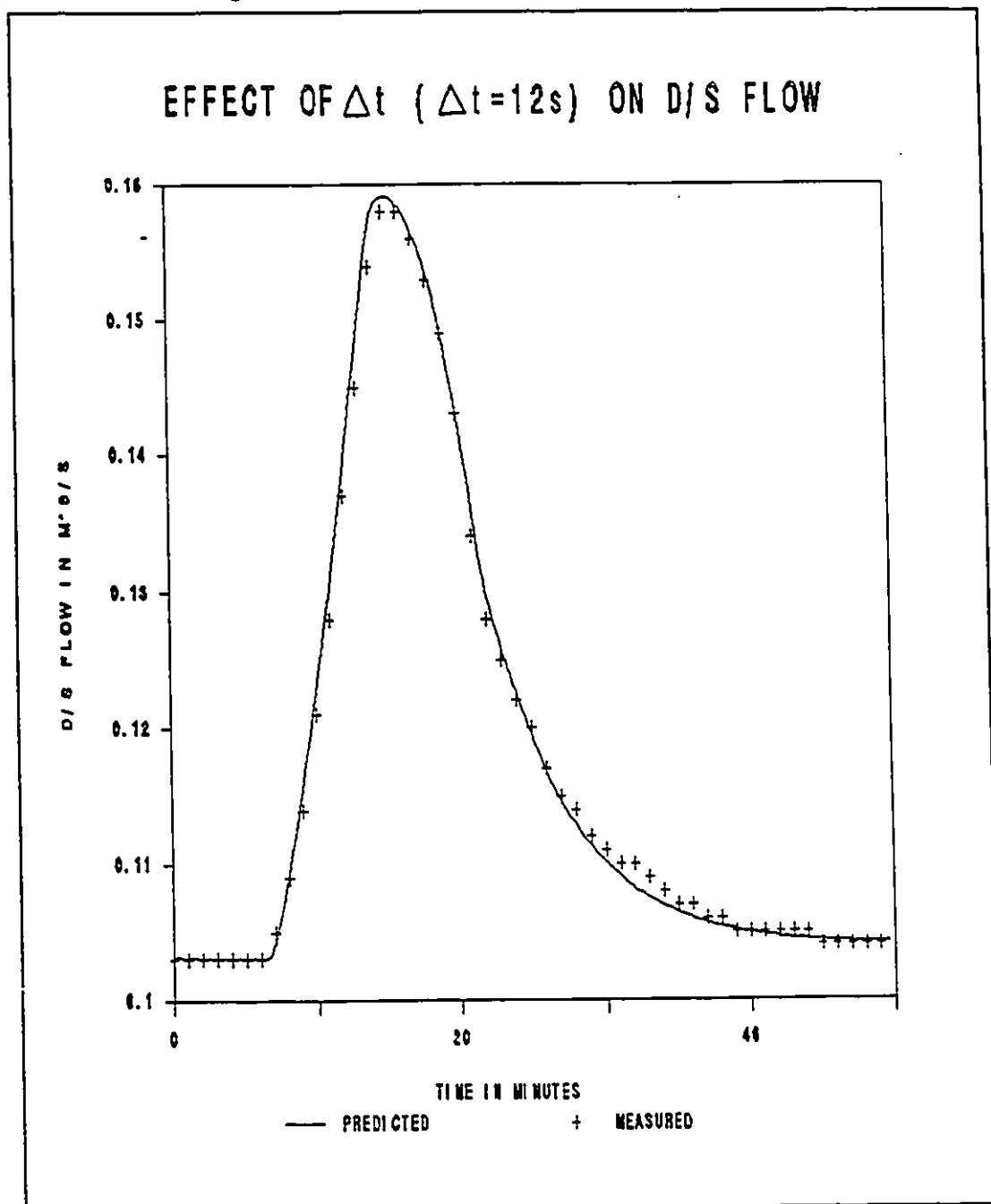


Figure 5.18 TRANSITION - UNCALIBRATED

MEASURED VERSUS PREDICTED U/S DEPTH

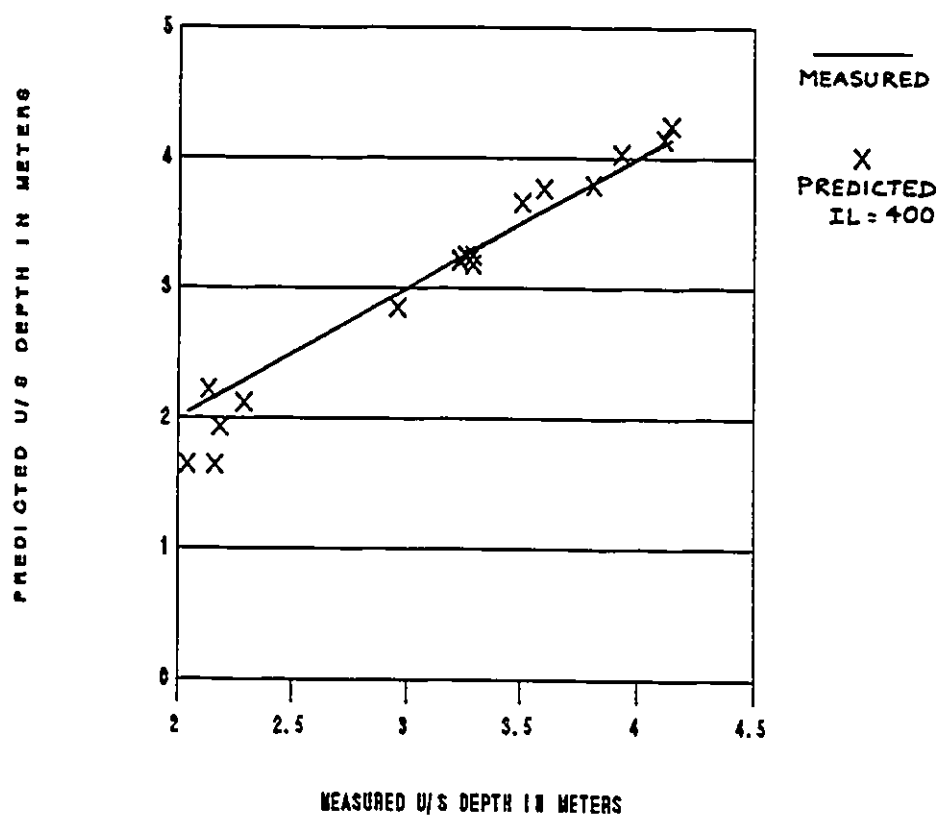


Figure 5.19 TRANSITION - UNCALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

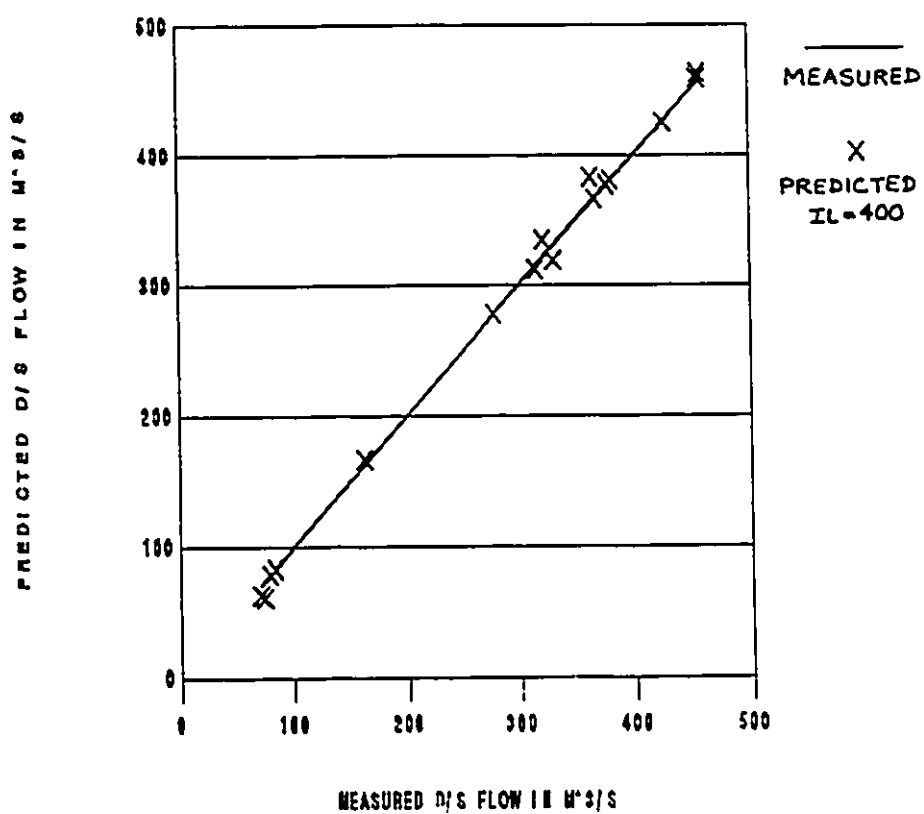


Figure 5.20 TRANSITION - CALIBRATED

MEASURED VERSUS PREDICTED U/S DEPTH

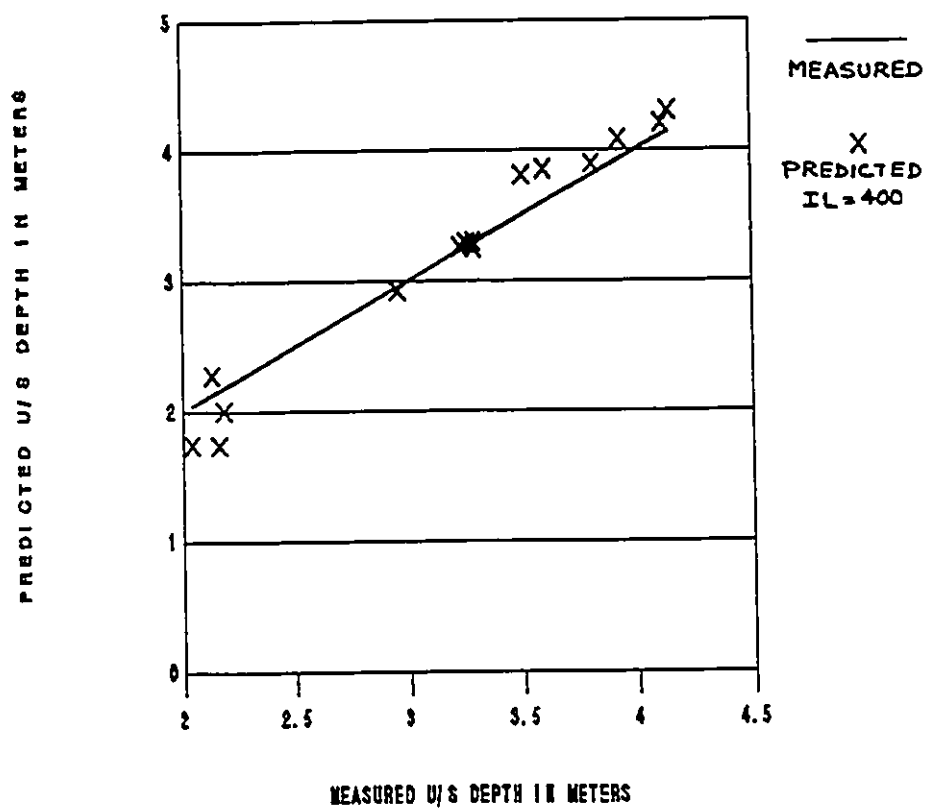


Figure 5.21 TRANSITION - CALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

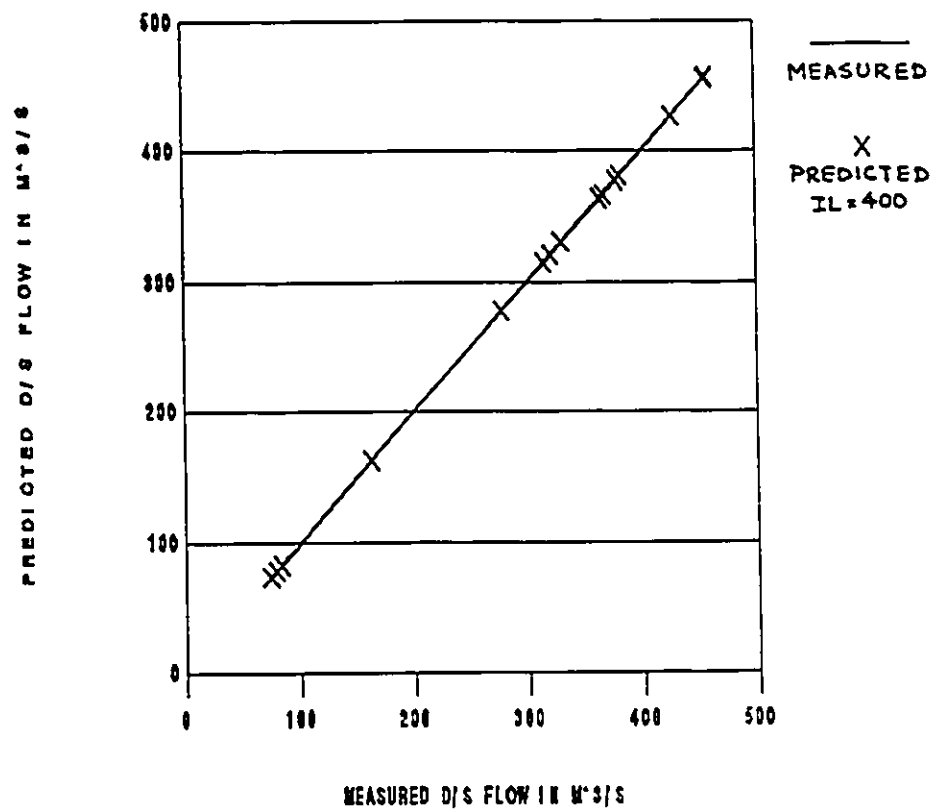


Figure 5.22 CASE OF DUNES - UNCALIBRATED

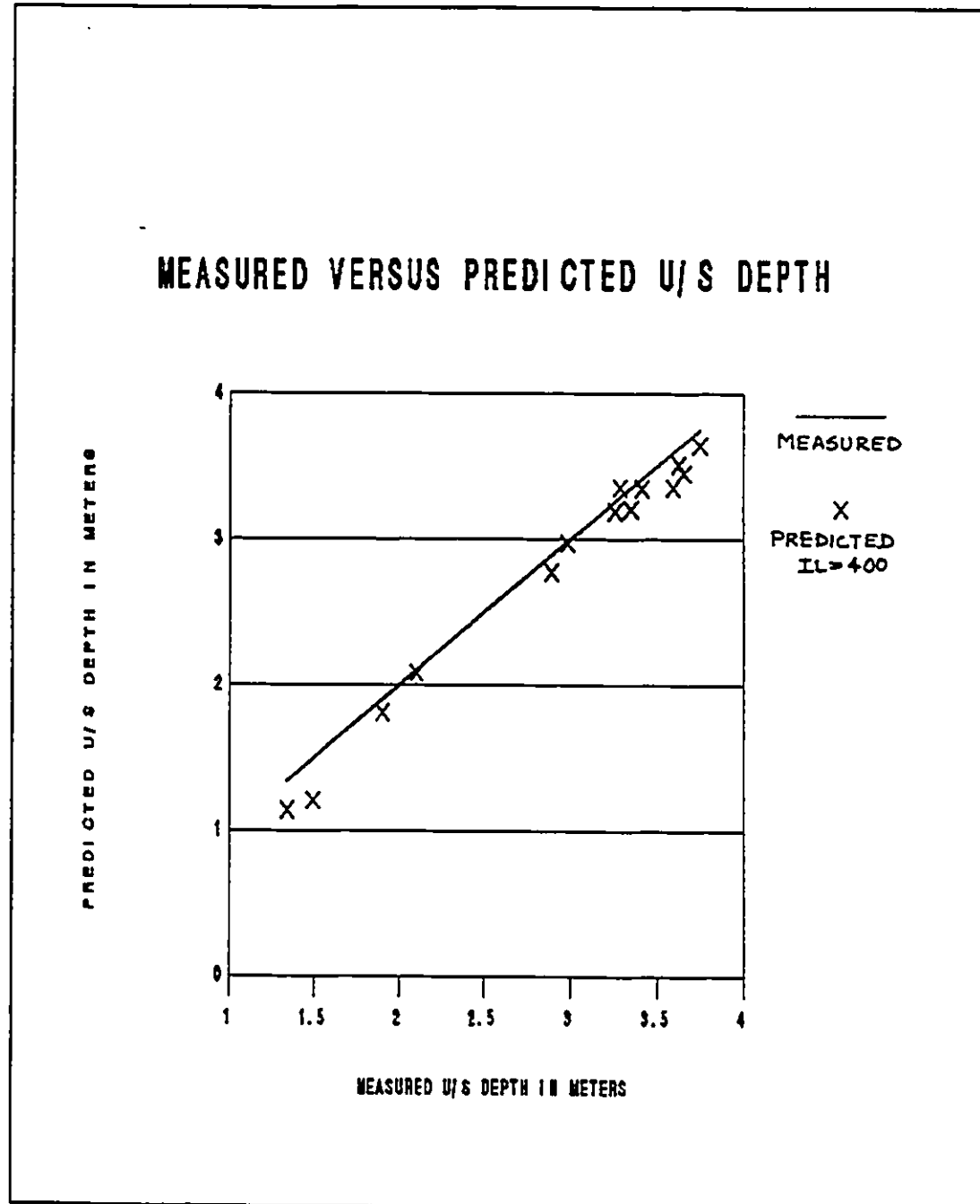


Figure 5.23 CASE OF DUNES - UNCALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

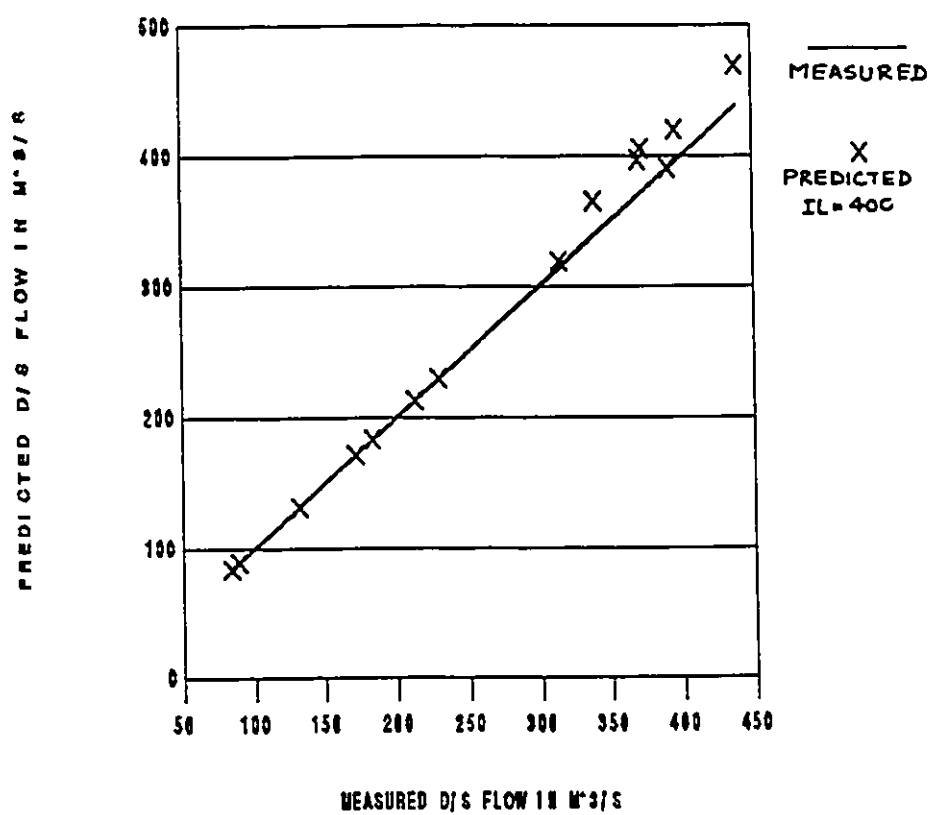


Figure 5.24 CASE OF DUNES - CALIBRATED

MEASURED VERSUS PREDICTED U/S DEPTH

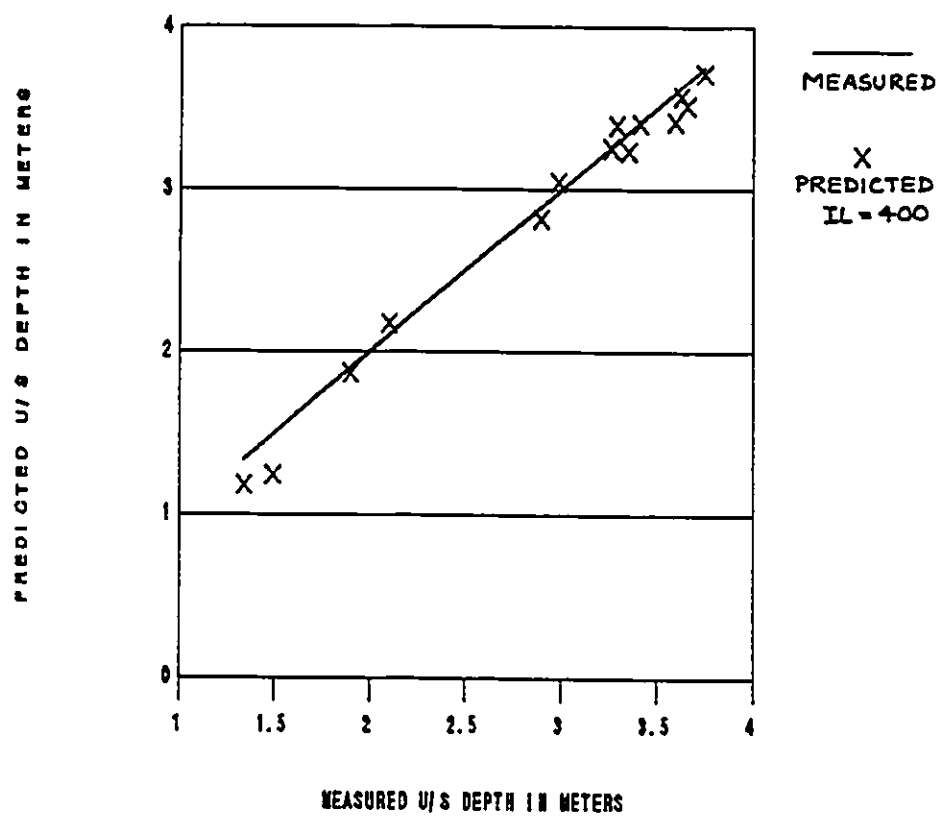


Figure 5.25 CASE OF DUNES - CALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

