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A comparative application of flood routing models on the rivers Wear and Tees with special reference to the state variable model

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A Comparative Application of Flood Routing Models on The Rivers Wear and Tees With Special Reference to The State Variable Model

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DECLARATION

I declare that no material in this thesis has previously been submitted for a degree at this or any other university.

To

My Brother Muthana, My Mother,

Memory Of My Father, Brothers,

Sisters, My Wife, And My

Daughter Ruaa

ACKNOWLEDGEMENTS

Abstract

An analysis of a number of flood routing methods has been carried out in this study. These methods are namely, the Muskingum-Cunge Method, the Variable Parameter Diffusion Method, the State Variable Kinematic Wave Model, and the state variable modelling of nonlinear Muskingum Model. The Muskingum-Cunge and Variable Parameter Diffusion Methods are recommended for use on British Rivers by the Natural Environment Research Council flood studies report, 1975.

In using numerical flood routing model, it is very important to calculate the model parameters. For instance storage routing models require a suitable form of storage-discharge relationship. Past flow records were used for the above calculation.

The state Variable Kinematic Wave Model has been applied for routing the flood hydrograph through river reaches. The stage and discharge are computed by a kinematic wave routing technique using the state variable approach in which the one-dimensional differential equations of unsteady flow are solved by state and output equations of the state variable model.

The nonlinear Muskingum equation has been solved using the state variable modelling technique. Two parameter estimation techniques namely, Hooke-Jeeves and linear regression, are employed for the calibration of the nonlinear Muskingum model parameters (α, x, and m).

The applicability of the flood routing model computer programs to different flood events of different seasons for reaches of both the Rivers Wear and Tees is demonstrated.

Discriptions of the geology and hydrological data for reaches of both the Rivers

Wear and Tees are given in this study.

The computed and observed hydrographs of flood routing models used in this study are compared.

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NOTATION

A	Wetted Channel Cross-section Area.
B	Channel Top Width.
C_1, C_2, C_3, C_4	Muskingum Coefficients.
$\bar{c}$	Convection Speed.
Dt	Finite Difference Time Step.
Dx	Finite Difference Distance Step.
dQ	Discharge Correction Element.
dy	Depth Correction Element.
E	Exponential.
E_t	Peak Time Error.
E_Q	Peak Discharge Error.
E_{abs}	Mean Absolute Error.
g	Acceleration Due to Gravity.
H-J	Hooke-Jeeves.
I	Inflow.
i	Space Node Model.
j	Time Label.
k	Muskingum Storage parameter.
L	Reach Length.
LR	Linear Regression.
n	Manning's Coefficient.
O	Outflow.
p	Wetted Channel Perimeter.
Q	Discharge.
Q_P	Peak Discharge.
Q^*	Attenuation of Peak Discharge.
q_1	Lateral Inflow.

R	Hydraulic Radius.
S	Storage.
S_f	Friction Slope.
S_o	Bed Slope of the Channel.
$\hat{S}_t$	Computed Channel Storage.
$\tilde{S}_t$	Observed Channel Storage.
T_p	Travel Time of Flood Wave Peak.
t	Time.
v	Velocity.
x	Distance From Upstream Boundary.
x	Muskingum Weighting Factor Parameter.
Y	Depth of Flow.
α	Muskingum Parameter Constant.
β	Coefficient.
$\propto$	Attenuation Parameter.
μ	Diffusion Coefficient.
Ω	Finite Difference Expression.
ω	Convection Speed.

CHAPTER 1

INTRODUCTION

1.1 General

Water is an essential commodity; life is simply not possible without it. Ever since man began to live in communities the need for water has increased enormously. With the further need for the systematic cultivation of food, human civilization started to develop around the places where water was freely available. The locations of some of the largest cities not only underline this fact and it will continue to obtain as long as the world remains in its present form.

The variability in hydrological conditions of a country may be so vast from region to region that it may affect the very pattern of life of the people in these regions. Therefore, a scientific study of hydrology and its application to water resources development and utilisation is of tremendous importance.

A flood is a relatively high flow which overbanks the natural channel. If the flood is large enough, then the effect could be disastrous to lives and economy.

One of the most common problems facing the civil engineer is the estimation of the hydrograph of the rise and fall of the water level at any given point on the river during the course of a flood event. The problem is solved by the techniques of flood routing.

The hydrograph of a river or channel shows the variation in flow rate with respect to time. It is defined as the graphical representation of the instantaneous rate of discharge of a stream plotted with time.

The shape of a hydrograph of a single storm follows a general pattern. This pattern shows a period of increasing discharge (rising limb), that culminates in a

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peak or crest. It is followed by a period of decreasing discharge (recession limb) which may or may not decrease to zero discharge, depending on the amount of groundwater flow. A typical hydrograph, divided into three principal parts, is shown in fig.(1.1)

A flood hydrograph is modified in two ways. Firstly, and obviously, the time of the peak rate of flow occurs later at downstream points. This is known as translation. Secondly, the magnitude of the peak rate of flow is diminished at downstream points, the shape of the hydrograph flattens out, and the volume of the flood water takes longer to pass a lower section. This modification to the hydrograph is called attenuation as shown in figure(1.2).

The generation of the downstream hydrograph B from an upstream known hydrograph A as shown in figure(1.2) is essential for river engineers concerned with forecasting floods in the lower parts of a river basin. The design engineer also needs to be able to route flood hydrographs in assessing the capacity of reservoir spillways, in designing flood-protection schemes or in evaluating the span and height of bridges or other river structures.

Flood routing is defined as a procedure by which the hydrograph at any section on a channel can be calculated from a known hydrograph at any other section; most probably from one upstream, or in other words flood routing is defined as a technique to compute the effect of system storage and system dynamics on the shape and movement of a flood wave.

A flood wave is defined as a temporal spatially propagated change in water surface, discharge or velocity in a river channel, canal, or reservoir. Flood waves are generated by an increase in the amount of water entering a channel following rain-storms, the operation of control gates, or the failure of water retaining structures.
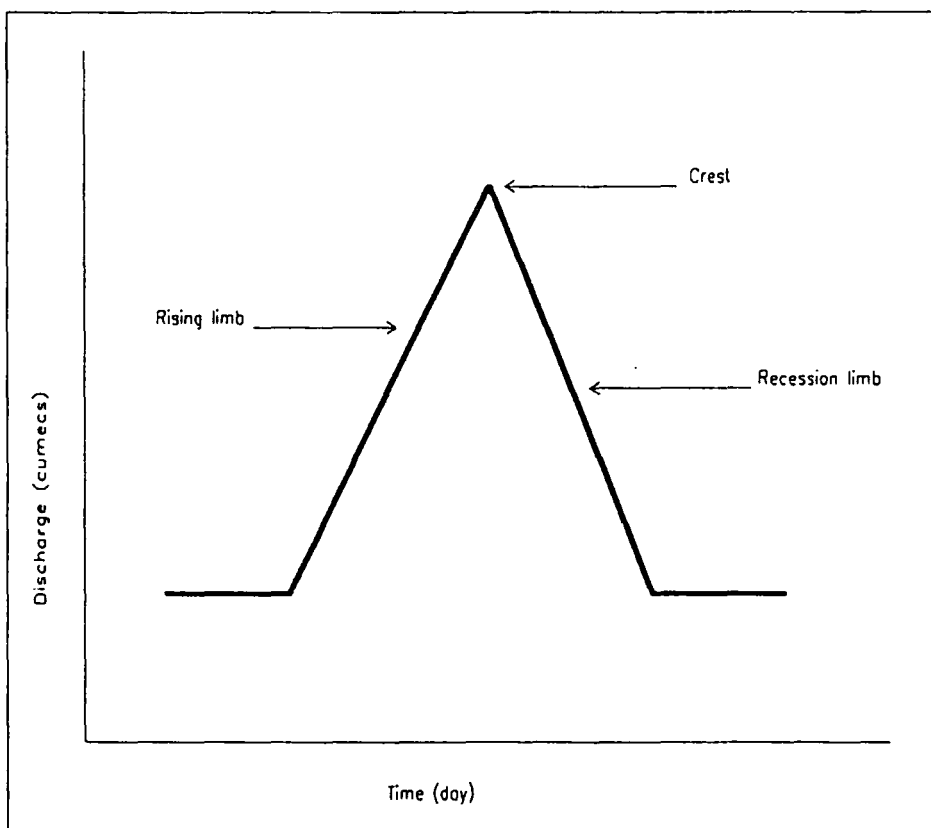
Fig. (1.1) The Principal Parts Of Hydrograph.

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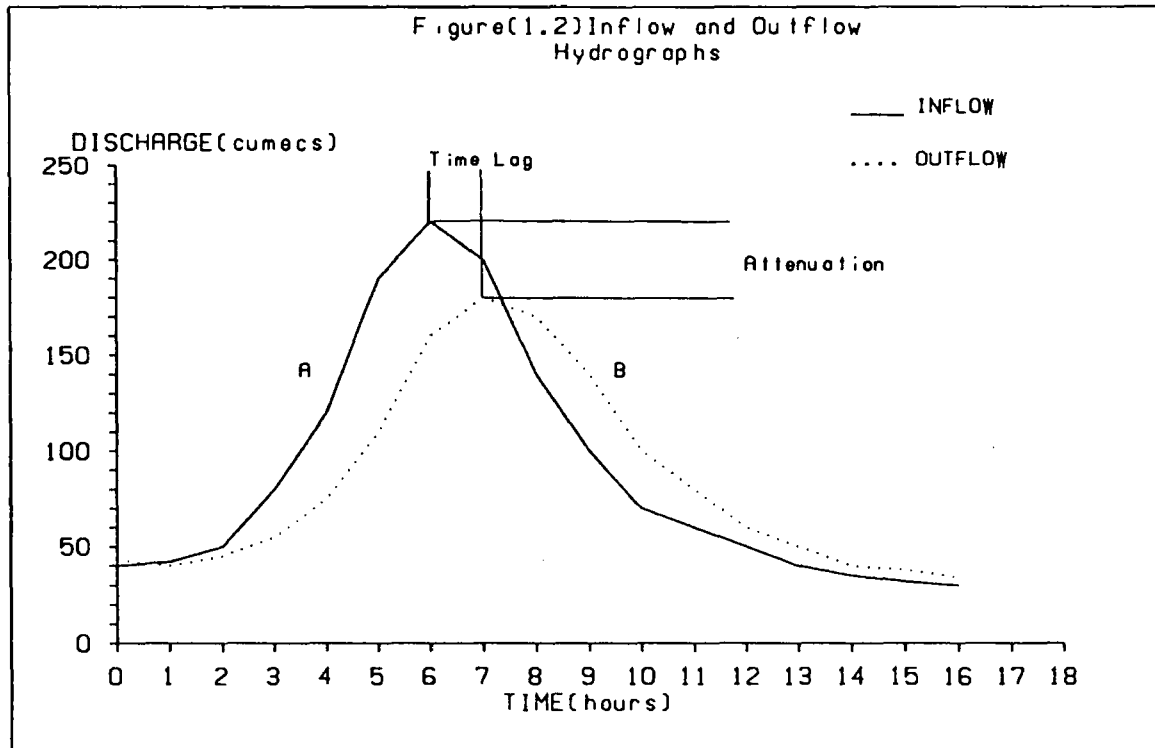
Fig.(1.2) Inflow And Outflow Hydrographs.

Flood routing methods are the group of techniques available for tracing the movement of flood waves along rivers, and simulating the celerity, and attenuation or simplification of these waves. The classical flood routing problem is the movement of long-shallow-water flood waves in non-tidal rivers, and traditional flood routing methods are utilised to derive the maximum flood discharge and its time of occurrence at a downstream site from a discharge hydrograph provided at an upstream site.

Over the years, various flood routing techniques have been developed. They range from simple empirical relationships to highly sophisticated mathematical models. The majority of these techniques to be found in the literature can be classified as either "hydraulic" or "hydrologic" depending on whether they are based on the equations of open channel flow or on some simplified assumptions about the flow regime in a river. The effectiveness of hydrologic routing depends on how closely the model approximates to the actual flow regime in the river.

The hydraulic methods are based on the solution of the basic differential equations for unsteady flow with a free surface whereas the hydrologic methods make use of simplifications of these basic equations, or may be completely empirically based.

Unsteady flow in rivers, reservoirs and estuaries is caused by the motion of long waves such as flood waves, tides, storm surges, and reservoir releases.

Modelling in hydrology has become an important tool in water resource development, since the development of high speed computers made it possible to solve the complicated mathematical equations involved in the application of hydrologic theories.

The basic choice of modelling technique is between hydraulic or electrical analogues and numerical models of greatly varying levels of sophistication. The

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primary factors governing the selection of the best method or methods for a specific problem are:

1. amount of suitable prototype data available;

2. type and accuracy of output required;

3. model cost; and

4. convenience of model construction, storage, and use.

For example, simpler semi-empirical numerical methods may be considered as "black box" techniques, wherein channel characteristics are represented by the value of universal parameters obtained from statistical records. These methods are normally inexpensive and easy to construct and store, but often require accurate discharge data for calibration, and are not generally suitable for analysis of the effects of channel modifications.

1.2 Importance Of Flood Routing

Flood routing techniques have been developed mainly for the study of floods travelling through channels, reservoirs and lakes. Flood routing is of important in the planning, design, construction, and operation of such engineering projects as reservoirs, diversion works, channel improvements, levees and flood walls.

The use of flood routing methods is an integral part of many river management schemes. It is employed for a wide variety of problems associated with water use. Some of these include:

1. producing discharge hydrographs, at downstream ungauged sections of a river in order to define rating curves;

2. determining the effects of channel and flood plain modification on flood wave characteristics;

3. evaluating past floods;

4. forecasting floods along the main course of a river by use of observed or predicted hydrographs at key points in the drainage network; and

5. studying the effects of water resource development on the down stream flow condition.

The analysis of historical events improves the data base for a river and can increase the water engineer's understanding of the hydrological and hydraulic characteristics of the river catchment.

The forecasting of the characteristics of future design floods is necessary for the development of an efficient flood warning system. If the accurate prediction of flood levels and discharges at site along a river may be obtained from rainfall, and recorded hydrograph at upstream sites on the main river and tributaries, the evacuation of threatened properties, and efficient allocation of resources may reduce flood damage considerably. Flood warning systems may be based on simple correlation of flood levels for previous floods, or sophisticated numerical models.

The calibration of control structures on a river is often difficult for high flows, when a large propagation of the flow may by-pass the structure along the flood plain. If an accurate discharge hydrograph for an upstream site is routed downstream and compared with the recorded stage hydrograph then a rating curve may be defined at the downstream site.

Determining the effects on flood levels and discharges due to channel and flood plain modifications is necessary for the design of flood alleviation scheme. Local channel deepening and widening, the construction of flood embankment along reaches subject to overtopping, the short circuiting of channel beds, and the removal of weirs and other obstruction, may reduce flooding problems locally

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but can increase discharge and hence flooding problems downstream. Detailed analysis of the overall effect on river behaviour of local channel improvement schemes normally requires the use of a numerical model based on full unsteady flow theory, particularly if reservoir operation or significant changes in flood plain storage are included in the scheme.

1.3 Scope Of The Project

The principal objectives of this work are:

1. to develop a mathematical model for natural stream flood routing using different methods for solving the unsteady flow equations in order to compute stages and discharge of flood wave propagation;

2. to compare these different methods of unsteady flow modelling; and

3. to assess the value of these methods in the solution of practical engineering problems of river management.

Different flood routing methods are selected for development and application to prototype river flow problems. The Muskingum-Cunge Method and the Variable Parameter Diffusion Method are recommended for use on British Rivers in volume III of Natural Environment Research Council, Flood Studies Report (N.E.R.C. 1975). The following were the objectives, with respect to the application of Muskingum-Cunge Method:

1. to investigate the relationship between space increment, wave velocity and storage coefficient to be used in the Muskingum-Cunge routing;

2. to investigate the use of linear storage-discharge relationship; and

3. to identify the coefficients for a storage flood routing model for natural flood flow situations.

The State Variable Model concept is a relatively new technique and its application to the analysis of the water resources system is even more recent. It is capable of describing systems which are linear or nonlinear, time variant or time invariant, deterministic or stochastic, while having multiple inputs and outputs at the same time. (Maidment, and Chow, 1976).

The basic form of the State Variable Model is given by a state equation and output equation. The former describes the change in the state of the system over time in response to the inputs while the later derives the result at the new time step in response to the state increment determined from the state equation. The following were the objectives, with respect to the application of the State Variable Model:

1. to develop the basic state variable model by choosing the cross-sectional area as the state variable and ignoring the lateral inflows; and

2. to develop the basic state variable model by choosing discharge as the state variable and ignoring the lateral inflows;

In achieving those objectives, wherever possible, sets of different events of different periods of natural flow data were used. Two British river reaches were used in this project see Figs. (1.3) and (1.4). They were:

1. The River Wear between Sunderland Bridge and Chester-le-Street.

2. The River Tees between Broken Scar and Low Moor.

The flood data of those reaches were supplied by the Northumbrian Water Authority, Newcastle upon Tyne.

1.4 Research Presentation

A review of the classification and development of the flood routing methods is provided in chapter 2. Chapter 3 contains a brief description of the hydrology,

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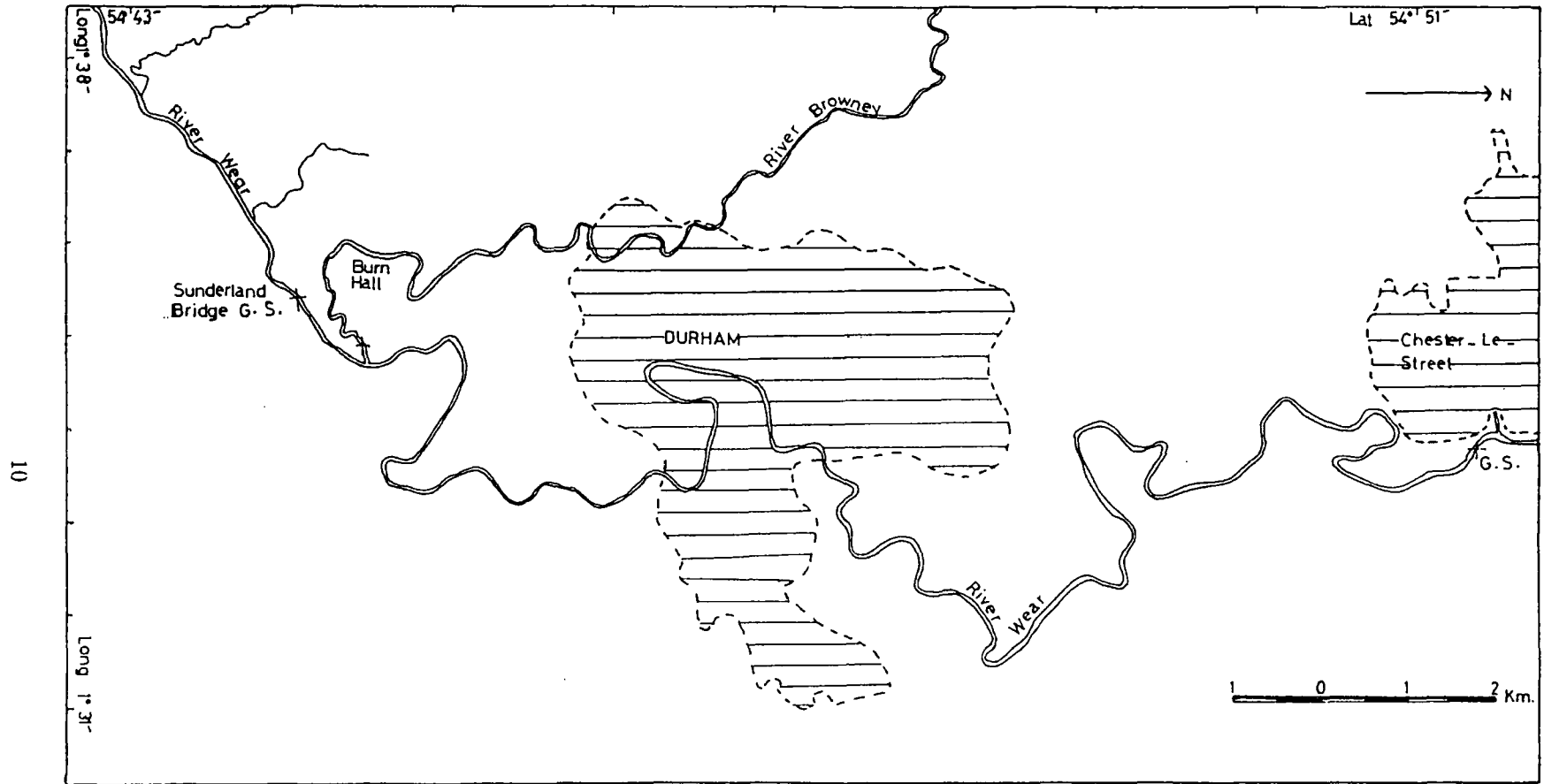
Fig.(1.3) The River Wear Reach.
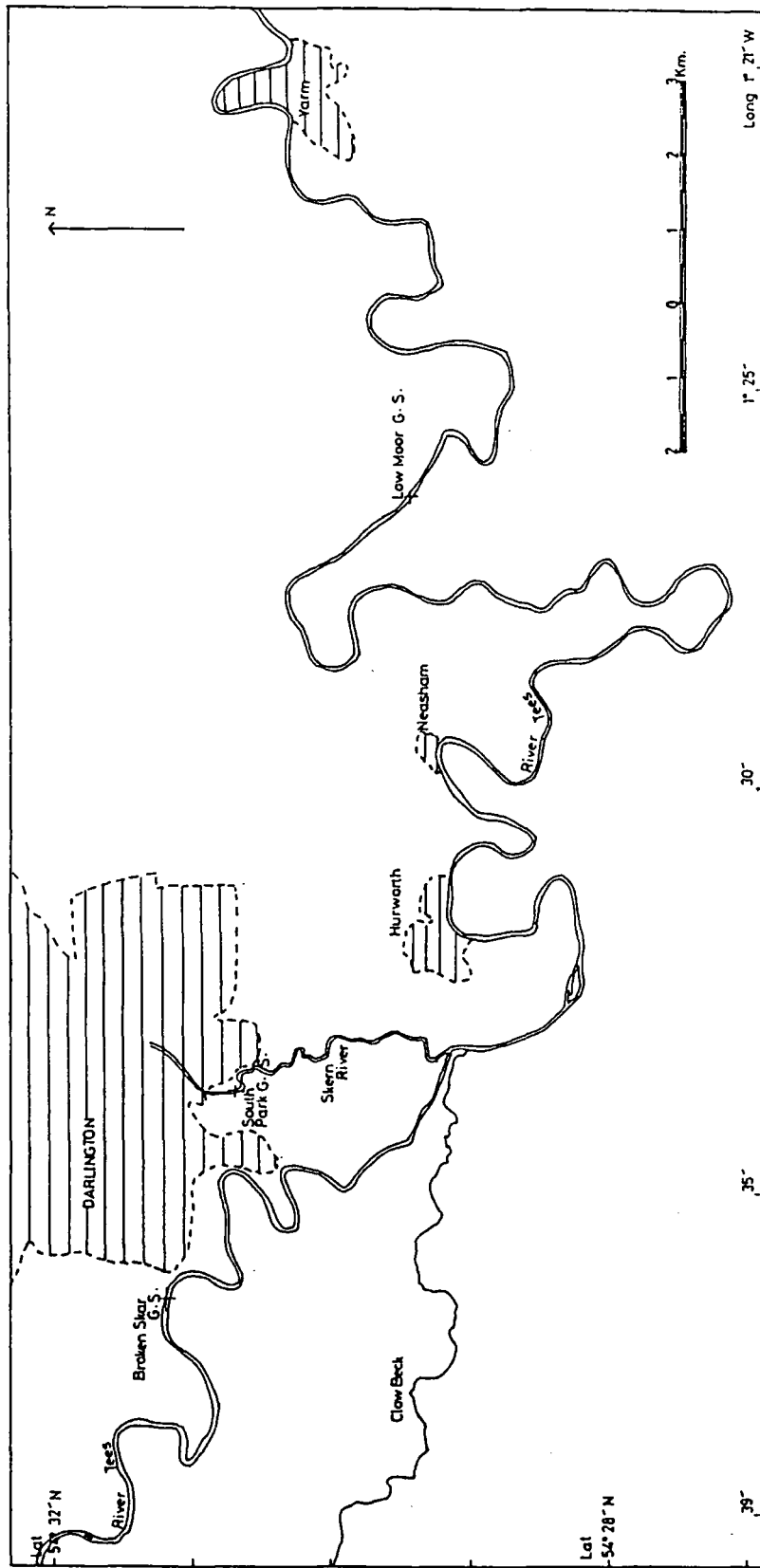
Fig.(1.4) The River Tees Reach.

geology, and topography of the catchments and the data used in the study.

In chapter 4 the basic models, the Muskingum-Cunge Method, the Variable Parameter Diffusion Method, and the State Variable model are introduced and explained. The theories of the three models are reviewed and presented.

Application and testing of the Muskingum-Cunge method and the Variable Parameter Diffusion method is described in chapter 5. Both models are presently suitable for use with both wear and Tees Rivers. The results obtained are presented and compared.

Chapter 6 deals with the mathematical modelling and application of the state variable kinematic model. The results obtained are presented and compared.

Chapter 7 covers the application of the nonlinear Muskingum model using state variable modelling.

The unique elements are the application of those new techniques described in chapter 6 and 7 to the Wear and Tees Rivers which could be easily extended to any river reach in Britain provided the suitable data are available.

The models are used in this study involved the use of the informations from topographical map and extensive field measurements and surveying and hydrological data required for model construction and calibration.

Chapter 8 contains a general conclusion and summary of the work done and recommendation for future work.

1.5 Organisation Of The Thesis

The text is contained in chapters 1 to 8 and the three main appendices. In the text the necessary theories are dealt with together with the main results obtained from the application of these theories to the two catchments under study.