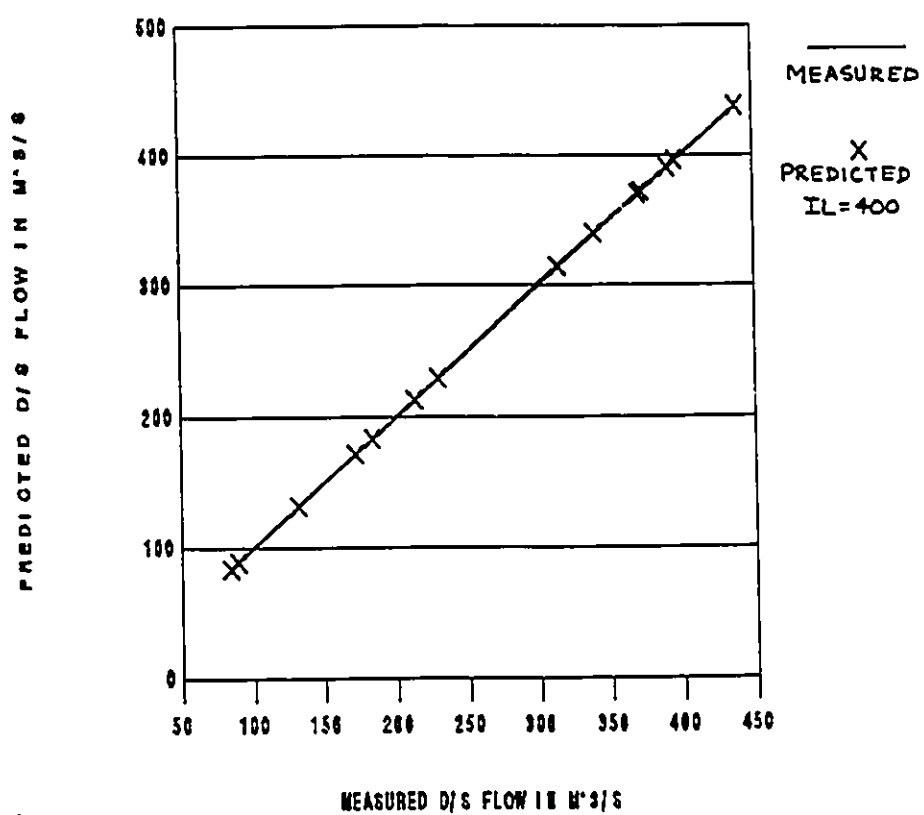


Figure 5.26 PLANE BED - UNCALIBRATED

MEASURED VERSUS PREDICTED U/S DEPTH

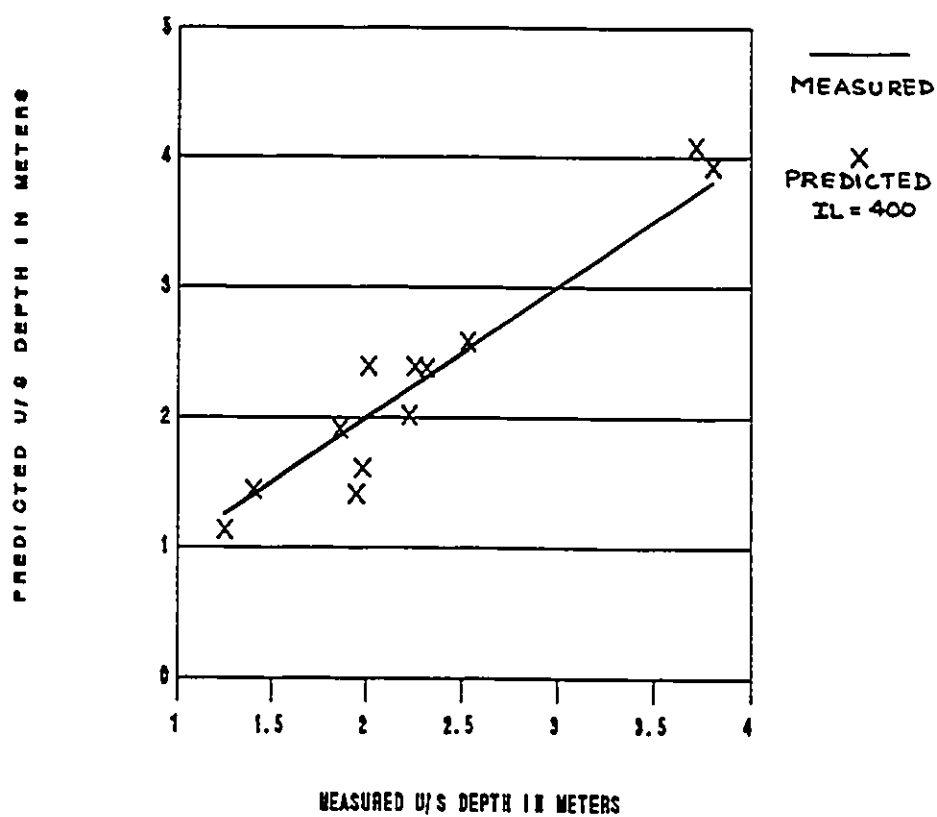


Figure 5.27 PLANE BED - UNCALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

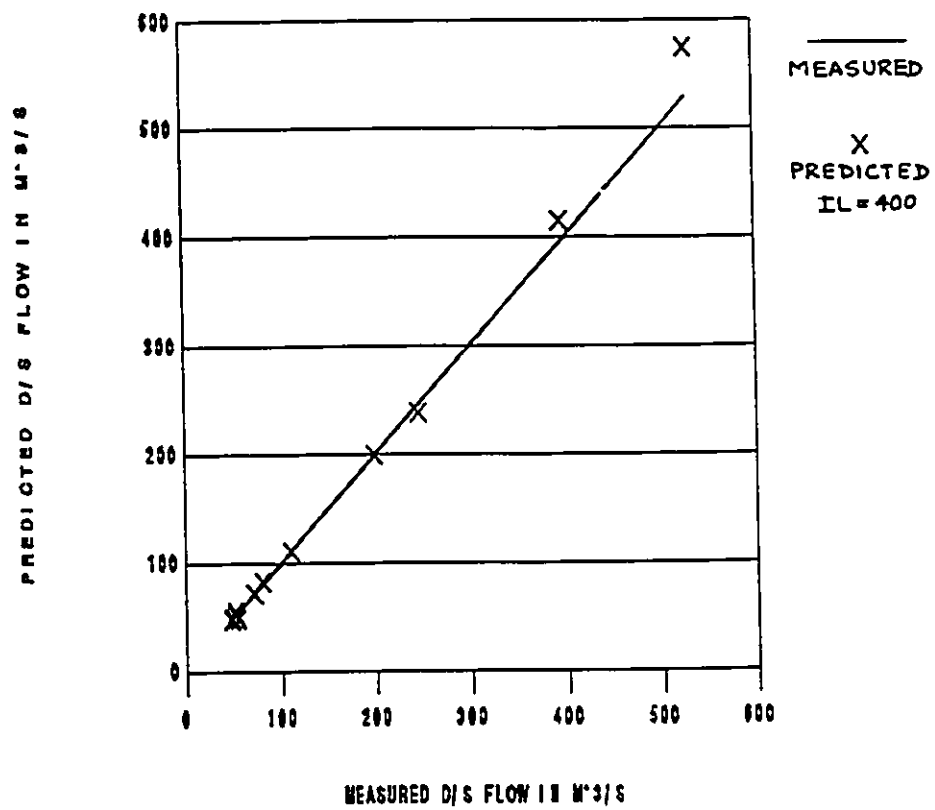


Figure 5.28 PLANE BED - CALIBRATED

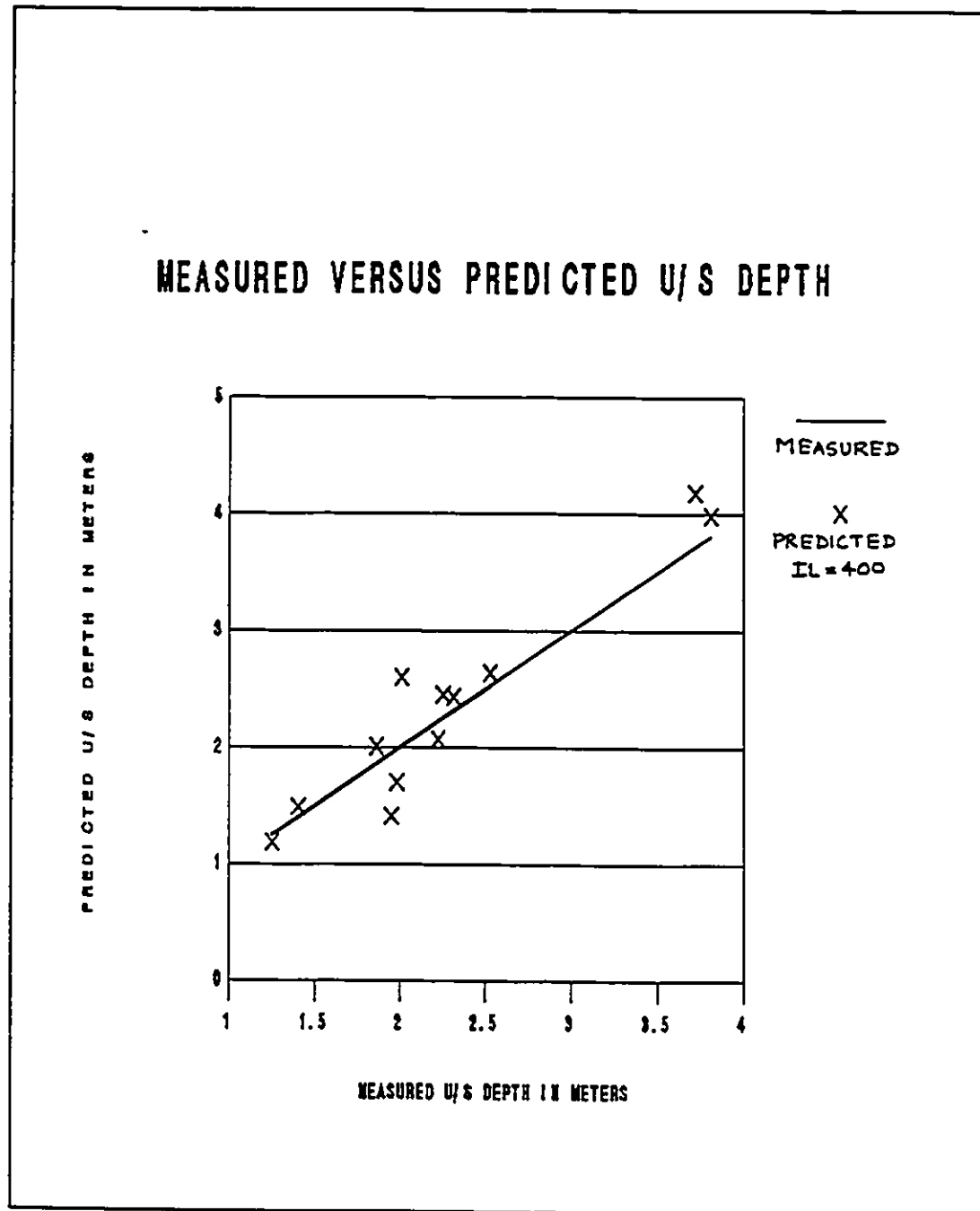


Figure 5.29 PLANE BED - CALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

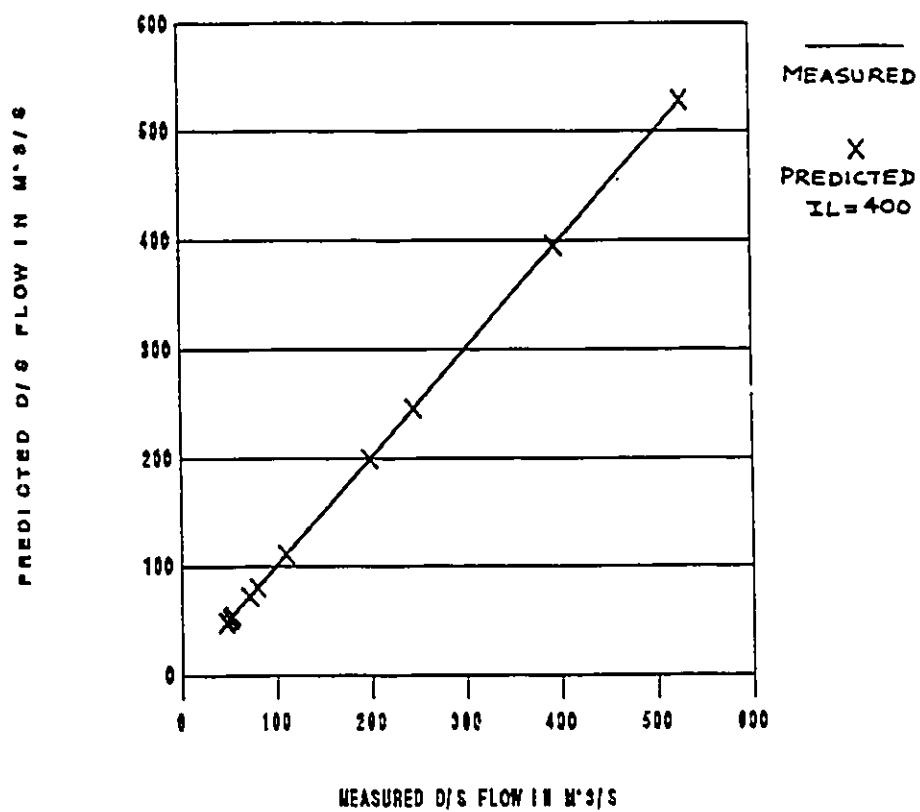


Figure 5.30 CASE OF RIPPLES - UNCALIBRATED

MEASURED VERSUS PREDICTED U/S DEPTH

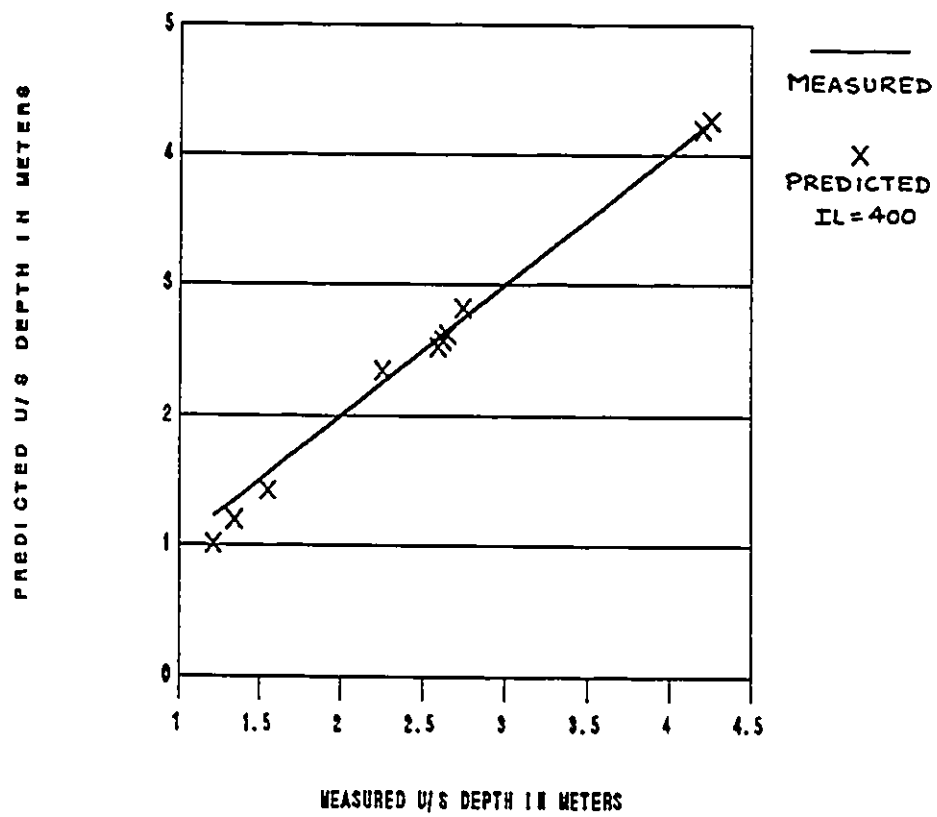


Figure 5.31 CASE OF RIPPLES - UNCALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

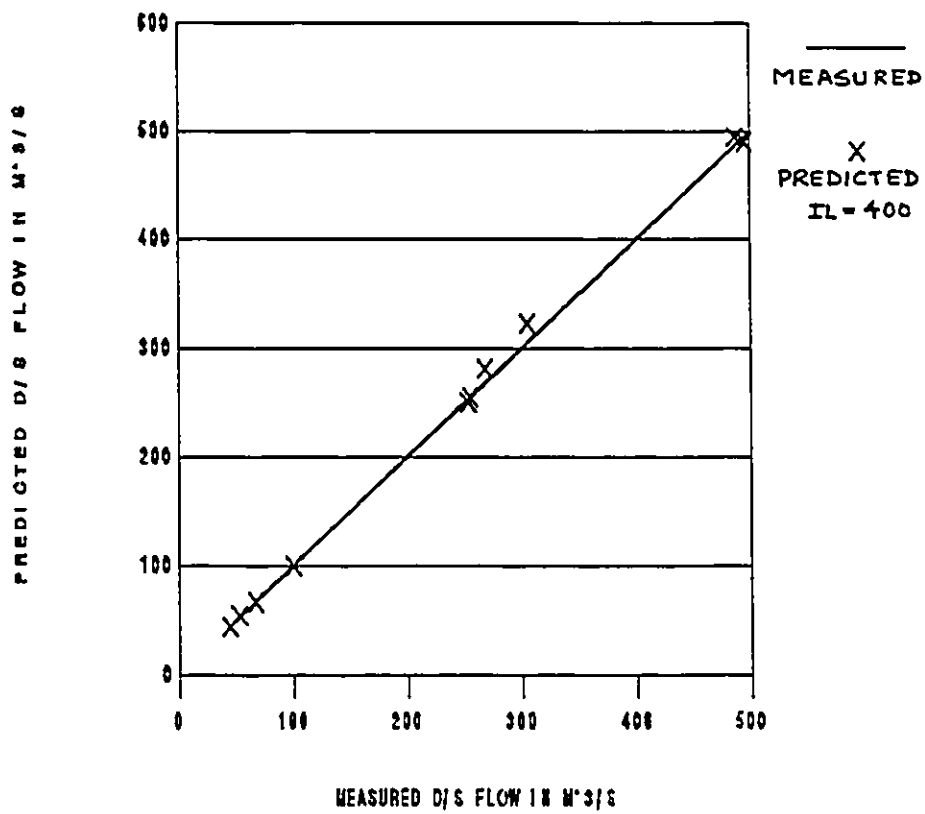


Figure 5.32 CASE OF RIPPLES - CALIBRATED

MEASURED VERSUS PREDICTED U/S DEPTH

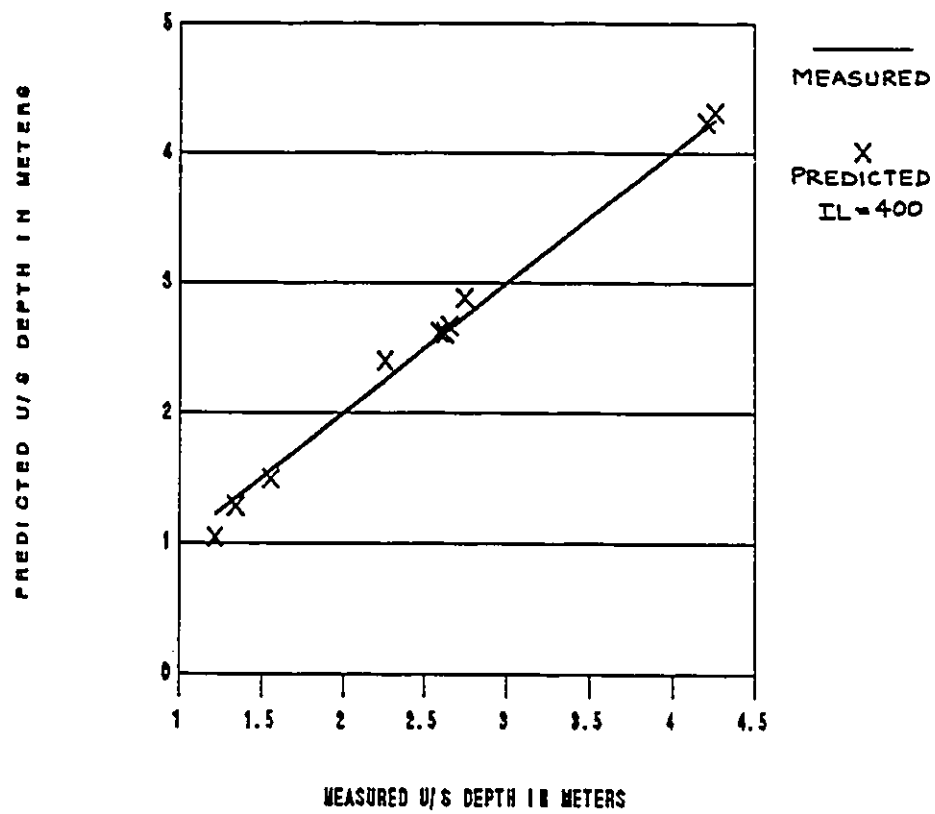


Figure 5.33 CASE OF RIPPLES - CALIBRATED

MEASURED VERSUS PREDICTED D/S FLOW

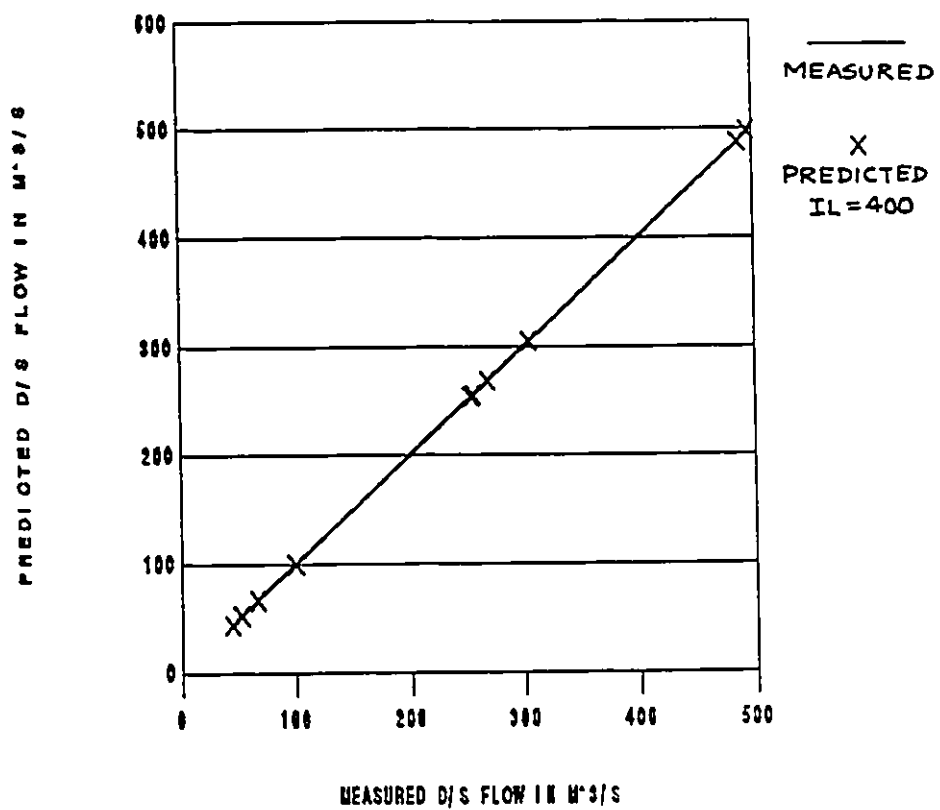


Figure 5.34 TRANSITION BED

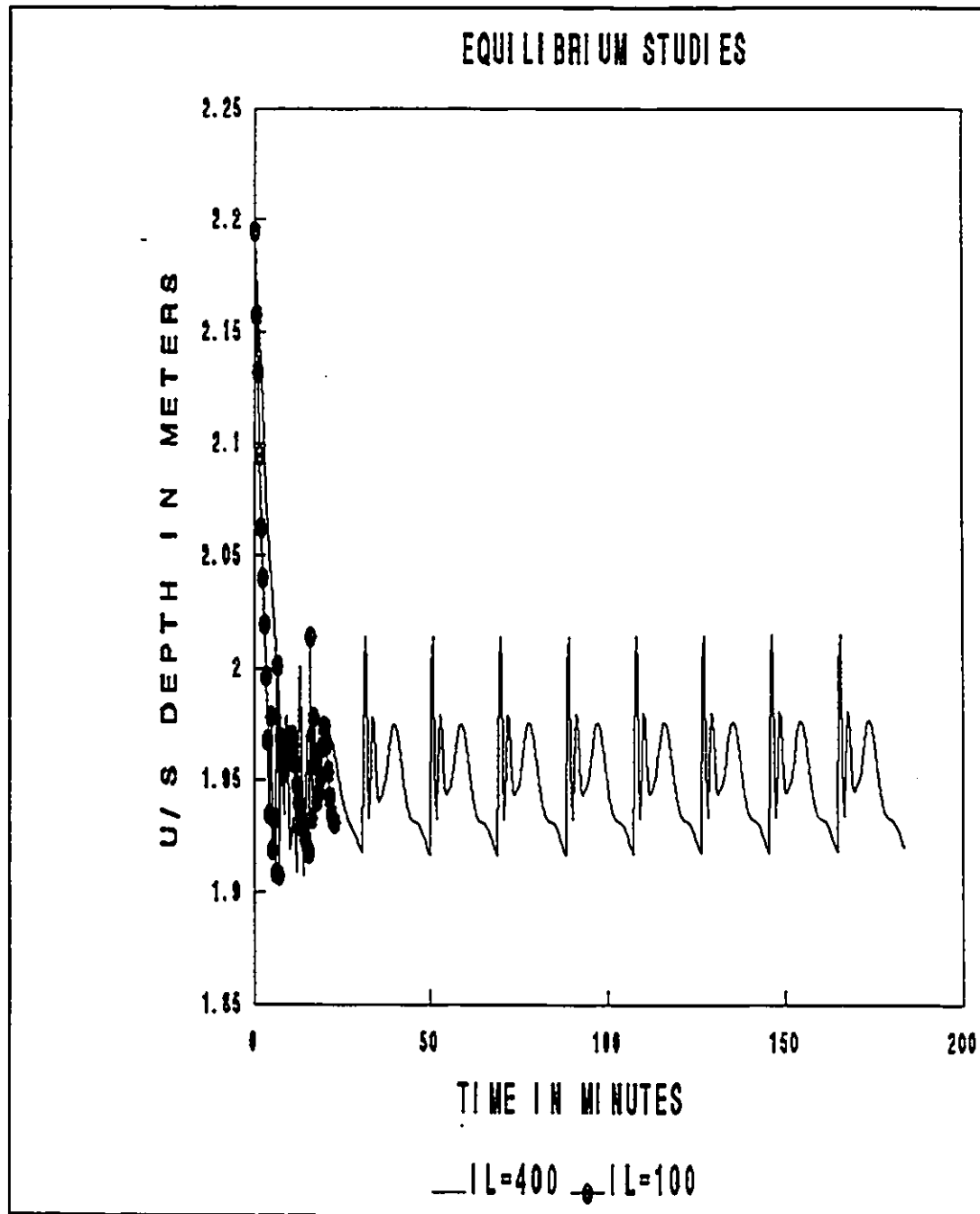


Figure 5.35 TRANSITION BED

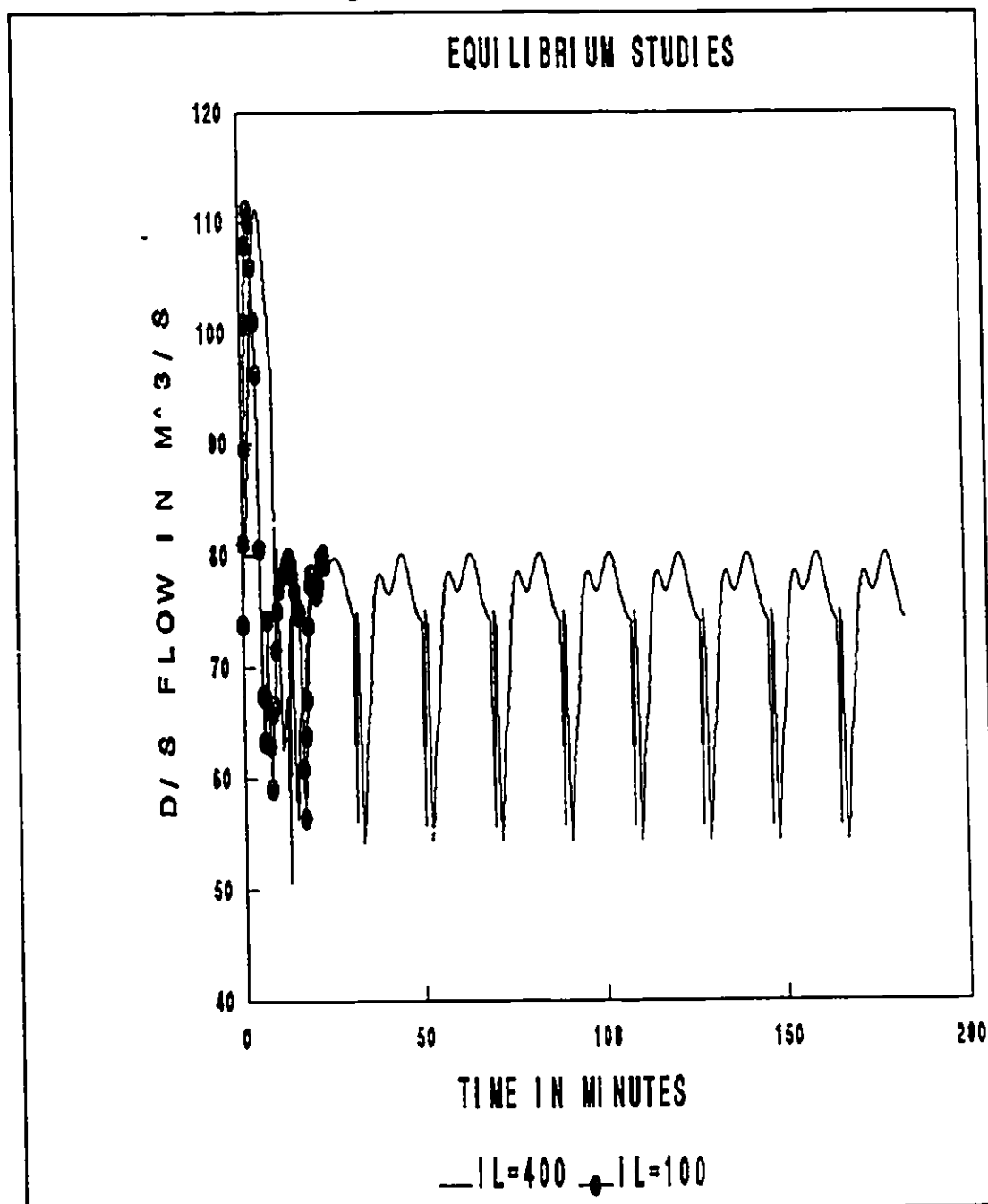


Figure 5.36 BED WITH DUNES

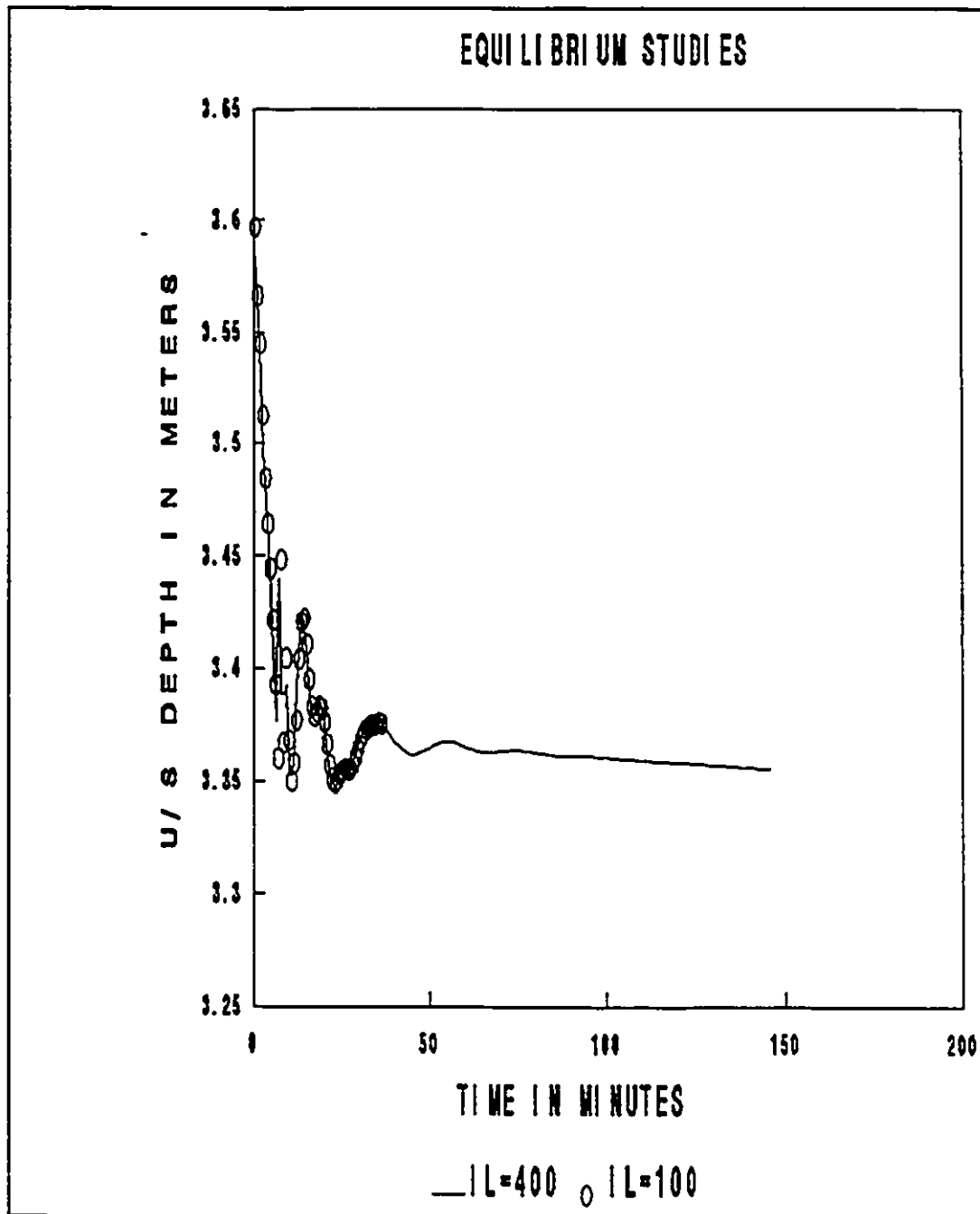


Figure 5.37 BED WITH DUNES

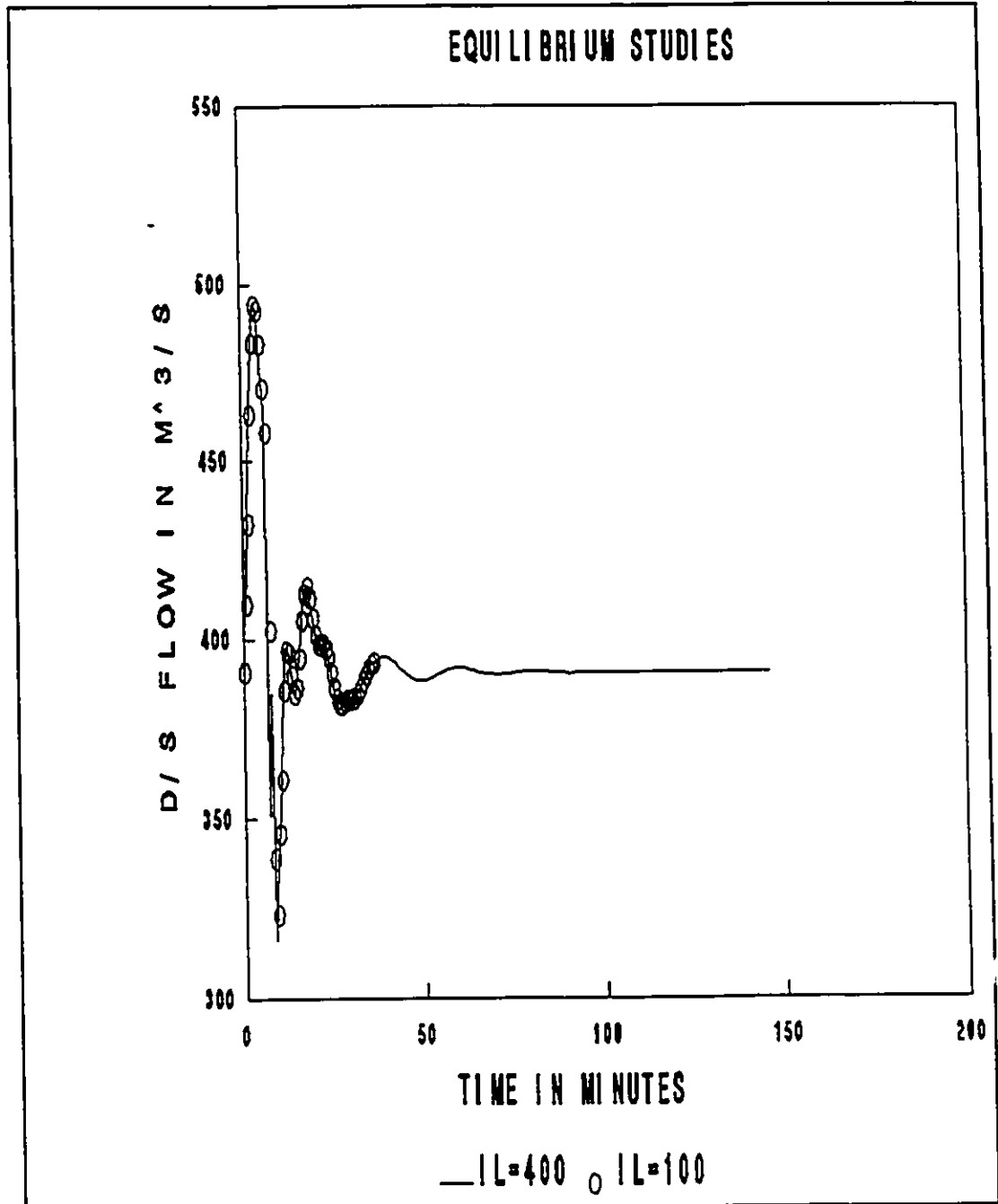


Figure 5.38 BED WITH DUNES

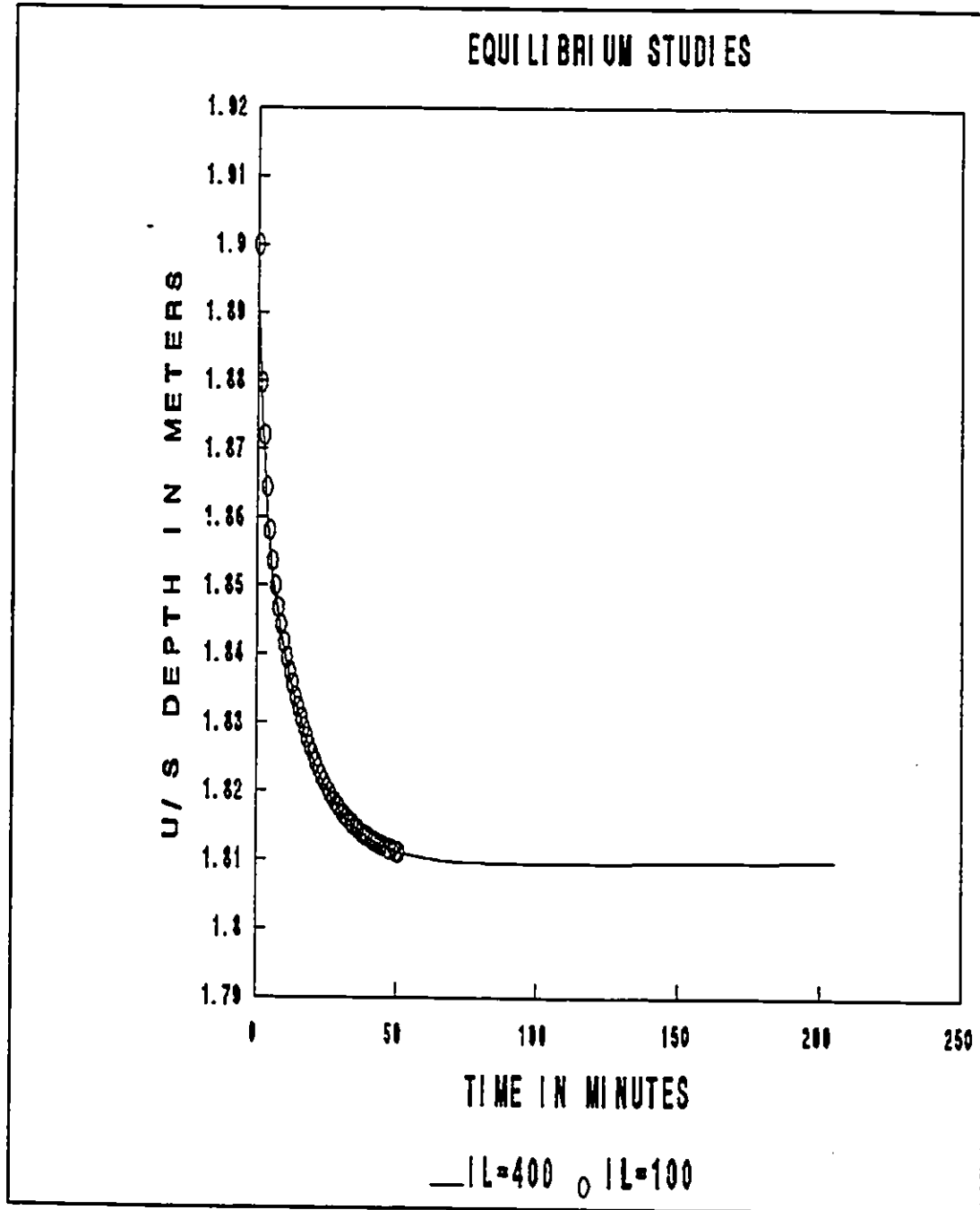


Figure 5.39 BED WITH DUNES