Appendix I presents the raw data used for the two catchments in tabulated form.

Appendix II presents the output calculations of the four models used in this study.

Appendix III lists the main programs used in this study.

Appendix IV Tables of daily measurement of rainfall for Tunstall and Allen-head stations.

Appendix V Arrangement of input data of STROUT3 program, and symbol definition of M-C2, VPDM, and SVNLMM programs.

CHAPTER 2

FLOOD ROUTING METHOD

2.1 INTRODUCTION

The prediction of a design flood hydrograph for any section on a river or channel may be based on the derivation of a discharge or stage hydrograph at an upstream section, together with a method to route this hydrograph along the rest of the river.

The movement of a flood wave down a channel reach and the associated change in timing or attenuation of the wave constitute an important topic in flood routing. It is essential to understand the theoretical and the practical aspects of flood routing to predict the temporal and spatial variations of a flood wave through a river reach.

Flood routing methods are useful techniques used for the study of flood wave propagation, particularly if the shape as well as the peak value of the hydrograph are required. The flood wave propagation is controlled by the balance of various forces included in the momentum equation and the shape of the wave is constantly changing as it proceeds downstream.

Flood routing methods apply both to channel reaches and reservoirs and also can be used to predict the outflow hydrograph from a watershed subjected to a known amount of precipitation.

The various flood routing methods which have been developed since the begining of this century could be divided into four groups:

1. the hydrologic routing method;

2. the routing method based on the convection-diffusion equation;

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3. the hydraulic routing method based on the numerical solution of the equations of motion and continuity; and

4. the method based on the kinematic wave model.

The nature of the problem and the data available are very important in the choice of the flood routing method. For example, problems such as determining the progress of a flow down a long river, where the discharge is more important, can successfully be evaluated by hydrological methods, while problems such as the back water effect when a flood comes through a junction and the effect of surges when a flood is regulated by a dam, where the depth, discharge and the rate of changes of depth and discharge are all important, can only be evaluated accurately by any method which is based on complete hydraulic principles such as the hydraulics method.

2.2 Unsteady Flow in Open Channel

Water flow in open channel is classified as either steady or unsteady. The flow of water in river channel, canals, reservoirs, for which the velocities change with time, is termed unsteady flow. Water flow in natural channels is almost always unsteady. When the change of flow with time is very gradual, unsteady flow is approximated by steady flow. These flows may be placed into very broad categories of rapidly varied unsteady flows, such as waves following the collapse of a dam, and gradually varied unsteady flows, such as the propagation of flood waves.

2.2.1 The Unsteady Flow Equation

There are two equations that govern unsteady flow in open channels. These equations were first published by Saint-Venant (1870). They are the equation of continuity and momentum which are respectively based on the conservation of

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mass and energy.

1. The Continuity Equation:

The general equation of continuity states that inflow minus outflow equals the rate of change of storage:

$$\frac{\partial Y}{\partial t} + \frac{\partial}{\partial x}(vY) = 0 \qquad 2.1$$

2. The Momentum Equation:

This equation is derived from the principle of the conservation of momentum applied to fluid flow (Newton's second law). It states that the net rate of change of momentum within a control volume equals the sum of the forces (gravity, frictional and hydrostatic) acting on that volume:

$$\frac{\partial Y}{\partial x} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{1}{g}\frac{\partial v}{\partial t} = S_o - S_f \qquad 2.2$$

where Y is the depth of flow; v is the mean velocity of flow; g is the acceleration due to gravity; x is the distance along the channel; t is the time; S_o is the bed slope of the channel and S_f is the friction slope.

The derivation of the basic unsteady flow equations from shallow water theory, using the concept of energy slopes, or momentum change in a control volume, is given in standard reference works (Chow, 1959, Henderson,1966, and Mahmood et al 1975). It is based on the following assumption:

1. the wave surface gradually varies, which is equivalent to stating that vertical pressure distribution is hydrostatic, or that the vertical acceleration;

2. velocity distribution across the wetted area does not substantially affect the wave propagation;

3. the wave movement can be considered as two-dimensional; and

4. the average bed slope of the channel is so small that sin α may be replaced by tan α, and cos α by unity, where α is the angle made by the channel bottom with the horizontal.

The continuity and momentum equations contain two independent variables x and t, and two basic dependent variables v and Y. the dependent variable v represents the velocity of flow, at a time when the Y variable represents the depth of flow in the cross section. Consequently, they may be considered in different forms: as the rate of flow, Q, and the area of flow, A. This means that although the equations can be mathematically expressed in different ways, the basic terms that constitute the equations remain the same (see Eqn. 2.18 and Eqn 2.19).

2.2.2 Type of Unsteady Flow

For analytical purpose, unsteady flow is often classified in to two types:

1. Gradually Varied Unsteady Flow:

Flood waves are a good example of gradually varied unsteady flows. In this type of unsteady flow, the curvature of the wave profile is small and the change in depth is gradual. Because of the mild nature of the profile , the vertical component of the acceleration of the water particles is negligible in comparison with the total acceleration. This implies that a hydrostatic pressure distribution may be assumed.

For this type of wave both of accelerations, local and convective, are significant. Likewise both the gravity body force due to bed slope and frictional force are appreciable. Therefore, a complete analysis of gradually varied unsteady flow should be based on the complete basic equations.

2. Rapidly Varied Unsteady Flow:

Surges, moving hydraulic jumps and hydraulic bores are rapidly varied un-

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steady flows, where the wave profile is very short in length, the change in depth is rapid, and the curvature is large. In the extreme, the surface of the profile may become vertically discontinuous. The vertical acceleration component therefore plays an important role in the phenomenon. The implications are:

1. hydrostatic pressure distribution may not be assumed;

2. effect of the convective acceleration is insignificant; and

3. both gravity body forces due to bed slope and frictional force are very small and may be dropped. This means that the momentum equation is reduced to only two terms, that of change in pressure force and local acceleration. This reduced form of the momentum equation is the same as Newton's second law of motion.

2.3 Hydrological Methods

Hydrological flood routing methods are also called storage routing methods. These methods concentrate on the concept of the storage for the flood water and do not directly include the effects of resistance to the flow. The routing of a flood by a hydrological method in a given reach of river is based on the continuity equation which equates the rate of change of the storage , $\frac{dS}{dt}$, in the reach to the difference between the inflow, I, at the upstream section and the outflow, O, at the downstream section. This statement is given mathematically by:

$$\frac{dS}{dt} = I - O, \qquad\qquad 2.3$$

where I is the inflow rate to a river reach, O is the outflow rate from the reach, and $\frac{dS}{dt}$ is the rate of change of storage within the reach.

This, the continuity equation, forms the basis of all the storage routing methods. It may look simple, but is difficult to solve. There are two unknowns in one equation, namely O and S. Since the outflow, O, is the variable for which the

differential equation is to be solved, it has to be retained and S must be replaced by expressing it as a function of known variables. This enables a solution to be found for the outflow when the inflow is given.

Hydrological methods completely ignore the dynamic effects on a flood wave. However, a recent method, the Muskingum-Cunge (Cunge, 1969), has been improved to include the dynamic effects to a certain extent, as will be described later.

Hydrological methods in general utilize statistical records of past flood events to estimate the celerity of the flood wave and the storage characteristics of the reach. Storage characteristics of a reach depend on the geometry and roughness of the channel and the flood plain, and hence the estimation of these characteristics directly from flood records precludes the necessity for a survey of the reach.

Conclusively hydrological methods are suitable for the traditional flood routing problem of estimating a downstream hydrograph from upstream conditions and the estimation of attenuation and time lag as shown in fig.(1.2) in a non-tidal river with no significant backwater effects.

Hydrological methods assume a unique relationship between the stage and discharge along the reach. This can be displayed graphically by the well-known loop rating curve shown in fig.(2.1). As shown in this figure, the discharges for the rising and falling stages are respectively greater and less than the discharge for uniform flow and the discharge-stage relationship for the condition of steady flow is represented by the dashed curve, which is approximately at the average position of the two limbs of the loop.

During rising stages a considerable volume of wedge storage may exist before any large increase of outflow occurs. During falling stages, inflow drops more rapidly than outflow, and the wedge-storage volume becomes negative. The con-

cept of prism storage and wedge storage is clearly shown in fig.(2.2) (Linsley, Kohler and Paulhus 1982). The wedge storage, which is superimposed on the prism exists because the inflow, I, differs from O, and so may be assumed to be a function of the difference between inflow and outflow, (I-O). The storage beneath a line parallel to the stream bed is called prism storage. It is taken to be a direct function of the stage at the down-stream end of the reach and so may be assumed to be a function of the outflow, O.

The development and use of hydrological methods, were initially for the purpose of routing flood waves through reservoirs. A number of reservoir routing methods exist, which differ only in the solution technique, which may be numerical or graphical, and in the treatment of the finite difference form of the storage differential form of the continuity equation (eqn. 2.3):

$$\frac{1}{2}(I_1 + I_2)\Delta T - \frac{1}{2}(O_1 + O_2)\Delta T = S_2 - S_1 \qquad 2.4$$

where ΔT is referred to as the routing time period, and subscripts 1 and 2 denote the begining and end of the time period, respectively. A simple and well-used method is the Puls method described by Wilson (Wilson, 1969), with alternative methods given in standard textbooks (eg. Chow, 1959, and Henderson, 1966)

Hydrological methods for river routing are more complicated than those for reservoir routing because water storage in a reach is dependent on both inflow and outflow while in the reservoir routing case, the storage is generally dependent only on the outflow from the reservoir.

Most of the hydrological methods are based on the finite difference storage equations (eqn.2.4). A large number of basically similar methods have been developed and used extensively for flood routing. The successful use of these methods is generally more dependent on the amount of the accurate data available than

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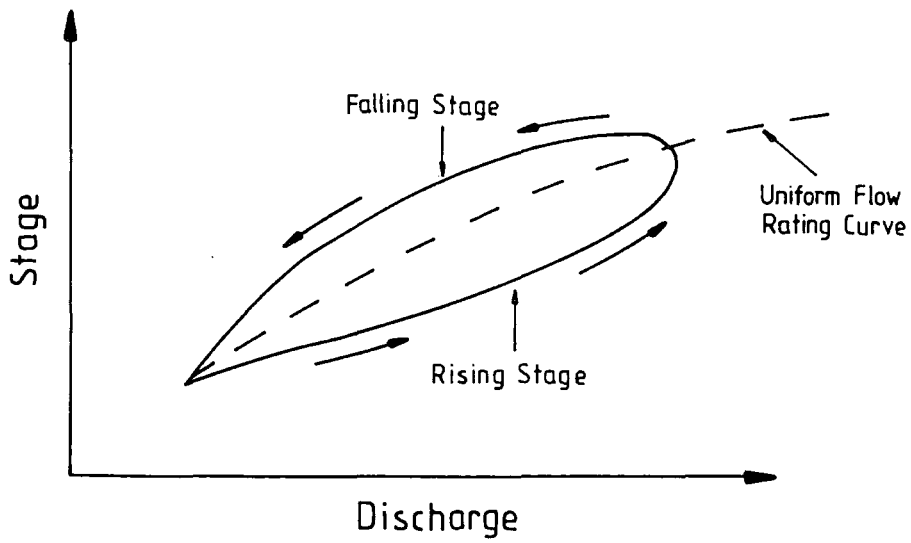
Fig. (2.1) Loop rating curve.
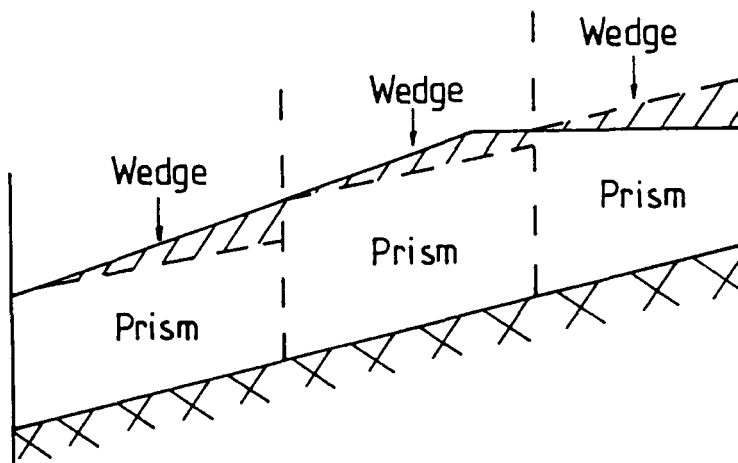
Fig. (2.2) Some possible water-surface profiles during the passage of a flood wave.

the solution technique. A graphical technique is provided by Henderson (Henderson, 1966), which utilises plots of the outflow versus storage for each value of inflow. A numerical technique, namely the Muskingum Method, stands out as the most widely used.

The Muskingum Method was one of the most satisfactory and popular methods. It was originated by McCarthy (1938) for the U.S. Army Corps of Engineers, and derives its name from its use in the study of flood control schemes for the Muskingum River, Ohio, in 1935.

The Muskingum Method has received considerable attention over the years; e.g., Nash (1959), Kulandaiswamy (1966), Overton (1966), Diskin (1967), Cunge (1969), Gill (1978), Price (1974), Tung (1985), and O'Donnell (1985). The advantages in the application of this method to British Rivers are demonstrated by Price (1974 and 1977)

The Muskingum Method utilizes the continuity equation and a storage relationship that depends on both inflow and outflow. The storage within the reach at a given time can be expressed by (Chow, 1959):

$$S = \frac{b[XI^{m/n} + (1 - X)O^{m/n}]}{a^{m/n}}, \qquad 2.5$$

where a and n are constants reflecting the stage discharge characteristics of control sections at each end of the reach, and b and m are constants reflecting the stage volume characteristics of the section.

The Muskingum Method assumes that $\frac{m}{n} = 1$ and $\frac{b}{a} = k$, resulting in a linear relationship of the form:

$$S = K[xI + (1 - x)O], \qquad 2.6$$

where K is the travel time constant for the reach and x is a dimensionless weighting factor which defines the relative importance of inflow and outflow in determining

storage volume in the reach. The value of x has limits of zero and 0.5. Typical values for most natural streams are in the range 0.2 to 0.4

The routing procedure uses the finite-difference form of the continuity equation (eqn. 2.4) with equation (2.6) in the form:

$$\frac{1}{2}(I_1 + I_2)\Delta T - \frac{1}{2}(O_1 + O_2)\Delta T = K[xI_2 - (1-x)O_2] - K[xI_1 + (1-x)O_1], \quad 2.7$$

to produce the Muskingum routing equation for a river reach:

$$O_2 = C_1 I_1 + C_2 I_2 + C_3 O_1, \qquad\qquad 2.8$$

where:

$$C_1 = \frac{Kx + 0.5\Delta T}{D}, \qquad\qquad 2.9$$

$$C_2 = \frac{-Kx + 0.5\Delta T}{D}, \qquad\qquad 2.10$$

$$C_3 = \frac{K - Kx - 0.5\Delta T}{D}, \qquad\qquad 2.11$$

$$D = K - Kx + 0.5\Delta T. \qquad\qquad 2.12$$

The coefficients C_1, C_2, and C_3 sum to 1.0. With K, x, and ΔT known, values of C_1, C_2, and C_3 are computed. The routing operation is accomplished by solving equation (2.8) for successive time increments, with the O_2 of one routing period becoming the O_1 of the succeeding period.

Coefficients K and x are calculated exclusively from recorded discharge hydrographs at the upstream and downstream boundaries for past flood events. Function [x I + (1 - x) O] is plotted against storage for different values of x until the best estimates of a straight line is obtained, and the optimum value of x, and a value of K are calculated from the average slope of the line selected as the Muskingum parameters. Details of the calculation of K and x are given in many standard text books (eg. Chow, 1959, Wilson, 1969, and Shaw, 1983).

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A nonlinear form of storage relationship is frequently quoted in text books, e.g., Linsley et al (1975) and Chow (1959), and is of the following type:

$$S = K[\epsilon Q_i^n + (1 - \epsilon)Q_o^n],$$ 2.13

where n is an exponent. Although the same exponent is used for both inflow and outflow, it should be recognised that different exponents can also be used as follows:

$$S = K[\epsilon Q_i^m + (1 - \epsilon)Q_o^n],$$ 2.14

Gill (Gill, 1977 and 1978) used the nonlinear storage-flow relationship of the following type:

$$S = \alpha[\epsilon Q_i + (1 - \epsilon)Q_o]^m + \sigma,$$ 2.15

where α is a coefficient and m is an exponent. He termed S the relative storage and σ the intercept on the weighted flow, $[\epsilon Q_i + (1 - \epsilon) Q_o]$ axis in a plot of weighted flow vs storage.

Another form of the non-linear Muskingum equation has been developed (Tung, 1985) by modifying the linear form of equation (2.6) to non-linear form by writing:

$$St = \alpha[X I_t + (1 - X)O_t]^m,$$ 2.16

where α and m are constants. A routing technique is proposed for the non-linear model expressed by equation (2.16) using the concept of state variable modelling (Tung, 1985).

Cunge (1969) provided a major improvement to the theoretical basis of the Muskingum Method which then become known as the Muskingum-Cunge Method. This is described in detail in chapter 4.

A second modified Muskingum Method has been developed by O'Donnell (1985) by extending the original 2- parameter Muskingum Model (K,x) to a

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3-parameter model (K,x,α) employing a simple assumption about lateral inflow. This modified method has two advantages:

1. it uses a numerical and direct best-fit solution technique for the estimation of the K and x parameter values; and

2. by treating the whole river as one reach, it avoids the need for multiple routing over many subreaches.

The modified Muskingum equation of O'Donnell (1985) is of the following type:

$$S = K[x(1 + \alpha)I + (1 - x)O], \qquad\qquad 2.17$$

where α is a constant taken to be fixed for any one event but takes different values for different events.

Hydrological methods are numerous and very simple in nature often giving a simple linear equation for the unknown value of the discharge. They require smaller storage and less computing time than any other routing technique and has been used extensively. A number of other successful hydrological methods are found in the text books (eg. Chow, 1959, and Raudkivi, 1981) and these methods are basically similar to the Muskingum Method. Another hydrological method which was developed in U.S.S.R. in 1958 is called The Kalinin - Miljukov method. This method is, in effect, a variation of the Muskingum Method.

Although hydrological methods have been used extensively, they have a tendency to be unreliable and in some cases dangerous. The selection of the coefficients must be based on accurate data, and any extrapolation to route larger floods must be treated with extreme caution. Despite these limitations, hydrological methods are still widely used by engineers for the analysis of flood movement (Price, 1977).

2.4 Hydraulic Routing Method

Hydraulic routing methods are more complex and accurate than hydrological methods and are based on the solution of Saint - Venant equations for unsteady flow in open channels. These equations consist of the equation of continuity and the momentum equation, which account for the physical and hydraulic characteristics of the channel system and more adequately describe the dynamic of flow than do the hydrologic routing techniques.

The continuity and momentum equations in terms of discharge and cross-sectional area generate the following form of the Saint - Venant equations. These equations are given respectively:

Continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_1, \qquad 2.18$$

Momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(\frac{Q^2}{A}) + gA\frac{\partial Y}{\partial x} = gA(S_o - S_f), \qquad 2.19$$

where Q is the discharge rate, A is the cross-sectional area of flow, x is the distance along the channel, g is the gravitational acceleration, t is the time, q_1 is the lateral inflow, S_o is the channel bed slope, S_f is the friction slope and Y is the depth of flow.

The friction slope, S_f, is usually evaluated by assuming that it is the same for steady, uniform flow condition, and Manning's equation could be used:

$$S_f = [\frac{nQ}{A}]^2 R^{\frac{-4}{3}}, \qquad 2.20$$

where n is Manning's friction factor and R is the hydraulic radius, defined by the ratio of area to wetted perimeter, P as:

$$R = \frac{A}{P} \qquad 2.21$$

Because of the mathematical difficulties, Eqn. (2.18) and (2.19) cannot be integrated in closed form unless some simplifications are made. For practical applications, solutions of the equations are obtained by the approximate step method or by methods based on simplifying assumptions. From a hydraulics view point, several approximations to the Saint-Venant equations have been proposed as shown in Fig. (2.3). The partial differential equations presented as Eqn. (2.18) and (2.19) cannot be solved by analytical techniques, but require numerical techniques for solution and large quantities of measured hydraulic data together with the aid of a computer due to the large amount of repetitious calculation.

The numerical integration of the full unsteady flow equations consists of re-placing the differential equation with corresponding finite difference expressions, and solving these resulting equations. The development of a complete numerical model of an unsteady flow system requires the inclusion of channel geometry and discharge at all sections along the reach before the arrival of the flood wave. This condition may be evaluated either by assuming the flow to be steady; or by the interpolation of the values between upstream and downstream sections, and the boundary conditions, which are normally stage or discharge hydrographs for the upstream end condition and stage-discharge relationship of a control section or from a rating curve of a gauging station for the downstream boundary condition.

Numerical solutions of the partial differential equations involved in unsteady flow in open channel by finite difference techniques have received considerable attention over the years; e.g., Thomas (1970), Stoker (1957), Gilcrest (1950), Isaacson et al (1958), Fox (1977), Abbott (1975) and Amein (1968).

Isaacson et al (1958) in particular, devised a numerical model employing the explicit finite difference formulation described by Stoker (1957).

Various numerical methods have been developed, since closed form solutions

$$\underbrace{\underbrace{\underbrace{\frac{1}{gA}\frac{\partial Q}{\partial t} + \underbrace{\frac{1}{gA}\frac{\partial}{\partial x}(\frac{Q^2}{A}) + \underbrace{\frac{\partial h}{\partial x}}_{} = S_o - S_f}_{}}_{}}_{}}_{}$$

$$\underline{Kinematic - Wave}$$

$$Approximation$$

$$\underline{Diffusion - Wave\,Model}$$

$$\underline{Quasi - Steady\,Dynamic - Wave\,Approximation}$$

$$\underline{Dynamic - Wave\,Model}$$

Fig. (2.3) Hydraulic Routing Schemes, Approximation to the Saint-Venant Equations.

do not exist for the Saint-Venant equations. The first is termed the characteristics method which employs the concept of characteristic curves in the x-t plane, produced by converting partial differential equations into ordinary differential equations. The second system is the explicit method which calculates values of velocity and depth over a grid system based on previously known data for the river reach. The third system is the implicit method which sets up a series of simultaneous numerical equations over a grid system for the entire flow field, and the equations are solved at each time step.

2.4.1 Characteristic Method

The characteristic form of Saint-Venant equation can be written as:

$$\frac{dQ}{dt} - (\frac{Q}{A} \pm \sqrt{gy})\frac{dA}{dt} = gA(S_o - S_f) - g(\frac{Q}{A} \pm \sqrt{gy}), \qquad 2.22$$

in which

$$\frac{dx}{dt} = \frac{Q}{A} \pm \sqrt{gy} \qquad 2.23$$

Early approaches to numerical flood routing were based on the characteristic form of the governing equations.

Methods which are based on the characteristic forms of the Saint- Venant equations are normally classified as characteristic methods whereas the methods which use finite difference approximations of equation (2.18) and (2.19) are classified as direct methods.

The characteristic form is based on the transformation of the two partial differential equations of unsteady flow (eqn. 2.18, and 2.19) into four ordinary differential equations called the characteristic equations given as:

$$dx = (v + \sqrt{gy})dt \qquad 2.24$$

$$dv + \sqrt{\frac{g}{y}}dy + dt[g(S_f - S) + \frac{v}{y}q_1 - \sqrt{\frac{g}{y}}q_1] = 0 \qquad 2.25$$

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$$dx = (v - \sqrt{gy})dt \qquad\qquad 2.26$$

$$dv - \sqrt{\frac{g}{y}}dy + dt[g(S_f - S) + \frac{v}{y}q_1 + \sqrt{\frac{g}{y}}q_1] = 0 \qquad\qquad 2.27$$

The two equations (2.24) and (2.25) are the equations of the forward characteristics (C_+) and equations (2.26) and (2.27) are the equations of backward characteristics (C_-). Both forward and backward characteristic curves are defined on an x-t plane as shown in fig. (2.4). Characteristic equations are given in standard textbooks, for example Henderson (1966), Abbott (1966), Stoker (1957).

Characteristic methods involves the integration of equation (2.22) along the two sets of characteristic curves given by equation (2.23) and illustrated in fig. (2.4). A network of points in the x-t plane is then located by the intersection of the forward and backward characteristic curves. The four unknowns, depth, velocity, distance and time, at each point in the curvilinear net are determined by the numerical integration of the four characteristic equations.

Characteristic methods have been utilised for the solution of many problems in the field of hydraulics and the application of these methods to unsteady flow in open channels employed numerical finite difference schemes with the advent of digital computers. Numerical schemes for characteristic methods have been limited by the fact that results are obtained on the distance/time grid at uneven intervals. The solution of the equations is obtained at the intersection of the characteristic curves, and not on a fixed grid, as with the direct method.