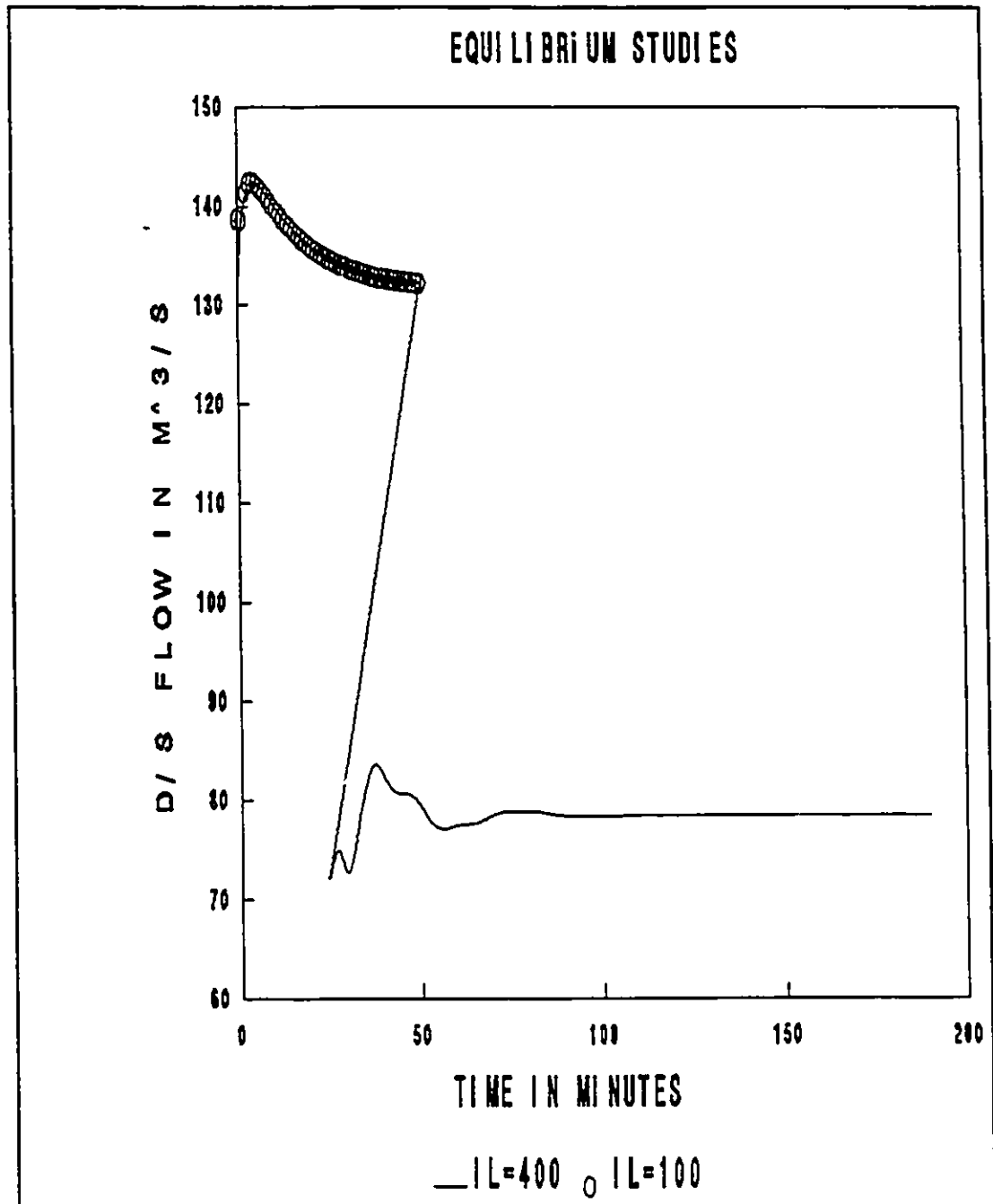


Figure 5.40 PLANE BED

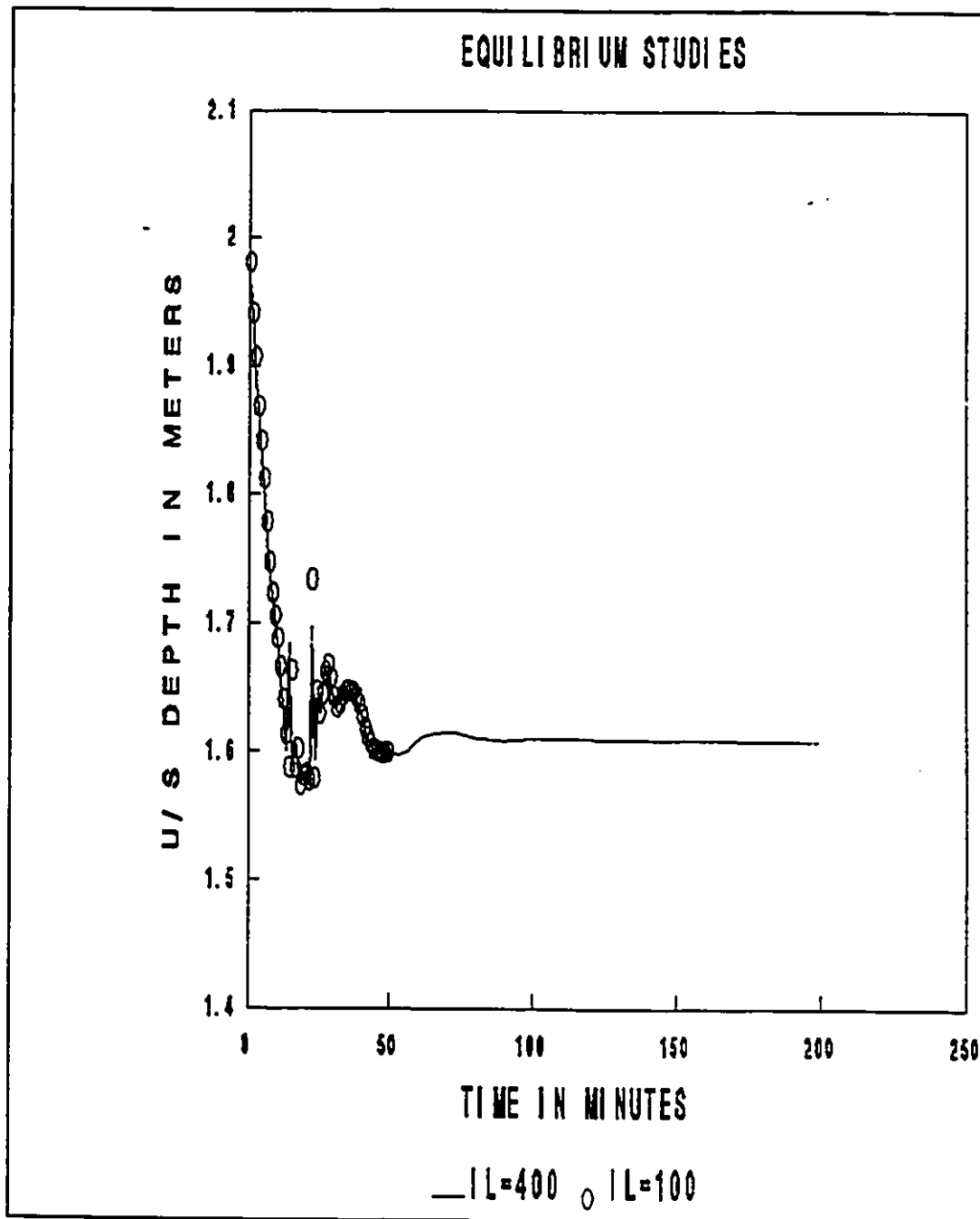


Figure 5.41 PLANE BED

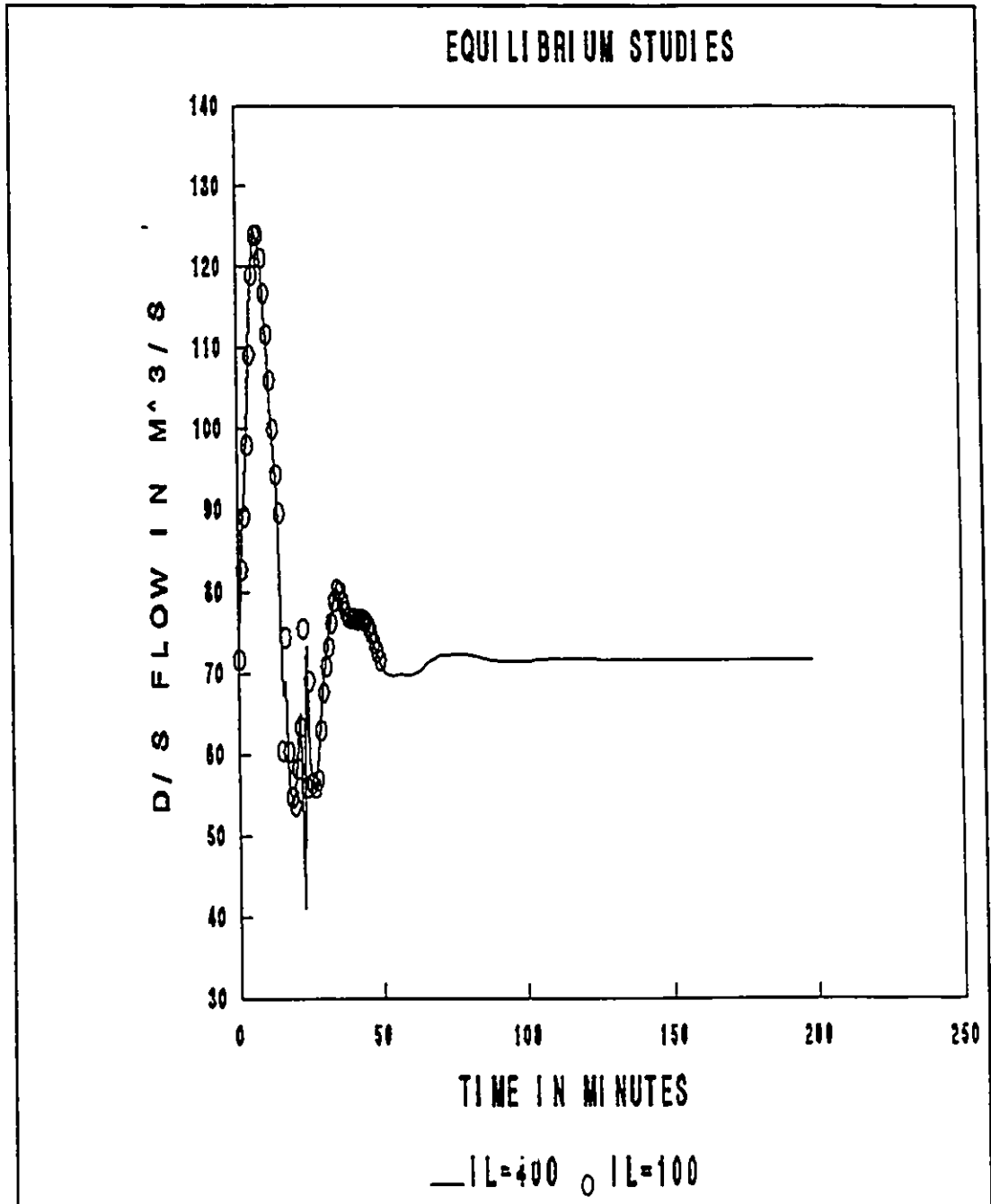


Figure 5.42 PLANE BED

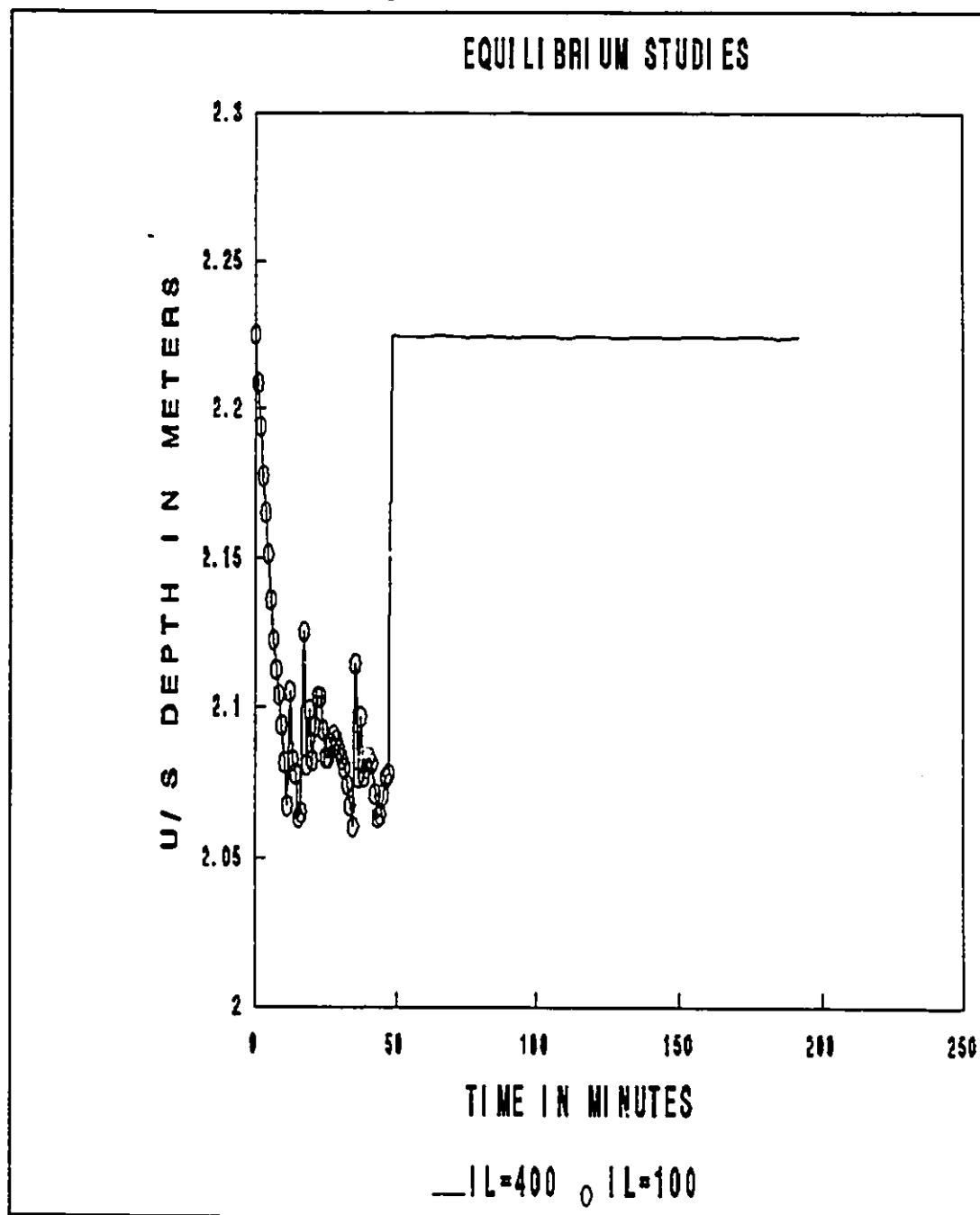


Figure 5.43 PLANE BED

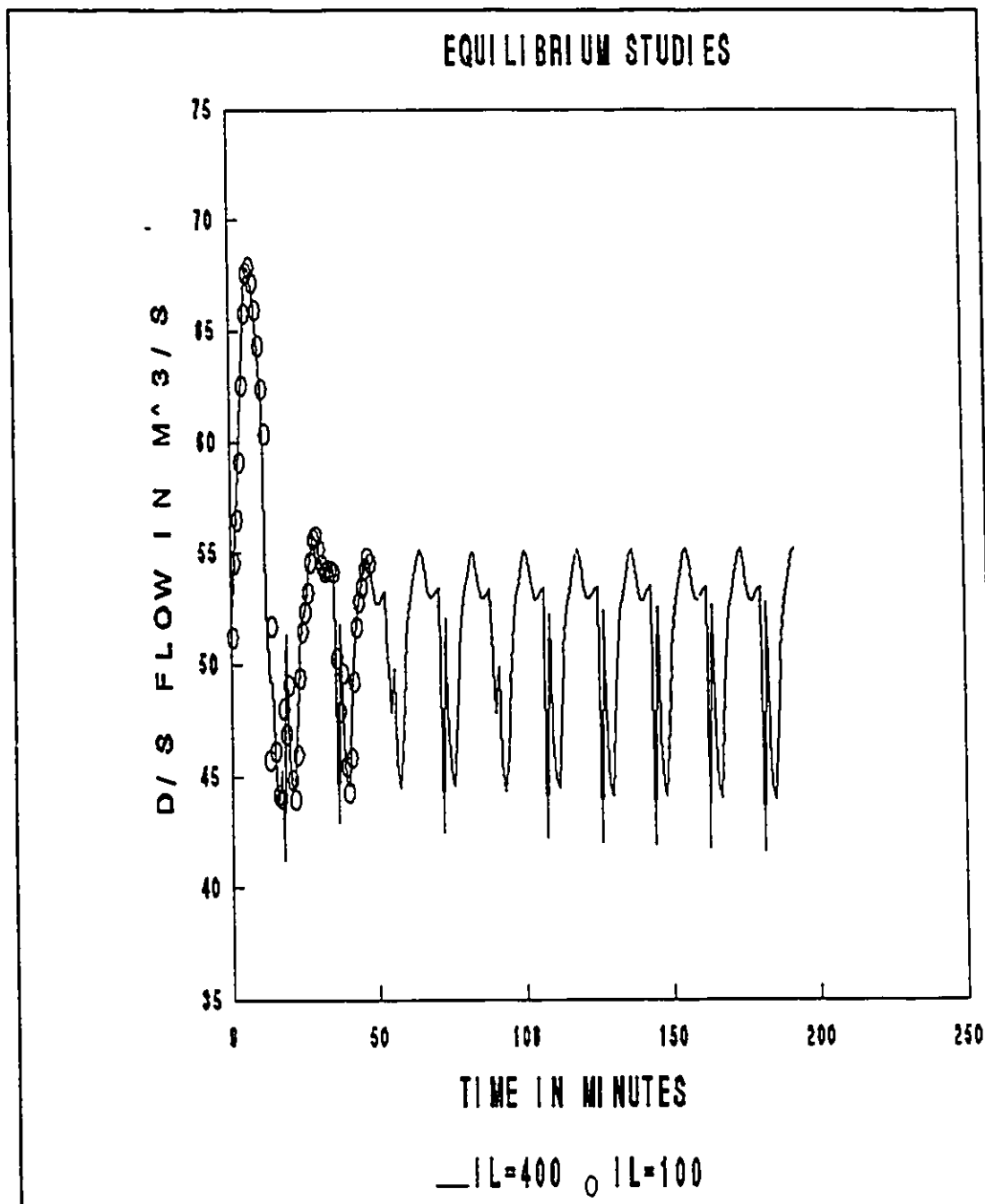


Figure 5.44 BED WITH RIPPLES

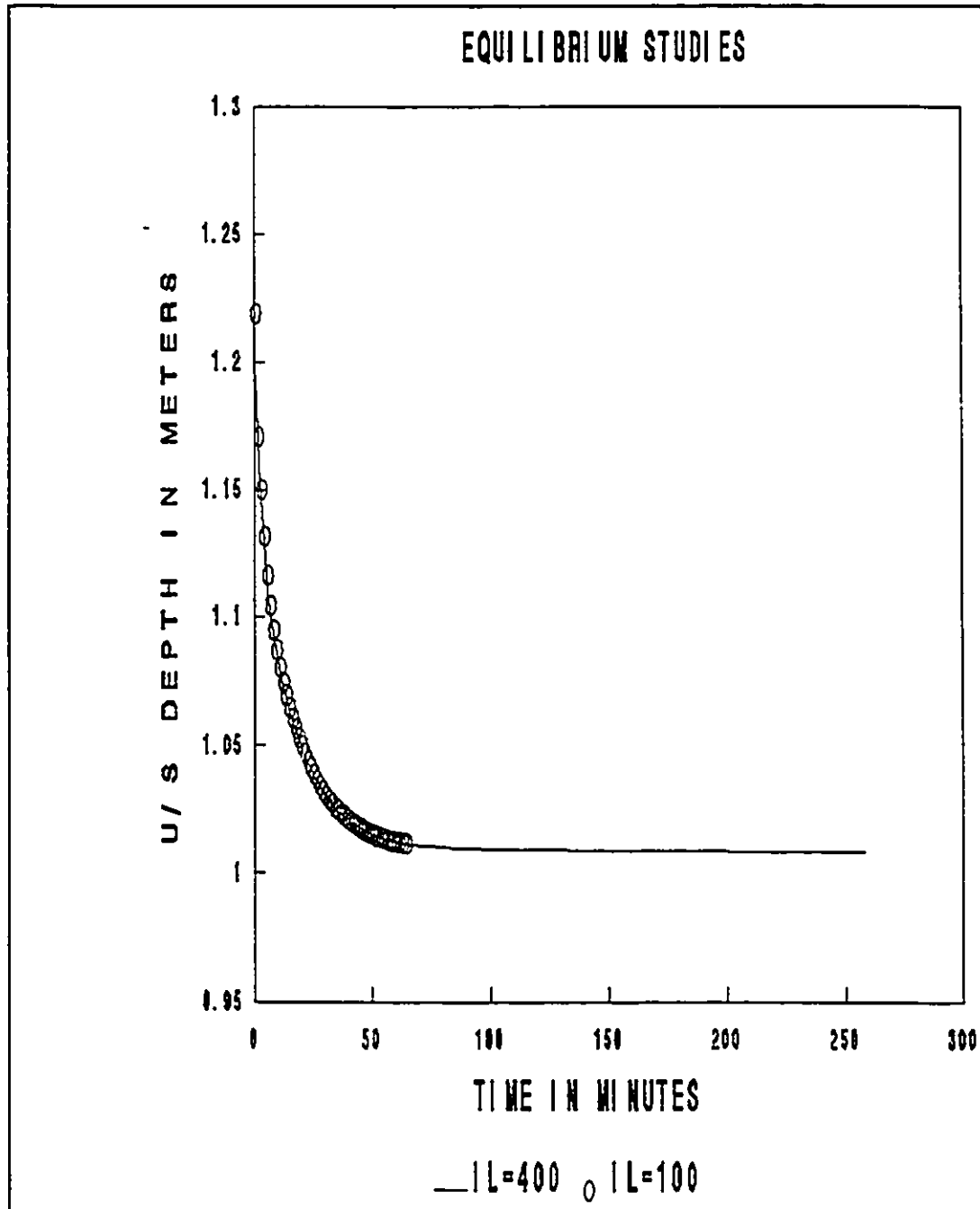


Figure 5.45 BED WITH RIPPLES

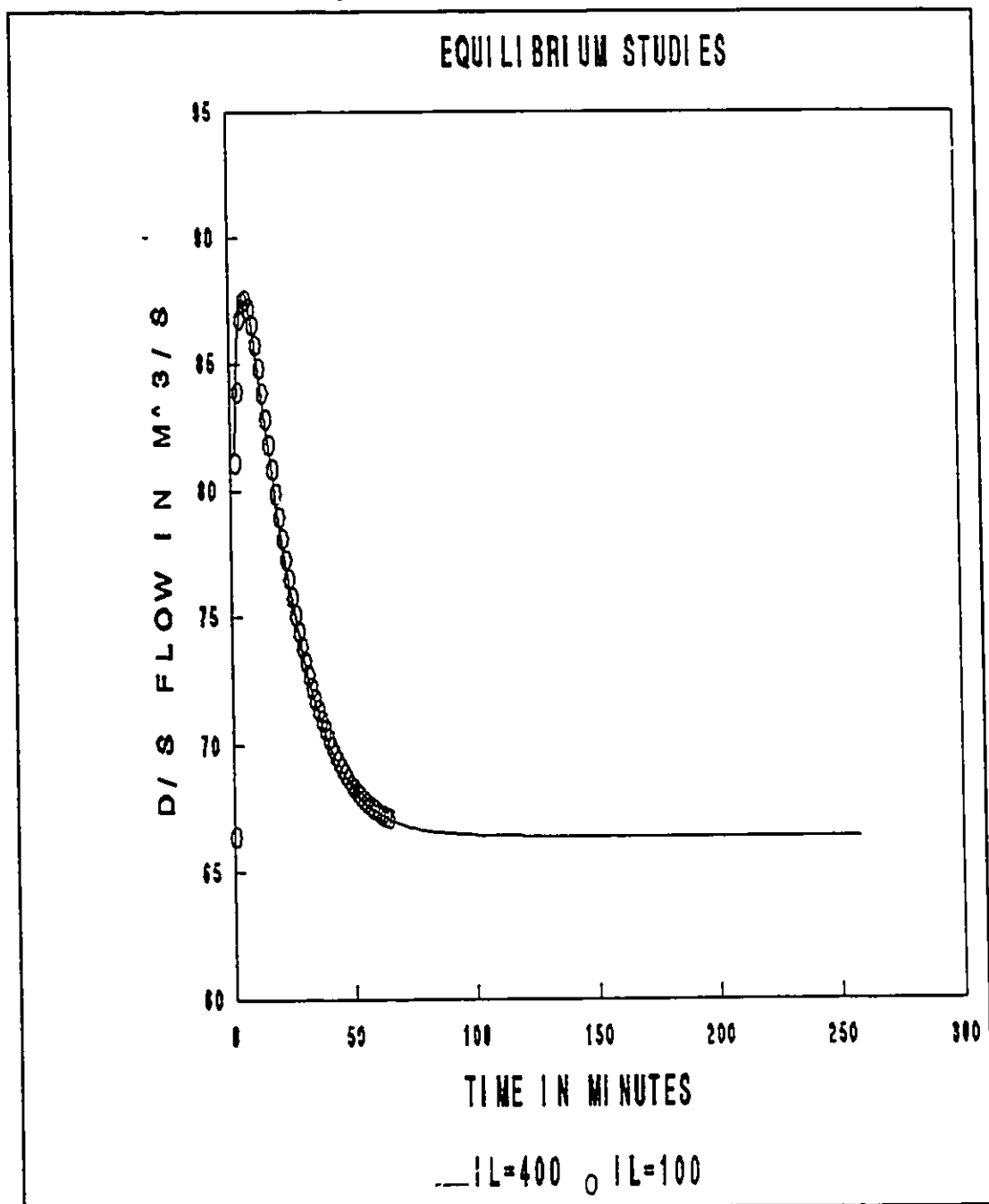


Figure 5.46 BED WITH RIPPLES

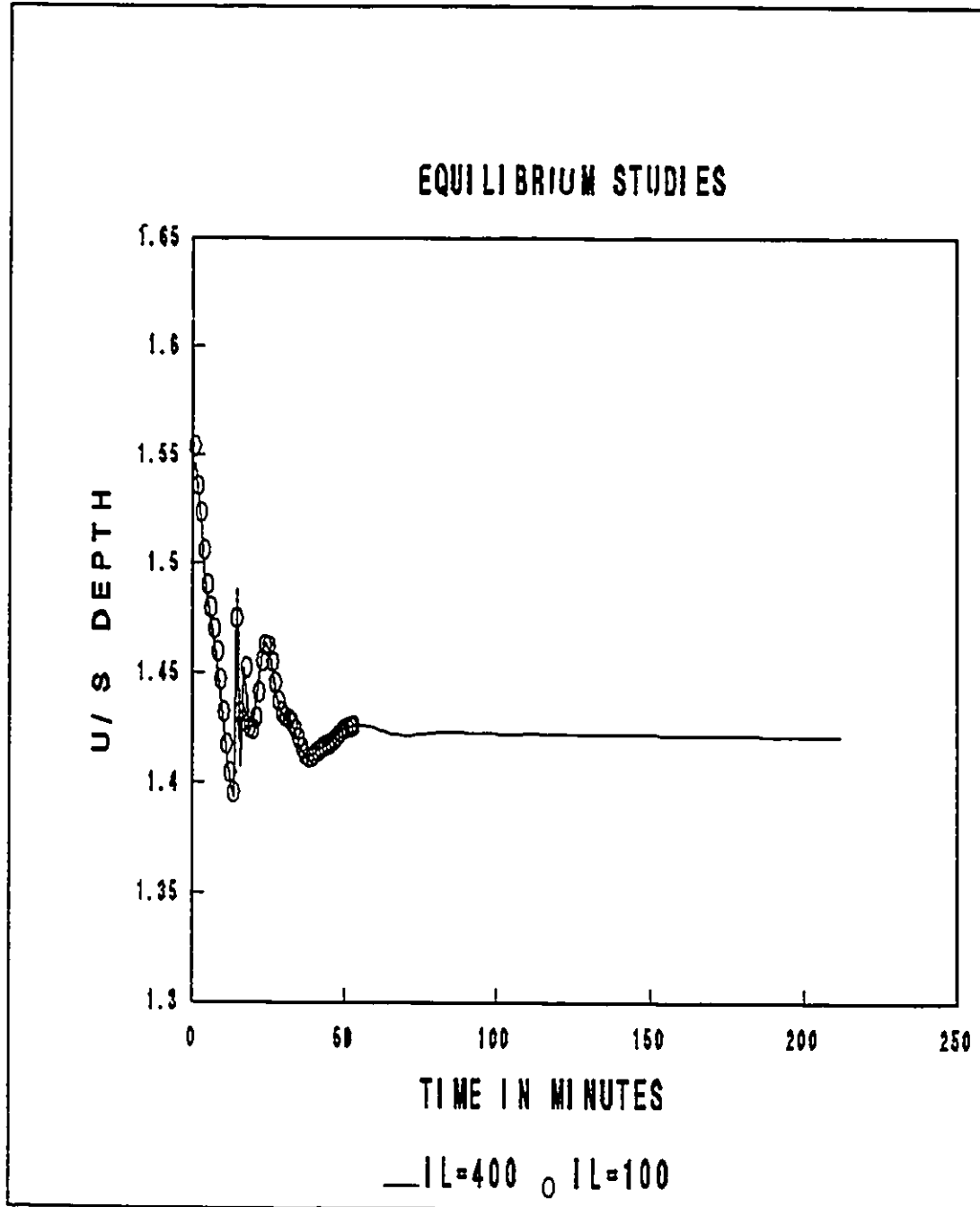


Figure 5.47 BED WITH RIPPLES

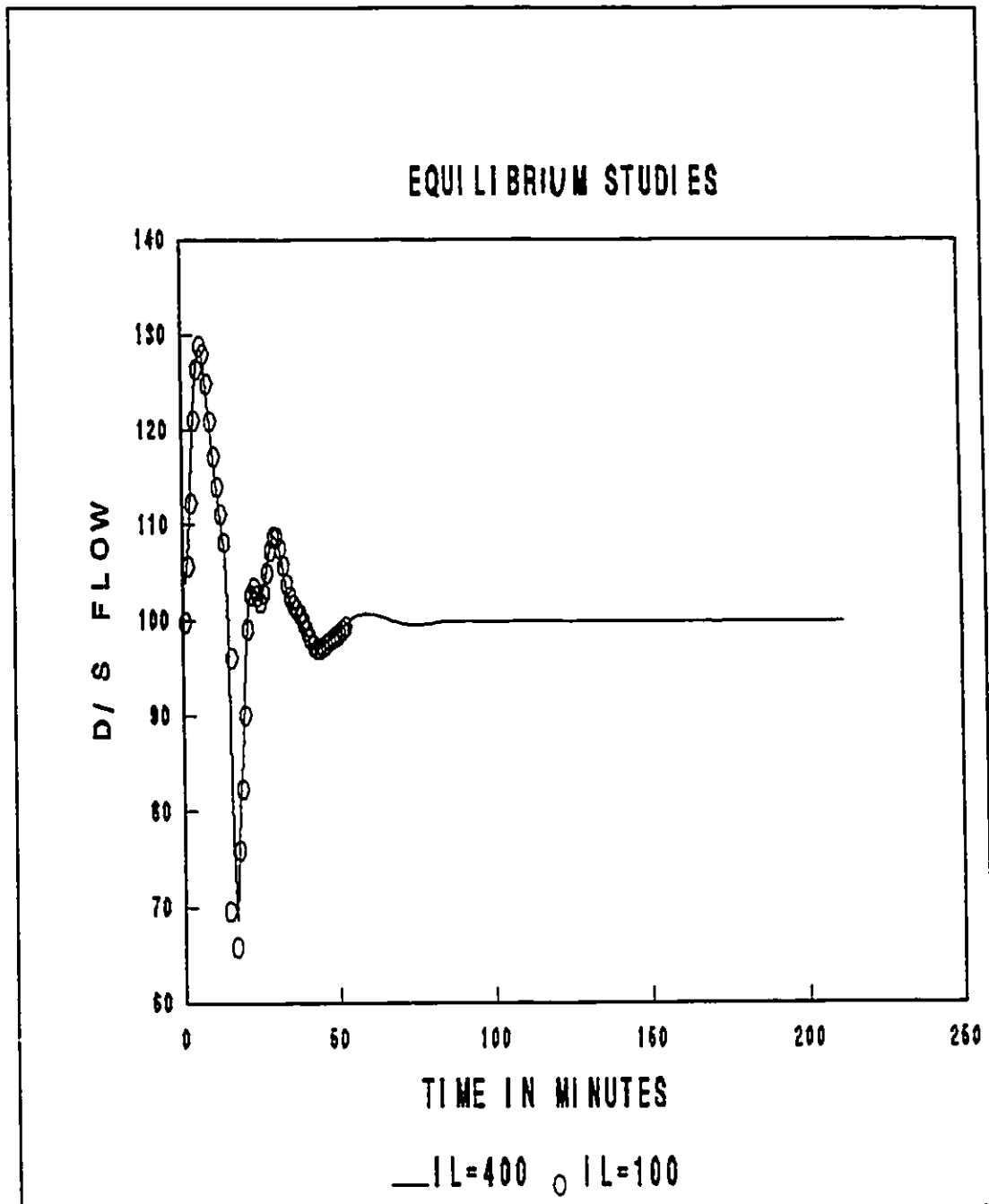


Table No. 5.1 ERROR RESULTS FOR MANNING'S "n" (n = 0.010)

Test No	Δt in secs	Δx in meters	No of Sec	Std. Error in U/S Flow in l/s	% Error in U/S Flow	Std. Error in Elev. in mm.	% Error in Elev.	Std. Error in D/S Flow in l/s	% Error in D/S Flow	Std. Error in D/S Elev. in mm.	% Error in D/S Elev	% Bias error in peak U/S elev.	% Bias error in peak D/S flow
1	2	30	8	3.468	1.864	10.28	2.651	2.366	1.497	2.661	0.758	-2.86	+1.08
2	4	30	8	2.538	1.364	11.12	2.867	1.810	1.145	2.500	0.712	-2.86	+1.08
3	6	30	8	2.538	1.364	11.12	2.866	1.809	1.145	2.493	0.710	-2.73	+1.08
4	8	30	8	2.543	1.367	11.12	2.868	1.809	1.145	2.485	0.708	-2.73	+1.08
5	10	30	8	2.538	1.364	11.12	2.867	1.803	1.141	2.491	0.709	-2.78	+1.08
6	12	30	8	2.538	1.364	11.12	2.868	1.802	1.141	2.486	0.708	-2.78	+1.08
7	14	30	8	2.542	1.367	11.11	2.865	1.803	1.141	2.489	0.709	-2.83	+1.08

Average overall percent errors:

u/s flow = 1.4

u/s elev. = 2.8

d/s flow = 1.2

d/s elev. = 0.7

Table No. 5.2 ERROR RESULTS FOR MANNING'S "n" (n = 0.016)

Test No	Δt in secs	Δx in meters	No of Sec	Std. Error in U/S Flow in l/s	% Error in U/S Flow	Std. Error in Elev. in mm.	% Error in Elev.	Std. Error in D/S Flow in l/s	% Error in D/S Flow	Std. Error in D/S Elev. in mm.	% Error in D/S Elev	% Bias error in peak U/S elev.	% Bias error in peak D/S flow
1	2	30	8	3.468	1.864	22.64	5.836	3.326	2.105	4.657	1.326	+6.83	+1.33
2	4	30	8	2.538	1.364	22.29	5.745	2.446	1.548	3.703	1.055	+6.83	+1.33
3	6	30	8	2.538	1.364	22.29	5.745	2.439	1.543	3.691	1.051	+6.86	+1.33
4	8	30	8	2.543	1.367	22.28	5.744	2.436	1.542	3.671	1.046	+6.86	+1.33
5	10	30	8	2.538	1.364	22.27	5.741	2.422	1.533	3.672	1.046	+6.86	+1.30
6	12	30	8	2.538	1.364	22.28	5.743	2.423	1.533	3.666	1.044	+6.86	+1.30
7	14	30	8	2.542	1.367	22.28	5.744	2.414	1.528	3.649	1.039	+6.88	+1.30

Average overall percent errors:

u/s flow = 1.4

u/s elev. = 5.8

d/s flow = 1.6

d/s elev. = 1.1

Table No. 5.3 ERROR RESULTS FOR BED SLOPE (So = 0.00022)

Test No	Δt in secs	Δx in meters	No of Sec	Std. Error in U/S Flow in l/s	% Error in U/S Flow	Std. Error in Elev. in mm.	% Error in Elev.	Std. Error in D/S Flow in l/s	% Error in D/S Flow	Std. Error in D/S Elev. in mm.	% Error in D/S Elev	% Bias error in peak U/S elev.	% Bias error in peak D/S flow
1	2	30	8	3.468	1.864	4.072	1.049	1.633	1.033	1.562	0.445	-0.52	+0.95
2	4	30	8	2.538	1.364	5.163	1.320	1.306	0.876	1.921	0.547	-0.52	+0.95
3	6	30	8	2.538	1.364	5.170	1.332	1.306	0.826	1.913	0.545	-0.54	+0.95
4	8	30	8	2.543	1.367	5.156	1.329	1.293	0.818	1.906	0.543	-0.54	+0.95
5	10	30	8	2.538	1.364	5.157	1.329	1.283	0.812	1.909	0.544	-0.54	+0.95
6	12	30	8	2.538	1.364	5.164	1.331	1.280	0.810	1.902	0.542	-0.54	+0.95
7	14	30	8	2.542	1.367	5.150	1.327	1.269	0.803	1.900	0.541	-0.54	+0.89

Average overall percent errors:

u/s flow = 1.4

u/s elev. = 1.3

d/s flow = .85

d/s elev. = .53

Table No. 5.4 ERROR RESULTS FOR BED SLOPE (So = 0.00015)

Test No	At in secs	Δx in meters	No of Sec	Std. Error in U/S Flow in U/s	% Error in U/S Flow	Std. Error in Elev. in mm.	% Error in Elev.	Std. Error in D/S Flow in U/s	% Error in D/S Flow	Std. Error in D/S Elev. in mm.	% Error in D/S Elev	% Bias error in peak U/S elev.	% Bias error in peak D/S flow
1	2	30	8	3.468	1.864	7.119	1.834	1.400	0.886	1.671	0.476	+2.39	+0.57
2	4	30	8	2.538	1.364	6.488	1.672	1.125	0.712	1.940	0.552	+2.39	+0.57
3	6	30	8	2.538	1.364	6.476	1.669	1.122	0.710	1.935	0.551	+2.37	+0.51
4	8	30	8	2.543	1.367	6.477	1.669	1.111	0.703	1.936	0.551	+2.37	+0.51
5	10	30	8	2.538	1.364	6.464	1.666	1.108	0.701	1.922	0.547	+2.35	+0.51
6	12	30	8	2.538	1.364	6.462	1.665	1.106	0.700	1.918	0.546	+2.35	+0.51
7	14	30	8	2.542	1.367	6.470	1.667	1.089	0.689	1.914	0.545	+2.35	+0.51

Average overall percent errors:
u/s flow = 1.4
u/s elev. = 1.7
d/s flow = .73
d/s elev. = .54

Table No. 5.5 ERROR RESULTS FOR STABILITY ANALYSIS
 $x = 30\text{m}$; $n^* = 0.012$

Test No	Δt in secs	Δx in meters	No of Sec	Std. Error in U/S Flow in l/s	% Error in U/S Flow	Std. Error in Elev. in mm.	% Error in Elev.	Std. Error in D/S Flow in l/s	% Error in D/S Flow	Std. Error in D/S Elev. in mm.	% Error in D/S Elev	% Bias error in peak U/S elev.	% Bias error in peak D/S flow
1	2	30	8	3.468	1.864	1.695	0.437	1.322	0.837	1.217	0.346	+0.72	+0.76
2	4	30	8	2.538	1.364	1.527	0.393	1.067	0.676	1.751	0.498	+0.72	+0.76
3	6	30	8	2.538	1.364	1.534	0.395	1.082	0.685	1.754	0.499	+0.69	+0.76
4	8	30	8	2.543	1.367	1.527	0.393	1.068	0.676	1.757	0.500	+0.69	+0.76
5	10	30	8	2.538	1.364	1.512	0.389	1.071	0.678	1.751	0.498	+0.67	+0.76
6	12	30	8	2.538	1.364	1.510	0.389	1.053	0.666	1.742	0.496	+0.67	+0.76
7	14	30	8	2.542	1.367	1.506	0.388	1.056	0.668	1.745	0.497	+0.67	+0.70

Average overall percent errors:

u/s flow = 1.4
u/s elev. = 0.39
d/s flow = 0.70
d/s elev. = 0.48

Table No. 5.6 ERROR RESULTS FOR STABILITY ANALYSIS

x = 15m ; "n" = 0.012

Test No	At in secs	Δx in meters	No of Sec	Std. Error in U/S Flow in l/s	% Error in U/S Flow	Std. Error in Elev. in mm.	% Error in Elev.	Std. Error in D/S Flow in l/s	% Error in D/S Flow	Std. Error in D/S Elev. in mm.	% Error in D/S Elev	% Bias error in peak U/S elev.	% Bias error in peak D/S flow
11	1	15	15	4.819	2.591	1.497	0.388	1.400	0.965	1.225	0.366	+0.64	+0.76
12	2	15	15	4.951	2.662	4.378	1.128	3.545	2.301	4.676	1.351	+0.64	+0.76
13	3	15	15	5.215	2.804	1.901	0.489	1.953	1.268	1.913	0.553	+0.64	+0.76
14	4	15	15	5.488	2.950	2.090	0.538	2.112	1.371	2.124	0.614	+0.64	+0.76
15	5	15	15	5.792	3.114	2.277	0.587	2.288	1.486	2.338	0.675	+0.64	+0.76
16	6	15	15	6.077	3.267	2.499	0.644	2.455	1.594	2.563	0.740	+0.64	+0.76
17	7	15	15	6.375	3.427	2.719	0.700	2.615	1.698	2.787	0.805	+0.64	+0.76

Average overall percent errors:

u/s flow = 2.9

u/s elev. = 0.6

d/s flow = 1.5

d/s elev. = .73

Table No. 5.7 ERROR RESULTS FOR STABILITY ANALYSIS
 $x = 45m$: " n " = 0.012

Test No	Δt in secs	Δx in meters	No of Sec	Std. Error in U/S Flow in l/s	% Error in U/S Flow	Std. Error in Elev. in mm.	% Error in Elev.	Std. Error in D/S Flow in l/s	% Error in D/S Flow	Std. Error in D/S Elev. in mm.	% Error in D/S Elev	% Bias error in peak U/S elev.	% Bias error in peak D/S flow
21	3	45	6	3.919	2.107	1.099	0.283	0.492	0.311	0.812	0.231	+0.34	-0.06
22	6	45	6	3.919	2.107	1.086	0.279	0.493	0.312	0.793	0.226	+0.34	-0.06
23	9	45	6	3.920	2.107	1.076	0.277	0.458	0.290	0.778	0.221	+0.28	-0.12
24	12	45	6	3.919	2.107	1.071	0.276	0.458	0.290	0.783	0.223	+0.28	-0.12
25	15	45	6	3.919	2.107	1.099	0.283	0.462	0.292	0.758	0.216	+0.28	-0.12
26	18	45	6	3.918	2.106	1.070	0.275	0.437	0.276	0.778	0.221	+0.28	-0.12
27	21	45	6	3.943	2.120	1.063	0.274	0.452	0.286	0.766	0.218	+0.26	-0.12

Average overall percent errors:

u/s flow = 2.1

u/s elev. = .28

d/s flow = .30

d/s elev. = .22

Table 5.8 ERROR ANALYSIS FOR TRANSITION USING KISHI'S RELATIONS

T. #	AT ... # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH	PREDI- CTED U/S DEPTH IL = 400	MEASU- RED D/S FLOW	PREDI- CTED D/S FLOW IL = 400	% BIAS ERROR IN D/S FLOW IL=400	% BIAS ERROR IN U/S DEPTH IL = 400	B E D - F O R M
1	23 ... 5	0.000	4.142	1.910	0.004	3.505	3.66	366.31	366.31	0.00	+4.42	D U N
2	23 ... 5	0.000	4.074	4.725	0.002	3.600	3.764	377.40	377.40	0.00	+4.58	D U N
3	24 ... 5	0.000	3.189	1.768	0.001	3.292	3.181	277.80	277.80	0.00	-3.34	D U N
4	22 ... 5	0.000	0.319	0.156	0.000	3.810	3.797	381.02	381.09	+0.02	-0.33	D U N
5	21 ... 5	0.000	2.450	2.416	0.003	3.932	4.034	426.73	425.34	-0.34	+2.60	D U N

Table 5.8 contd:

6	21 ... 5	0.000	0.892	1.619	0.001	4.115	4.144	455.84	459.34	+0.73	+0.76	T R N
7	21 ... 5	0.000	2.607	1.783	0.002	4.145	4.250	456.80	463.35	+2.55	+1.43	T R N
8	23 ... 4	0.000	0.792	5.64	0.002	3.261	3.245	363.54	383.08	-0.49	+5.37	T R N
9	23 ... 4	0.000	1.246	4.280	0.003	3.292	3.252	330.58	318.71	-1.19	-3.59	T R N
10	23 ... 4	0.000	0.459	1.335	0.001	3.231	3.217	314.83	311.99	-0.42	-0.90	T R N
11	24 ... 4	0.000	2.825	8.830	0.010	2.957	2.847	320.95	334.62	-3.70	-4.26	T R N
12	28 ... 5	0.000	3.770	3.451	0.006	2.134	2.213	162.67	166.45	+3.74	-2.32	T R N
13	28 ... 5	0.000	21.72	16.37	0.060	2.164	1.642	83.18	83.18	-24.08	0.00	T R N
14	29 ... 5	0.000	19.41	14.94	0.096	2.042	1.642	78.47	78.47	-19.57	0.00	T R N

Table 5.8 conti:

15	28 ... 4	0.000	6.500	8.279	0.021	2.286	2.117	70.49	63.11	-7.38	-10.46	T R N
16	28 ... 4	0.000	11.02	12.39	0.041	2.185	1.934	73.80	61.12	-11.47	-17.18	T R N

Table 5.9 ERROR ANALYSIS FOR DUNES USING KISHI'S RELATIONS

T. #	ΔT ... # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH	PREDI- CTED U/S DEPTH IL = 400	MEASU -RED D/S FLOW	PREDI- CTED D/S FLOW IL = 400	% BIAS ERROR IN U/S DEPTH IL=400	% BIAS ERROR IN D/S FLOW IL=400	B E D - F O R M
1	22 ... 4	0.000	2.175	7.379	0.005	3.749	3.646	438.6	468.9	-2.72	+6.92	T R N
2	22 ... 4	0.000	4.860	10.04	0.035	3.658	3.453	396.2	420.0	-5.60	+5.99	T R N
3	26 ... 4	0.000	3.940	2.262	0.003	2.896	2.778	183.2	183.2	-4.06	0.00	D U N
4	23 ... 4	0.000	1.542	7.412	0.007	3.414	3.349	339.5	365.5	-1.90	+7.67	T R N
5	22 ... 4	0.000	6.373	4.780	0.026	3.597	3.355	390.8	390.8	-6.71	0.00	T R N

Table 5.9 contd:

T. #	AT --- # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH	PREDI- CTED U/S DEPTH IL = 400	MEASU -RED D/S FLOW	PREDI- CTED D/S FLOW IL = 400	% BIAS ERROR IN D/S FLOW IL=400	% BIAS ERROR IN U/S DEPTH IL=400	B E D - F O R M
6	24 --- 4	0.000	2.043	1.086	0.002	3.261	3.191	229.5	229.5	0.00	-2.11	D U N
7	23 --- 4	0.000	2.015	5.952	0.011	3.292	3.357	314.5	319.1	+1.48	+1.99	T R N
8	22 --- 4	0.000	2.409	7.083	0.008	3.627	3.514	370.2	397.1	+7.24	-3.10	T R N
9	23 --- 4	0.000	4.464	11.56	0.027	3.353	3.209	372.2	405.9	+9.03	-4.27	T R N
10	25 --- 4	0.000	0.351	0.185	0.000	2.987	2.976	212.8	212.8	0.00	-0.34	D U N
11	36 --- 4	0.000	18.41	9.219	0.009	1.494	1.208	89.12	89.11	0.00	-19.11	D U N
12	37 --- 4	0.000	14.19	6.834	0.010	1.341	1.143	83.96	83.96	0.00	-14.69	D U N

Table 5.9 contd:

T. #	ΔT --- # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH	PREDI- CTED U/S DEPTH IL = 400	MEASU -RED D/S FLOW	PREDI- CTED D/S FLOW IL = 400	% BIAS ERROR IN U/S DEPTH IL=400	% BIAS ERROR IN D/S FLOW IL=400	B E D . F O R M
13	29 --- 4	0.000	0.928	0.346	0.001	2.103	2.081	171.5	171.4	-1.04	0.01	D U N
14	31 --- 4	0.000	4.563	2.013	0.006	1.900	1.809	131.6	131.6	-4.75	0.00	D U N

Table 5.10 ERROR ANALYSIS FOR PLANE BED USING KISHI'S FRICTION EQUATIONS

T #	AT ... # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH IL =400	PREDI- CTED U/S DEPTH IL =400	MEASU -RED D/S FLOW	PREDI- CTED D/S FLOW IL = 400	% BIAS ERRO R IN D/S FLOW IL=400	B E D F O R M
1	26 ... 4	0.000	2.303	5.519	0.007	2.530	2.586	245.56	238.16	-3.01	T R N
2	30 ... 5	0.000	1.548	0.648	0.033	1.859	1.914	199.20	199.20	0.00	T R N
3	30 ... 5	0.000	18.50	15.10	0.056	1.981	1.608	71.70	71.70	0.00	T R N
4	29 ... 5	0.000	7.364	9.236	0.030	2.225	2.019	51.23	55.250	+7.84	T R N

Table 5.10 conti:

5	30 ... 5	0.000	10.59	2.351	0.573	2.012	2.395	47.52	47.538	+19.0	0.04	T R N
6	21 ... 5	0.000	8.354	14.08	0.378	3.719	4.085	528.7	574.6	+9.86	+8.69	T R N
7	22 ... 4	0.000	4.028	6.706	0.015	3.810	3.926	395.1	414.9	+3.06	+4.99	T R N
8	38 ... 4	0.000	8.525	8.640	0.025	1.250	1.134	79.66	82.44	-9.22	+3.49	T R N
9	35 ... 4	0.000	2.738	1.107	0.005	1.402	1.440	110.7	110.69	+2.77	0.00	D U N
10	33 ... 6	0.000	26.89	45.27	0.208	1.951	1.410	51.85	52.59	-27.6	+1.44	D U N
11	28 ... 5	0.000	2.837	2.854	0.021	2.316	2.383	48.62	49.14	+2.93	+1.07	T R N

Table 5.10 contd:

1	28	0.000	5.507	8.441	0.079	2.256	2.394	54.11	48.68	+6.14	-10.03	T R N
2	...											
	5											

Table 5.11 ERROR ANALYSIS FOR RIPPLES OR DUNES USING KISHI'S FRICTION EQUATIONS

T #	Δt ... # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH	PREDI -CTED U/S DEPT H IL =400	MEASU -RED D/S FLOW	PREDI- CTED D/S FLOW IL = 400	% BIAS ERROR IN U/S DEPTH IL=400	% BIAS ERROR IN D/S FLOW IL=400	B E D . F O R M
1	35 ... 5	0.000	10.03	6.084	0.025	1.341	1.190	43.98	43.97	-11.19	-0.02	T R N
2	28 ... 5	0.000	3.818	6.513	0.037	2.256	2.345	52.25	54.40	+3.97	+4.12	T R N
3	39 ... 4	0.000	16.61	8.051	0.005	1.219	1.008	66.44	66.42	-17.28	-0.02	D U N
4	26 ... 4	0.000	1.112	4.855	0.000	2.652	2.620	268.3	281.5	-1.19	+4.92	T R N

Table 5.11 contd:

5	25 ... 4	0.000	2.066	8.930	0.001	2.621	2.574	304.9	322.4	-1.78	+5.72	T R N
6	21 ... 5	0.000	0.370	1.911	0.001	4.261	4.261	487.5	494.7	+0.01	+1.47	T R N
7	21 ... 5	0.000	0.380	2.354	0.000	4.206	4.195	498.1	490.7	-0.26	-1.49	T R N
8	26 ... 5	0.000	2.693	2.240	0.009	2.591	2.526	254.9	254.9	--2.49	0.00	T R N
9	32 ... 4	0.000	8.271	6.275	0.068	1.554	1.421	99.80	99.79	-8.54	0.00	T R N
10	25 ... 5	0.000	2.769	3.723	0.004	2.743	2.817	253.6	250.1	+2.72	-1.38	T R N

Table 5.12 ERROR ANALYSIS FOR TRANSITION BED USING MODIFIED CONSTANT
WITH $C^* = 1.122$; $IL=400$

T #	ΔT ... # OF SEC	% ERRO R IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH	PREDI- CTED U/S DEPTH IL = 400	MEASU- RED D/S FLOW	PREDI- CTED D/S FLOW IL = 400	% BIAS ERROR IN U/S DEPTH IL=400	% BIAS ERROR IN D/S FLOW IL = 400	B E D . F O R M
1	23 ... 5	0.000	7.672	3.343	0.007	3.505	3.805	366.31	366.32	+8.57	0.0	T R N
2	23 ... 5	0.000	6.874	3.490	0.006	3.600	3.851	377.40	377.39	+6.99	0.0	T R N
3	24 ... 5	0.000	1.124	0.616	0.000	3.292	3.253	277.80	277.80	-1.18	0.0	D U N

Table 5.12 contd:

4	22 ... 5	0.000	2.168	1.083	0.001	3.810	3.897	381.02	381.02	+2.30	0.0 0	D U N
5	21 ... 5	0.000	3.906	4.299	0.004	3.932	4.087	426.72	426.73	+3.94	0.0 0	T R N
6	21 ... 5	0.000	2.266	2.847	0.002	4.115	4.207	455.84	455.84	+2.26	0.0 0	T R N
7	21 ... 5	0.000	3.914	3.914	0.003	4.145	4.305	456.79	456.80	+3.87	0.0 0	T R N
8	23 ... 4	0.000	0.679	0.493	0.001	3.261	3.285	363.54	363.54	+0.75	0.0 0	T R N
9	23 ... 4	0.000	0.096	0.228	0.000	3.292	3.296	330.58	330.58	+0.15	0.0 0	T R N
10	23 ... 4	0.000	0.916	0.786	0.001	3.231	3.262	314.83	314.83	+0.96	0.0 0	T R N

Table 5.12 contd:

1 1	24 ...	0.000	1.264	1.066	0.005	2.957	2.922	320.95	320.95	-1.17	0.0 0	T R N
1 2	28 ...	0.000	6.701	5.570	0.011	2.134	2.279	162.67	162.67	+6.80	0.0 0	T R N
1 3	28 ...	0.000	17.77	12.63	0.051	2.164	1.736	83.16	83.18	-19.75	0.0 1	T R N
1 4	29 ...	0.000	15.01	11.51	0.081	2.042	1.737	78.46	78.47	-14.89	0.0 0	T R N
1 6	28 ...	0.000	8.758	6.760	0.036	2.185	2.003	73.79	73.80	-8.29	0.0 0	T R N

Table 5.13 ERROR ANALYSIS FOR DUNES USING MODIFIED VALUES
WITH $C^* = 1.30$; $IL=400$; $DELTA X = 2000'$

T. #	ΔT ... #. of Sec	% Error in U/S Flow	% Error in U/S Depth	% Error in D/S Flow	% Error in D/S Depth	Measured U/S Depth	Predicted U/S Depth $IL=400$	Measured D/S Flow	Predicted D/S flow $IL=400$	% Bias Error in U/S depth $IL=400$	% Bias error in D/S Flow $IL=400$	Bed Form Prediction
1	22 ... 4	0.000	1.090	0.988	0.003	3.749	3.711	438.6	438.6	-0.99	0.00	TRN
2	22 ... 4	0.000	4.060	3.602	0.003	3.658	3.518	396.2	396.2	-3.82	0.00	TRN
3	26 ... 4	0.000	2.471	1.368	0.002	2.896	2.822	183.2	183.2	-2.55	0.00	DUNES I
4	23 ... 4	0.000	0.406	0.545	0.002	3.414	3.406	339.5	339.5	-0.22	0.00	TRN
5	22 ... 4	0.000	4.761	3.806	0.020	3.597	3.419	390.8	390.8	-4.95	0.00	TRN
6	24 ... 4	0.000	0.200	0.164	0.000	3.261	3.254	229.5	229.5	-0.21	0.00	DUNES I

Table 5.13 contd:

T. #	ΔT ... #. of Sec	% Error in U/S Flow	% Error in U/S Depth	% Error in D/S Flow	% Error in D/S Depth	Measu- red U/S Depth	Predl- cted U/S Depth IL=400	Measu- red D/S Flow	Predl- cted D/S flow IL=400	% Bias Error in U/S depth IL=400	% Bias error in D/S Flow IL=400	Bed Form Predi- ction
7	23 ... 4	0.000	3.012	3.210	0.016	3.292	3.396	314.5	314.5	-1.47	0.00	TRN
8	22 ... 4	0.000	1.371	1.158	0.005	3.627	3.573	370.2	370.2	-3.48	0.00	TRN
9	23 ... 4	0.000	3.660	2.935	0.026	3.353	3.236	372.2	372.2	-3.48	0.00	TRN
10	25 ... 4	0.000	1.964	0.872	0.003	2.987	3.049	212.8	212.8	+2.07	0.00	DU NES I
11	36 ... 4	0.000	15.84	7.849	0.009	1.494	1.248	89.12	89.11	-16.44	0.00	DU NES I
12	37 ... 4	0.000	11.40	5.451	0.009	1.341	1.182	83.96	83.96	-11.81	0.00	DU NES I
13	29 ... 4	0.000	3.193	1.551	0.003	2.103	2.169	171.5	171.5	+3.18	0.00	TRN
14	31 ... 4	0.000	1.741	0.794	0.003	1.900	1.865	131.6	131.6	-1.79	0.00	DU NES I

Table 5.14 ERROR ANALYSIS FOR PLANE RED WITH MODIFIED CONSTANTS
WITH $C^* = 1.125$; $IL=400$

T. #	AT ... # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU -RED U/S DEPTH	PREDI-CTED U/S DEPTH IL =400	MEASU-RED D/S FLOW	PREDI-CTED D/S FLOW IL = 400	% BIAS ERROR IN U/S DEPTH IL=400	% BIAS ERROR IN D/S FLOW IL=400	B E D . F O R M
1	26 ... 4	0.000	4.345	4.156	0.012	2.530	2.641	245.5	245.5	+4.41	0.00	T R N
2	30 ... 5	0.000	5.738	2.039	0.114	1.859	2.007	199.2	199.2	+7.97	0.01	T R N
3	30 ... 5	0.000	14.16	11.11	0.046	1.981	1.701	71.70	71.70	-14.0	0.00	T R N
4	29 ... 5	0.000	4.929	3.165	0.018	2.225	2.071	51.23	51.22	-6.92	0.00	T R N
5	30 ... 5	0.000	17.48	0.699	0.074	2.012	2.602	47.52	47.54	+29.3	+0.05	T R N

Table 5.14 contd:

6	21 ... 5	0.000	8.882	6.542	0.357	3.719	4.180	528.7	528.6	-12.4	-0.02	T R N
7	22 ... 4	0.000	4.856	6.145	0.018	3.810	3.981	395.1	395.1	+4.51	0.00	T R N
8	38 ... 4	0.000	5.190	3.840	0.016	1.250	1.187	79.66	79.66	-5.02	0.00	T R N
9	35 ... 4	0.000	6.084	2.413	0.011	1.402	1.489	110.7	110.6	+6.26	0.00	D U N
10	33 ... 6	0.000	26.65	42.71	0.208	1.951	1.413	51.85	52.12	-27.5	+0.53	D U N
11	28 ... 5	0.000	4.786	4.971	0.041	2.316	2.433	48.62	48.62	+5.08	0.00	T R N
12	28 ... 5	0.000	7.897	8.024	0.118	2.256	2.450	54.11	54.12	+8.63	0.00	T R N

Table 5.15 ERROR ANALYSIS FOR RIPPLES/DUNES/ USING MODIFIED CONSTANTS
WITH $C^* = 1.30$; $IL=400$.