Applications of the characteristic methods in the field of flood routing, although not as numerous as direct methods, have been proved by many authors to be generally accurate and stable; for example, Amein (1966), Amein and Fang (1970), Baltzer and Lai (1968), Fletcher and Hamilton (1967), Forsythe and Wason (1960), Liggett (1968), Liggett and Woolhiser (1967), Wylie (1969, 1970), Yevjevich and Barnes (1970), Fox (1977), Ellis (1977), and Karmegam (1982).
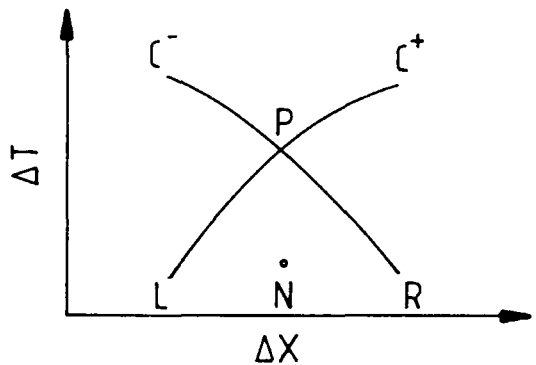
Characteristic Curves
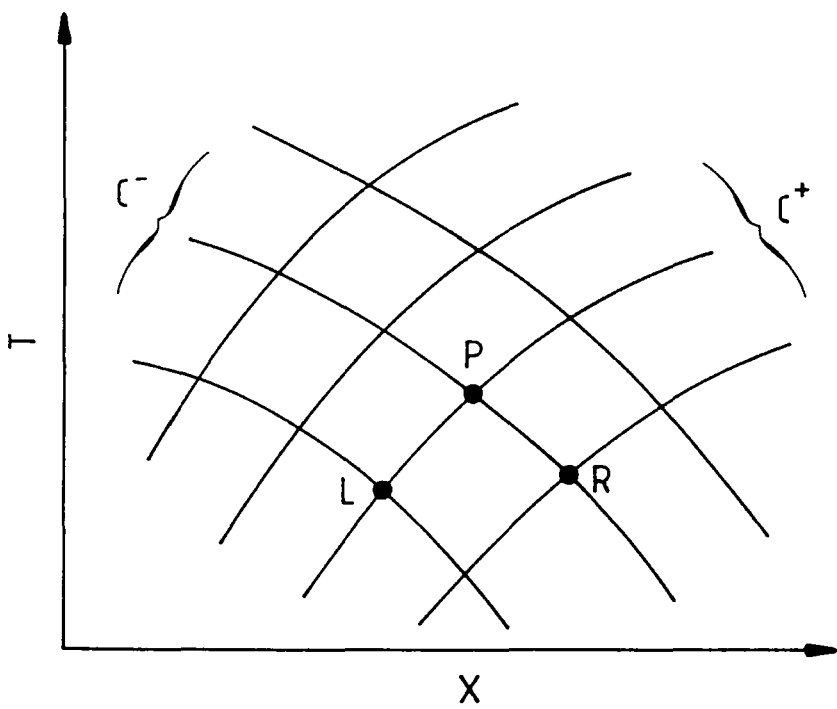
Characteristic Net in X-t Plane

Fig. (2.4) Characteristics Method.

Amein (1966) used characteristic method for flood routing in the Neuse River, North Carolina. This is also described by Amein and Fang (1970).

Fletcher and Hamilton (1967) constructed a characteristics model of a four-miles reach of the Emory River, Tennessee. Reasonably accurate water surface profiles and stage hydrographs were obtained.

Liggett and Woolhiser (1967) concluded that the characteristic method is both accurate and stable when they provided a comparison of a number of unsteady flow modelling techniques, including a characteristic method, for application to overland flow problems.

Fox (1977) and Ellis (1977) have demonstrated the practicality of characteristic methods in the study of open channel transitions and control structures, and the usefulness of these methods for the study of simpler open channel flow problems.

Generally the characteristic methods have been shown to be accurate and are still used for the numerical study of flood routing and associated unsteady flow problems requiring a solution of the full unsteady flow equations.

2.4.2 Explicit Method

Explicit methods are primarly the outcome of the pioneering work of Stoker (1957) and Issacson, et al. (1956). The following numerical approximations with their relations shown in Fig. (2.5) represent the form of Saint-Venant equations, equation (2.18) and equation (2.19), for the explicit schemes:

$$\frac{\partial v(M)}{\partial x} = \frac{V_R - V_L}{2\Delta x} \qquad 2.28$$

$$\frac{\partial v(P)}{\partial t} = \frac{V_P - V_M}{\Delta t} \qquad 2.29$$

$$\frac{\partial y(M)}{\partial x} = \frac{Y_P - Y_L}{2\Delta x} \qquad 2.30$$
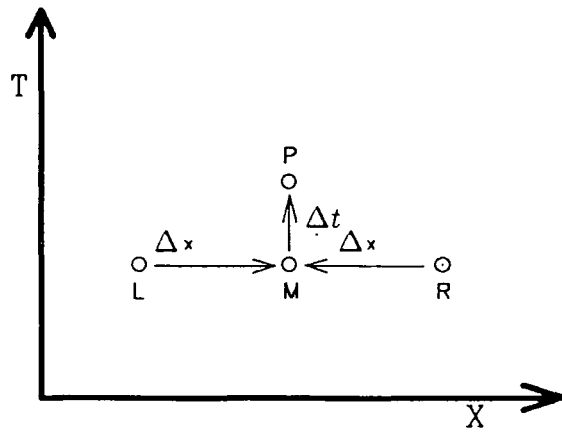
a. Explicit Scheme Grid
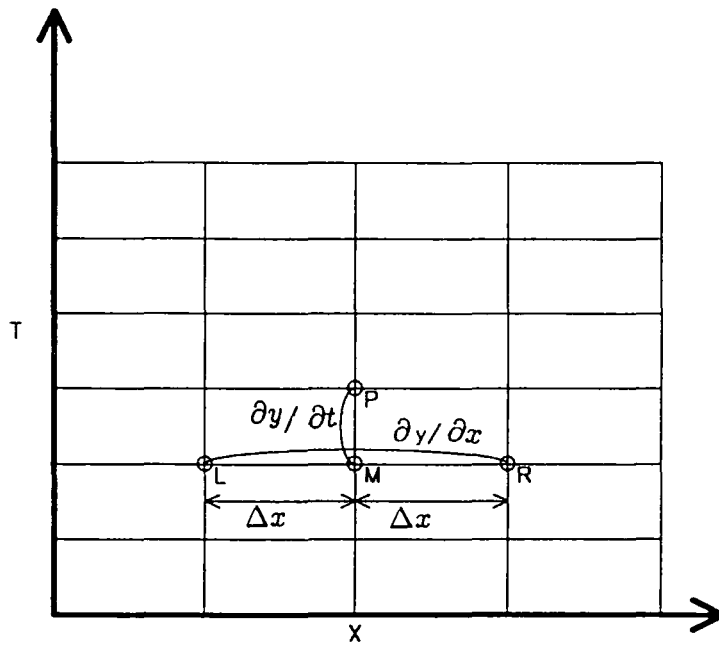
b.Explicit Network in xt-plane

Fig. (2.5) Finite Difference Approximation For Explicit Scheme.

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$$\frac{\partial y(P)}{\partial t} = \frac{Y_P - Y_M}{\Delta t}.$$ 2.31

When these approximations are inserted into the governing Saint-Venant equations they result in algebraic equations with two unknowns, depth, Y_P, and velocity, V_P, which can be computed for each spatial increment.

The most popular explicit methods which have been developed are listed below. They differ primarily in the finite difference representation of the differential equations:

1. Leap-Frog method;

2. Diffusive method; and

3. Lax-Wendroff method.

Explicit methods solve explicitly for flow parameters at one point at a time. Refering to Fig. (2.6) conditions at point (i,j+1) may be found from the known conditions on row (j) independently of any other conditions at the new time level on row (j+1).

Refering to Fig. (2.6) the time derivative for the diffusive scheme, which was developed for gradually varying flows, is written:

$$\frac{\partial Q}{\partial t} = Q_i^{j+1} - (\Theta Q_i^j + \frac{1-\Theta}{2}(Q_{i-1}^j + Q_{i+1}^j)).$$ 2.32

The Leap-Frog scheme, which was more popular and used by Issacson et al. (1958), employ centred differences in both space and time. Referring to Fig. (2.6):

$$\frac{\partial Q}{\partial x} = \frac{Q_{i+1}^j - Q_{i-1}^j}{2\Delta x},$$

$$\frac{\partial Q}{\partial t} = \frac{Q_i^{j+1} - Q_i^{j-1}}{2\Delta t}$$ 2.33

The Lax-Wendroff scheme given by Richtmyer (1957), provides second order accuracy with the finite difference expression.

t

j+2 +   col. + i-1+   i   + i+1 + i+2 +
        i-2

j+1 +   +   i-1,j+1 + i,j+1(A) + i+1,j+1(B) + +

row j +   +   i-1,j + i,j(C) + i+1,j(D) + +

j-1 +   +   i-1,j-1 + i,j-1 + i+1,j-1 + +

Δt

Δx

i-2 +   +   + i,j-2 + + +

x
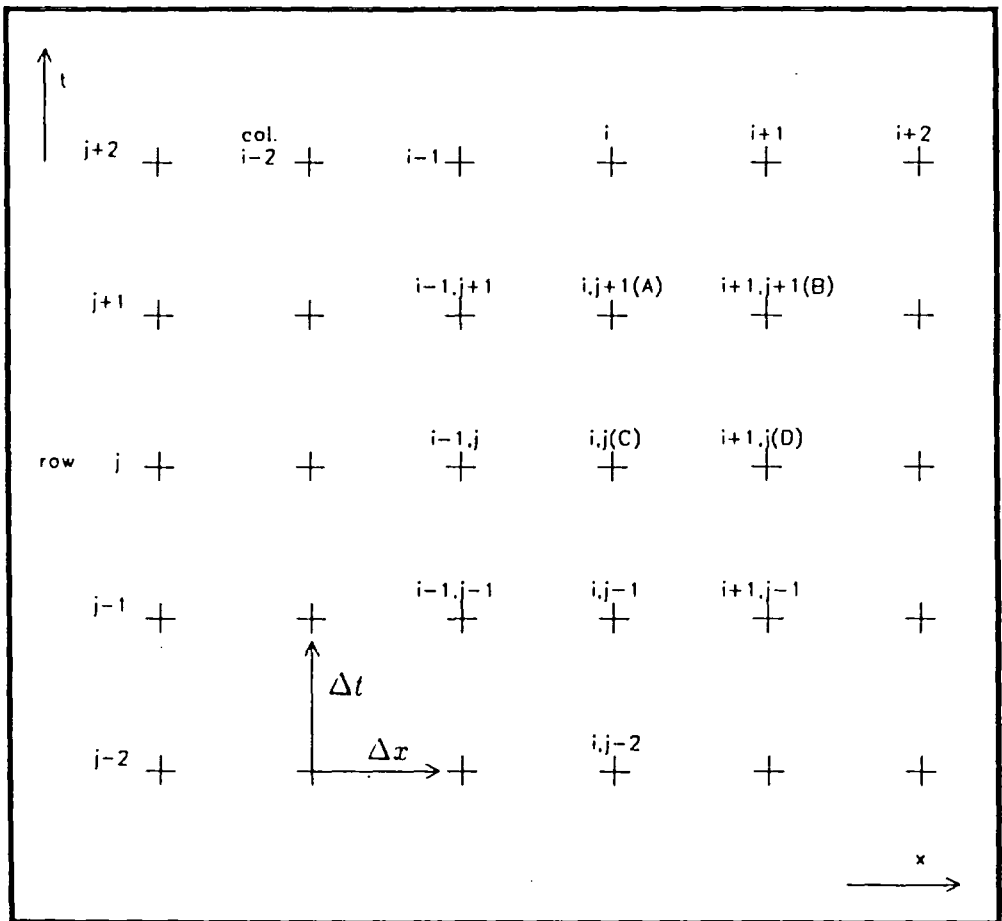
Fig. (2.6) Fixed rectangular space/time grid.

Explicit schemes, unfortunately have serious computational stability problems. The computational space and time intervals are constrained by the Courant criterion (Courant and Friedrichs, 1948), or more often the 'Courant' condition. The Courant condition can be stated mathematically:

$$\Delta t \leq \frac{\Delta x}{V + \sqrt{\frac{gA}{B}}}, \qquad\qquad 2.34$$

where Δx is the distance step, Δt is the time step, A is the wetted cross-section area, B is the top width and V is the velocity.

Explicit methods have received considerable attention from many authors. Among those who have studied explicit methods are Amein and Fang (1969), Liggett and Woolhiser (1967) and Prandle and Crookshank (1974) applied the explicit method to analyze tidal movement in estuaries. Garrison et al. (1969) and Johnson (1974) applied the explicit method to simulate flood routing in rivers and reservoirs. Ballofet et al. (1974) selected an explicit method for modelling the travel of a dam-collapse wave along a 20 km. reach of the Bou Regrreg River, Morocco. Ridgeway (1975) describes a numerical model of a small experimental rectangularl estuary and suggests that an explicit scheme is preferable for modelling the experimental tidal propagation. Smith (1977) reports the use of an explicit mathematical model for an analysis of flood relief schemes for the White Cart Water, near Glasgow.

It has been shown that explicit methods have been applied to various open channel flow problems such as tidal rivers, estuaries, dam-break waves and tidal propagation and have been used extensively for two and three-dimensional models.

2.4.3 Implicit Method

Implicit methods were available in the 1950s for the study of heat propagation and gas dynamics, and were adapted in the early 1960s for the study of unsteady

open channel flow. Implicit methods have been increasingly used because of the prohibitive restriction on the time step size when using explicit schemes. A number of different implicit schemes have subsequently been developed, but they all adhere to one fundamental principle. Three methods do, however, stand out as being the basis of most other methods. The first implicit scheme is called the Preissman (SOGREAH) scheme as it was developed by Preissman of SOGREAH in France (1961). The second implicit scheme is called The Amein Four-Point scheme and is described by Amein (1968). A third implicit scheme is that described by Abbott and Ionescu (1967) and is usually called Abbott's scheme. Mention is made in this section to the Amein Four-Point scheme, because it is well used by large research organisations and investigators, forinstance Chaudhry and Contractor (1973), Kamphuis (1970) and Lai (1967). Price (1974) compared a number of different methods for routing monoclinal waves. He concludes from analytical and empirical work that the four-point implicit method (Amein) is most accurate when $\frac{\Delta x}{\Delta t}$ approximates to the speed of a kinematic wave. A major study of the numerical properties of four-point implicit methods was carried out by Fread (1973, 1974).

The Saint-Venant equations, equation (2.18) and equation (2.19), are expressed in finite difference form using difference approximations to the partial terms. For example the finite difference approximations for the four- point non-central implicit scheme follows with their relations as shown in Fig. (2.7):

$$\frac{\partial y}{\partial x} = \frac{1}{2\Delta x}(y_{i+1,j+1} + y_{i+1,j} - y_{i,j+1} - y_{i,j}) \qquad 2.35$$

$$\frac{\partial y}{\partial t} = \frac{1}{2\Delta t}(y_{i,j+1} + y_{i+1,j+1} - y_{i,j} - y_{i+1,j}) \qquad 2.36$$

$$\frac{\partial Q}{\partial y} = \frac{1}{2}(\frac{\partial Q}{\partial y}\Big|_{i,j+1} + \frac{\partial Q}{\partial y}\Big|_{i+1,j+1}) \qquad 2.37$$

$$\frac{\partial A}{\partial y} = \frac{1}{2}(\frac{\partial A}{\partial y}\Big|_{i,j+1} + \frac{\partial A}{\partial y}\Big|_{i+1,j+1}) \qquad 2.38$$
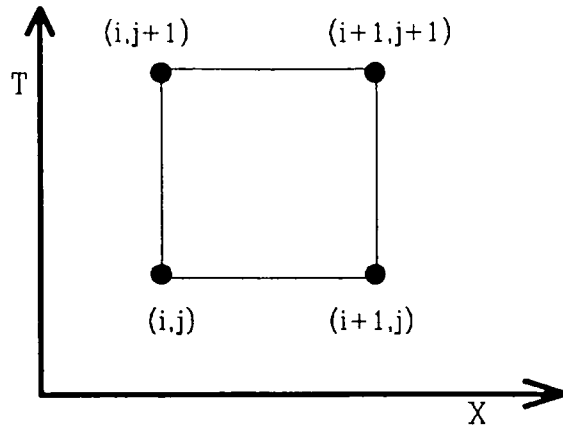
a. Implicit Scheme Grid
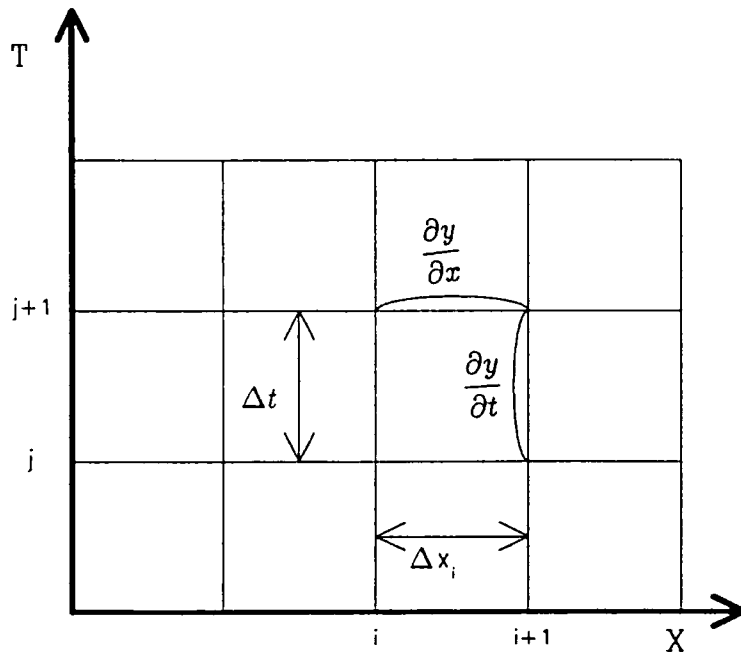
b. Implicit Network in xt−plane

Fig. (2.7) Finite Difference Approximation For Implicit Scheme.

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These approximations are substituted in the continuity and momentum equations, so that the depth and velocities at each point (i,j+1) and (i+1,j+1) for a given time step are unknown. The depth and velocities at each point for time t + Δt are solved from the set of the algebraic equations resulting in the finite difference approximations.

From a stability analyses view point, implicit finite difference schemes appear to be unconditionally stable, consequently, Δt and Δx can be chosen independently. However, convergence requires that the time step be limited to a degree which is largely dependent on the time rate of change of flow. When the rate of change of flow is low, the implicit method should permit use of longer reaches and hence require less computational time than the other methods.

A number of analyses have been carried out of the stability and accuracy characteristics of implicit methods. Unlike explicit methods, the choice of time step size with implicit method applications is unaffected by the Courant condition, and hence in many cases ridiculously large time steps will not adversely affect the stability of the method.

Boundary conditions are generally more straightforward to include in a model with implicit methods than with explicit methods. Boundary conditions are either a discharge hydrograph Q = f(t), a stage hydrograph Y = f(t), or a stage/discharge relationship Q = f(Y).

A large number of different implicit methods have been developed and used successfully in the study of rapidly varying conditions in open channels, such as surge waves in canals and reservoirs following sluice gate operation. Despite the utilisation of implicit methods for the study of the tidal propagation and rapidly varying flow, the methods have been applied most successfully in the field of flood routing in non-tidal rivers, where explicit methods are often inappropriate. An

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early application of implicit methods to flood routing problems is described by Amein (1968), and Amein and Fang (1969, 1970).

Smith (1977) criticises the large number of different implicit methods still in use for solving similar problems, and considers that this lack of standardisation has severely hindered the improvement of numerical modelling techniques.

2.5 Convection - Diffusion Method

Convection-diffusion methods are based on the principle of neglecting the acceleration terms of the momentum equation (2.19) which may be written:

$$\frac{\partial y}{\partial x} = (S_o - S_f) \qquad 2.39$$

The modified momentum equation (2.39) can be combined with the continuity equation (2.18) to form the covection-diffusion equation which is the basis of the convection-diffusion methods, and the equation is:

$$\frac{\partial y}{\partial t} + \omega \frac{\partial y}{\partial x} = \mu \frac{\partial^2 y}{\partial x^2} \qquad 2.40$$

in which ω and μ are dispersion parameters. Hayami (1951) and Henderson (1966) identified ω as the velocity of a kinematic flood wave and μ as a diffusion coefficient.

The convection-diffusion method which was based on the analytical solution of the linear convection-diffusion equation was first derived by Hayami (1951). He argued that the diffusion of disturbances in channels caused by local geometrical irregularities is satisfactorily represented by the equation of particle diffusion. A description of Hayami's original derivation of the method is provided by Henderson (1966).

Wormleaton (1968) used a convective-diffusion equation based on river depth

for a study of the River Dee in Wales:

$$\frac{\partial y}{\partial t} + \frac{3}{2}v\frac{\partial v}{\partial x} = \frac{1}{2}\frac{y}{\left(S_o - \frac{\partial y}{\partial x}\right)}\frac{\partial^2 y}{\partial x^2} \qquad 2.41$$

in which ω and μ were considered to be constant for each flood event.

Thomas and Wormleaton (1970, 1970) produced a numerical flood routing technique on the basis of the linear convection-diffusion equation including the lateral inflow as given below:

$$\frac{\partial y}{\partial t} + \omega\frac{\partial y}{\partial x} = \mu\frac{\partial^2 y}{\partial x^2} \qquad 2.42$$

Their method was based on the finite difference solution of equation (2.42) in the x-t plane with the constant parameters of ω and μ. They tried to find both dispersion parameters by fitting the peak value of at the downstream section and the travel time of the peak through the reach.

The most significant improvement in the use of a diffusion wave model is the development of the variable parameter diffusion method, (which is discussed in details in chapter 4), by Price (1973, 1974, 1977), in which the coefficients ω and μ are considered to be variables dependent on the discharge in the channel. The variable parameter diffusion method is recommended in volume III of the N.E.R.C. flood studies report (N.E.R.C. 1975) as suitable for use on British rivers. All methods discussed by Price are based on a convection-diffusion equation with discharge Q as the diffusion quantity:

$$\frac{\partial Q}{\partial t} + \omega\frac{\partial Q}{\partial x} = \mu\frac{\partial^2 Q}{\partial x^2} \qquad 2.43$$

Convection - diffusion methods are not as numerous or well-used as the hydrological methods described in section 2.3, due to their increased complexity and the requirement for more accurate flood data.

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2.6 Methods Based On The Kinematic Wave Model

Kinematics is defined as the study of motion exclusive of the influences of mass and force, in contrast with dynamics, in which these influences are included.

The kinematic wave method of routing overland and river flows, although simple in form, offers the benefits of nonlinear response without needing an unduly complicated or costly solution procedure. In addition, for the purpose of modelling unsteady overland flow, any model will require considerable parameter adjustment to account for the complexities of the basin and the specific flows which occur within the basin.

The kinematic method was presented by Lighthill and Whitham in 1955. They introduced a new simplified flood routing model based on a modification of the momentum equation. By neglecting all terms except the friction and channel bottom slope, the new equation, describes the movement of kinematic waves as opposed to dynamic waves described by the full equations. For the kinematic wave model Equ. (2.39) can be further approximated to:

$$S_o - S_f = 0 \qquad 2.44$$

which implies that the friction slope is approximately equal to the channel bottom slope.

The kinematic waves are based primarily on the continuity equation, and the basic equation can be written as:

$$\frac{\partial Q}{\partial t} + \omega \frac{\partial Q}{\partial x} = 0 \qquad 2.45$$

where ω is the wave velocity. Equation (2.45) is known as the kinematic wave equation and this name was appropriately chosen by Lighthill and Whitham (1955) because it is based on continuity only. A kinematic wave is a wave of constant

amplitude travelling with the same celerity as a monoclinal wave:

$$C = v + A\frac{dv}{dA} \qquad\qquad 2.46$$

Kinematic waves can flow only in a downstream direction without crest subsidence and possess only one wave velocity. The flood wave will be observed as a uniform rise and fall in water surface over a relatively long period of time. Thus kinematic waves represent the characteristic changes in discharge, velocity and water surface elevation with time at any one location on an overland flow plane or a long stream channel.

A state variable kinematic wave model is applied for routing floods through rivers, where the stages and discharges are computed by a kinematic wave routing techniques. Detail of the state variable model and the mathematical modelling and application of the state variable kinematic wave model are discussed later in chapter 4 and 6 respectively.

CHAPTER 3

CATCHMENTS AND THE DATA

3.1 Location

Two catchment areas within the northeast of England are considered in this study. For convenience these are referred to as The Wear river and Tees river catchments. The relative position and the adjacent area of each catchment are shown in Fig. (3.1). The two catchment areas lie between latitude $(54^{o}27^{'} - 54^{o}52^{'} N)$ and longitude $(1^{o}26^{'} - 1^{o}36^{'} E)$.

3.2 The Wear River Catchment And The Study Reach.

3.2.1 General Description

The River Wear rises on the Pennine plateau with a significant area of its catchment above 300m OD Fig. (3.1). Headwater catchments have steep gradients and a predominant peat cover which give rise to rapid runoff response and a high percentage runoff . Annual and storm rainfall are also highest in this area, where the greatest proportion of flood volume is generated. In the middle part of the river, from Witton-le-Wear to Durham, the river meanders on an active flood plain. Through Durham and for 10 kms. downstream, the meanders become entrenched with little overbank storage before the valley opens out again in the reach to the tidal limit just below Chester-le-Street.

Man-made changes in the catchment which may have increased flood potential include urbanisation and the confinement of the river within flood banks. The principal source of potential flood reduction is from reservoir construction. There are two sub-catchments with reservoirs, namely Tunstall and Burnhope.

The reach of the River Wear investigated lies between two gauging stations,
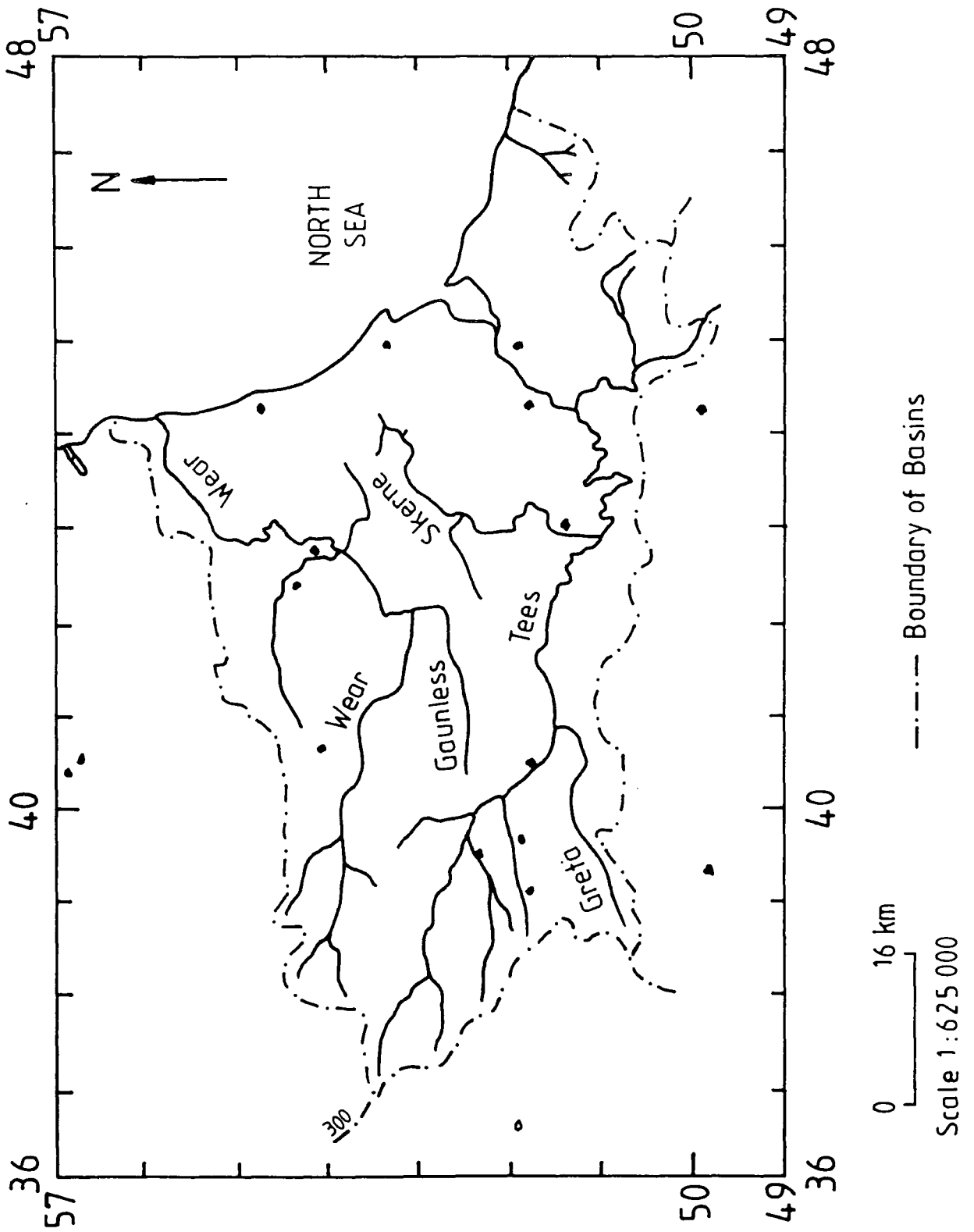
Fig. (3.1) Wear And Tees Rivers Catchment Area.

of which the upstream is at Sunderland Bridge, 11.5 kms above Durham city and the downstream is at Chester-le-Street see Fig. (1.3).

A major tributary, the river Browney, joins just below Sunderland Bridge and has been gauged at Burn Hall near the confluence. The Browney contributes an average of 12 % of the combined peak flood flow and in major floods the maximum contribution has been 25 % (Archer, 1988). Peak flood flows over each period of record are estimated as the sum of the peak discharge at Sunderland Bridge and the concurrent flow at Burn Hall.

The catchment area of River Wear to Sunderland Bridge is approximately 657.8 km^2 , while that to Chester le Street is approximately 1008.3 km^2. Some parts of it are grassland, others are a varying pattern of crops.

The headwater of upstream river reach lies at an elevation up to 80 m above sea level. The downstream river reach descends to 20 m above sea level.

The river reach used in this study is of 28.87 kms long with channel slope of 1.235 m/km. The width of the channel along the reach ranges from about 24 m to over 45 m with an average about 34.5 m.

The River Wear flows in a general easterly direction to its confluence with the North Sea, a distance of approximately 90 km. The main towns in the River Wear catchment are Durham, Chester-le-Street and Sunderland.

The average annual rainfall for the catchment above Durham is 880 mm. The flow input is comparatively small since rainfall totals are lower and the permeable soils and magnesian limestone bed rock lead to much lower percentage runoff.

Generally, the River Wear has slightly extended flood plains in different places along the reach which are inundated regularly, affording some attenuation in peak flows.

N

NORTH SEA

River Wear

DURHAM

River Tees

0 5 10 15
Scale in Miles

0 5 10 15 20
Scale in Kilometres

Jurassic	Middle Jurassic	□
	Lower Jurassic	▨
Trias	Rhaetic / Keuper	▨
	Bunter	▨
Permian	Upper Permian Marl / Magnesian Limestone / Marl Slate / Basal Yellow Sands	▨
	Penrith Sandstone and Brockram Breccias	▨
Carbonif-erous	Coal Measures	▨
	Millstone Grit	▨
	Carboniferous Limestone	□
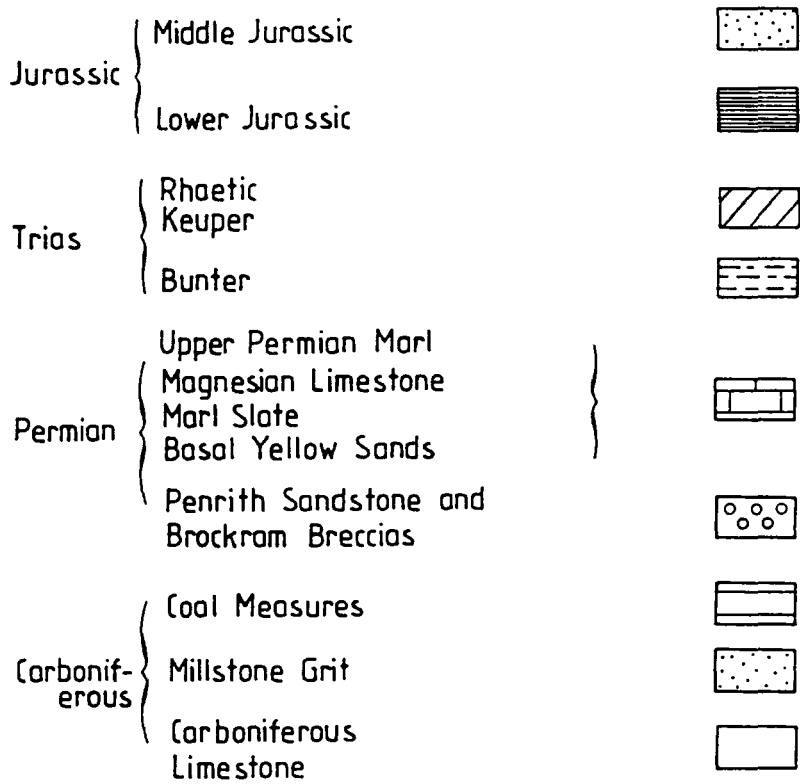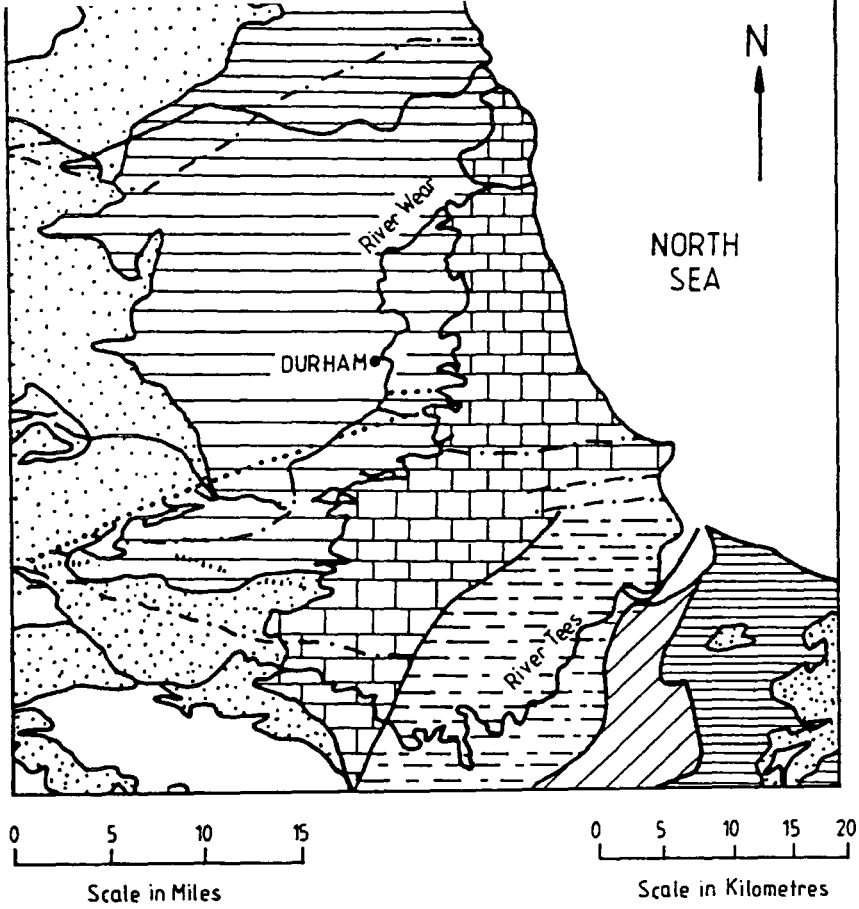
Fig. (3.2) Geological Map Of Wear And Tees Rivers Catchment.

3.2.2 Geology of Wear River Reach

The geology of Durham County is dominated by a gently warped mass of Carboniferous sediments overlain by Permian and Trias to the south-east.

A geological map of the Wear and Tees river catchments is shown in Fig. (3.2).

The major part of the reach passes through Durham City which is underlain by thick glacial and fluvioglacial deposits except in the vicinity of the cathedral and castle where the Coal Measures reach the surface and are exposed on the steep banks of the River Wear (Johnson and Hopkins, 1973). The geological formations that cover the study channel reach will be described in detail.

Coal Measures

Coal Measures are of Carboniferous age. The proved thickness of Coal Measures is of order of 2000 ft. (610 m.) which can be divided into three divisions: the Lower, Middle and Upper Coal Measures. The upper part is erosional and is overlain unconformably by the Permian in the east and south of the County Durham Fig. (3.2).

The Coal Measures consist of a series of sedimentary cycles, each of which is composed of the general strata:sequence shale- siltstone- sandstone- seat earth - coal in ascending order. Within the Durham Coal Measures, sandstones are predominant near the base, thick coal seams characterize much of the middle sequence, while shale and siltstone predominate near the top. The Coal Measures were laid down in a low lying coastal swamp with wide deltas, estuaries, shallow lagoons and lakes which spread south and west from the land mass in the north.

In the Lower and Middle Coal Measures, the dominant rock types are shale or mudstone, and sandstone. The colour varies from dark to light grey, but marine shales are usually dark. The Coal Measures sandstones are mainly cross-bedded,

and fine to medium grained rock. Seat earths, leached by the action of plant roots, vary from light-coloured fireclays to mudstone with rootlets, and the more arenaceous seat earths from sandstone to hard siliceous ganister.

Permian Deposits

The Permian sediments consist mainly of basal yellow sand, marl slate, magnesian limestone, and Upper Permian marl.

The Lower Permian is represented in north-eastern Durham by up to 60 m. of weakly cemented aeolian sandstone, the 'yellow sand', which forms long ridges trending west-south-west, interpreted as fossil seif-dunes and in south eastern Durham as thin discontinuous piedmont breccias.

The basal Permian Deposits are breccias and sandstones. They contain fragments of Carboniferous limestone probably derived from the higher ground. The poorly cemented sandstone form the characteristic basal Permian Deposits and are known as 'yellow sands'.

The marl slate is taken as the base of the Upper Permian, ranges up to 5.5m.in thickness that is generally 0.6 to 1.2 m. thick. It is finely laminated and grey in colour when unweathered but yellow or brown at outcrop. Heavy metal sulphides of copper, lead and zinc together with pyrite are also present in the marl-slate.

The marl slate is followed up to 76 m. of relatively pure fine-grained dolomite and limestone, grey-buff in colour, which is called the lower magnesian limestone.

Deposition of the middle magnesian limestone commenced in northern Durham. It is divided into lagoonal and basin facies by a major barrier reef. The lagoonal beds are mainly composed of oolitic and pisolitic shallow-water dolomite. Basin facies are composed of fine grain dolomite. Generally speaking, the Magnesian Limestone is extensively fractured and thus highly permeable to water flow and

has, in addition a high primary porosity which gives it a relatively high storage.

In summary, the inflow hydrograph of the reach is influenced by the type of sediments or geological formations. This is evident from the difference in peak flow both upstream and downstream of the reach. For instance in the case of impervious strata, a high percentage of direct runoff is produced and consequently a rapidly rising hydrograph, while in the case of permeable soil, a very low percentage runoff has resulted.

3.3 The Tees River Catchment And The Study Reach

3.3.1 General Description

The reach of the River Tees investigated lies between the gauging station at Broken Scar near Darlington and Low Moor Fig. (1.4). Broken Scar has a compound crump weir modular sited near the highest observed flow, confirmed by confirmed by current meter. At Low Moor, there is a natural channel control at high flows defined by current meter over 92 % of the observed range of level.

The catchment area to Broken Scar is 818 km^2 and that to Low Moor is 1264 km^2. There are two principal tributary catchments draining to the reach, namely the Skerne and the Clow Beck. Both these tributaries join the River Tees near the upstream end of the reach.

The Tees river above Broken Scar is an upland river rising on the Pennine plateau. The predominant peat cover has a high degree of impermeability, and percentage runoff in flood events which commonly exceeds 60 %. The main channel in this upper and middle reach is steeply sloping with a number of rapids and falls. The runoff response is rapid.

Below Broken Scar, there is a marked change both in the channel and in the characteristics of the contributing catchments.

The channel length from Broken Scar to Low Moor is 34.5 km and the average slope is 0.92 m/km. The width of the channel along the reach ranges from about 24.5 m. to over 48 m. with an average about 36 m. The alluvial channel meanders over a wide flood plain. The catchment contributing to this reach generally lies below 100m OD and has an average annual rainfall of 665 mm.

The headwater of upstream river reach lies at an elevation up to 76 m. above sea level. The down stream river reach descends to 20 m. above sea level.

The River Tees flows in a general easterly direction to its confluence with the North Sea, a distance of approximately 77 km. The main towns in the River Tees catchment are Darlington, Yarm, and Teesside.

3.3.2 Geology Of Tees River Reach

The geological formations exposed in the Tees River reach is of Triassic age Fig. (3.2).

The Triassic sediments are composed mainly of Rhaetic black shale, Keuper marls and Bunter sandstone.

The Bunter sandstone is composed of about 213 m. of soft fine-grained, thick bedded red sandstones with grey colour bands and bands of mudstone and siltstone.

The main outcrop of the Keuper marls lies to the south of the River Tees Fig. (3.2). It is covered almost everywhere by deep drift deposits. Keuper marls are composed of dull reddish brown and banded siltstone and mudstone, with much anhydrite and halite near the base. The Rhaetic black shale and green marls overlying the Keuper at the top of the Triassic have been mapped on the flanks of the Cleveland Hills in north-east Yorkshire, and are exposed on the coast near the mouth of the River Tees.

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3.4 Hydrological Data

Rainfall, water level, and discharge data of different events over different years were obtained from the Northumbrian Water Authority in Newcastle upon Tyne. Additional informations such as channel geometry and flood plain geometry were extracted from topographical maps and fieldwork.

3.4.1 Rainfall

Three storms from Jan. 1982 and Feb. 1984 at Tunstall station, and March 1986 at Allenheads station (see appendix IV), have been selected to show varied rainfall characteristics and their effect on runoff.

The catchment area under study has wet winters, the total rainfall varies from one season to another.

The average monthly rainfall of the area under study according to the above storms is 948mm, 1500mm, and 898mm.

In general, from November to March there is high precipitation; more than 80 % of the annual total rainfall occurs at this time. On the other hand, during the period of the current study which has lasted three years; 1987-1989, a little precipitation has been observed during summer months.

In winter, from December to March, most of the precipitation and particularly the heavy storms occur. The heavy storms usually contribute to a very high level of the daily mean flows in the output of the river reach.

It has also been observed from the three storms that the average monthly rainfall does not exceed 50 mm. Furthermore, throughout the study period there have been no heavy storms and consequently no rapid rise in flow level has occurred in either river. Thus no serious flood damage has been observed.

3.4.2 Discharge Records

Both the Wear and the Tees reaches are adequately served by gauging station in order to provide a reliable flood frequency analysis.

Referring to Figs. (1.3) and (1.4), gauging stations records for which are used in this study are named as the Sunderland Bridge and Chester le Street gauging stations for River Wear reach, and Broken Scar and Low Moor gauging stations for River Tees reach. Details of each station are given below. Lateral inflow to the both Wear and Tees River reaches are also gauged in Burnhall and Southpark stations.

1. Sunderland Bridge Gauging Station

Sunderland Bridge gauge station has been situated on the River Wear (plate 3.1) since 1957, 11.5 km above Durham City and 60 km from the North Sea confluence. It measures the runoff of 657.8 km^2 catchment area of the upper River Wear. Sunderland Bridge gauge station is a compound broad-crested weir constructed specifically for flow measurment.

Water level records from an automatic level recorder have been converted into discharge hydrographs for a number of flood events: Feb. 1981, Oct.1981, Feb. 1984, Mar. 1986, April 1986, and Aug. 1986. Peak flow discharges of these events are: 181.7, 318.9, 232.6, 191.2, 302.4, and 451.1 cumecs respectively. Added to that, Sunderland Bridge gauge station has well defined flood ratings.

Additional discharge flow enters the River Wear reach from the Browney tributary which joins just below Sunderland Bridge gauge station and has been gauged at Burn Hall near the confluence since 1954. Flood events records from Sunderland Bridge gauge station are used in the flood routing models described in chapter 4.

2. Chester-le-Street Gauging Station

Chester-le-Street gauge station (plate 3.2), is flat vee weir of triangular crest constructed specifically for flow measurment. It is situated 30 km from the North Sea confluence. The weir becomes drowned out at a discharge of approximately 15 cumecs.

Discharge hydrographs have been derived for the flood events of Feb.1981, Oct.1981, Feb.1984, Mar.1986, April 1986, and Aug. 1986 with peak flows of 182.3, 273.2, 248.0, 227.4, 278.6, and 354.2 cumecs respectively which are used in the flood routing models described in chapter 4.

3. Broken Scar gauging Station

Broken Scar gauge station is situated 75 km from the North Sea confluence on a flumed section of the River Tees near Darlington (plate 3.3). It has a compound crump weir modular sited near the highest observed flow, confirmed by current meter. Three flood events of the best recording of Broken Scar gauge station have been obtained from the Northumbrian Water Authority for Jan. 1982, Jan. 1984, and Aug. 1986 with peak flows of 616.3, 275.7, and 713.8 cumecs respectively. Broken Scar has a reliable gauge record from 1956 to 1986. It has well-defined flood ratings.

Additional discharge enters the River Tees reach from two tributaries namely, the Skerne gauged presently at South Park, and the Clow Beck, gauged at Croft only until 1980. Discharge records at Broken Scar gauge station are used in the flood routing models described in chapter 4.

Plate (3.1) The Sunderland Bridge Gauge Station

Plate (3.2) The Chester le Street Gauge Station

4. Low Moor Gauge Station

Low Moor gauge station is situated 40 km from the North Sea confluence. At Low Moor, there is natural channel control at high flows as defined by current meter over 92 % of the observed range of the level of the river (plate 3.4).

The peak discharges of the three flood events used in this study are 440.2, 231.0, and 441.8 cumecs. Discharge records at Low Moor are used in the flood routing models described in chapter 4.

Low Moor gauge station has a common gauged record from 1969 to 1986. It has also well-defined flood ratings.

3.4.3 Water Level Records

The water level at a gauging station, the most important measurement in hydrometry, is generally known as the stage. It is measured with respect to a datum, either a local bench mark or the crest level of the control. All continuous records of the discharge are derived from a continuous stage record and depend on the accuracy of the stage values.

Records of water level, relating to the analysed flood events, were obtained from the Northumbrian Water Authority, and were extracted from continuous automatic level recorder graphs, and from manually observed gauge board data for periods of high discharge.

Observers must be very careful in reading the water level at the stage gauge, and in recording immediately the correct level. All instrumentation should be checked regularly including all parts of the recorders, clockwork, mechanical or electronic, and should receive routine maintenance and testing for correct settings. The production of reliable river flow records relies on the quality of the basic measurements.

Plate (3.3) The Broken Scar Gauge Station

Plate (3.4) The Low Moor Gauge Station

Flood forecasting and warning system are, however, based principally on manually observed water levels at a number of gauge boards over periods of high flow. Gauge boards are sited at all gauging stations considered in the preceding section.

3.5 Flood Events Used In This Study

The coefficients of the storage-discharge relationship were calculated with the help of pre-recorded flood events in a river reach. Obviously, the result of such an investigation would be improved if more flood events were analysed. This may eventually enable the calculated coefficients to be easily established in a convenient form for future use. Although the flood data are readily available from the Northumbrian Water Authority, in order to analyse more flood events, one has to spend a considerable amount of time on data collection and processing.

The flood events used for this study were selected by D. Archer (Principal hydrologist in Northumbrian Water Authority) and the author. In such a selection, attempts were made to ensure that the samples contained both high and low flows.

For the River Wear reach, the different recorded events chosen were of different times over the years 1981, 1984, and 1986. The recorded inflow and outflow are plotted in Figs. 3.3-3.8. The flows are instantaneous values measured at the stated time (in cumecs).

For the River Tees reach, the data sets from Jan.1982, Jan. 1984, and Aug. 1986, were chosen for both hourly mean inflow and outflow (in cumecs). The raw data are plotted in Figs. 3.9-3.11.

In all, 9 flood events were used in this study. Table 3.1 presents the date of occurrence of the events, together with peaks of inflow and outflow of the two reaches. The necessary data in the form of water level recording and discharge

Fig.(3.3) Inflow And Outflow Hydrographs For The Event of Aug. 1986 of Wear River Reach.
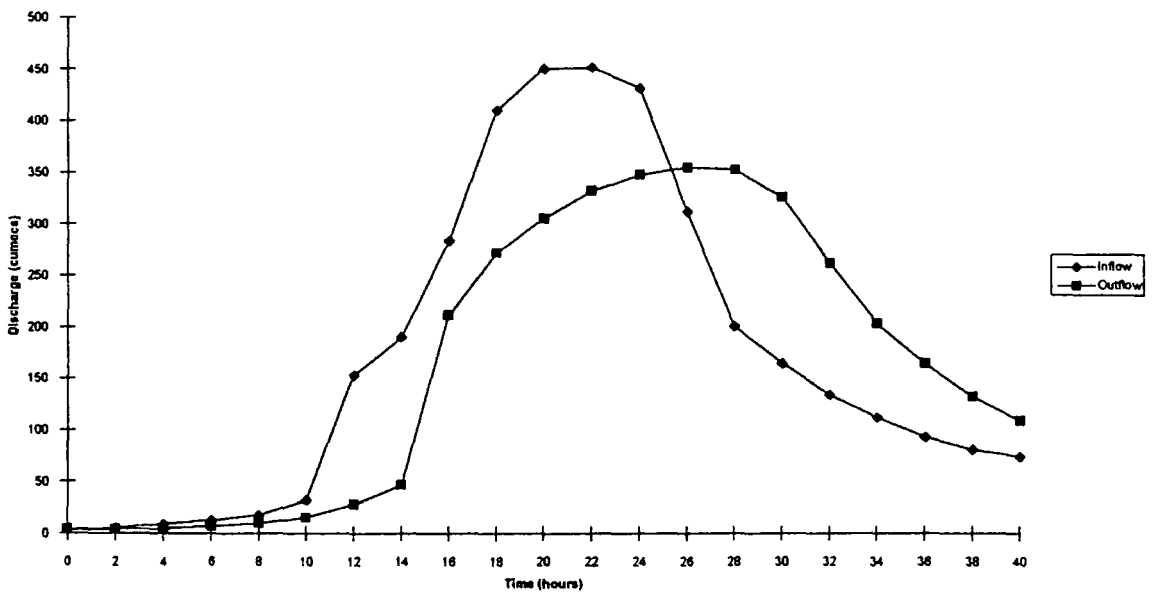
Fig.(3.4) Inflow And Outflow Hydrographs For The Event of Oct. 1981 of Wear River Reach.