T. #	ΔT ... # OF SEC	% ERROR IN U/S FLOW	% ERROR IN U/S DEPTH	% ERROR IN D/S FLOW	% ERROR IN D/S DEPTH	MEASU- RED U/S DEPTH	PREDI- CTED U/S DEPTH IL. = 400	MEASU- RED D/S FLOW	PREDI- CTED D/S FLOW IL. = 400	% BIAS ERROR IN U/S DEPTH IL.=400	% BIAS ERROR IN D/S FLOW IL.=400	B E D . F O R M
1	35 ... 5	0.000	3.320	1.504	0.006	1.341	1.282	43.98	43.97	-4.36	-0.02	T R N
2	28 ... 5	0.000	6.256	6.701	0.061	2.256	2.405	52.25	52.25	+6.62	0.00	T R N
3	39 ... 4	0.000	13.95	6.693	0.004	1.219	1.041	66.44	66.42	-14.5	-0.02	D U N
4	26 ... 4	0.000	0.682	0.648	0.000	2.652	2.667	268.3	268.3	+0.59	0.00	T R N

Table 5.15 contd:

5	25 ... 4	0.000	0.077	0.237	0.000	2.621	2.617	304.9	304.9	-0.13	0.00	T R N
6	21 ... 5	0.000	1.560	2.168	0.003	4.261	4.317	487.5	487.5	+1.31	0.00	T R N
7	21 ... 5	0.000	1.041	1.322	0.002	4.206	4.236	498.1	498.1	+0.73	0.00	T R N
8	26 ... 5	0.000	0.932	0.580	0.002	2.591	2.620	254.9	254.9	+1.15	0.00	T R N
9	32 ... 4	0.000	4.007	2.496	0.037	1.554	1.490	99.79	99.80	-4.06	0.00	T R N
10	25 ... 5	0.000	5.170	4.953	0.008	2.743	2.884	253.6	253.6	+5.14	0.00	T R N

CHAPTER 6

CONCLUSION

6.0 GENERAL

Conclusions drawn from the numerical experiments are described in this chapter in three parts, namely:

1. Discussion related to sensitivity and stability analyses for the unsteady rigid bed case.
2. Accuracy of the model in simulating the unsteady rigid bed case.
3. Accuracy of the model in simulating the steady mobile bed case.

6.1 SENSITIVITY AND STABILITY ANALYSES

The model predicts the u/s elevation in direct proportion to the value of Manning's "n". Considering the results for Manning's "n" = 0.012 as the reference test case, the model underpredicts the peak u/s depths by 3.8% relative to the case of Manning's "n" = 0.010. The peak d/s flows are overpredicted by 0.31% with respect to the case of $n = 0.012$. For the case of bed roughness equal to 0.016, the peak u/s depths are 6.8% higher than the reference case and the peak d/s flows are 0.56% higher than the reference test case. Thus, the model is slightly sensitive to changes in the bed roughness.

The predicted results show that the model is not very sensitive to the bed slope. Upon comparing the results for steeper slopes ($S_o = 0.00022$) with the results for the base case of bed slope ($S_o = 0.00019$), it was found that the model underpredicts the peak u/s depths by 1.4% and overpredicts the d/s flows by 0.19%. For $S_o = 0.00015$, the model overpredicts the peak u/s depths

by 1.8% and underpredicts the d/s flows by 0.25%.

Several test runs made for the unsteady rigid bed case to test the stability of the model show that the model MOBED is very stable. Variation of Δt ($\Delta t = 2s$ to $120s$) for fixed Δx ($\Delta x=30m$) did not change the model results. Selection of Δt was based on the Eq. (3.3) and Δx ranged from $15m$ to $45m$. For higher Δx ($\Delta x=45m$) and fixed Δt the model underpredicted the peak u/s depths by 0.46% and the peak d/s flows by 0.8% when compared to results for the base case of $\Delta x = 30m$. Decreasing Δx ($\Delta x = 15m$) did not affect the model results when compared to the base case.

It was found that the total measured inflow, predicted inflow, measured outflow, and predicted outflow were almost equal with an error of less than 1%. This shows that the model formulation is accurate.

6.2 ACCURACY OF THE MODEL IN SIMULATING UNSTEADY RIGID BED CASE

The model is capable of predicting the flow within the expected range of the observational errors in measured flows (1% to 2%). For most of the test cases, the difference in predicted and measured peak depths exceed the observational error of 0.5mm. However, the error in depths at the crest was generally less than 3% which is considered acceptable for engineering applications. The times to peak in all cases were accurately simulated.

6.3 ACCURACY OF THE MODEL IN SIMULATING UNSTEADY MOBILE BED CASE

The predictive accuracy of the original model in simulating mobile bed unsteady flows was

only fair. The predicted depths differ from the measured depths by more than the field errors. The field error in depth is ± 6 inches, which accounts for the undulations of the bed forms. The original model does not predict flow errors within the range of field error of $\pm 5\%$. The original model with Kishi and Kuroki (1974) friction factor relations appeared to give good results for $R/D_{65} < 2000$. For the link canals of Pakistan where $R/D_{65} > 2000$, the model was modified to incorporate the new friction parameters. The modification done on the basis of Section 5.2.2 gave constant C^* for bed forms as 1.122 for transition regime, 1.30 for dunes and ripples, and 1.125 for the plane bed form. After the modification, the field errors in depth slightly improved as compared to the original model but the field errors in flow showed considerable improvement and were within $\pm 5\%$. The success rate in predicting the correct bed form improved with the modification in friction parameters for the case of transition bed and the bed covered with dunes. However, the model performance still needs to be improved in order to predict the correct bedform, especially for plane bed and ripples.

6.4 RECOMMENDATIONS

The study has given rise to numerous alternatives to further research. Some of the recommendations that should be investigated are described briefly as follows:

1. Considerable potential exists for further numerical testing for the case of antidunes bed form.
2. Improved criteria of predicting the bedform is needed.
3. The model should also be tested for other types of channels such as trapezoidal channel, and meandering channel.
4. The model should also be tested for unsteady mobile bed cases.

APPENDIX A
EXPRESSIONS AND CONSTANTS USED
IN THE
DERIVATION OF THE NUMERICAL SCHEME

Definitions of a_i , b_i , c_i , d_i , and e_i :

$$a_i = \left[\frac{B_{i+1} + B_i}{2\Delta t} \right] - \frac{2\theta}{\Delta x} \left[\frac{Q_{i+1} - Q_i}{B_{i+1} + B_i} \right] \frac{dB}{dy}_{i+1} + \theta \left[\frac{q_{i+1} + q_i}{B_{i+1} + B_i} \right] \frac{dB}{dy}_{i+1}$$

Eq. (A.1)

$$b_i = \frac{2\theta}{\Delta x}$$

Eq. (A.2)

$$c_i = - \left[\frac{B_{i+1} + B_i}{2\Delta t} \right] + \frac{2\theta}{\Delta x} \left[\frac{Q_{i+1} - Q_i}{B_{i+1} + B_i} \right] \frac{dB}{dy}_{i_1} - \theta \left[\frac{q_{i+1} + q_i}{B_{i+1} + B_i} \right] \frac{dB}{dy}_{i_1}$$

Eq. (A.3)

$$d_i = \frac{2\theta}{\Delta x}$$

Eq. (A.4)

$$e_i = \frac{2}{\Delta x} (Q_{i+1} - Q_i) + (q_{i+1} + q_i) + \theta (\Delta q_{i+1} + \Delta q_i)$$

Eq. (A.5)

Definitions of a'_i , b'_i , c'_i , d'_i and e'_i :

$$\begin{aligned}
 a'_i &= \frac{\theta}{\Delta x} \left[\frac{Q_{i+1} + B_{i+1}}{A_{i+1}^2} (Q_i - Q_{i+1}) \right] + \frac{g\theta}{\Delta x} [(y_{i+1} - y_i) B_{i+1} + A_{i+1} + A_i] + \\
 &\frac{\theta}{2\Delta x} \left[\left(\frac{2B_{i+1}^2 Q_{i+1}^2}{A_{i+1}^3} - \frac{dB}{dy_{i+1}} \frac{Q_{i+1}^2}{A_{i+1}^2} \right) (y_{i+1} - Y) - \frac{B_{i+1} Q_{i+1}^2}{A_{i+1}^2} - \frac{B_i Q_i^2}{A_i^2} \right] - \\
 &\frac{g\theta}{2\Delta x} [B_{i+1} (z_i - z_{i+1})] + \frac{g\theta}{2} \text{const} \left(\frac{R_{i+1}}{D_{65}} \right)^m Fr_{i+1}^n [B_{i+1}^{(m-3n)} - \frac{A_{i+1}}{P_{i+1}} \frac{dP}{dy_{i+1}} (m-n) + \\
 &B_{i+1}] + \theta \frac{Q_{i+1}^2 B_{i+1}}{A_{i+1}^3} A_{i+1}^{n_{i+1}}
 \end{aligned}$$

Eq. (A.6)

$$\begin{aligned}
 b'_i &= \frac{1}{2\Delta t} + \frac{\theta}{\Delta x} \left[\frac{Q_{i+1}}{A_{i+1}} + \frac{Q_i}{A_i} + \frac{Q_{i+1} - Q_i}{A_{i+1}} \right] + \frac{\theta}{2\Delta x} \left[\frac{2Q_{i+1} B_{i+1}}{A_{i+1}^2} (y_i - y_{i+1}) \right] \\
 &+ g\theta \text{const} \left(\frac{R_{i+1}}{D_{65}} \right)^m Fr_{i+1}^n \frac{A_{i+1}}{Q_{i+1}} - \theta \frac{Q_{i+1}}{A_{i+1}^2} A_{i+1}^{n_{i+1}}
 \end{aligned}$$

Eq. (A.7)

$$\begin{aligned}
& c_i^2 - \frac{\theta}{\Delta x} \left[\frac{Q_i + B_i}{A_i^2} (Q_i - Q_{i-1}) \right] + \frac{g\theta}{2\Delta x} [(y_{i-1} - y) B_i + A_{i-1} + A_i] + \\
& \frac{\theta}{2\Delta x} \left[\left(\frac{2B_i^2 Q_i^2}{A_i^3} - \frac{dB}{dy_i} \frac{Q_i^2}{A_i^2} \right) (y_{i-1} - Y) - \frac{B_{i-1} Q_{i-1}^2}{A_{i-1}^2} - \frac{B_i Q_i^2}{A_i^2} \right] - \\
& \frac{g\theta}{2\Delta x} [B_i (z_i - z_{i-1})] + \frac{g\theta}{2} \text{const} \left(\frac{R_i}{D_{65}} \right)^m Fr^* [B_i^{(m-3n)} - \frac{A_i}{P_i} \frac{dP}{dy_i} (m-n) + \\
& B_i] + \theta \frac{Q_i^2 B_i}{A_i^3} A_i^* z_i
\end{aligned}$$

Eq. (A.8)

$$\begin{aligned}
-d_i^2 - \frac{1}{2\Delta x} + \frac{\theta}{\Delta x} \left[-\frac{(Q_{i+1}-Q_i)}{A_i} - \frac{Q_{i+1}}{A_{i+1}} \frac{Q_i}{A_i} \right] + \frac{\theta}{2\Delta x} \left[-\frac{2Q_i B_i}{A_i^2} (y_i - y_{i+1}) \right] \\
+ g\theta \cdot \text{const.} \left(\frac{R_i}{D_{65}} \right)^m Fr^* A_i^* \frac{A_i}{Q_i} - \theta \frac{Q_i}{A_i^2} A_i^* A_i
\end{aligned}$$

Eq. (A.9)

$$\begin{aligned}
-e_i^2 - \frac{1}{\Delta x} \left[(Q_{i+1}-Q_i) \left(\frac{Q_{i+1}}{A_{i+1}} + \frac{Q_i}{A_i} \right) \right] + \frac{g}{2\Delta x} \left[(A_{i+1}+A_i)(y_{i+1}-y_i) \right] + \frac{1}{2\Delta x} \left[-\frac{B_{i+1}Q_{i+1}^2}{A_{i+1}^2} \right. \\
\left. + B_i \frac{Q_i^2}{A_i^2} (y_{i+1}-y_i) \right] + \frac{g}{2\Delta x} \left[(A_{i+1}+A_i)(z_{i+1}-z_i) \right] + \frac{g}{2} \cdot \text{const.} \left(\frac{R_{i+1}}{D_{65}} \right)^m Fr^* A_{i+1}^* A_{i+1} + \\
\frac{g}{2} \cdot \text{const.} \left(\frac{R_i}{D_{65}} \right)^m Fr^* A_i^* A_i - \frac{1}{2} \cdot \frac{Q_{i+1}^2}{A_{i+1}^2} A_i^* A_{i+1} - \frac{1}{2} \cdot \frac{Q_i^2}{A_i^2} A_i^* A_i
\end{aligned}$$

Eq.(A.10)

Expressions that were used in deriving the relations shown earlier in the Appendix.

$$\frac{1}{f_i + \Delta f_i} - \frac{1}{f_i(1 + \frac{\Delta f_i}{f_i})} = \frac{1}{f_i} \left(1 - \frac{\Delta f_i}{f_i}\right)$$

Eq.(A.11)

$$\frac{1}{(f_i + \Delta f_i)^2} - \frac{1}{f_i^2(1 + \frac{\Delta f_i}{f_i})^2} = \frac{1}{f_i^2} \left(1 - \frac{2\Delta f_i}{f_i}\right)$$

Eq.(A.12)

$$(f_i + \Delta f_i)^2 = f_i^2 + 2f_i\Delta f_i$$

Eq.(A.13)

$$\Delta A_t = \frac{dA}{dy_{l_t}} \Delta y_t$$

Eq.(A.14)

$$\Delta B_t = \frac{dB}{dy_{l_t}} \Delta y_t$$

Eq.(A.15)

$$\Delta S_A = \frac{2nS_A \Delta Q_t}{Q_t} + [S_A \frac{B_t}{A_t} (m-3n) - S_A \frac{1}{P_t} \frac{dP}{dy_{l_t}} (m-3n)] \Delta y_t$$

Eq.(A.16)

APPENDIX B
DOUBLE SWEEP METHOD
DERIVATION OF EQUATIONS

DOUBLE SWEEP METHOD: DERIVATIONS OF EQUATIONS

Substitution of Eq. (2.28) in Eq. (2.26) results in:

$$a_i \Delta y_{i-1} + b_i \Delta Q_{i-1} - c_i \Delta y_i + d_i (E_i \Delta y_i + F_i) = e_i$$

Eq. (B.1)

from which Δy_i can be evaluated as:

$$\Delta y_i = (L_i \Delta y_{i-1} + M_i \Delta Q_{i-1}) - K_i$$

Eq. (B.2)

where

$$L_i = \frac{a_i}{c_i + d_i E_i}$$

Eq. (B.3)

$$M_i = \frac{b_i}{c_i + d_i E_i}$$

Eq. (B.4)

and

$$K_i = \frac{e_i + d_i F_i}{c_i + d_i E_i}$$

Eq. (B.5)

Similarly, substitution of Eq. (2.29) in Eq. (2.27), results in:

$$a_i \Delta y_{i+1} + b_i \Delta Q_{i+1} - c_i \Delta y_i + d_i (E_i \Delta y_i + F_i) = e_i$$

Eq. (B.6)

When the value of Δy_i as given by Eq. (B.2) is substituted in the above equation and the terms are rearranged, we get:

$$\Delta Q_{i+1} - E_{i+1} \Delta y_{i+1} + F_{i+1}$$

Eq. (B.7)

where

$$E_{i+1} = \frac{a_i(c_i + d_i E_i) - a_i(c_i + d_i E_i)}{b_i(c_i + d_i E_i) - b_i(c_i + d_i E_i)}$$

Eq. (B.8)

and

$$F_{i+1} = \frac{(c_i + d_i F_i)(c_i + d_i E_i)(c_i + d_i F_i)(c_i + d_i E_i)}{b_i(c_i + d_i E_i)b_i(c_i + d_i E_i)}$$

Eq. (B.9)

APPENDIX C
EVALUATION OF CONSTANTS
 $E_1, F_1, \Delta V_N$

EVALUATION OF E_I AND F_I FOR EACH OF THE THREE BOUNDARY CONDITIONS:

Case 1:

When the upstream flow depth y_I is expressed as a known function of time, it is possible to compute Δy_I as:

$$\Delta y_I = f_{y_I}(t + \Delta t) - f_{y_I}(t)$$

Eq. (C.1)

Applying Eq.(2.28) to the upstream boundary, we get:

$$\Delta Q_I - E_I \Delta y_I + F_I$$

Eq. (C.2)

or

$$\Delta y_I = \frac{\Delta Q_I}{E_I} - \frac{F_I}{E_I}$$

Eq. (C.3)

Since Δy_I and ΔQ_I are, in general, independent parameters, the above equation can be considered to be valid only for large values of E_I compared to ΔQ_I so that the first term on the right hand side of Eq.(C.3) approaches zero. By equating E_I to a very large value, say ∞ , we can determine the value of F_I as follows:

$$F_I = -\Delta Q_I - f_{Q_I}(t + \Delta t) - f_{Q_I}(t)$$

Eq. (C.4)

In practice, the value of Δt should be of the order of 10^4 to 10^6 .

Case 2:

When the upstream flow rate Q_I is expressed as a known function of time, we can write:

$$\Delta Q_I = f_{Q_I}(t + \Delta t) - f_{Q_I}(t)$$

Eq. (C.5)

Again considering Eq. (C.2) and arguing that Δy_I and ΔQ_I are independent parameters, we conclude that the value of E_I should be zero and F_I is given by the following equation:

$$F_I = \Delta Q_I - f_{Q_I}(t + \Delta t) - f_{Q_I}(t)$$

Eq. (C.6)

Case 3:

When the upstream flow rate Q_I is expressed as a known function of upstream flow depth y_I , i.e. when the upstream boundary rating curve f_U (f_U could be a polynomial or a tabulated function) is given, then the coefficients E_I and F_I can be determined as follows.

Using Eq. (2.23), Q_1^{j+1} is expressed as:

$$Q_1^{j+1} = Q_1^j + \Delta Q_1$$

Eq. (C.7)

where Q_1^j is the computed flow rate at time t . From the boundary condition, we get:

$$Q_1(t+\Delta t) - f_u(y^j) + \frac{df_u}{dy_1} \Delta y_1$$

Eq. (C.8)

A comparison of Eqs.(C.7) and (C.8) gives:

$$Q_1^j + \Delta Q_1 - f_u(y^j) + \frac{df_u}{dy_1} \Delta y_1$$

Eq. (C.9)

from which ΔQ_1 can be evaluated as:

$$\Delta Q_1 - [f_u(y_1') - Q^*_1] + \frac{df_u}{dy_1} \Delta y_1$$

Eq. (C.10)

Therefore, we get:

$$E_1 = \frac{df_u}{dy_1}$$

and

$$F_1 - [f_u(y_1') - Q^*_1]$$

Eqs. (C.11)

Ideally, F_I should be zero, but because of numerical errors, F_I may take a small non-zero value, thereby playing the role of a correctional parameter.

EVALUATION OF Δy_N

Case 1:

When the downstream flow depth y_N is expressed as a known function of time, it is possible to compute Δy_N as:

$$\Delta y_N = [f_{y_N}(t + \Delta t) - f_{y_N}(t)]$$

Eq. (C.12)

Case 2:

When the downstream flow rate Q_N is expressed as a known function of time, we can compute ΔQ_N as:

$$\Delta Q_N = [f_{Q_N}(t + \Delta t) - f_{Q_N}(t)]$$

Eq. (C.13)

Applying Eq. (2.28) to the downstream boundary, we get:

$$\Delta Q_N = E_N \Delta y_N + F_N$$

Eq. (C.14)

The value of Δy_N can, therefore, be determined as:

$$\Delta y_N = \frac{[f_{QN}(t+\Delta t) - f_{QN}(t)] - F_N}{E_N}$$

Eq. (C.15)

Case 3:

When the downstream boundary rating curve f_D is given, Δy_N could be calculated as shown below:

Expressing Q_N^{j+1} as:

$$Q_N^{j+1} = Q_N^j + \Delta Q_N$$

Eq. (C.16)

and evaluating $Q_N(t+\Delta t)$ from the rating curve f_D as:

$$Q_N(t+\Delta t) = f_D(y_N^j) + \frac{df_D}{dy_N} \Delta y_N$$

Eq. (C.17)

we get the following relation:

$$f_D(y_N) + \frac{df_D}{dy_{N_1}} \Delta y_N - Q_N' + \Delta Q_N$$

Eq. (C.18)

Substituting $(E_N \Delta y_N + F_N)$ for ΔQ_N , the above relation can be rearranged to give the value of Δy_N as:

$$\Delta y_N = \frac{[f_D(y_N) - f_N - Q_N']}{[E_N - \frac{df_D}{dy_{N_1}}]}$$

Eq. (C.19)

APPENDIX. D
RESULTS OF DISCRETIZATION
OF
SEDIMENT CONTINUITY EQUATION

DEFINITION OF RESULTS OF DISCRETIZATION OF SEDIMENT CONTINUITY EQUATION:

$$\begin{aligned} \Delta z_{i-0.5} &= \frac{\Delta t}{p} \left(\frac{2}{P_{i-0.5}^j P_{i-0.5}^{j+1}} \right) \left[\left(\frac{q_{i-0.5}^j + q_{i-0.5}^{j+1}}{2} \right) - \right. \\ &\quad \left. \frac{1}{2} \left[\frac{Q_{i-1}^j - Q_{i-1}^{j+1}}{\Delta x} + \frac{Q_i^{j+1} - Q_i^j}{\Delta x} \right] - \right. \\ &\quad \left. \frac{1}{2} \left[\frac{(AC_{\sigma})_i^{j+1} - (AC_{\sigma})_i^j}{\Delta t} + \frac{(AC_{\sigma})_{i-1}^{j+1} - (AC_{\sigma})_{i-1}^j}{\Delta t} \right] \right] \end{aligned}$$

Eq. (D.1)

$$\begin{aligned} \Delta z_{i+0.5} &= \frac{\Delta t}{p} \left(\frac{2}{P_{i+0.5}^j P_{i+0.5}^{j+1}} \right) \left[\left(\frac{q_{i+0.5}^j + q_{i+0.5}^{j+1}}{2} \right) - \right. \\ &\quad \left. \frac{1}{2} \left[\frac{Q_{i+1}^j - Q_{i+1}^{j+1}}{\Delta x} + \frac{Q_{i+1}^{j+1} - Q_i^j}{\Delta x} \right] - \right. \\ &\quad \left. \frac{1}{2} \left[\frac{(AC_{\sigma})_i^{j+1} - (AC_{\sigma})_i^j}{\Delta t} + \frac{(AC_{\sigma})_{i+1}^{j+1} - (AC_{\sigma})_{i+1}^j}{\Delta t} \right] \right] \end{aligned}$$

Eq. (D.2)

APPENDIX E
DESCRIPTION OF THE MODEL CODE
AND
MODIFICATION-INPUT FORMATTING

DESCRIPTION OF SUBROUTINES USED IN PROGRAM

COMPARE: This subroutine, from a given data set, forms a subset of data points arranged in ascending order of their lateral distances which have elevations less than or equal to $(y_{min} + 0.30\text{m})$.