60
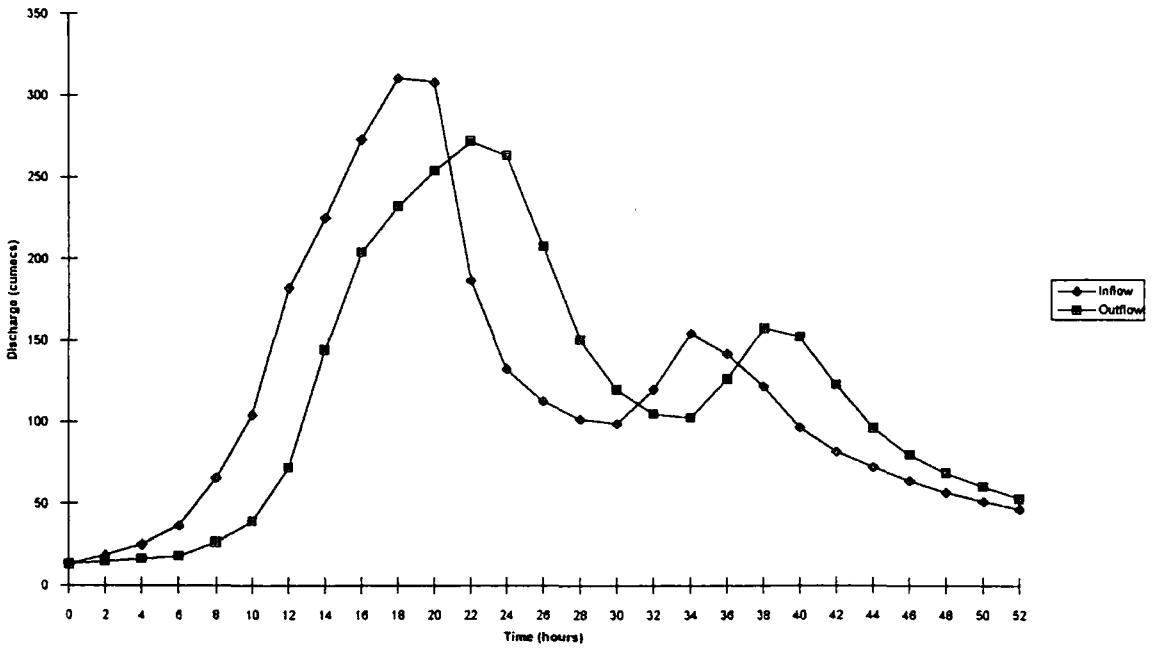
Fig. (3.5) Inflow And Outflow Hydrographs For The Event of April 1986 of Wear River Reach.
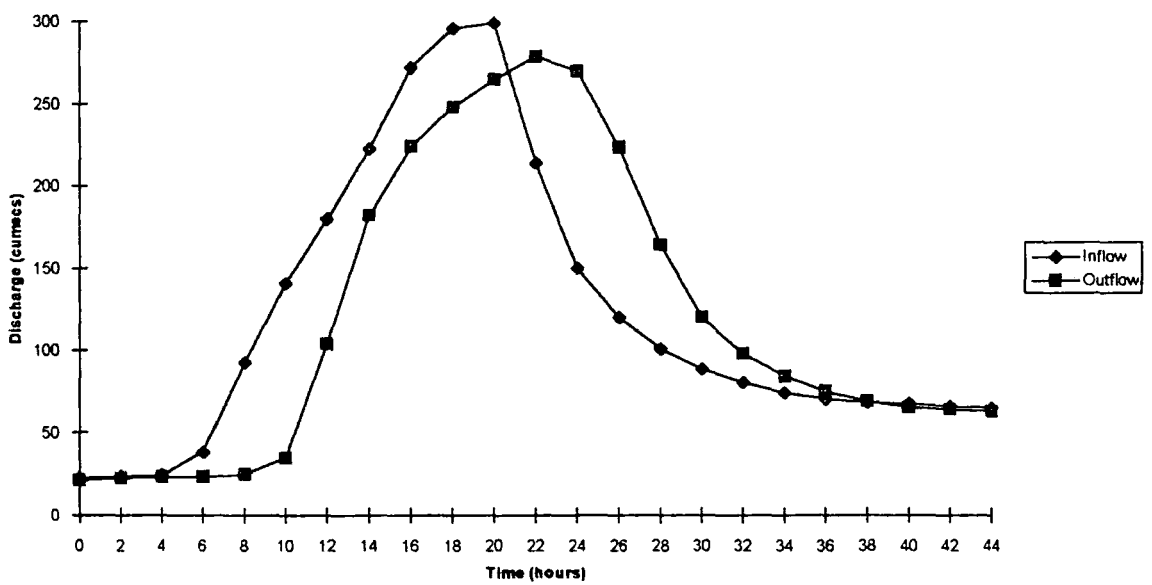
Fig. (3.6) Inflow And Outflow Hydrographs For The Event of Feb. 1981 of Wear River Reach.
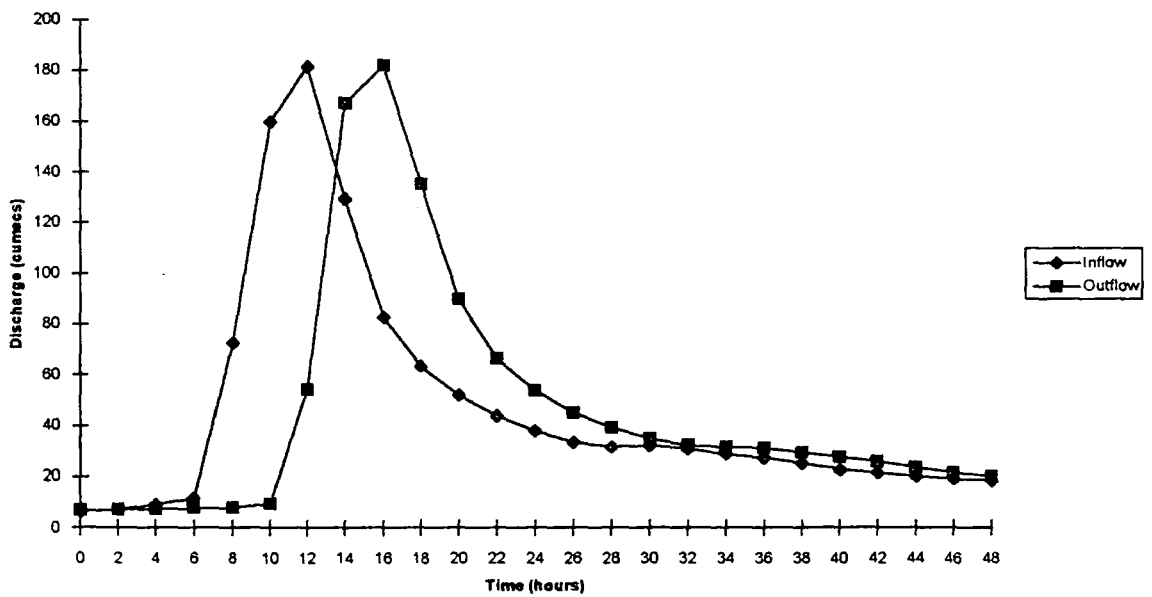
Fig. (3.7) Inflow And Outflow Hydrographs For The Event of Mar. 1986 of Wear River Reach.
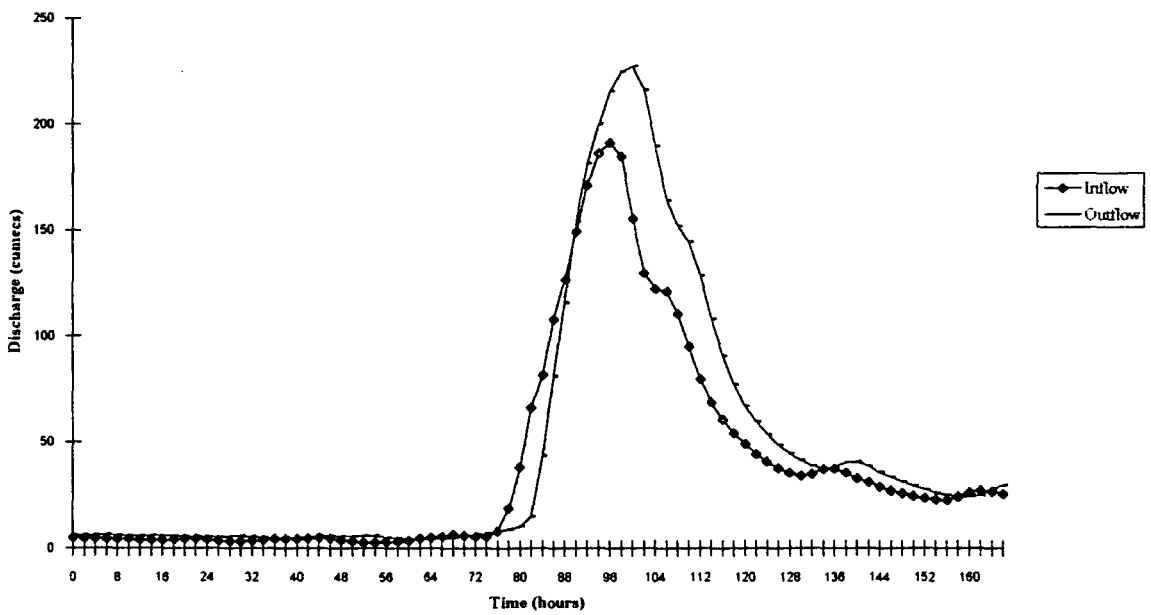
Fig. (3.8) Inflow And Outflow Hydrographs For The Event of Feb. 1984 of Wear River Reach.
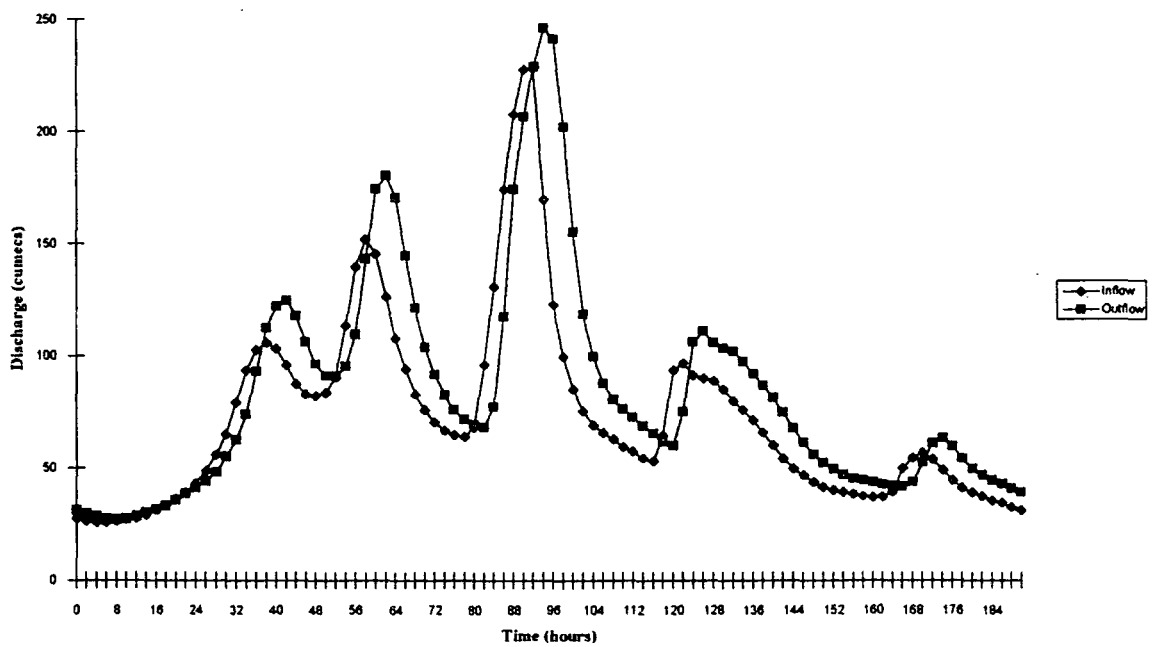
Fig.(3.9) Inflow And Outflow Hydrographs For The Event of Jan. 1984 of Tees River Reach.
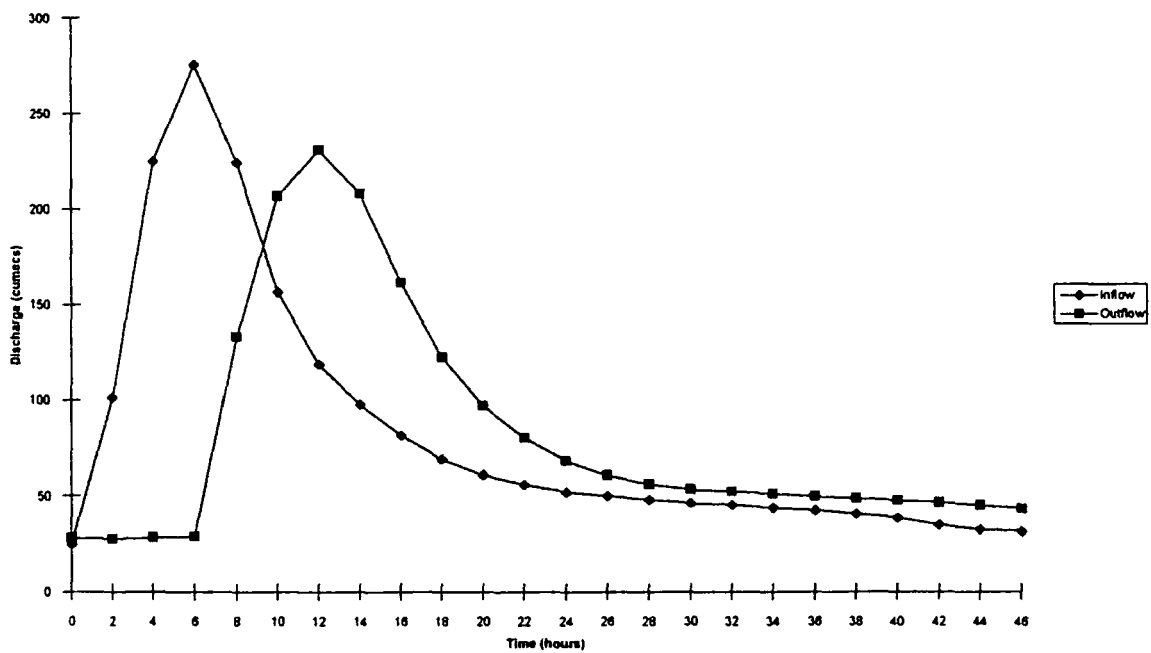
Fig.(3.10) Inflow And Outflow Hydrographs For The Event of Jan. 1982 of Tees River Reach.
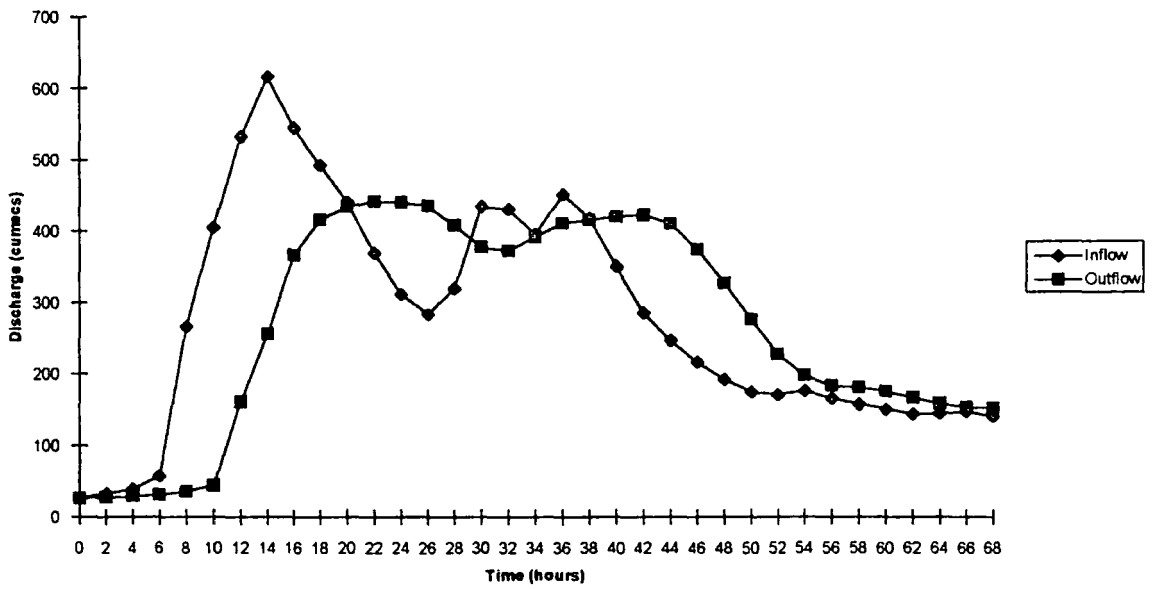
Fig. (3.11) Inflow And Outflow Hydrographs For The Event of Aug. 1986 of Tees River Reach.

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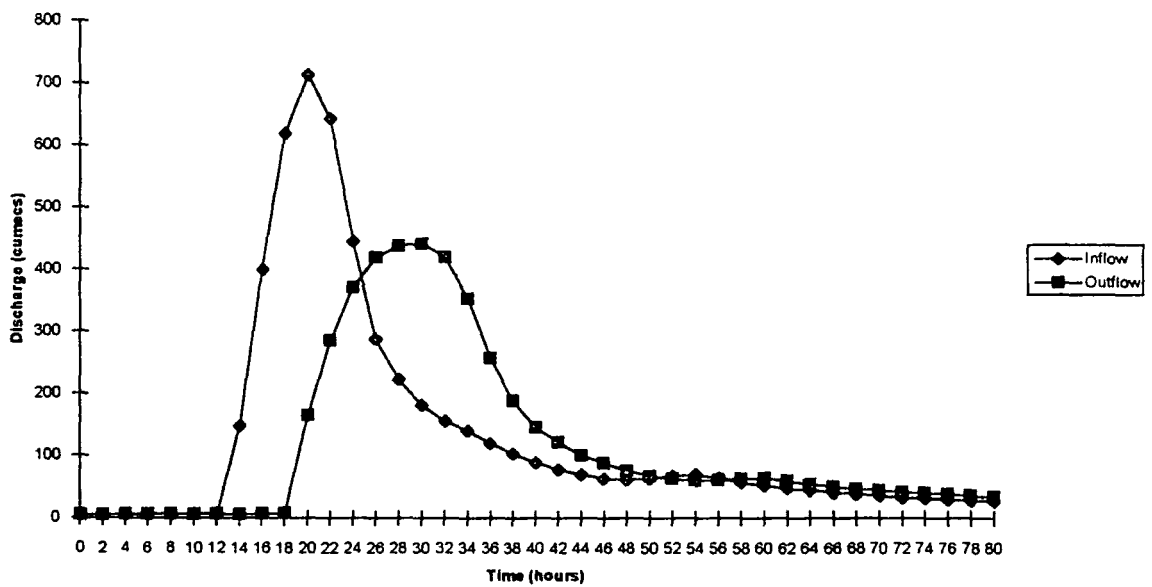
Table 3.1

Flood Events Used in This Study

Flood Number	Date of Occurrence	Peak Inflow (Cumecs)	Peak Outflow (Cumecs)
Wear River Reach			
1	2- 2-1981	181.7	182.3
2	1-10-1981	318.0	273.2
3	1-2-1984	232.6	248.0
4	1-3-1986	191.2	227.4
5	15-4-1986	302.4	278.6
6	26-8-1986	451.1	354.2
Tees River Reach			
7	2-1-1982	616.3	440.2
8	13-1-1984	275.7	231.0
9	25-8-1986	713.8	441.8

at all gauging stations which are tabulated in Appendix I, were supplied by the Northumbrian Water Authority.

3.6 Topographical Data

Topographical data required for the construction of a numerical model of both river reaches used in this study, include channel and flood plain geometry, and details of structures significantly affecting hydraulic conditions, such as bridges and weirs. Most information was obtained from topographical maps, and fieldwork measurements.

3.6.1 Channel Reaches And Flood Plain Geometry

The channel reaches and flood plain geometry includes channel cross- section area, wetted perimeter, width of channel, length of the reaches, length of sub-reaches, width of flood plain, and flood plain area. The benefit behind its use is that it plays a role in the calculation of some parameters of flood routing models used in this study.

As a part of the fieldwork, the author divided each reach into five subreaches so as to use them in the numerical models. He further prepared and measured five cross-sections of each reach used in the study when the water level is at its steady state condition. These are shown in the (Figs. 3.12-3.21).

This was also done in an attempt to use them in the state variable model to measure the cross-section area of different water levels. The latter had been estimated from the calculated outflows of each subreach by applying the Muskingum-Cunge Method.

Field investigations of flood plain inundation along both river reaches indicated that water is principally stored overbank. This is due to the fact that water velocity on the flood plains is relatively much smaller than its velocity in the main

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channel flow. Flood plain flow is restricted by high boundary textural roughness, and numerous obstructions, such as raised highways and hedges.

Flood plain data were obtained from the flood map for the River Tees where an area inundated in 1968 is shown in Fig. (3.22). This flood map provided only a qualitative indication of flood plain width, and assistance in the initial identification of area liable to be inundated. However, in some places along the rivers there are flood plain areas whereas in other places there are not. Moreover, it is observable that both Wear and Tees rivers have meandering. In the presence of meandering flow is normal in direction to the channel cross section line which may have to change direction on the flood plain.

As for River Wear, the author's failure to obtain flood maps has led him to estimate flood plain width and flood plain area from the topographical maps, and also from measurements during fieldwork. Moreover, information was also provided by a large number of observations and photographs of overbank flooding taken during the study period. Variation in the width of the flood plain along the two reaches under study was observed (i.e becomes wide in some places and very narrow in others). The flood plain plays a crucial part in reducing peak discharge at the downstream end, and so gives important protection to the cities situated downstream of the reach.

3.6.2 Structures

Structures considered in this section are those comprising weirs and bridges which have a significant effect on flow condition in both river reaches used in this study.

Water levels through Durham City are controlled by a number of structures mostly medieval in origin but which in some instances have undergone alterations or reconstruction that may have affected the nature of the control and

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Fig. (3.12) Cross-Section of Wear River Reach Near Shincliff Road Bridge.
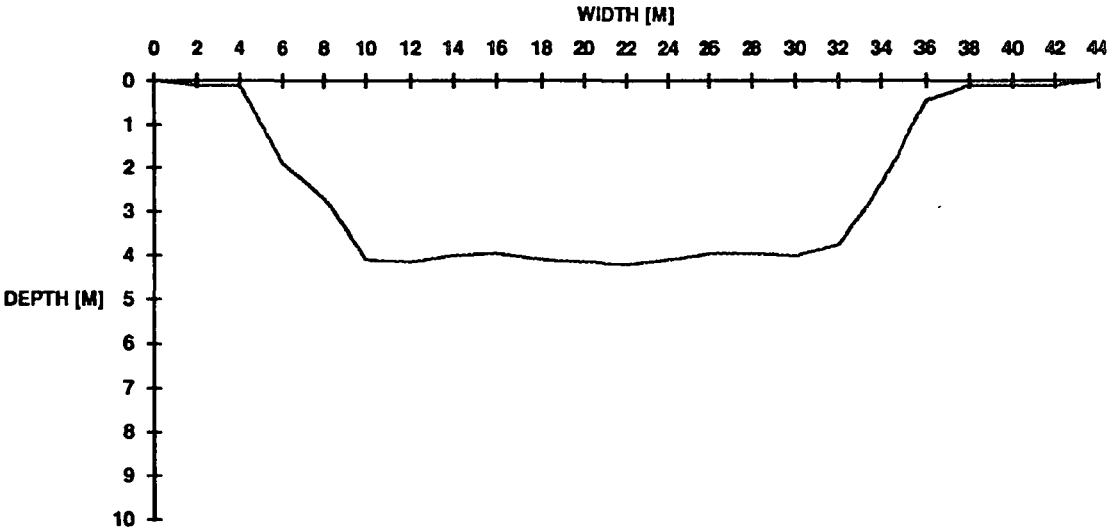
Fig.(3.13) Cross-Section Of Wear River Reach At Durham
End Of Sand.
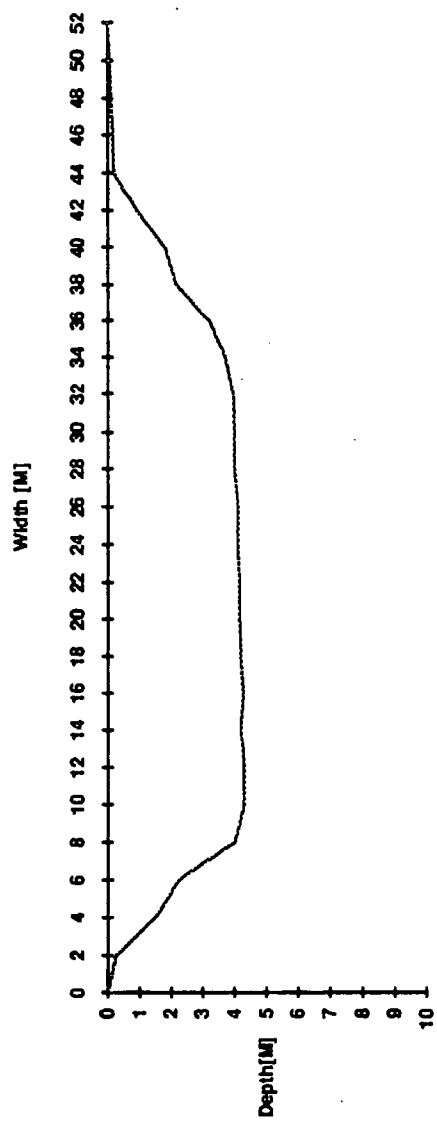
Fig. (3.14) Cross Section of Wear River Reach Near Mally Gill Wood.

Width [M]

2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 56 56 58 60

Depth [M]

0
1
2
3
4
5
6
7
8
9
10
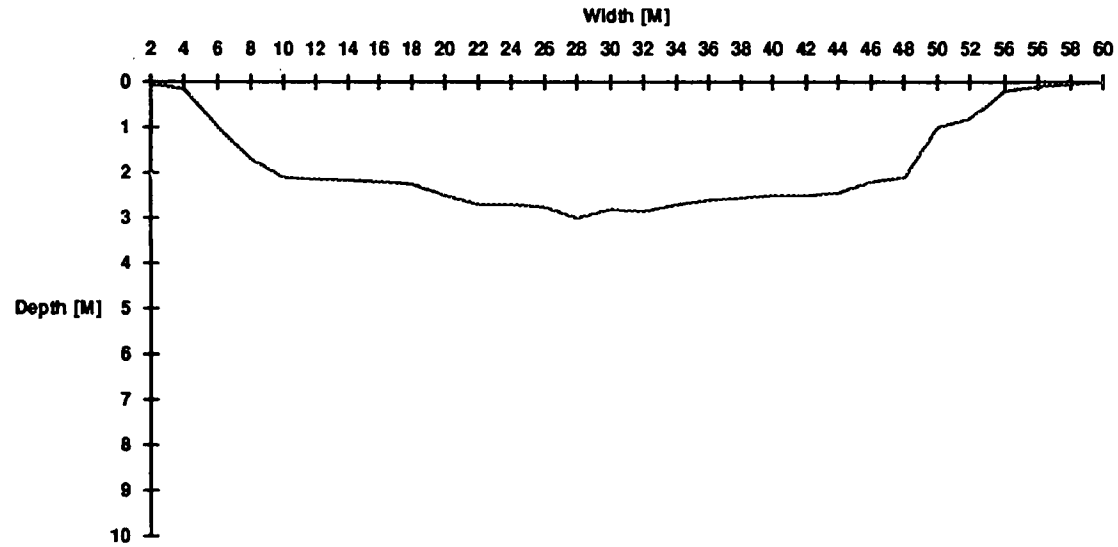
Fig. (3.15) Cross Section of Wear River Reach Below Old Mill Lane Lumley

Width [M]

2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54

Depth [M]
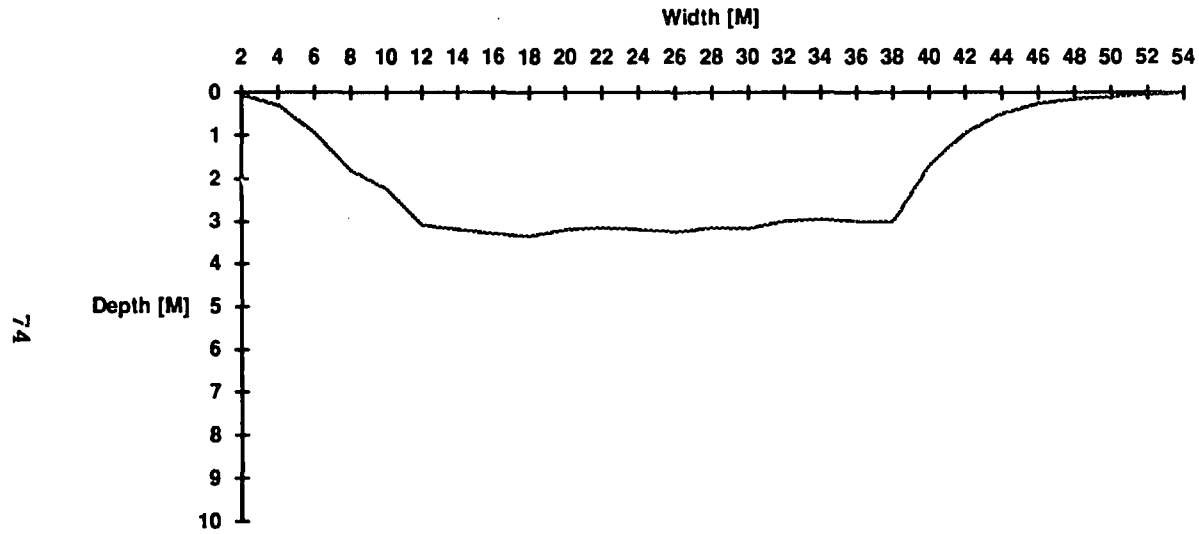
Fig. (3.16) Cross Section ofWear River Reach at Chester-Le-Street.
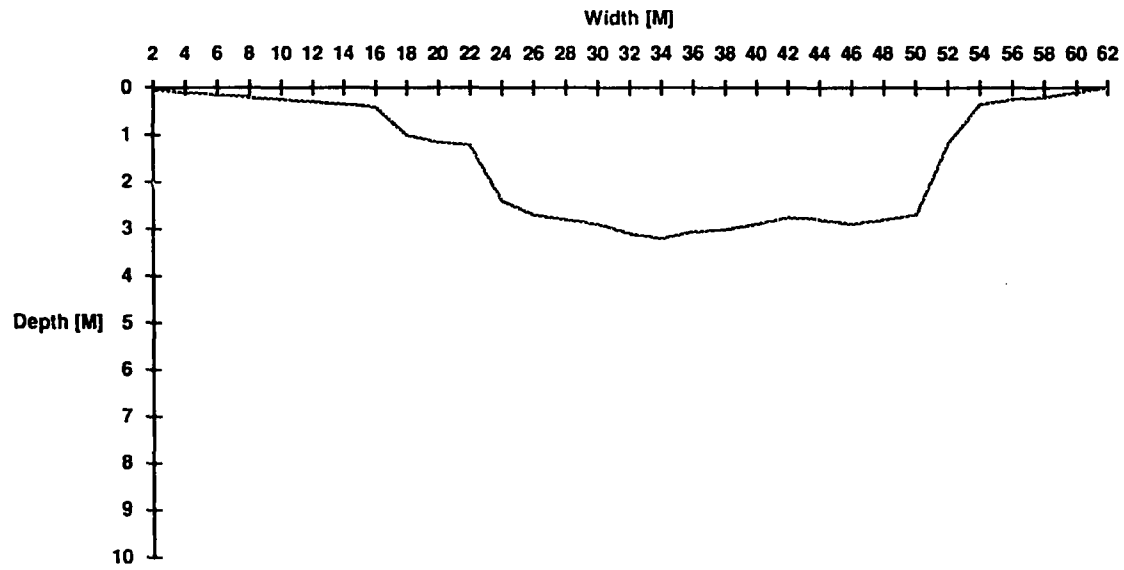
Fig. (3.17) Cross Section of Tees River Reach Near Croft.

Width [M]
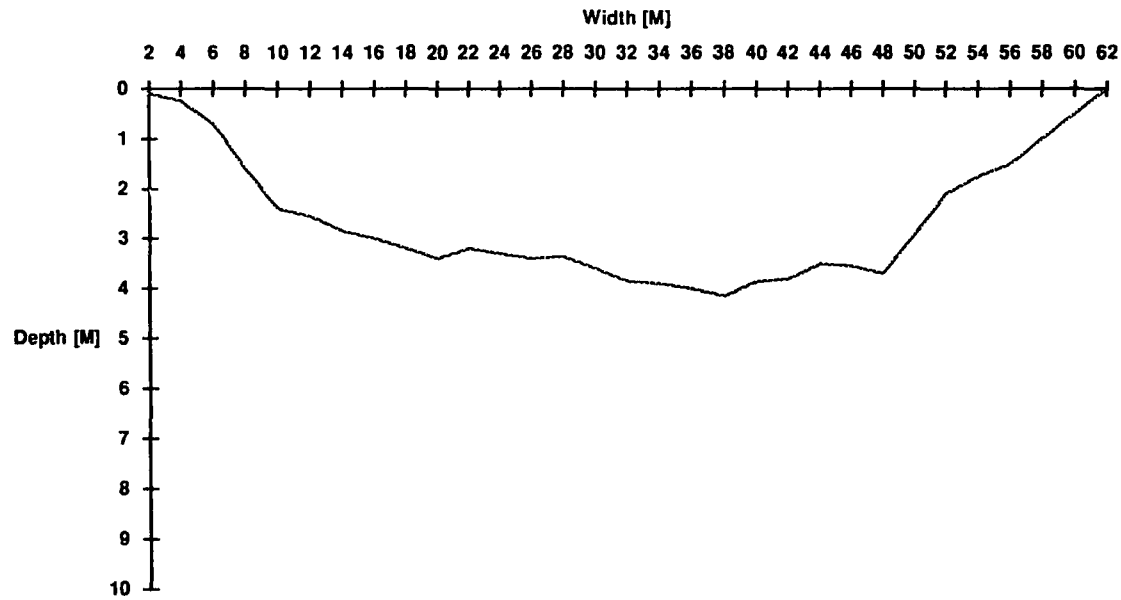
Fig. (3.18) Cross Section of Tees River Reach Near Newbus.

77
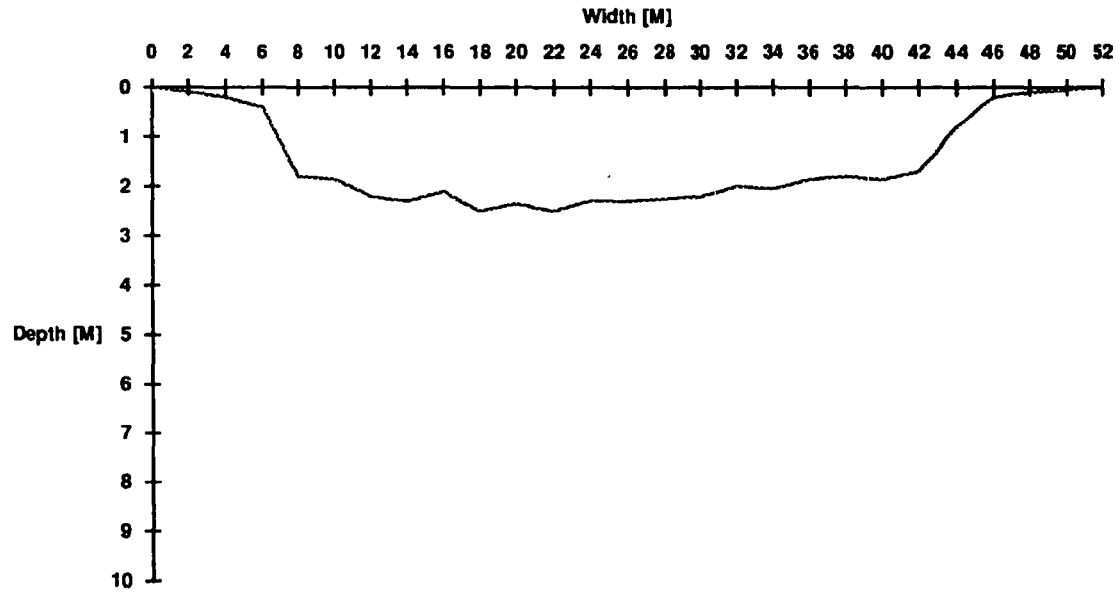
Fig. (3.19) Cross Section of Tees River Reach Near Pettals.

78
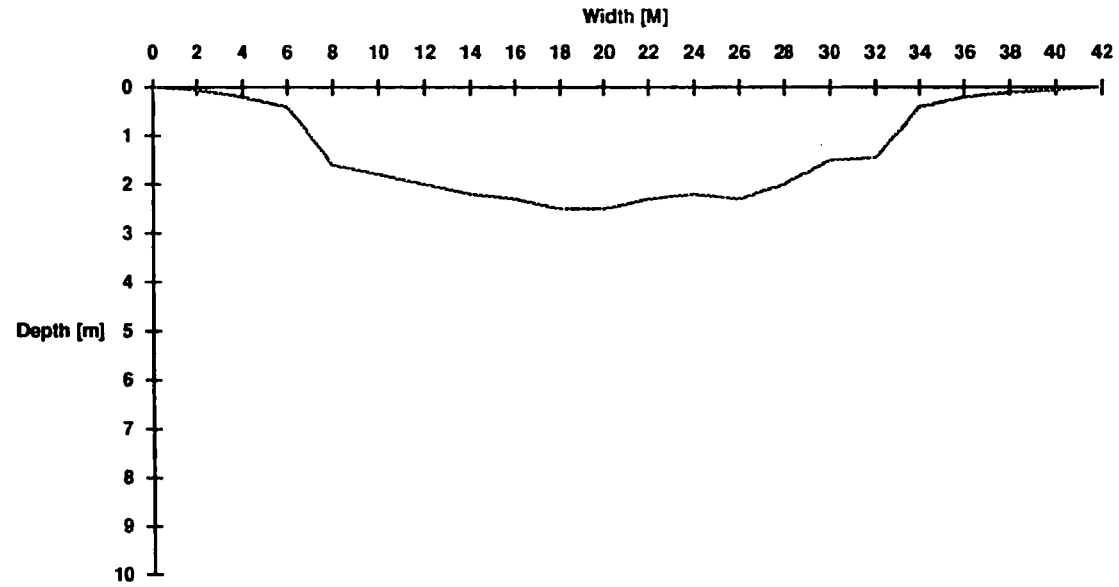
Fig. (3.20) Cross Section of Tees River Reach Near Hill House Farme.

Width [M]

Depth [M]
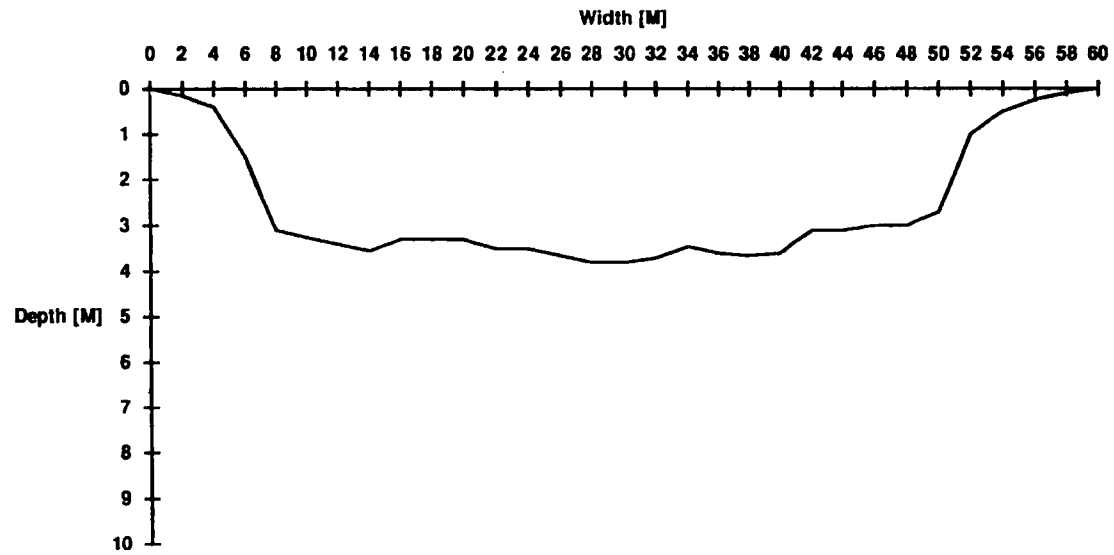
Fig. (3.21) Cross Section of Tees River Reach at Low Moor.
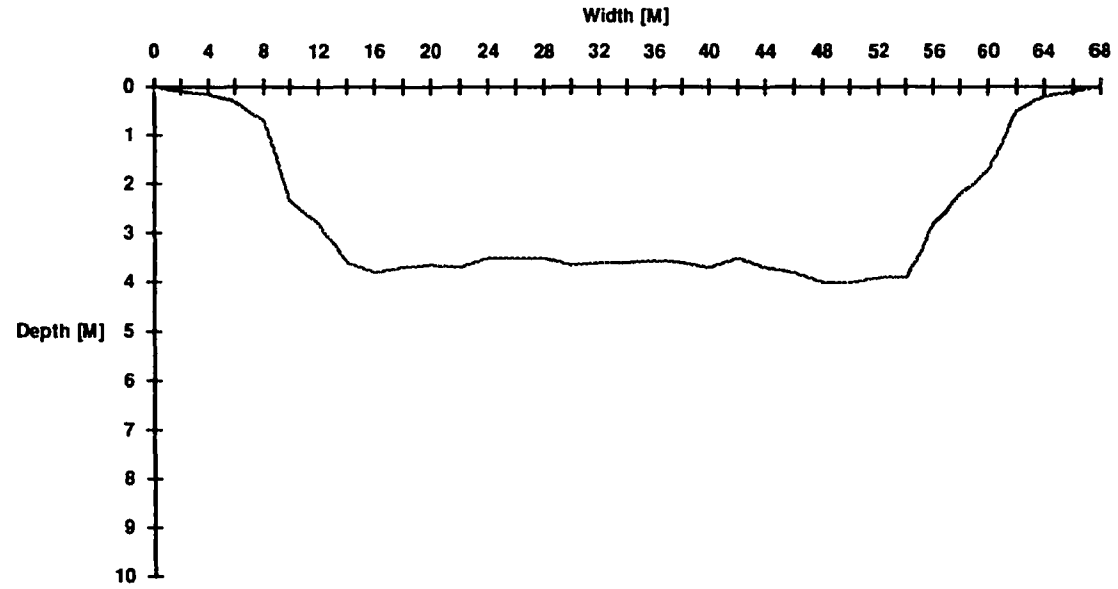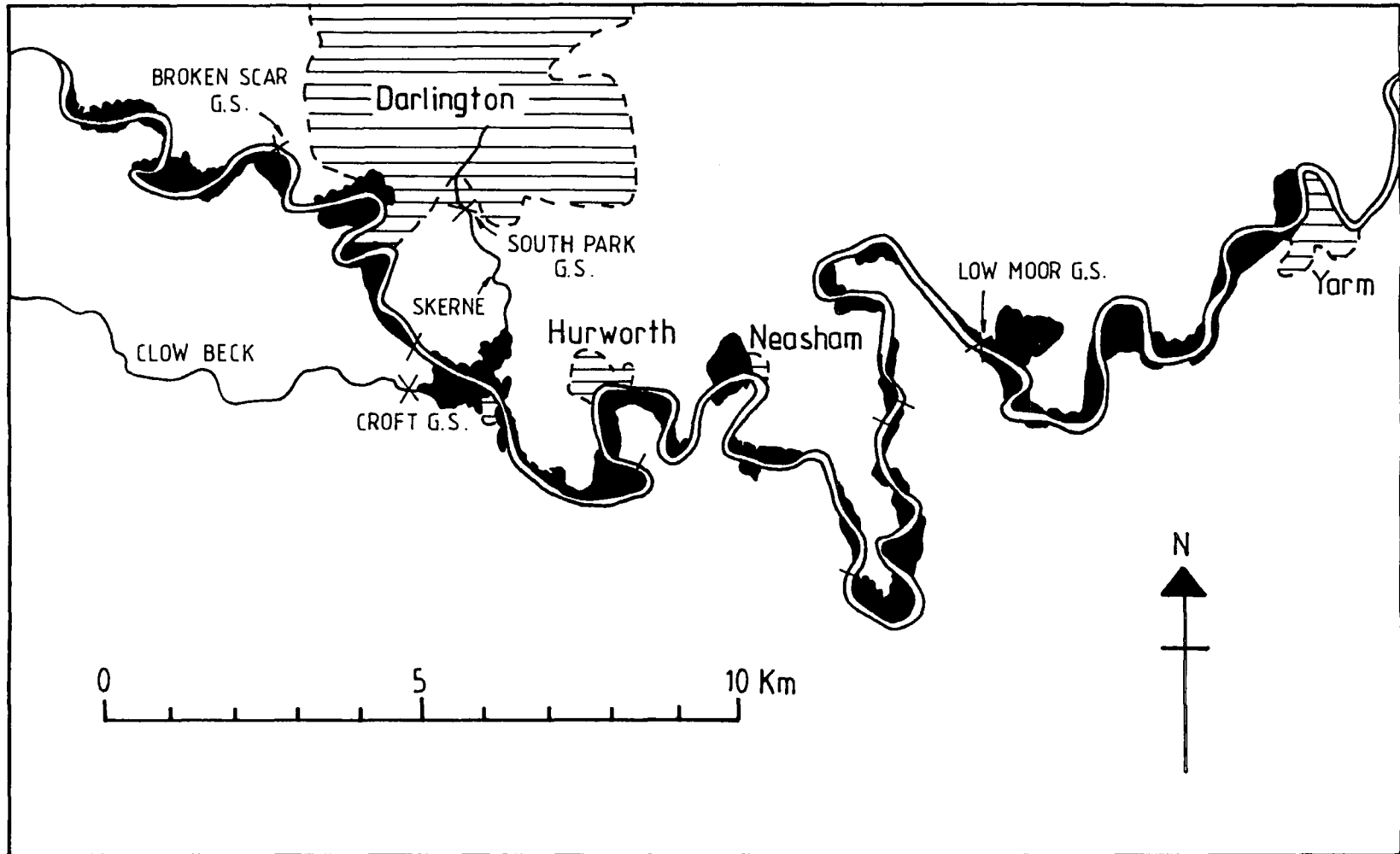
Fig.(3.22) River Tees Between Broken Scar And Low Moor Gauging Station
Showing Extent Of Overbank Flooding In Mar. 1968.(Archer, 1987).

hence altered the level discharge relationship at vulnerable sites. It was therefore been necessary to investigate the system of the structures that control water level.

Two weirs were identified on the topographical map and during fieldwork; the Museum Weir and the Framwellgate Weir. Furthermore, there are 10 other bridges spanning the River Wear reach between Sunderland Bridge gauge station and Chester-le-Street gauge station. They include 6 road bridges and 4 foot bridges. Along the River Tees reach between Broken Scar gauge station and Low Moor gauge station, there are 4 road bridges and 2 foot bridges, making in total 6 structures that affect the flow condition of the river.

Some of the important bridges and weirs on the two reaches will be described.

Elvet Bridge is situated on the bend as the river turns sharp southward and exerts little control through the city of Durham. It is said originally to have had 14 arches but most of these were soon blocked off. At present only 4 arches span the river channel and there are two land arches, one on each bank (Plate 3.5). However, the control appears to have been stable. Because of the eccentricity of approach and the width of the stone piers, the bridge causes considerable afflux (increase in height) believed to be more than 1 metre in extreme events (Archer, 1988).

Prebends Bridge is situated 1 km downstream from Elvet Bridge, with three high wide arches. The present bridge offers little obstruction to flow though its predecessor may influence levels in the reach up to Elvet Bridge.

Framwellgate Bridge is situated 600 m downstream from Prebends Bridge. It has two wide arches and appears to cause little afflux. Other structures affecting flow conditions are the existence of weirs within the channel reach.

Museum Weir is situated 200 m downstream from Prebends Bridge (Plate

Plate (3.5) The Old Elvet Bridge

Plate (3.6) The Museum Weir

3.6). It is flanked by former mills, a fulling mill on the right bank and a corn mill on the left bank; both mills rapidly fell into disuse and the fulling mill became a museum in 1833. The weir was breached in Feb. 1945 by a flood accompanied by ice floes; it was rebuilt the following year at the same level. This control which affects the level up through Elvet Bridge has therefore been considered stable at its present level since the 1880's and prior to that for at least a century at 0.46 m lower (Archer 1988).

The second important weir is the Framwellgate Weir. It is of medieval origin and provides the head to operate the bishop's mill. No record can be found of changes in the structure until the present century. In 1929 the water wheel at the mill on the right bank was replaced by a turbine to generate electricity for an ice manufacturing plant. The turbine still provides power for an ice rink. The dam was raised by the addition in 1935 of a timber crest which had been replaced by a cement bridge before 1944, raising the level by 0.84 m. The weir runs diagonally (Plate 3.7) and at a narrow angle across the channel and its considerable length gives an upstream stage discharge relationship of low sensitivity.

During flood flows, both weirs are completely drowned out, with only a relatively small discrete head loss caused by a general turbulence.

There are no cross channel structures for some distance below Framwellgate but there is a channel width constriction 100 to 400 m downstreams as the River Wear bends to the rest. This acts as a sensitive control for levels in the roadway at Framwellgate Waterside and the tailwater level to the weir. Furthermore the channel is confined on the left bank by a retaining wall (Stocker Wall), built early last century (Plate 3.8).
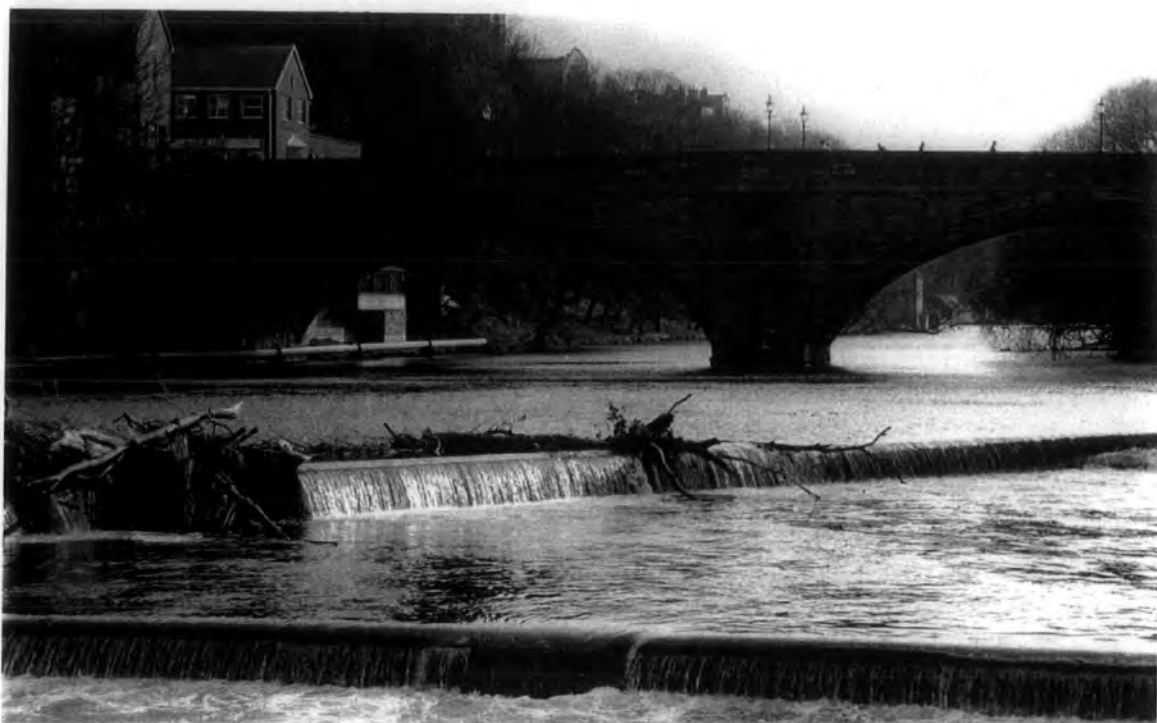
Plate (3.7) The Framwellgate Weir

Plate (3.8) The Stocker Wall

3.7 Conclusion

The Rivers Wear and Tees have been selected for this study due to the historical and existing flood problems, against which the benefit likely to accrue from unsteady flow modelling may be assessed.

Catchment geology and hydrology have been also investigated and identified as a characteristic of the river reaches partly responsible for the catastrophic flooding events.