CROSS: This subroutine calculates the cross-sectional area under water, the wetted perimeter, and the width.

DSTREAM: The value of Δy_n is calculated from the downstream boundary condition using this subroutine.

FORMULA: This subroutine assists the subroutine COMPARE in performing the function described in subroutine COMPARE.

FRICT: This subroutine is active only for mobile boundary flows and calculates frictional parameters namely, Constr, Em, and En. It also computes the reach average slopes of the energy grade line and the stream bed and the type of the bed form present.

GEOMET: This subroutine is used to establish the geometric characteristics of the river section such as A, P, B, dP/dy , dB/dy , and A_x^y for the initial flow depths specified.

KLIST: Subroutine KLIST assigns the correct areas, top widths, wetted perimeters to each grid location of the river reach.

PROFILE: Subroutine PROFILE like the subroutine GEOMET computes the geometric characteristics of the river reach but differs from GEOMET in calculating them for each grid location.

SEDI: Subroutine SEDI is called by the main program for mobile boundary flows to calculate the sediment transport rate Q_s and the average concentration of the sediment C_{av} .

SEEK: Subroutine SEEK establishes a reach average relative roughness parameter Z for any instant of time t , which is then used in determining the regime of bed form shapes.

USTREAM: This subroutine computes the upstream boundary double sweep coefficients, i.e., E_1 and F_1 .

INPUT DATA ARRANGEMENT

Input data to the model are specified in two files: Tape8 and Tape1. Tape8 contains the data pertaining to flow conditions, total simulation time, initial and boundary conditions, frictional parameters, and all other data except the data pertaining to the river geometry. The geometric characteristics of the river reach are read in the file called Tape1.

There are 14 data group cards in Tape8 input file. Fig.E1 specifies the input data arrangement for the model. Each of the parameters is specified below. The format and field columns are specified in the manual. However, the sample input file has been marked to show the field columns of each parameter.

DATA GROUP 1:

IL - the number of time steps for which model simulation is carried out.

IP - is an integer value representing the time at the start of the model simulation.

ITEST -control parameter to print out all the results of the model calculations.

DATA GROUP 2:

N - number of grid locations along the river reach

INFLOW- control parameter which indicates the presence or absence of a tributary in the river reach

IN- an integer varying from 1 to N representing the position of the tributary

INT- an integer, indicating the time (in seconds) of start of tributary inflow

IS- an integer between 1 to N, to indicate the position of a storage basin in terms of the grid

positions. IS=0 indicates absence of storage basin.

ISED- control parameter to indicate the nature of river reach, i.e., rigid or mobile bed

IFRICT- control parameter to choose the friction factor relation.

METRIC- conversion factor to convert the geometric data specified in Tape1 from british to metric units.

XIN- location of the first cross-section for which the geometric data are specified.

DATA GROUP 3:

THETA- a weighting coefficient

DELTA X- distance in meters between grid locations

DELTA T- time increments in seconds

XLENGTH- total distance of reach

G- acceleration due to gravity (m/s^2)

QIN- tributary flow rate in $\text{m}^3/\text{s}/\text{m}$

QSED- sediment inflow rate in $\text{m}^3/\text{s}/\text{m}$

SAR- water surface area of storage basin in m^2

DATA GROUP 4:

Y(I), I=1 TO N- Initial flow depth values for N grid locations

DATA GROUP 5:

Q(I), I=1 TO N- Initial flow rate values for N grid locations

DATA GROUP 6:

Z(I), I=1 TO N- The bottom elevations for N grid locations

DATA GROUP 7:

IYEAR- an identifier for the geometric data

IDEEP- maximum flow depth expected

IPRNT- control parameter to print out all the geometric properties of the river reach, IPRNT=1

DATA GROUP 8:

GAM- specific weight of water (1000kg/m^3)

GAMS- submerged specific weight of sediment (1650kg/m^3)

D35- sediment size in meters for which 35% are finer than this size

D65- sediment size in meters for which 65% are finer than this size

ANU- kinematic viscosity of water in m^2/sec

DATA GROUP 9:

PORS- porosity of sediment bed

DATA GROUP 10:

TQS(I), I=1 TO IL- sediment transport rate at upstream boundary in kg/s for IL number of time steps

DATA GROUP 11:

ITYPEUP- type of upstream boundary condition

ITYPEDN- type of downstream boundary condition

AAU- for ITYPEUP=3, this is the parameter of stage-discharge relationship expressed as $Q_u =$

$$(AAU)Y_u^{(BBU)} + (CCU)$$

BBU- parameter of u/s stage-discharge relationship

CCU- parameter of u/s stage-discharge relationship

AAD- for ITYPEDN=3, this is the parameter of stage-discharge relationship expressed as $Q_d =$

$$(AAD)Y_d^{(BBD)} + (CCD)$$

BBD- parameter for d/s stage-discharge relationship

CCD- parameter for d/s stage-discharge relationship

DATA GROUP 12:

TQ(I), I=1 TO IL- flow rate as a function of time at the u/s or d/s boundary

DATA GROUP 13:

TY(I), I=1 TO IL- flow depth as a function of time at the u/s or d/s boundary

DATA GROUP 14:

CONSTR- If friction factor relationship is chosen to be other than Kishi and Kuroki's, this parameter is given from the relationship expressed as

$$S_f = \text{CONST}(R/D65)^{EM} (V^2/gR)^{EN}$$

EM- friction parameter

EN- friction parameter

IBED- parameter defining the bed form (for mobile bed cases only), otherwise give IBED=4

FIG. E1 INPUT DATA ARRANGEMENT
TAPE8 (FLOW DATA)

<u>DATA GROUPS</u>	<u>PARAMETERS IN DATA GROUPS</u>
DATA GROUP 1:	IL, IP, ITEST
DATA GROUP 2:	N, INFLOW, IN, INT, IS, ISED, IFRICT, METRIC, XIN
DATA GROUP 3:	THETA, DELTAX, DELTAT, XLENGH, G, QIN, QSED, SAR
DATA GROUP 4:	Y(I), I=1 TO N
DATA GROUP 5:	Q(I), I=1 TO N
DATA GROUP 6:	Z(I), I=1 TO N
DATA GROUP 7:	IYEAR, IDEEP, IPRNT
DATA GROUP 8:	GAM, GAMS, D35, D65, ANU
DATA GROUP 9:	PORS
DATA GROUP 10:	TQ(I), I=1 TO IL
DATA GROUP 11:	ITYPEUP, ITYPEDN, AAU, BBU, CCU, AAD, BBD, CCD
DATA GROUP 12:	TQ(I), I=1 TO IL
DATA GROUP 13:	TY(I), I=1 TO IL
DATA GROUP 14:	CONSTR, EM, EN, IBED

Tape1 input file specifies the shapes of river cross-section at different stations along the length of the river reach as well as the distance between these stations. Fig E.2 shows the schematic arrangement of geometric parameters in Tape1. A brief description of the parameters is given as follows:

DATA CARD X1:

SECNO- an identifier for the cross-section

NUMST- an integer value specifying the number of coordinate points to define the shape of the cross-section

XLCH- the distance between the adjacent stations where the shape of the cross-sections are specified

DATA CARD GR:

GR card specifies the shape of the cross-section in terms of coordinate points



X(1)- is the lateral distance of a point on the perimeter of the cross-section

Y(1)- is the elevation of the same point

X(2)- lateral distance of the second point and so on.

This group contains coordinates of NUMST points and then repeats from X1 group for the next station until all the cross-section shapes are defined.

FIG. E2. INPUT DATA ARRANGEMENT
TAPE1 (GEOMETRIC DATA)

<u>DATA GROUP</u>	<u>PARAMETERS IN DATA GROUP</u>
DATA GROUP X1:	SECNO. NUMST. XLCH
DATA GROUP GR:	X(1). Y(1): X(2). Y(2):.....
DATA GROUP GR:X(NUMST). Y(NUMST)
DATA GROUP X1:	SECNO. NUMST. XLCH
DATA GROUP GR:	X(1). Y(1): X(2). Y(2):.....
DATA GROUP GR:X(NUMST). Y(NUMST)
<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;">  </div> <div style="text-align: center;">  </div> </div>	
DATA GROUP X1:	SECNO. NUMST. XLCH
DATA GROUP GR:	X(1). Y(1):.....

LISTING OF HYDROG.FOR
SUBROUTINE HYDROG(IL,IP,JCTL)

SDEBUG

IMPLICIT REAL*8 (A-H,O-Z)

COMMON/D/ TQ(1000),TY(1000),E(61),F(61),DELY(61),Q(61)

COMMON/E/ DELTAX,DELTAT,N

DIMENSION TCTL(61),QCTL(61)

READ(60,100) (TCTL(I),QCTL(I),I=1,JCTL)

J=1

I=1

T=FLOAT(IP)*DELTAT

IF(T.LT.TCTL(1)) GOTO 40

10 J=J+1

20 IF(T.LE.TCTL(J)) GOTO 30

C ==> T > TCTL(J)

IF(J.LT.JCTL) GOTO 10

GOTO 40

30 TQ(I)=QCTL(J-1)+((QCTL(J)-QCTL(J-1))/(TCTL(J)-TCTL(J-1)))

S*(T-TCTL(J-1))

IF(LGT.IL) GOTO 40

I=I+1

T=T+DELTAT

GOTO 20

```
100  FORMAT(8F10.3)
```

```
40   RETURN
```

```
      END
```

SAMPLE OF MODIFIED INPUT FILE

TAPES INPUT FILE

```

800 0 0 0 1
8 0 0 0 0 0 0 1.0000 0.0000
0.667 30.000 2.000 210.000 9.810 0.000 0.000 0.000
.2250 .2250 .2250 .2250 .2250 .2250 .2250 .2250
.1030 .1030 .1030 .1030 .1030 .1030 .1030 .1030
.040 .034 .029 .023 .017 .011 .006 .000
1989 3 1
.1000E+04 .1650E+04 .1500E-03 .1500E-03 .1000E-05
.00
2 3 .000 .000 .000 .744 1.000 -0.064
5
0. 0.103 300. 0.103 750. 0.1955 1200. 0.104
3000. 0.104
.0266-0.3333333 1.000000 0
.000000 .000000 .000000 .000000 .000000 .000000 .000000 .000000
.000000 .000000 .000000 .000000 .000000 .000000 .000000 .000000

```


SAMPLE OF MOBED OUTPUT

RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
.00	.032	.000	.00	.76
.00	.337	.305	.38	1.25
.00	.642	.610	1.75	5.75
.00	.946	.914	3.50	5.75
RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
30.00	.027	.000	.00	.76
30.00	.332	.305	.38	1.25
30.00	.637	.610	1.75	5.75
30.00	.941	.914	3.50	5.75
RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
60.00	.023	.000	.00	.76
60.00	.328	.305	.38	1.25
60.00	.633	.610	1.75	5.75
60.00	.937	.914	3.50	5.75
RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
90.00	.018	.000	.00	.76
90.00	.323	.305	.38	1.25
90.00	.628	.610	1.75	5.75
90.00	.932	.914	3.50	5.75
RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
120.00	.014	.000	.00	.76
120.00	.319	.305	.38	1.25
120.00	.624	.610	1.75	5.75
120.00	.928	.914	3.50	5.75
RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
150.00	.009	.000	.00	.76
150.00	.314	.305	.38	1.25
150.00	.619	.610	1.75	5.75
150.00	.923	.914	3.50	5.75
RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
180.00	.005	.000	.00	.76
180.00	.310	.305	.38	1.25
180.00	.615	.610	1.75	5.75
180.00	.919	.914	3.50	5.75
RANGE	ELEVATION	DEPTH	AREA	WETTED PERIMETER
TOP WIDTH				
210.00	.000	.000	.00	.76
210.00	.305	.305	.38	1.25
210.00	.610	.610	1.75	5.75
210.00	.914	.914	3.50	5.75

RANGE NUMBERS ASSIGNED

.00
30.00
60.00
90.00
120.00
150.00
180.00
210.00

NUMBER OF GRID POINTS ALONG THE RIVER REACH N= 8
CONTROL PARAMETER FOR TRIBUTORY PRESENCE INFLOW= 0
LOCATION OF TRIBUTORY IN= 0
TIME WHEN TRIBUTORY INFLOW BEGINS INT= 0
CONTROL PARAMETER FOR STORAGE BASIN IS= 0
CONTROL PARAMETER SIGNIFYING THE NATURE OF FLOW BOUNDARY ISED= 0
WEIGHTING COEFFICIENT THETA= .667
DISTANCE IN METERS BETWEEN GRID POINTS DELTAX= 30.00
TIME INCREMENTS IN SECONDS DELTAT= 14.0
TOTAL LENGTH OF RIVER REACH MODELLED XLENGTH= 210.00
ACCELERATION DUE TO GRAVITY G= 9.8100
FLOW RATE OF TRIBUTORY QIN= .0000
RATE OF SEDIMENT INFLOW QSED= .0000
WATER SURFACE AREA OF STORAGE BASIN SAR= .0000
THE GRAIN SIZE FOR SEDIMENTS IS= .000150
THE GRAIN SIZE OF SEDIMENT RESPONSIBLE FOR ROUGHNESS .000150
THE VALUE OF KINEMATIC VISCOSITY IS= .000001
UPSTREAM BOUNDARY TYPE= 2
DOWNSTREAM BOUNDARY TYPE= 3
BOUNDARY VALUES

[illegible]

DISTANCE ELEVATION	FLOW RATE TOP WIDTH	FLOW DEPTH FLOW AREA	SEDIMENT RATE FRICTION FACTOR	ROUDE N	BOTTOM HYDRAULIC RADIUS			
.00	.1030	.2770	.000000	.0458	.032000	1.2058	.3463	17.4363
30.00	.1030	.2770	.000000	.0458	.027000	1.2058	.3463	17.4363
60.00	.1030	.2770	.000000	.0458	.023000	1.2058	.3463	17.4363
90.00	.1030	.2770	.000000	.0458	.018000	1.2058	.3463	17.4363
120.00	.1030	.2770	.000000	.0458	.014000	1.2058	.3463	17.4363
150.00	.1030	.2770	.000000	.0458	.009000	1.2058	.3463	17.4363
180.00	.1030	.2770	.000000	.0458	.005000	1.2058	.3463	17.4363
210.00	.1030	.2770	.000000	.0458	.000000	1.2058	.3463	17.4363
SOLUTION AT TIME T=								
.00DAYS			.00HOURS		.00MINUTES		14.00SECONDS	

DISTANCE ELEVATION	FLOW RATE TOP WIDTH	FLOW DEPTH FLOW AREA	SEDIMENT RATE FRICTION FACTOR	ROUDE N HYDRAULIC RADIUS	BOTTOM			
.00	.1030	.2773	.000000	.0457	.032000	1.2062	.3466	17.2147
.1968								
30.00	.1017	.2774	.000000	.0445	.027000	1.2065	.3468	16.9759
.1969								
60.00	.1015	.2766	.000000	.0447	.023000	1.2052	.3458	17.0194
.1966								
90.00	.1015	.2774	.000000	.0444	.018000	1.2064	.3467	16.9606
.1969								
120.00	.1015	.2766	.000000	.0447	.014000	1.2052	.3458	17.0178
.1966								
150.00	.1016	.2774	.000000	.0444	.009000	1.2064	.3467	16.9648
.1969								
180.00	.1013	.2767	.000000	.0445	.005000	1.2053	.3459	16.9766
.1967								
210.00	.1034	.2762	.000000	.0465	.000000	1.2045	.3453	17.3604
.1965								

SOLUTION AT TIME T= .00DAYS .00HOURS .00MINUTES 28.00SECONDS

DISTANCE ELEVATION	FLOW RATE TOP WIDTH	FLOW DEPTH FLOW AREA	SEDIMENT RATE FRICTION FACTOR	ROUDE N HYDRAULIC RADIUS	BOTTOM			
.00	.1030	.2780	.000000	.0454	.032000	1.2074	.3476	16.8226
.1971								
30.00	.1015	.2777	.000000	.0443	.027000	1.2070	.3472	16.6062
.1970								
60.00	.1005	.2769	.000000	.0437	.023000	1.2056	.3461	16.4935
.1967								
90.00	.1003	.2772	.000000	.0434	.018000	1.2061	.3465	16.4433
.1968								
120.00	.1003	.2768	.000000	.0436	.014000	1.2054	.3460	16.4782
.1967								
150.00	.1001	.2773	.000000	.0431	.009000	1.2063	.3467	16.3910
.1969								
180.00	.1013	.2762	.000000	.0447	.005000	1.2044	.3452	16.6882
.1965								
210.00	.1028	.2755	.000000	.0463	.000000	1.2033	.3443	16.9892
.1963								

SOLUTION AT TIME T= .00DAYS .00HOURS .00MINUTES 42.00SECONDS

DISTANCE ELEVATION	FLOW RATE TOP WIDTH	FLOW DEPTH FLOW AREA	SEDIMENT RATE FRICTION FACTOR	ROUDE N HYDRAULIC RADIUS	BOTTOM
-----------------------	------------------------	-------------------------	----------------------------------	-----------------------------	--------

APPENDIX F
PROGRAMS FOR ERROR ESTIMATION

LISTING OF PROGRAM "EXTRACTR.RIG"

```
DECLARE FUNCTION Interpolate! (y2!, y1!, t2!, t1!)
```

```
PRINT "Formatting mobed.out"
```

```
INPUT "FileName used to create mobed.out"; MobedInput$
```

```
INPUT "Which input file # was used to create mobed.out"; MobedInput
```

```
INPUT "Give the section numbers for printing"; SecX, SecY, SecZ
```

```
DIM Distance      AS SINGLE
DIM FlowRate      AS SINGLE
DIM FlowDepth     AS SINGLE
DIM MeasuredFlow  AS SINGLE
DIM MeasuredDepth AS SINGLE
DIM MaxFlow1      AS SINGLE
DIM MaxFlowN      AS SINGLE
DIM MaxDepth1     AS SINGLE
DIM MaxDepthN     AS SINGLE
DIM DiffFlow1     AS DOUBLE
DIM DiffFlowN     AS DOUBLE
DIM PrevFlow1     AS SINGLE
DIM PrevDepth1    AS SINGLE
DIM PrevFlowN     AS SINGLE
DIM PrevDepthN    AS SINGLE
DIM DiffDepth1    AS DOUBLE
DIM DiffDepthN    AS DOUBLE
DIM BottomElev1   AS SINGLE
DIM BottomElevN   AS SINGLE
DIM Temp          AS SINGLE
```

```
BottomElev1 = .092
```

```
BottomElevN = .052
```

```
SELECT CASE MobedInput
```

```
  CASE 1
```

```
    N = 8
```

```
    DeltaT = 2
```

```
    SectionLength = 30
```

```
  CASE 2
```

```
    N = 8
```

```
    DeltaT = 4
```

```
    SectionLength = 30
```

```
  CASE 3
```

```
    N = 8
```

```
    DeltaT = 6
```

```
    SectionLength = 30
```

CASE 4
 N = 8
 DeltaT = 8
 SectionLength = 30
 CASE 5
 N = 8
 DeltaT = 10
 SectionLength = 30
 CASE 6
 N = 8
 DeltaT = 12
 SectionLength = 30
 CASE 7
 N = 8
 DeltaT = 14
 SectionLength = 30
 CASE 11
 N = 15
 DeltaT = 1
 SectionLength = 15
 CASE 12
 N = 15
 DeltaT = 2
 SectionLength = 15
 CASE 13
 N = 15
 DeltaT = 3
 SectionLength = 15
 CASE 14
 N = 15
 DeltaT = 4
 SectionLength = 15
 CASE 15
 N = 15
 DeltaT = 5
 SectionLength = 15
 CASE 16
 N = 15
 DeltaT = 6
 SectionLength = 15
 CASE 17
 N = 15
 DeltaT = 7
 SectionLength = 15
 CASE 21
 N = 6
 DeltaT = 3
 SectionLength = 45

```

CASE 22
  N = 6
  DeltaT = 6
  SectionLength = 45
CASE 23
  N = 6
  DeltaT = 9
  SectionLength = 45
CASE 24
  N = 6
  DeltaT = 12
  SectionLength = 45
CASE 25
  N = 6
  DeltaT = 15
  SectionLength = 45
CASE 26
  N = 6
  DeltaT = 18
  SectionLength = 45
CASE 27
  N = 6
  DeltaT = 21
  SectionLength = 45
END SELECT

```

```

REM MobedInput$ = "F" + LTRIMS(STR$(MobedInput)) + "_"
MobedInput$ = MobedInput$ + "_"

```

```

FileNum = 1
Section$ = LTRIMS(STR$(FileNum))
FileName$ = "d:\temp\" + MobedInput$ + Section$ + ".fmt"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, MobedInput, FileNum, DeltaT, SectionLength, N

```

```

FileNum = SecX
Section$ = LTRIMS(STR$(FileNum))
FileName$ = "d:\temp\" + MobedInput$ + Section$ + ".fmt"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, MobedInput, FileNum, DeltaT, SectionLength, N

```

```

FileNum = SecY
Section$ = LTRIMS(STR$(FileNum))
FileName$ = "d:\temp\" + MobedInput$ + Section$ + ".fmt"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, MobedInput, FileNum, DeltaT, SectionLength, N

```



```

FileNum = SecZ
Section$ = LTRIMS(STR$(FileNum))
FileName$ = "d:\temp\" + MobedInput$ + Section$ + ".fmt"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, MobedInput, FileNum, DeltaT, SectionLength, N

```

```

FileNum = N
Section$ = LTRIMS(STR$(FileNum))
FileName$ = "d:\temp\" + MobedInput$ + Section$ + ".fmt"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, MobedInput, FileNum, DeltaT, SectionLength, N

```

```

ErrorFile = FREEFILE
FileName$ = "d:\temp\" + MobedInput$ + "ERR" + ".fmt"
OPEN FileName$ FOR OUTPUT AS #ErrorFile
InputFile = FREEFILE
OPEN "c:\usha\major-pa\mobed.out" FOR INPUT AS #InputFile

```

```

Measure1 = FREEFILE
OPEN "c:\usha\major-pa\measure1" FOR INPUT AS #Measure1

```

```

MeasureN = FREEFILE
OPEN "c:\usha\major-pa\measureN" FOR INPUT AS #MeasureN

```

```

NumOfMinutes = 0
NumOfSeconds = 0
DiffFlow1 = 0
DiffFlowN = 0
DiffDepth1 = 0
DiffDepthN = 0
MaxFlow1 = 0
MaxFlowN = 0
MaxDepth1 = 0
MaxDepthN = 0

```

Discard:

```

    LINE INPUT #InputFile, Junk$
    IF INSTR(Junk$, "SOLUTION") = 0 THEN GOTO Discard