Nine flood events have been analysed for both Wear and Tees Rivers over the years 1981, 1984, and 1986. Hydrological data of discharge and river stage which are essential for the investigation of the Muskingum-Cunge Method, Variable Parameter Diffusion Method, and State Variable Model, have been obtained from the Northumbrian Water Authority.

The geometry of the channel and flood plain has also been analysed, and expressed in a functional form suitable for the calculation of the parameters of the flood routing models.

In summary, hydrometric and morphometric data, presented in this chapter define the level of sophistication to which the flood routing models described in chapter 4, have been constructed.

CHAPTER 4

CHANNEL FLOW MODEL

1.1 Introduction

In addition to the river flow forecasting, the development of the theoretical basis of three numerical flood-routing models is described: the Muskingum-Cunge model, the variable parameter diffusion model and the state variable kinematic wave model.

The Muskingum-Cunge and the variable parameter diffusion models are based directly on the work of Price(1973, 1974) and are recommended for use on British rivers in volume III of the Natural Environment Research Council Flood Studies Report (1975). A state variable kinematic wave model which is based primarily on the work of Chang (1975), has been applied for this study.

The Muskingum-Cunge and the variable parameter models have been applied on a number of British rivers, and the basic theory and the results of application have been well documented in a number of reports, including the Flood Studies Report(N. E. R. C. 1975).

The Muskingum-Cunge method is described in section 4.3.1 of the current work. This method forms one of the modified methods that has worked well. It is based on the storage equation with the coefficients k and x determined by considering the hydraulics of the flow.

The variable parameter diffusion method which is a technique based on the convective-diffusion equation, is described briefly in section 4.3.2.

Section 4.3.3 describes the basic form of the state variable model. This model is developed for the analysis and computing the stages and discharges by a kine-

matic wave routing technique using the state variable approach in which the one-dimensional differential equations of unsteady flow are solved by state and output equations of the state variable model. The state equation describes the change in the state of the system over time in response to the inputs while the output equation derives the result at the new time step in response to the state increment determined from the state equation. The successive iterations follow the principle that the output of the former time step will be the input of the latter time step.

4.2 River Flow Forecasting

River forecasts are required so as to give advance warning of an approaching flood. Added to that, there is an increasing demand for day-to-day forecasts of river stages and discharges in matters concerning water supply, water pollution, navigation and related fields.

There are many river forecasting techniques ranging from the most highly sophisticated to the very simple and while the scientific literature is replete with descriptions of the more elaborate, their application to practical problems has lagged. Most real life forecasting appears to depend on simple empirical relations observed and applied.

The term "forecasting" is used to describe statements made, concerning a future value of a variable, at a specified time using observed information available up to the time of making the forecast.

In order to forecast the behaviour of the complex hydrological system, a simplified system, or model, is necessary. The model itself may be relatively sophisticated or simple depending on the computation facilities as well as the data available for calibration of the model, since the development of high speed computers have made it possible to solve the complicated mathematical equations involved in the study of hydrologic models. More sophisticated models imply that

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more information is required about the catchment or more work has to be done in calibrating the necessarily greater number of parameters.

Since river forecasts are made for different purposes and different variables may be involved, a variety of forecasting models has been used. For example for irrigation planning perhaps only the yearly mean flow is required. This can usually be obtained from simple empirical relations between seasonal rainfall and seasonal discharge. For the purpose of forecasting the hydrograph of daily mean values on relatively small headwater catchment more elaborate rainfall-discharge models are required. These must be calibrated using corresponding records of rainfall and, usually, potential evaporation and discharge. The "Layers Model" (O'Connell et al, 1970) provided one of the earlier studies on this context.

Such rainfall-discharge models may be considered as consisting of two parts. The first part determines the volumetric relation between rainfall and discharge , while the second part separates the routing or damping effect of the various storages in the catchment and connects the runoff generated each day with the discharge subsequently occurring at the gauging station. For large rivers on the other hand, with longer time intervals, forecasts of discharge at downstream points are usually based on observed discharges at points further upstream either on the main river alone or the main river and tributaries, with or without a relatively simple rainfall-discharge component for any ungauged areas between the upstream and downstream gauging sites.

4.3 Flow Routing Models

4.3.1 The Muskingum-Cunge Method

The basic theory of the Muskingum method presented in section 2.3 is based on the continuity equation and the storage-discharge relation. Cunge (1969) improved the basic Muskingum method, permitting the calculation of the Musk-

ingum parameters directly from channel characteristics, and in effect, producting a method based on the convective-diffusion equation. Cunge criticises the Muskingum method for being based on a unique relationship between depth and discharge. As no attenuation would occur theoretically under this condition, attenuation and the predicted time lag are dependent primarily on errors introduced by the finite difference representations of the analytical equations, rather than modelled physical conditions.

For the sake of the completeness, the improvement by Cunge is described here briefly.

Suppose that Q_i represents inflow I to the subreach at space node (i) and Q_{i+1} represents outflow O from the subreach at node (i+1). If S is replaced by equation 2.6, the continuity equation 2.3 leads to:

$$Kx\frac{d}{dt}(Q_i) + K(1-x)\frac{d}{dt}(Q_o) = Q_i - Q_o, \qquad 4.1$$

With reference to Fig.(4.1), rewriting the above equation in finite difference form results in:

$$Kx\frac{1}{\Delta t}(Q_i^{j+1} - Q_i^j) + K(1-x)\frac{1}{\Delta t}(Q_{i+1}^{j+1} - Q_{i+1}^j) = \frac{1}{2}$$
$$(Q_i^{j+1} + Q_i^j - Q_{i+1}^{j+1} - Q_{i+1}^j), \qquad 4.2$$

where subscripts j and j+1 refer to condition before and after the time step Δt respectively. It is possible to show that equation 4.2 is also a finite difference representation of the kinematic wave Eq. 2.43 provided K is defined as:

$$K = \frac{\Delta x}{\omega}, \qquad 4.3$$

where ω is the average speed of the flood wave. Cunge then derived a suitable expression for the weighting parameter x by expanding equation 4.2 as a Taylor series, and showing that this expression is also a finite difference representation of a general convective-diffusion equation:
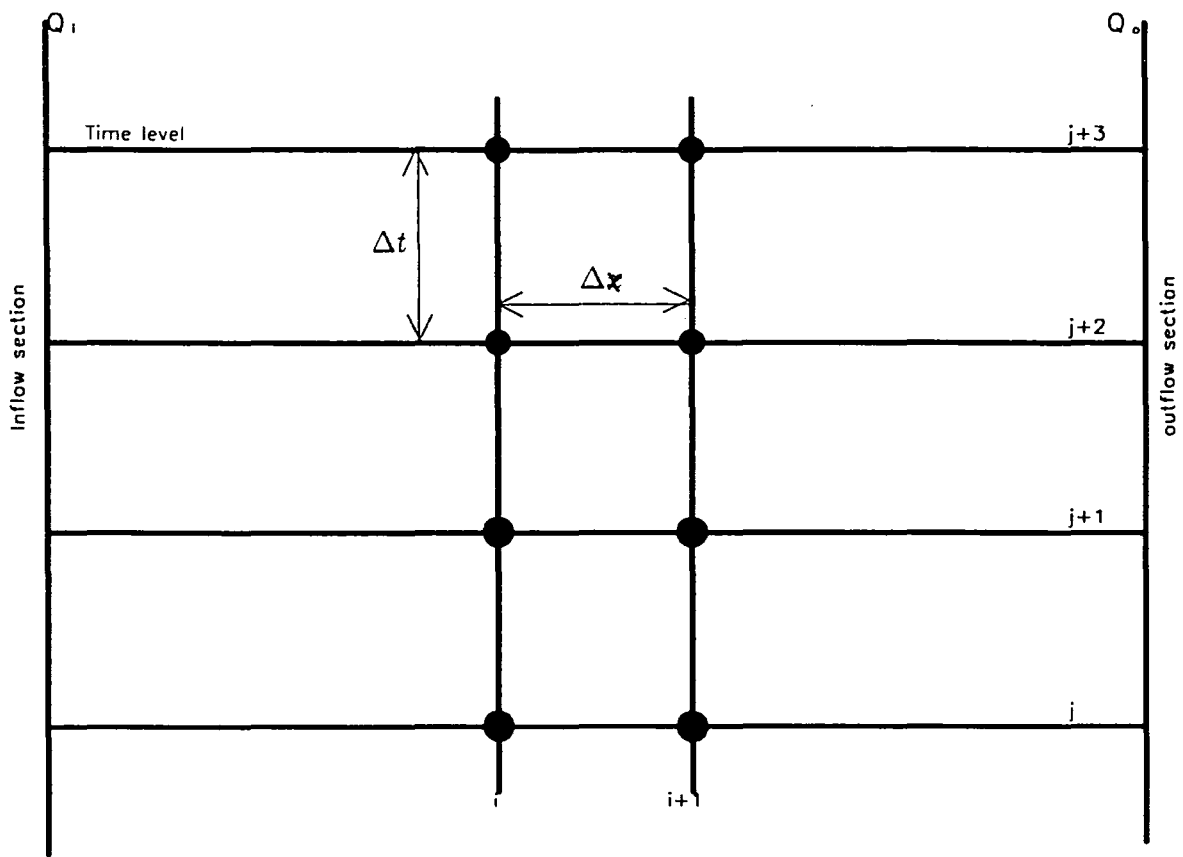
Fig.(4.1) Rectangular net of points for the Muskingum-Cunge method.

$$\frac{\partial Q}{\partial t} + \omega \frac{\partial Q}{\partial x} = \mu \frac{\partial^2 Q}{\partial x^2}, \qquad\qquad 4.4$$

where μ is defined by:

$$\mu = (\frac{1}{2} - x)\omega \Delta x \qquad\qquad 4.5$$

On this basis, Cunge defined x in terms of channel top width and average slope. Subsequently, Price (1973) obtained an expression for the diffusion coefficient μ based on the work of Hayami (1951) which provides an algebraic expression for x relating to physical condition:

$$x = \frac{1}{2} - \frac{\propto \bar{Q}_p}{L\omega \Delta x}, \qquad\qquad 4.6$$

where $\propto$ is the attenuation parameter corresponding to the average discharge $\bar{Q}_p$; L is the length of the whole reach which is divided in to a number of sub-reaches of length Δx ; and ω is the speed. The attenuation parameter $\propto$ is defined by Price (1973, 1974) in terms of channel and flood plain characteristics, with ω and $\bar{Q}_p$ obtained from records of past flood events. Details of their derivation are given in chapter 5.

Therefore, with K and x calculated as above, equation 4.2 may be rewritten to determine the flow hydrograph at the downstream section of the reach by the recurrence formula:

$$Q_{i+1}^{j+1} = c_1 Q_i^j + c_2 Q_i^{j+1} + c_3 Q_{i+1}^j + c_4, \qquad\qquad 4.7$$

where c_1, c_2, c_3, c_4 are constants and calculated from the value of K, x, Δt, Δx and q_1 as:

$$c_1 = \frac{Kx + \frac{1}{2}\Delta t}{K(1 - x) + \frac{1}{2}\Delta t}$$

$$c_2 = \frac{\frac{1}{2}\Delta t - Kx}{K(1 - x) + \frac{1}{2}\Delta t}$$

$$c_3 = \frac{K(1 - x) - \frac{1}{2}\Delta t}{K(1 - x) + \frac{1}{2}\Delta t}$$

$$c_4 = \frac{q_1 \Delta x \Delta t}{K(1 - x) + \frac{1}{2}\Delta t} \qquad 4.8$$

The accuracy of the finite difference scheme in equation 4.2 or equation 4.7 depends largely on the magnitudes of Δx and Δt.

The major advantage of Muskingum and Muskingum-Cunge is that few data are required for calibration and calculation. In the Muskingum method K and x are deduced from the records of the past floods with no informations relating to the channel characteristics normally required. Using the Muskingum-Cunge method, K and x are defined from $\propto$, related to channel characteristics, and ω, the recorded celerity of flood waves. Data necessary for the definition of $\propto$ include the plan area of the flood plain, the channel length, and the average channel slope.

The Muskingum method has been and is still used extensively, yet it suffers from a number of limitations despite the major improvement by Cunge. Extrapolation to route larger design floods must be treated with extreme caution especially if the traditional Muskingum method is utilised.

The Muskingum-Cunge method is included in a computer program M-C2, a modified version of program FLDS1, which was constructed by Price (1973) and included in volume III of N. E. R. C. Flood Studies Report (1975). Details and application of the M-C2 model are explained in chapter 5.

4.3.2 The Variable Parameter Diffusion Model

The development of the variable parameter diffusion method by Price (1973, 1974) is probably the most significant improvement in the use of a wave diffusion model. Price argued that the variations in the diffusion parameters due to the irregularities of the channel reach could be quantified. Consequently, such parameters were taken as functions of discharge and reach length as ω (Q,x) and μ (Q,x).

Price (1973) developed the variable parameter diffusion method in order to alleviate some of the limitations imposed on linear convection-diffusion methods utilised by Hayami (1951) and Thomas and Wormleaton (1970, 1970, 1968), described in section 2.3, which are based on a linear convection-diffusion equation (Eq. 4.4), where ω and μ are found from a trial and error process for a river reach using a number of recorded flood data.

The variable parameter diffusion method is capable of modelling in-bank and floodplain flows. In short, it was based on the following convection-diffusion equation:

$$\frac{\partial Q}{\partial t} + \bar{c}\frac{\partial Q}{\partial x} = \frac{\propto}{L}Q\frac{\partial^2 Q}{\partial x^2} + \bar{c}q, \qquad 4.9$$

in which $\bar{c}$ is average convection speed along the reach, $\propto$ is an attenuation parameter, L is the length of the reach and q is the lateral inflow. $\bar{c}$ and $\propto$ are prescribed as functions of Q. The calculations of the attenuation parameter $\propto$, is also required for the Muskingum-Cunge method (section 4.3.1), and defined from channel and flood plain characteristics and the convection speed $\bar{c}$ are discussed in detail later in chapter 5.

Price (1973), and Price and Kawecki (1977) have subsequently improved the variable parameter diffusion method provided in the N. E. R. C. Flood Studies Report (1975) by including a modification to equation 4.9:

$$\frac{\partial Q}{\partial t} + \bar{c}\frac{\partial Q}{\partial x} = Q\frac{\partial}{\partial x}\left(\frac{\propto}{L}\frac{\partial Q}{\partial x} + \frac{2\propto_c}{3L}\frac{\partial Q}{\partial x}\right)^2 + \bar{c}q, \qquad 4.10$$

where $\propto_c$ relates to an in-bank flood.

Price (1973) gives a succinct description of the numerical solution technique of the variable diffusion method, and it is well documented in the N. E. R. C. Flood Studies Report (1975).

Equation (4.9) is expressed in finite difference form using the Crank - Nicholson scheme (Richtmyer and Morton, 1967)

$$\Omega_j \equiv Q_j^{n+1} - Q_j^n + \frac{\Delta t}{4\Delta x}\bar{c}(Q_a)[Q_{j+1}^{n+1} - Q_{j-1}^{n+1} + Q_{j+1}^n - Q_{j-1}^n]$$

$$-\bar{c}(Q_a)q_j^{n+1} - \frac{\Delta t}{2L\Delta x^2} \propto (Q_a)Q_a[Q_{j+1}^{n+1}$$

$$-2Q_j^{n+1} + Q_{j-1}^{n+1} + Q_{j+1}^n - 2Q_j^n + Q_{j-1}^n] = 0 \qquad 4.11$$

for all $1 \leq j \leq J\text{-}1$, where

$$Q_a = \frac{1}{2}[Q_j^{n+1} + Q_j^n] \qquad 4.12$$

Ω_j denotes the finite difference expression in equation 4.11 and J is the label for the downstream boundary. The subscript j refers to a variable evaluated at the point distance j Δx downstream of the upstream boundary, where Δx is the space step. Similarly, the superscript n refers to the variable evaluated at the time n Δt after the begining of the calculations, where Δt is the time step (Fig. 4.2)

Discharge at the downstream boundary Q_j^{n+1} is found from a characteristic curve, while the values of discharge Q_j^{n+1} at the new time level are found from a set of non-linear simultaneous equation. The most convenient way of solving these equations is to use the generalised Newton-Raphson iteration procedure (Amein and Fang, 1970). This procedure involves the evaluation of Ω_j for estimated values of the Q_j^{n+1}. The Q_j^{n+1} are then replaced by the set $Q_j^{n+1} + dQ_j^{n+1}$, where the dQ_j^{n+1} are the solution of the simultaneous linear equations.
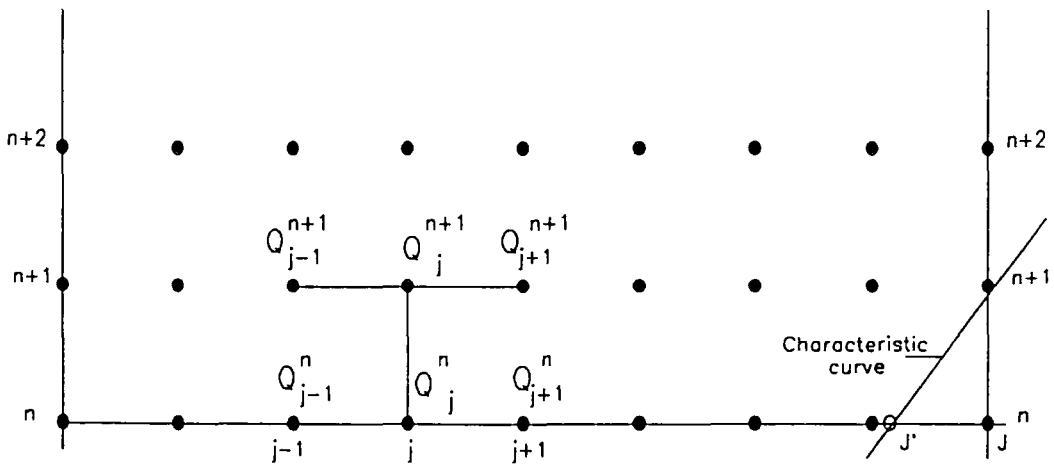
Fig.(4.2) Finite difference net.

$$a_{j,j-1}dQ_{j-1}^{n+1} + a_{j,j}dQ_j^{n+1} + a_{j,j+1}dQ_{j+1}^{n+1} = \Omega_j \qquad 4.13$$

The matrix $a_{j,k}$ is defined by:

$$a_{j,k} = 0 \ldots k = 1, 2, \ldots, \text{j-2}$$

$$a_{j,j-1} = [\frac{\Delta t}{4\Delta x}\bar{c} + \frac{\Delta t}{2L\Delta x^2} \propto Q_a]$$

$$a_{j,j} = 1 + \frac{\Delta t}{8\Delta x}\frac{d\bar{c}}{dQ_a}[Q_{j+1}^{n+1} - Q_{j-1}^{n+1} + Q_{j+1}^n - Q_{j-1}^n] - \frac{\Delta t}{2}\frac{d\bar{c}}{dQ_a}$$

$$q_j^{n+1} - \frac{\Delta t}{4L\Delta x^2}[Q_a\frac{dx}{dQ_a} + \propto][Q_{j+1}^{n+1} - 2Q_j^{n+1}$$

$$+Q_{j-1}^{n+1} + Q_{j+1}^n - 2Q_j^n + Q_{j-1}^n] + \frac{\Delta t}{L\Delta x^2} \propto Q_a \qquad 4.14$$

$$a_{j,j+1} = \frac{\Delta t}{4\Delta x}\bar{c} - \frac{\Delta t}{2L\Delta x} \propto Q_a$$

$$a_{j,k} = 0 \ldots k = j + 2, \ldots, J$$

Because of the banded nature of the matrix $a_{j,k}$, it is a simple matter to set up a Gaussian elimination procedure to solve the linear equations. First define:

$$\acute{a}_{2,2} = a_{2,2}$$

$$\acute{a}_{2,3} = a_{2,3}$$

$$\acute{a}_{j,j-1} = 0$$

$$\acute{a}_{j,j} = a_{j,j} - \frac{a_{j,j-1}\acute{a}_{j-1,j+2}}{\acute{a}_{j-1,j}} \qquad 4.15$$

$$\acute{a}_{j,j+1} = a_{j,j+1}$$

$$\acute{\Omega}_j = \Omega_j - \frac{\acute{\Omega}_{j-1}\acute{a}_{j-1,j+1}}{\acute{a}_{j-1,j}}$$

for j=3, 4, ..., J-1. Then

$$dQ_{J-1}^{n+1} = \frac{\acute{\Omega}_{J-1}}{\acute{a}_{J-1,J-1}} \qquad\qquad 4.16$$

and

$$dQ_j^{n+1} = \frac{(\acute{\Omega}_j - a_{j,j+1} dQ_{j+1}^{n+1})}{\acute{a}_{j,j}} \qquad\qquad 4.17$$

for j=J-2, J-3, ..., 2. So it is a matter of sweeping in each direction along the band of the matrix $a_{j,k}$. When the values of the dQ_j^{n+1} have been calculated, the new values for Q_j^{n+1} are evaluated and another set of values for the Ω_j is found. The iteration continues until the maximum value of $\mid dQ_j^{n+1} \mid$ for a particular iteration is less than a certain error value. As a rough guide, this error value can be taken as 10^{-4} times the peak discharge of the largest floods in the particular river.

The variable parameter diffusion method is included in a computer program VPDM1, a modified version of program FLDS2, which was constructed by Price (1973), and included in volume III of the N. E. R. C. Flood Studies Report (1975). Details and application of the model are explained in chapter 5.

4.3.3 The State Variable Model

The state variable approach is a scheme which solves ordinary or partial differential equations. From a mathematical view point, the state variable approach means the use of matrix and vector methods to handle the large number of variables which contribute to such problems. From a physical point of view, the state variable approach aids conceptual thinking and provides a unifying basis for the solution of the linear and nonlinear problems.

The state of the system is a measure of the level of activity in each of its components and can be thought of as the interface between the past and the future of the system's time history. In the view of the development of the fundamental concept of state variable modelling, the so-called "classical" and "modern" system theory has been distinguished. On the one hand, in the "classical" system theory,

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the output is directly related to the input through a transfer function, Φ, as:

$$Y = \Phi\underline{u} \qquad\qquad 4.18$$

On the other hand, in the so-called "modern" system theory, the system structure is given an explicit representation as a vector $\underline{x}$, where $\underline{x} = (x_1, x_2, ..., x_n)$ and the state variables $x_1, x_2, ..., x_n$, are a function of time. Maidment (1976) presented a comprison between the 'classical' and 'modern' approaches to dynamic system modelling visualizing the approaches in vector space mapping as shown in Fig. 4.3.

For the 'classical' approach, the transfer function is seen as a mapping from the input space directly to the output space, at a time when in the 'modern' approach, the input space is first related to the state space through the state equation and then to the state space, and in some cases the input space is related to the output space through the output equation as shown in Fig.4.3b. Added to that, in the modern approach a state equation is used to describe the change in the state of the system over time in response to various inputs. An output equation is used for each output variable to relate the output to the state of the system and in some cases to the inputs.

From the modern system view point, state variable modelling can be classified in to two alternatives: "continuous-time models", and "discrete-time models". The major difference between the two is that the continuous-time model alternative describes that the rate of change of the state, x(t), is continuously integrated with the current state to produce the new state. The discrete-time model alternative divides the input instruction to the system in to several stages and solves the state equation and output equation recursively for each stage.
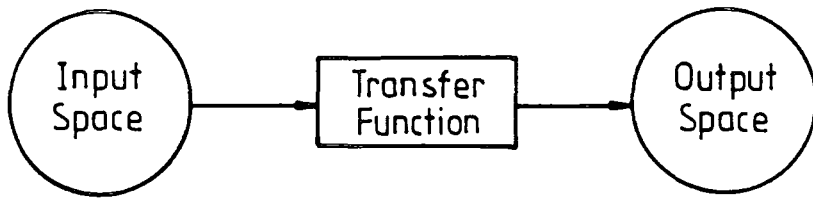
(a) "Classical" Approach
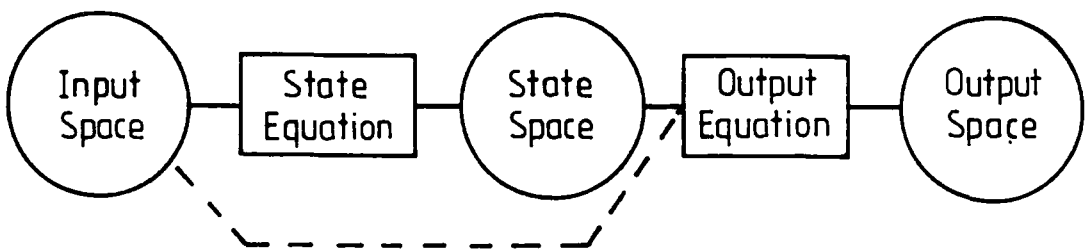
(b) "Modern" Approach

Fig.(4.3) Comparison between "Classical" and "Modern" Approaches to Dynamic System Modelling. (Maidment, 1976).

4.3.3.1 Continuous Time System

The relationship of the input, state, and output variables over time is described by the a state equation (4.19) and an output equation (4.20).

The state equation expresses the change of the state of the system over time in response to the inputs.