```

DO

```

    LINE INPUT #InputFile, Junk$
    LINE INPUT #InputFile, Junk$

```

FOR LineNum = 1 TO N STEP 1

```

    INPUT #InputFile, Distance, FlowRate, FlowDepth
    LINE INPUT #InputFile, Junk$

```

```

IF (LineNum <> 1) AND (LineNum <> SecX) AND (LineNum <> SecY) AND
(LineNum <> SecZ) AND (LineNum <> N) THEN GOTO NextLine

```

```

FileNum = LineNum
PRINT #FileNum, USING "###.#####"; (NumOfMinutes + NumOfSeconds / 60);
PRINT #FileNum, " ";
PRINT #FileNum, USING "###.#####"; FlowRate;
PRINT #FileNum, " ";
Temp = FlowDepth
IF LineNum = 1 THEN Temp = Temp + BottomElev1
IF LineNum = N THEN Temp = Temp + BottomElevN
PRINT #FileNum, USING "###.#####"; Temp;
PRINT #FileNum, " ";

```

```

IF (NumOfSeconds = 0 AND NumOfMinutes = 0) OR (NumOfSeconds >= 60) THEN
GOTO DoErrorAnalysis

```

```

GOTO EndErrorAnalysis

```

```

DoErrorAnalysis:

```

```

IF LineNum <> 1 THEN GOTO 30

```

```

INPUT #Measure1, MeasuredFlow, MeasuredDepth
IF MeasuredFlow > MaxFlow1 THEN MaxFlow1 = MeasuredFlow
IF MeasuredDepth > MaxDepth1 THEN MaxDepth1 = MeasuredDepth
IF (NumOfSeconds MOD 60) = 0 THEN GOTO 10
CalcFlow = Interpolate(FlowRate, PrevFlow1, NumOfSeconds, NumOfSeconds - DeltaT)
CalcDepth = Interpolate(FlowDepth, PrevDepth1, NumOfSeconds, NumOfSeconds -

```

```

DeltaT)

```

```

GOTO 20

```

```

10 : CalcFlow = FlowRate

```

```

CalcDepth = FlowDepth

```

```

20 : DiffFlow1 = DiffFlow1 + (MeasuredFlow - CalcFlow) ^ 2

```

```

DiffDepth1 = DiffDepth1 + (MeasuredDepth - (CalcDepth + BottomElev1)) ^ 2

```

```

GOTO PrintMeasuredValues

```

```

30 :

```

```

IF LineNum <> N THEN GOTO EndErrorAnalysis

```

```

INPUT #MeasureN, MeasuredFlow, MeasuredDepth

```

```

IF MeasuredFlow > MaxFlowN THEN MaxFlowN = MeasuredFlow

```

```

IF MeasuredDepth > MaxDepthN THEN MaxDepthN = MeasuredDepth

```

```

IF (NumOfSeconds MOD 60) = 0 THEN GOTO 40

```

```

CalcFlow = Interpolate(FlowRate, PrevFlowN, NumOfSeconds, NumOfSeconds - DeltaT)

```

```

CalcDepth = Interpolate(FlowDepth, PrevDepthN, NumOfSeconds, NumOfSeconds -
DeltaT)

```

```

GOTO 50

```

```

40 : CalcFlow = FlowRate

```

```

CalcDepth = FlowDepth

```

```

50 : DiffFlowN = DiffFlowN + (MeasuredFlow - CalcFlow) ^ 2

```

```

DiffDepthN = DiffDepthN + (MeasuredDepth - (CalcDepth + BottomElevN)) ^ 2

```

```

        IF (NumOfSeconds = 0) AND (NumOfMinutes = 0) THEN GOTO EndRollOver
        NumOfSeconds = NumOfSeconds - 60
        NumOfMinutes = NumOfMinutes + 1
EndRollOver:
PrintMeasuredValues:
    IF (NumOfSeconds MOD 60 = 0) THEN GOTO 60
REM insert a new line
    PRINT #FileNum, " "
    PRINT #FileNum, USING "###.#####"; (NumOfMinutes + NumOfSeconds \ 60);
    PRINT #FileNum, " ";
    PRINT #FileNum, USING "###.#####"; CalcFlow;
    PRINT #FileNum, " ";
    PRINT #FileNum, USING "###.#####"; CalcDepth;
60 :
    PRINT #FileNum, USING "###.#####"; MeasuredFlow;
    PRINT #FileNum, " ";
    PRINT #FileNum, USING "###.#####"; MeasuredDepth;

EndErrorAnalysis:
    PRINT #FileNum, " "

NextLine:
    IF LineNum = 1 THEN PrevFlow1 = FlowRate: PrevDepth1 = FlowDepth
    IF LineNum = N THEN PrevFlowN = FlowRate: PrevDepthN = FlowDepth
    NEXT LineNum

    NumOfSeconds = NumOfSeconds + DeltaT

    IF EOF(InputFile) THEN GOTO ExitLoop
    LINE INPUT #InputFile, Junk$
LOOP
ExitLoop:

PRINT #ErrorFile, USING "#####"; MobedInput;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; DeltaT;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; SectionLength;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; N;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "###.#####"; 1000 * SQR(DiffFlow1 / NumOfMinutes);
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "###.#####"; 100 * SQR(DiffFlow1 / NumOfMinutes) / MaxFlow1;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "###.#####"; 1000 * SQR(DiffDepth1 / NumOfMinutes);

```

```

PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "##.#####"; 100 * SQR(DiffDepth1/NumOfMinutes)/MaxDepth1;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "###.#####"; 1000 * SQR(DiffFlowN / NumOfMinutes);
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "##.#####"; 100 * SQR(DiffFlowN/NumOfMinutes) / MaxFlowN
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "###.#####"; 1000 * SQR(DiffDepthN / NumOfMinutes);
PRINT #ErrorFile, " ";

```

```

CLOSE #1
CLOSE #SecX
CLOSE #SecY
CLOSE #SecZ
CLOSE #N
CLOSE #ErrorFile
CLOSE #InputFile
CLOSE #Measure1
CLOSE #MeasureN

```

```

FUNCTION Interpolate (y2, y1, t2, t1)

```

```

    Interpolate = y1 + ((y2 - y1) / (t2 - t1)) * (60 - t1)

```

```

END FUNCTION

```

LISTING OF PROGRAM "EXTRACTR.MOB"

```

PRINT "Formatting mobed.out"
INPUT "FileName used to create mobed.out"; MobedInput$
INPUT "What output file prefix do you want to use ?"; OutPrefix$

INPUT "Give the intermediate section number for printing"; SecX

DIM FlowRate      AS SINGLE
DIM FlowDepth     AS SINGLE
DIM Temp          AS SINGLE
DIM MeasuredFlow  AS SINGLE
DIM MeasuredDepth AS SINGLE
DIM DiffFlow1     AS DOUBLE
DIM DiffFlowN     AS DOUBLE
DIM DiffDepth1    AS DOUBLE
DIM DiffDepthN    AS DOUBLE
DIM IL            AS SINGLE
DIM DeltaX, Theta AS SINGLE
DIM DeltaT        AS SINGLE

MobedInput = 80
MobedInput$ = "c:\usha\major-pa'pak-dat\" + MobedInput$
OPEN MobedInput$ FOR INPUT AS #MobedInput

REM read the first line of MobedInput file
LINE INPUT #MobedInput, Junk$
REM read the second line of MobedInput file
INPUT #MobedInput, N
LINE INPUT #MobedInput, Junk$
REM read the third line of MobedInput file
INPUT #MobedInput, Theta, DeltaX, DeltaT
LINE INPUT #MobedInput, Junk$
REM read 4th line
INPUT #MobedInput, MeasuredDepth
LINE INPUT #MobedInput, Junk$
REM read the 5th line
INPUT #MobedInput, MeasuredFlow
LINE INPUT #MobedInput, Junk$

FileNum = 1
Section$ = LTRIMS(STR$(FileNum))
FileName$ = "d:\kish\" + OutPrefix$ + "-" + Section$ + ".pak"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, FileName$, "  No Of Sections = "; N; "DeltaT= "; DeltaT

```

```

PRINT #FileNum, " "
PRINT #FileNum, "Bedform = 1 ==> DUNES OF TYPE 1; 2 ==> DUNES OF TYPE 2; 3
==> BED IN TRANSITION"
PRINT #FileNum, "Bedform = 4 ==> BED IS FLAT ; 5 ==> ANTIDUNES ; 9 ==>
ERROR "
PRINT #FileNum, " "
PRINT #FileNum, " Time FlowRate FlowDepth SediRate Bedform"

FileNum = SecX
Section$ = LTRIMS(STR$(FileNum))
FileName$ = "d:\kish\" + OutPrefix$ + "-" + Section$ + ".pak"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, FileName$; " No Of Sections = "; N; "DeltaT= "; DeltaT
PRINT #FileNum, " "
PRINT #FileNum, "Bedform = 1 ==> DUNES OF TYPE 1; 2 ==> DUNES OF TYPE 2; 3
==> BED IN TRANSITION"
PRINT #FileNum, "Bedform = 4 ==> BED IS FLAT ; 5 ==> ANTIDUNES ; 9 ==>
ERROR "
PRINT #FileNum, " "
PRINT #FileNum, " Time FlowRate FlowDepth SediRate Bedform"

FileNum = N
FileName$ = "d:\kish\" + OutPrefix$ + "-" + "N" + ".pak"
OPEN FileName$ FOR OUTPUT AS #FileNum
PRINT #FileNum, FileName$; " No Of Sections = "; N; "DeltaT= "; DeltaT
PRINT #FileNum, " "
PRINT #FileNum, "Bedform = 1 ==> DUNES OF TYPE 1; 2 ==> DUNES OF TYPE 2; 3
==> BED IN TRANSITION"
PRINT #FileNum, "Bedform = 4 ==> BED IS FLAT ; 5 ==> ANTIDUNES ; 9 ==>
ERROR "
PRINT #FileNum, " "
PRINT #FileNum, " Time FlowRate FlowDepth SediRate Bedform"

ErrorFile = FREEFILE
FileName$ = "d:\kish\" + OutPrefix$ + "-" + "ERR" + ".pak"
OPEN FileName$ FOR OUTPUT AS #ErrorFile

InputFile = FREEFILE
OPEN "c:\usha\major-pa\pak-dat\mobed.out" FOR INPUT AS #InputFile

NumOfMinutes = 0
NumOfSeconds = 0
DiffFlow1 = 0
DiffFlowN = 0
DiffDepth1 = 0
DiffDepthN = 0
IL = 0

```

Discard:

```
LINE INPUT #InputFile, Junk$
IF (INSTR(Junk$, "SOLUTION") = 0) THEN GOTO Discard
```

DO

```
LINE INPUT #InputFile, Junk$
LINE INPUT #InputFile, Junk$
```

FOR LineNum = 1 TO N STEP 1

```
INPUT #InputFile, Distance, FlowRate, FlowDepth, SedimentRate
LINE INPUT #InputFile, Junk$
```

IF (LineNum <> 1) AND (LineNum <> SecX) AND (LineNum <> N) THEN GOTO
NextLine

```
IF LineNum = 1 THEN DiffFlow1 = DiffFlow1 + (MeasuredFlow - FlowRate) ^ 2:
DiffDepth1 = DiffDepth1 + (MeasuredDepth - FlowDepth) ^ 2
```

```
IF LineNum = N THEN DiffFlowN = DiffFlowN + (MeasuredFlow - FlowRate) ^ 2:
DiffDepthN = DiffDepthN + (MeasuredDepth - FlowDepth) ^ 2
```

FileNum = LineNum

REM skip every alternate value

```
IF (IL MOD 2) = 1 THEN GOTO EndPrint1
```

```
PRINT #FileNum, USING "###.####"; (NumOfMinutes + NumOfSeconds / 60);
```

```
PRINT #FileNum, "  ";
```

```
PRINT #FileNum, USING "###.####"; FlowRate;
```

```
PRINT #FileNum, "  ";
```

```
PRINT #FileNum, USING "###.####"; FlowDepth;
```

```
PRINT #FileNum, "  ";
```

```
PRINT #FileNum, USING "###.####"; SedimentRate;
```

```
PRINT #FileNum, "  ";
```

EndPrint1:

NextLine:

```
NEXT LineNum
```

```
LINE INPUT #InputFile, Junk$
```

```
LINE INPUT #InputFile, Junk$
```

```
LINE INPUT #InputFile, Junk$
```

```
LINE INPUT #InputFile, Junk$
```

```
LINE INPUT #InputFile, Junk$
```

```
LINE INPUT #InputFile, Junk$
```

```

IF (INSTR(Junk$, "TYPE 1") <> 0) THEN Bedform = 1: GOTO 10
IF (INSTR(Junk$, "TYPE 2") <> 0) THEN Bedform = 2: GOTO 10
IF (INSTR(Junk$, "TRANSITION STATE") <> 0) THEN Bedform = 3: GOTO 10
IF (INSTR(Junk$, "BED IS FLAT") <> 0) THEN Bedform = 4: GOTO 10
IF (INSTR(Junk$, "COVERED WITH ANTIDUNES") <> 0) THEN Bedform = 5: GOTO 10
Bedform = 9
10

REM skip every alternate value
IF (IL MOD 2) = 1 THEN GOTO EndPrint2

PRINT #1, USING "#"; Bedform
PRINT #SecX, USING "#"; Bedform
PRINT #N, USING "#"; Bedform
EndPrint2:

NumOfSeconds = NumOfSeconds + DeltaT

IF EOF(InputFile) THEN GOTO ExitLoop
LINE INPUT #InputFile, Junk$

IL = IL + 1
LOOP
ExitLoop:

PRINT #ErrorFile, MobedInput$
PRINT #ErrorFile, USING "#####"; DeltaT;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; N;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; 100 * SQR(DiffFlow1 / IL) / MeasuredFlow;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; 100 * SQR(DiffDepth1 / IL) / MeasuredDepth;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; 100 * SQR(DiffFlowN / IL) / MeasuredFlow;
PRINT #ErrorFile, " ";
PRINT #ErrorFile, USING "#####"; 100 * SQR(DiffDepthN / IL) / MeasuredDepth

CLOSE #1
CLOSE #SecX
CLOSE #N
CLOSE #InputFile
CLOSE #ErrorFile

```


APPENDIX G
MODIFICATIONS MADE IN MOBED CODE-
FRICTION FACTOR CONSTANTS

```
COMMON/F/ QROUGH(8),ROUGH(8)
DIMENSION Z(61),B(61),A(61),P(61),R(61),DERB(61),DERP(61),
$   QL1(61),C(61),AYX(61),A1(61),B1(61),C1(61),D1(61),E1(61),
$   A2(61),B2(61),C2(61),D2(61),E2(61),L(61),M(61),K(61),DELQ(61),
$   D(61),T(61),QL2(61),QS1(61),QS2(61),QST1(61),QST2(61),ZZ(61),
$   DELZ(61),CAV1(61),CAV2(61),Y1(61),Y2(61),AVY(61),CAV(61),
$   QST(61),P1(61),P2(61),BT1(61),BT2(61),AR1(61),AR2(61),FR(61),
$   RANGE(61),RNEW(61),CONST(61),AD(61)
INTEGER H
```

```
C      modifications for link canals
      INTEGER JCTL, SED CTL
      REAL*8 LANG, L, M, K, METRIC, ER
      CHARACTER*1 TOP
      TQ(1)=999999.
      TY(1)=999999.
      T1=86400.
      T2=3600.
      T3=60.
      TOP=CHAR(12)
```

CHAPTER AAAA ***** INPUT PARAMETERS *****

SECTION A1

THE FOLLOWING IS THE LIST OF SYMBOLS USED IN THIS PROGRAM.

C N
REACH. IS THE NUMBER OF GRID POINTS ALONG THE RIVER

INFLOW IS A CONTROL PARAMETER FOR TRIBUTARY.

INFLOW=1 INDICATES PRESENCE OF A TRIBUTARY INFLOW IN THIS REACH.

INFLOW=0 INDICATES ABSENCE OF TRIBUTARY.

IN IS AN INTEGER BETWEEN 1 TO N TO INDICATE THE POSITION OF THE TRIBUTARY.

C INT IS AN INTEGER WHICH INDICATES THE TIME IN
C SECONDS
C
C WHEN THE TRIBUTARY INFLOW BEGINS.

```

C          (1.0**-6 M**2/SEC).
C
C      PORS          IS THE POROSITY OF SEDIMENT BED.
C
C      TQS          IS THE SEDIMENT INPUT RATE AT THE UPSTREAM
SECTION      AS A FUNCTION OF TIME
C
C
C      READ (60,540) GAM,GAMS,D35,D65,ANU
      WRITE(62,540) GAM,GAMS,D35,D65,ANU
C
C
C      READ (60,550) PORS
      WRITE(62,550) PORS
C
C      MODIFICATION TO BYPASS SED INFLOW WHEN RIGID BOUNDARY IS USED
C                                  NK.
C      IF(ISED.EQ.1) THEN
C          modification for link canals
C          READ (60,65) SED_CTL
C          IF (SED_CTL.LE.1) THEN
C              READ (60,560) (TQS(I),I=1,IL)
C              WRITE(62,560) (TQS(I),I=1,IL)
C          ELSE
C              READ (60,560) TQS(1)
C              DO 61 I=2,IL
61          TQS(I) = TQS(1)
C              ENDIF
C          ELSE
C              DO 62 I=1,IL
62          TQS(I)=0.0
C              ENDIF
C
C          SECTION A5
C          *****
C
C      ITYPEUP AND ITYPEDN SPECIFY THE TYPE OF BOUNDARY CONDITIONS
AT      THE UPSTREAM AND DOWNSTREAM SECTIONS RESPECTIVELY.
C      IF THEY TAKE A VALUE OF :
C          1      Y IS GIVEN BY A FUNCTION OF T
C          2      Q IS GIVEN BY A FUNCTION OF T
C          3      Q IS GIVEN BY A FUNCTION OF Y (I.E. STAGE-DISCHARGE
RELATIONSHIP)
C
C
C      AAU,BBU,CCU
C      AAD,BBD,CCD,          ARE CONSTANTS APPEARING IN THE
STAGE-DISCHARGE IN THE
C      FORM  $Q = A*(Y**B)-C$ . SET TO ZEROES IF STAGE
DISCHARGE

```


MODIFICATIONS IN FRICT.FOR

```

$DEBUG
$NOFLOATCALLS
C
  SUBROUTINE FRICT (Y,Z,Q,A,R,CONST,EM,EN,ASF,BSLOPE,IBED,IFRICT)
C
C SUBROUTINE TO ESTABLISH THE FRICTIONAL PARAMETERS NAMELY
C CONST , M , AND N FOR MOBILE BOUNDARY FLOWS
C
  IMPLICIT REAL*8 (A-H,O-Z)
  COMMON/B/ GAM,GAMS,D35,D65,ANU,G
  COMMON/E/ DELTAX,DELTAT,N
  COMMON/F/ QROUGH(8),ROUGH(8)
  DIMENSION Y(61),Z(61),Q(61),A(61),R(61),EL(61),X(61),CONST(61)
  DO 100 I=1,N
    EL(I) = Z(I)+Y(I)+Q(I)*Q(I)/(A(I)*A(I)*2.0*G+1.0D-100)
    X(I) = DELTAX*(I-1)
100  CONTINUE
    SUM1 = 0.00
    SUM2 = 0.00
    SUM3 = 0.00
    SUM4 = 0.00
    SUM5 = 0.00
    DO 110 I=1,N
      SUM1 = SUM1+1.0
      SUM2 = SUM2+X(I)
      SUM3 = SUM3+X(I)*X(I)
      SUM4 = SUM4+EL(I)
      SUM5 = SUM5+EL(I)*X(I)
110  CONTINUE
    S0 = SUM1
    S1 = SUM2
    S2 = SUM3
    T0 = SUM4
    T1 = SUM5
    A1 = (S0*T1-S1*T0)/(S0*S2-S1*S1)
    A0 = (S2*T0-S1*T1)/(S0*S2-S1*S1)
    ASF = DABS(A1)
C
C
    SUM4 = 0.00
    SUM5 = 0.00
    DO 120 I=1,N
      SUM4 = SUM4+Z(I)
      SUM5 = SUM5+Z(I)*X(I)
120  CONTINUE
    T0 = SUM4
    T1 = SUM5
    A1 = (S0*T1-S1*T0)/(S0*S2-S1*S1)
    A0 = (S2*T0-S1*T1)/(S0*S2-S1*S1)
    BSLOPE = DABS(A1)
C  IF (IFRICT.NE.1) go to 200

```

```

        IF(IFRICT.NE.1) RETURN
        SUM = 0.00
        DO 130 I=1,N
            SUM = SUM+R(I)
130    CONTINUE
C
REM      IF ((AVR/D65).GT.2000) GO TO 250
        DO 190 I=1,N
        AVR = SUM/N
        AYD = GAM*AVR*ASF/(GAMS*D65)
        AL1 = 0.02*(AVR/D65)**0.50
        AL2 = 0.02*(AVR/D65)**0.56
        AL3 = 0.07*(AVR/D65)**0.40
        IF(AL3.LT.AL2)AL3 = AL2
        AL1L = AL1-0.000001
        AL1H = AL1+0.000001
C
C  TRANSFERING CONTROL TO SET PROPER FRICTION PARAMETERS
C  FOR AVR/D65<2000
        IF (AYD.LT.AL1L) GO TO 140
        IF ((AYD.GT.AL1L).AND.(AYD.LT.AL1H)) GO TO 150
        IF ((AYD.GT.AL1).AND.(AYD.LT.AL2)) GO TO 160
        IF ((AYD.GT.AL2).AND.(AYD.LT.AL3)) GO TO 170
        IF (AYD.GT.AL3) GO TO 180
140    CONST(I) = .0052
        EM = 1.0
        EN = 3.00
        IBED = 1
        GO TO 190
150    CONST(I) = .013
        EM = 0.00
        EN = 1.0
        IBED = 2
        GO TO 190
160    CONST(I) = 1.0/(53.43*(GAM/GAMS)**0.857)
        EM = -0.429
        EN = 0.143
        IBED = 3
        GO TO 190
170    CONST(I) = 1.0/47.6
        EM = -0.333
        EN = 1.00
        IBED = 4
        GO TO 190
180    CONST(I) = (GAM/GAMS)**2/482.00
        EM = 0.20
        EN = 3.00
        IBED = 5
190    CONTINUE
        RETURN

250  DO 350 I=1,N

```

```

AVR = SUM/N
AYD = GAM*AVR*ASF/(GAMS*D65)
AL1 = 0.02*(AVR/D65)**0.50
AL2 = 0.02*(AVR/D65)**0.56
AL3 = 0.07*(AVR/D65)**0.40
IF(AL3.LT.AL2)AL3 = AL2
AL1L = AL1-0.00001
AL1H = AL1+0.00001

```

```

C   TRANSFERRING CONTROL TO SET PROPER FRICTION PARAMETERS
C   FOR (AVR/D65)>2000

```

```

      IF (AYD.LT.AL1L) GO TO 260
      IF ((AYD.GT.AL1L).AND.(AYD.LT.AL1H)) GO TO 270
      IF ((AYD.GT.AL1).AND.(AYD.LT.AL2)) GO TO 280
      IF ((AYD.GT.AL2).AND.(AYD.LT.AL3)) GO TO 290
      IF (AYD.GT.AL3) GO TO 300

```

```

260  CONST(I) = .0068
      EM = 1.0
      EN = 3.00
      IBED = 1
      GO TO 350
270  CONST(I) = .017
      EM = 0.00
      EN = 1.0
      IBED = 2
      GO TO 350
280  CONST(I) = 1.122/(53.43*(GAM/GAMS)**0.857)
      EM = -0.429
      EN = 0.143
      IBED = 3
      GO TO 350
290  CONST(I) = 1.125/47.6
      EM = -0.333
      EN = 1.00
      IBED = 4
      GO TO 350
300  CONST(I) = (GAM/GAMS)**2/482.00
      EM = 0.20
      EN = 3.00
      IBED = 5
350  CONTINUE
      RETURN

```

```

CTHIS SECTION WAS ADDED TO ALLOW A TABLE OF MANNING'S N VALUES
C   TO BE USED

```

```

CTHE TABLE IS INPUT IN THE MAIN PROGRAM AS THE LAST TWO DATA LINES

```

```

C
C200 DO 220 I=1,N
C     DO 210 J=2,8
C       JJ=J-1
C       IF(Q(I).LT.QROUGH(J))GO TO 220

```

```

C210  CONTINUE
C220  CONST(I)=ROUGH(JJ)+(ROUGH(JJ+1)-ROUGH(JJ))*(Q(I)-QROUGH(JJ))
C     $/(QROUGH(JJ+1)-QROUGH(JJ))
C
C     NOTE THAT BOTH ENDS OF THE CURVE ARE LINEARLY EXTRAPOLATED
C
C     RETURN
C     END

```


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