The output equation describes the production of outputs from the state and input variables.

$$\underline{\dot{x}}(t) = B\underline{x}(t) + C\underline{u}(t) \qquad\qquad 4.19$$

$$\underline{Y}(t) = D\underline{x}(t) + E\underline{u}(t) \qquad\qquad 4.20$$

where $\underline{\dot{x}}(t) = \frac{dx(t)}{dt} = $ the time rate of change of the state vector; $\underline{u}_t = $ the input vector; $\underline{Y}(t) = $ the output vector; and A, B, C and D $=$ matrices that can be constants or functions of time or space, or both.

$$\underline{x}(t) = \begin{pmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{pmatrix} \quad \underline{\dot{x}}(t) = \begin{pmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \vdots \\ \dot{x}_n(t) \end{pmatrix}$$

$$\underline{Y}(t) = \begin{pmatrix} Y_1(t) \\ Y_2(t) \\ \vdots \\ Y_n(t) \end{pmatrix} \quad \underline{u}(t) = \begin{pmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_n(t) \end{pmatrix}$$

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{pmatrix} \quad C = \begin{pmatrix} c_{11} & c_{12} & \cdots & c_{1p} \\ c_{21} & c_{22} & \cdots & c_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{np} \end{pmatrix}$$

$$D = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{r1} & d_{r2} & \cdots & d_{rn} \end{pmatrix} \quad E = \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1p} \\ e_{21} & e_{22} & \cdots & e_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ e_{r1} & e_{r2} & \cdots & e_{rp} \end{pmatrix}$$

In general, an nth order differential equation system can be reduced to n simultaneous first order systems by introducing n state variables, while the state equation

is a set of ordinary, first-order differential equations, one for each state variable. Since there are n state variables, p input variables, and r output variables, B is an n × n matrix, and C is a n × p matrix, D is a r × n matrix, and E is a r × p matrix. The element of B, C, D and E may be functions of the current state vector and time. The equations (4.19) and (4.20) thus from a nonlinear and time varying, dynamic system model,can also be shown as below:

The state equation:

$$
\begin{pmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \vdots \\ \dot{x}_n(t) \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & \ldots & b_{1n} \\ b_{21} & b_{22} & \ldots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \ldots & b_{nn} \end{pmatrix} \begin{pmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{pmatrix} + \begin{pmatrix} c_{11} & c_{12} & \ldots & c_{1p} \\ c_{21} & c_{22} & \ldots & c_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \ldots & c_{np} \end{pmatrix} \begin{pmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_n(t) \end{pmatrix}
$$
4.21

The output equation:

$$
\begin{pmatrix} Y_1(t) \\ Y_2(t) \\ \vdots \\ Y_n(t) \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & \ldots & d_{1n} \\ d_{21} & d_{22} & \ldots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{r1} & d_{r2} & \ldots & d_{rn} \end{pmatrix} \begin{pmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{pmatrix} + \begin{pmatrix} e_{11} & e_{12} & \ldots & e_{1p} \\ e_{21} & e_{22} & \ldots & e_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ e_{r1} & e_{r2} & \ldots & e_{rp} \end{pmatrix} \begin{pmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_n(t) \end{pmatrix}
$$
4.22

The matrix elements may be functions of time alone in which case the model is linear and time varying. If the matrix elements are all constant, then the model is linear and time invariant. In practical application, many matrix elements are zero and the E matrix is often not required. The matrix B is the most important of the four system matrices because it represents the proportion of the current system state, x(t), which contributes to the changing of the state. The results of the output, Y(t), from the known input, u(t), may be obtained by recursive computation from the system's initial state $\underline{x}_0$ at time t_0. By substituting $\underline{x}_0$ as x(t) and $\underline{u}$ (1) as $\underline{u}$ (t), $\underline{\dot{x}}$ (1) and $\underline{Y}$ (1) are produced from equations (4.19) and

(4.20) respectively. $\dot{\underline{x}}$ (1) is added to $\underline{x}_0$ to produce $\underline{x}$ (2), which together with $\underline{u}$ (2) are used to produce $\dot{\underline{x}}$ (2) and $\underline{Y}$ (2) as before and the computations proceed for all periods in the same manner.

4.3.3.2 Discrete Time System

The time horizon is discretized into several time stages where time intervals need not be equal. Using $\dot{\underline{x}}(t) = \frac{\Delta x}{\Delta t}$, this implies that the process is linear over the interval Δt, then

$$\Delta \underline{x}(i) = \begin{pmatrix} \Delta x_1(i) \\ \Delta x_2(i) \\ \vdots \\ \Delta x_n(i) \end{pmatrix}$$

$$\frac{\Delta \underline{x}(i)}{\Delta t} = Bx(i) + C\underline{u}(i) \qquad 4.23$$

$$Y(i) = Dx(i) + Eu(i) \qquad 4.24$$

Crossmultiplying equation (4.23) by Δt , which is a scalar, gives:

$$\Delta \underline{x}(i) = B\Delta t \underline{x}(i) + C\Delta t u(i) \qquad 4.25$$

where i is an index. By definition:

$$x(i+1) = x(i) + \Delta \underline{x}(i) \qquad 4.26$$

The general formulation of a deterministic discrete time model which arises naturally from the discretized continuous equations (4.23) to (4.26) is expressed as:

$$\dot{\underline{x}}(i+1) = B\underline{x}(i) + C\underline{u}(i) \qquad 4.27$$

$$\underline{Y}(i) = D\underline{x}(i) + E\underline{u}(i) \qquad 4.28$$

For stage i=1 the initial state is $\underline{x}(i) = \underline{x}_0$, $\Delta \underline{x}$ (1) and $\underline{Y}$ (1) are produced using

equations (4.24) and (4.25) with $\underline{u}$ (1) . The final state for stage 1 which is the initial state for stage 2 is found from equation (4.26) then the same computation are performed again to produce $\Delta \underline{x}$ (2) and $\underline{Y}$ (2) and so on for all time periods.

There have been a number of applications of state variable modelling concepts to wastewater treatment water quality control (Fan, Shah, Periera and Erickson, 1973 and Young and Beck, 1974), the operation of hydroelectric power stations Erchler, Roubellat and Vernhes, 1975), rainfall-runoff process modelling (Duong, Wynn and Johnson, 1975, Muzik, 1974 and Tung and Mays, 1981), reservoir operation (Maidments, 1976) and flow routing in storm sewers and channels (Chang, 1979, Mays and Tung, 1978, and Napiorkowski, Strupczewski and Dooge, 1981).

A computer program STROUT3 which is a modified version of program STROUT (Chang, 1979) is used in this study, the details and the application of which are explained in chapter 6.

A state variable modelling is also applied for solving the nonlinear Muskingum model in this study. Details and application are explained in chapter 7.

4.4 Conclusion

The Muskingum-Cunge and variable parameter diffusion methods are suitable for the Modelling of flood wave propagation in non-tidal rivers and are not suitable for analysing local effects. Both methods provide solutions of similar accuracy, but many accurate recorded flood discharge hydrographs are necessary for the definition of functions $\bar{c}$ (Q) and $\propto$ (Q) in the variable parameter diffusion method.

State variable modelling is a relatively new technique and it appears to have considerable potential for application to water resource system. Models using the concept of state variable modelling for river routing have been developed. These models are based on the simplified one-dimensional Saint-Venant equations and

belong to the category of kinematic wave flood routing type.

CHAPTER 5

APPLICATION OF MUSKINGUM-CUNGE AND VARIABLE PARAMETER DIFFUSION METHODS

5.1 Introduction

The problems of parameter calculation for numerical flood routing techniques such as the Muskingum-Cunge method and the Variable Parameter Diffusion method, are presented in this chapter.

The justification for the use of these methods of flood routing is that there is evidence in the literature that they have been successfully used in the past. They have been very popular over the years because of their simplicity, reduced requirements in data preparation, computer storage and time, and most of all, the satisfactory results that were obtained (N. E. R. C. 1975).

Cunge (1969) has proved that, with the Muskingum parameters (k and ϵ) properly defined it is possible to show that the method includes dynamic effects on the flood wave. The variable parameter diffusion method was derived to simulate the propagation of a flood wave which inundates a large flood plain along the reach (Price, 1973). All computer runs utilised the computing facilities available at Durham University. Most runs were carried out on the Amdahl 5860 computer 32MB.

Unfortunately suitable prototype data for the application of the Muskingum-Cunge and the variable parameter diffusion methods could not be obtained independently by the author, and hence applications, described in section 5.3 and section 5.4, use data recorded by the Northumbrian Water Authority.

5.2 Rating Curve

A continuous record of stream flow requires the establishment of a relation between the rate of flow and the water level in a channel. A rating curve is a plot of water level (stage) versus discharge on a suitable arithmatic scale. This is developed from continuous records of water level coupled with discrete discharge measurements made at various river stages to produce a unique relationship between the two for a particular location and cross section. The array of points usually lies on a curve which is approximately parabolic and a best fit curve should be drawn through the points by eye. If the station is located just upstream from rapids or other natural control which fixes a definite relation between stage and discharge, an accurate and permanent rating is obtained.

The rating curve of a streamflow measuring station is affected by different conditions:

1. backwater from an intersecting stream;

2. erosion and deposition of sediments;

3. change in the slope of the river, in which case the points do not describe a single smooth curve; and

4. river stage (another break in the curve at high stages can often be related to the normal bankfull level above which the discharge versus water level relationship could be markedly different from the within-banks curve owing to the very different hydraulics of flood plain flow).

Conditions in a natural river are rarely stable for any length of time and thus the stage-discharge relationship must be checked regularly and, certainly after flood flows, new discharge measurment should be made throughout the range of stages.

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5.3 Muskingum-Cunge Method

5.3.1 Calculation Of The Muskingum-Cunge Coefficients (k, ϵ)

For the calculation of the Muskingum-Cunge coefficients (k, ϵ), a number of quantities for a particular flood are required to be known. These quantities which can be calculated from past flood data are:

1. the attenuation parameter of the reach;

2. the attenuation of the peak discharge of the upstream hydrograph;

3. the curvature at the peak of the upstream discharge hydrograph;

4. the peak value of the upstream discharge hydrograph; and

5. the speed parameter of the flood wave along the reach.

Details and calculations of these quantities are given below.

Calculation Of The Attenuation Parameter $\propto$ Of The Reach:

Data necessary for the definition of the attenuation parameter $\propto$ include the area of flood plain, the channel length, and the average channel slope.

The attenuation parameter is considered as a prescribed function of the discharge (Q).

Definition of the functional form of the attenuation parameter $\propto$ (Q) requires geometrical data of average channel width and bed slope, and an estimation of the flood plain area inundated for an out-of-bank flood of recorded peak discharge.

The most convenient way of evaluating $\propto$ for a given reach of a river is:

1. define the flood plain as the known area inundated by the largest recorded flood, or as estimated from a survey map;

2. divide the reach of the river into a number of subreaches, so that the geographical width of the flood plain in each sub-reach is approximately uniform;

3. for each sub-reach measure the length, L_m, of the channel, the average slope S_m of the channel, and the plan area P_m, of the flood plain (including the plan area of the channel); and

4. for the whole reach measure the length L, of the channel, and the average width, $\overline{W}_c$, of the channel.

The value of $\propto$ (Q) for the largest recorded flood can be calculated from:

$$\propto = \frac{1}{2}\{\frac{1}{L}\sum\frac{P_m}{S_m^{\frac{1}{3}}}\}^{-3}\sum(\frac{P_m^2}{L_m S_m^2}) \qquad 5.1$$

In addition the attenuation parameter $\propto$ can be calculated for an in-bank flood from:

$$\propto = \frac{1}{2\overline{W}_c}\{\frac{1}{L}\sum\frac{L_m}{S_m^{\frac{1}{3}}}\}^{-3}\sum(\frac{L_m}{S_m^2}) \qquad 5.2$$

Values of $\propto$ (Q) for intermediate conditions are much more difficult to obtain unless there are data available on the extent of flooding by different over-bank floods. If the data are not available, then the curve for $\propto$ (Q) between the inbank and out-of bank flood values has to be estimated.

The necessary data for the calculation of $\propto$ for both Rivers Wear and Tees reaches are shown in Table (5.1).

Table 5.1

Data Used For The Calculation Of $\propto$

Length Of Subreach (km)	Width Of Subreach (km)	Plan Area Of Subreach (km^2)	Slope Of Subreach (m/km)
Wear River Reach			
5.774	0.045	0.260	1.235×10^{-3}
5.774	0.059	0.341	1.235×10^{-3}
5.774	0.072	0.420	1.235×10^{-3}
5.774	0.074	0.430	1.235×10^{-3}
5.774	0.068	0.390	1.235×10^{-3}
Total: 28.87	Average: 0.0636	Total: 1.841	Average: 1.235×10^{-3}
Tees River Reach			
6.920	0.078	0.5397	2.43×10^{-3}
6.920	0.086	0.5950	2.37×10^{-3}
6.920	0.075	0.5190	2.32×10^{-3}
6.920	0.078	0.5397	1.98×10^{-3}
6.920	0.074	0.5121	1.98×10^{-3}
Total: 34.6	Average: 0.0786	Total: 2.7055	Average: 2.24×10^{-3}

Calculation Of The Curvature At The Peak

The curvature at the peak of the upstream discharge hydrograph is calculated from:

$$\frac{d^2 Q_p}{dt^2} = \frac{Q_1 + Q_{-1} - 2Q_p}{(\delta t)^2} \qquad 5.3$$

where Q_p is the discharge at the peak and Q_1 and Q_{-1} are the two discharges either side of the peak of time interval δt which is defined to the nearest hour by:

$$\delta t = \frac{t_p}{5} \qquad 5.4$$

δt need not however be greater than 3 hours.

Calculation Of The Attenuation Of The Peak Discharge

The attenuation of the peak discharge Q^* can be obtained by using the formula:

$$Q^* = \frac{\propto}{(\frac{L}{T_p})^3} Q_p \mid \frac{d^2 Q_p}{dt^2} \mid \qquad 5.5$$

where $\propto$ is the attenuation parameter of the reach, Q_p is the peak discharge, L is the length of the channel, T_p is the time to peak, and $\mid \frac{d^2 Q_p}{dt^2} \mid$ is the curvature at the peak discharge.

If $\frac{Q^*}{Q_p} > 0.1$, then Q^* can be redefined by:

$$Q^*_{new} = Q_p[1 - exp(-\frac{Q^*}{Q_p})] \qquad 5.6$$

If ω is known, then the storage coefficient k can be calculated by:

$$k = \frac{\Delta x}{\omega} \qquad 5.7$$

where Δx is subreach length.

ϵ calculated by an equation given in Flood Studies Report (N. E. R. C. 1975) as:

$$\epsilon = \frac{1}{2} - \frac{\propto \overline{Q}_p}{L \omega \Delta x} \qquad 5.8$$

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where L is the length of the whole reach which is divided into a number of sub-reaches, each of length Δx. Again $\propto$ is the value of the attenuation parameter corresponding to the discharge $\overline{Q}_p$, and ω is the speed.

$\overline{Q}_p$ can be calculated using the equation:

$$\overline{Q}_p = Q_p - \frac{1}{2}Q^*$$
<div align="right">5.9</div>

Once k and ϵ have been determined, the discharge hydrograph at any section downstream of the reach is determined using the equation (4.7).

Values of $\propto$, ω, $\overline{Q}_p$ and ϵ for the events used in this study for reaches of both Rivers Wear and Tees are summarised in Table (5.2).

Calculation Of The Wave Speed ω

The times of travel, T_p, of the peak of the largest recorded flood and the inbank flood are extracted from records. The speed is then defined by $\frac{L}{T_p}$.

A correction to the observed speed of the flood peak which gives the convection speed who proposed by Hayami (1951) as:

$$\omega = \frac{L}{T_p} - \frac{2 \propto Q^*}{L^2}$$
<div align="right">5.10</div>

Where T_p is the travel time of the flood peak and Q^* is the attenuation of peak discharge.

5.3.2 Relationship Between The Coefficients And The Numerical Grid Size For The Muskingum-Cunge Method

The accuracy with which one is able to route a flood depends largely on the parameters that are used in the routing procedure. The Muskingum-Cunge is no exception.

Table 5.2

The Calculation Values Of α, ω, $\overline{Q}_p$, And ϵ

Flood events	α	ω (m/sec.)	$\overline{Q}_p$ (Cumecs)	ϵ
Wear River Reach				
1-10-1981	1.97×10^5	1.332	314	0.221
2-02-1981	2.45×10^5	1.6015	179.7	0.335
26-8-1986	1.88×10^5	1.333	457.6	0.110
15-4-1986	1.99×10^5	1.231	299.27	0.210
-02-1984	2.21×10^5	1.1425	229.7	0.233
-03-1986	2.27×10^5	1.1448	190.6	0.272
Tees River Reach				
2-01-1982	1.16×10^5	1.599	591.95	0.179
13-1-1984	1.24×10^5	1.371	260.1	0.401
25-8-1986	1.14×10^5	1.747	691.94	0.300

The main sources of error that may affect the accuracy of the results are:

1. the errors in the data;

2. the coefficients of storage-discharge relationship; and

3. the computational errors that are associated with the numerical procedure.

Unless k, ϵ, Δx, and Δt are properly selected, the Muskingum-Cunge numerical routing may have a considerable amount of computational error even with very accurate flow data. The equations 5.7 and 5.8 for k and ϵ, include the space increment, Δx, but not the time increment, Δt. With the help of the above equations, k and ϵ can be chosen for a particular Δx. However, if Δx and ΔT are not compatible, then they can cause large computational errors in the numerical routing. Therefore, the coefficients (k and ϵ) and the grid size must all be rightly chosen in order to make sure that the computational errors are minimum.

For the selection of Δt, the Flood Studies Report III (N.E.R.C. 1975) provides a graphical relationship between ϵ and $\frac{\Delta x}{(\omega \Delta t)}$ as shown in Fig. 5.1.

Normally the reach length will be divided into a number of subreaches, each of length Δx. Now, if ϵ is known, then the curve in Fig. 5.1 will provide the relevant value of $\frac{\Delta x}{(\omega \Delta t)}$ and hence a suitable value for Δt with respect to Δx and ϵ. It is claimed in the flood routing studies report (N.E.R.C. 1975) that the values of Δx, Δt, and ϵ of any point which lies below the curve will ensure sufficient accuracy in the results. This could be used to advantage in selecting Δt as an integral number of hours so that it will be convenient to read the flow data. On the other hand, if Δt is known then ϵ could be chosen in a similar way. However, the graph in Fig. 5.3 is useful for the selection of ϵ or Δt only when one of them is known in advance.
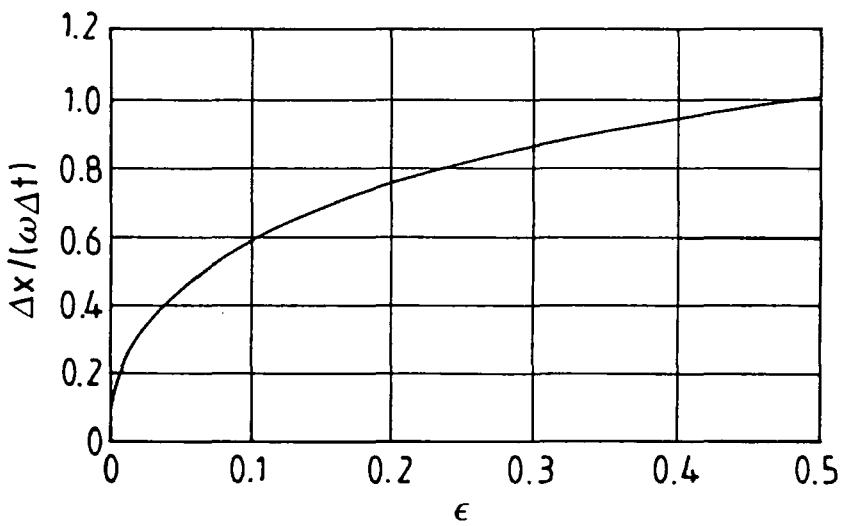
Fig. (5.1) Relationship Between $\frac{\Delta x}{(\omega \Delta t)}$ and ϵ (Reproduced From The Flood Routing Studies Report (N.E.R.C. 1975)

5.3.3 Application Of The Muskingum-Cunge Method

5.3.3.1 Computer Model

The Muskingum-Cunge method is included in a computer program M-C2, which is a modified version of program FLOODS1, constructed by Price (1973), and included in volume III of the N.E.R.C. Flood Studies Report (N.E.R.C. 1975). The computer program M-C2 is written in Fortran 77; the listing of the program is in Appendix III-1.

The equation to be solved by this model is equation (4.7), which gives the discharge hydrograph at the downstream end of each subreach. For the traditional Muskingum method, equation (4.7) is solved directly for the whole reach. Availability of digital computers now permits the division of the whole reach into smaller subreaches, enabling the use of small time steps in order to increase accuracy.

Output from M-C2 are discharge hydrographs at each space node along the reach, with an option for the generation of flow depths from the continuity equation as suggested by Cunge (1969).

The M-C2 computer program is applied to 6 flood events from the River Wear reach and 3 flood events from the River Tees reach.

A sample of the output from M-C2 computer program is given in Appendix II. The Symbol definitions of M-c2 computer program are given in Appendix V-1.

5.3.3.2 Data Requirement

The Muskingum-Cunge method as represented in the computer program M-C2 requires the following data:

1. the length of the reach and the number of subreaches;

2. the number of time steps and the time step Δt, which can be calculated by reading the value of $\frac{\Delta x}{(\omega \Delta t)}$ corresponding to the value of ϵ in Fig. (5.1), and then round up the value of Δt to the nearest integral number of hours;

3. derived curves for the wave speed and the attenuation parameter as shown in Figs. (5.11) and (5.12);

4. the boundary condition upstream inflow hydrograph to be routed through the reach;

5. the boundary condition downstream outflow hydrograph to be compared with the predicted hydrograph;

6. the initial discharge along the reach of the river to be routed;

7. the value of wave speed along the reach;

8. the value of the attenuation parameter of the reach; and

9. the value of the average peak discharge $\bar{Q}_p$.

5.3.3.3 Test Application

The Muskingum-Cunge method was applied to different flood events from the two river reaches (i.e Wear and Tees) using the computer program M-C2, to draw a comparison with the other flood routing models used in this study, in which each reach is divided into subreaches of length Δx. For the River Wear Δx =5.774 km, while for the River Tees Δx =6.92 km. Δt is calculated from the graph shown in Fig. (5.1) for each event for both river reaches, and and the value of Δt is rounded up to the nearest integral number of hours. The time step Δt is found to be equal 2 hours for all the events of both river reaches.

Muskingum-Cunge parameters (k and ϵ) were calculated from the recorded time of travel of flood wave peaks along the reach $\frac{L}{T_p}$, and the attenuation param-

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eter $\propto$ related to over land storage area.

Recorded and calculated hydrographs for the 9 flood events of both river reaches are presented in Figs 5.2 - 5.10 (M-C is the Muskingum-Cunge hydrograph and VPDM is the variable parameter diffusion method hydrograph). For the River Wear reach, the predicted hydrographs of event Oct.1981, Feb. 1981, and April 1986 show a good results and reconstruction with the downstream hydrograph and show little variation in the attenuation of peak discharge which caused by the inundated flood plain, while the graphs of event Oct. 1986, Mar. 1986, and Feb. 1984 show a good results but not good reconstruction especially between the peak of the recorded downstream hydrograph and the peak of the three flood events. For the River Tees reach, the predicted hydrographs of event Jan. 1984, and event Jan. 1982 show a good results and reconstruction with the recorded downstream hydrographs and also show little variation in the the attenuation of peak discharge, while event of Aug. 1986 give good result but the recorded downstream hydrograph shows a large attenuation in the peak discharge in comparison with the calculated hydrograph.

The lateral inflow to the both Wear and Tees Rivers is taken into consideration in testing M-C2 Model.

Time lag is also predicted well and the average errors in most of the flood events is less than 30 %. Error in predicted time lag generally increases with the peak flow of a flood, and hence with the amount of over bank storage.

In conclusion it has been shown that a minimum attenuation of peak discharge took place with the inbank flood events and time of travel is also reduced considerably, while the large attenuation happened with the overbank flood and was caused by the extensive inundated flood plain. It has been shown also that the Muskingum-Cunge method as represented in the computer program M-C2,

Fig. (5.2) Recorded And Predicted Hydrographs of Feb. 1981 Flood Event of Wear River Reach.
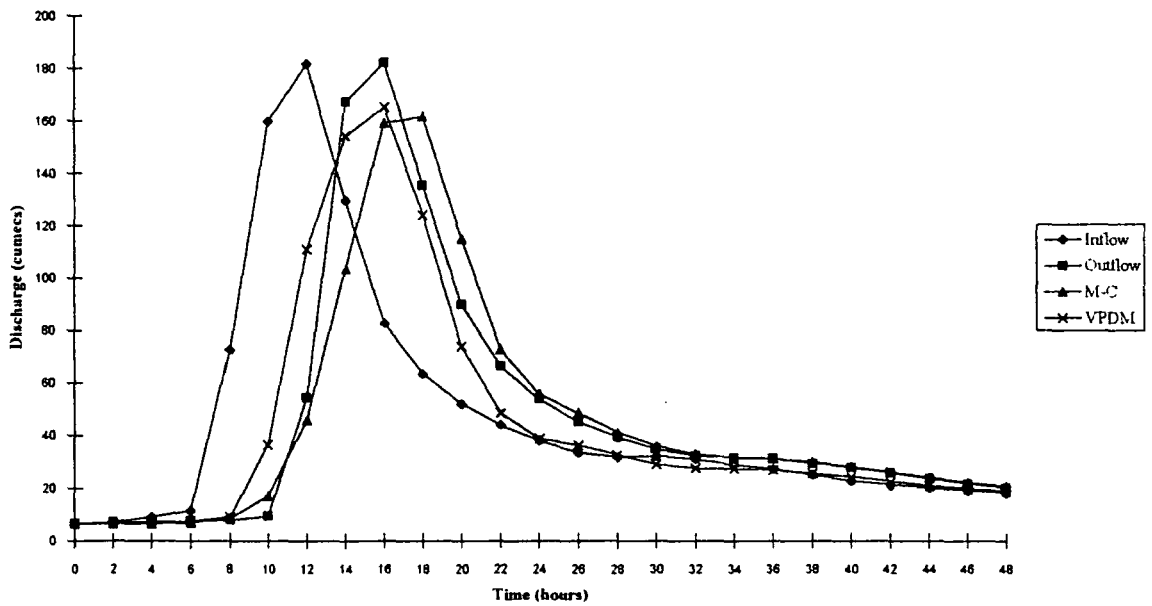
Fig. (5.3) Recorded And Predicted Hydrographs of Aug. 1986 Flood Event of Wear River Reach.
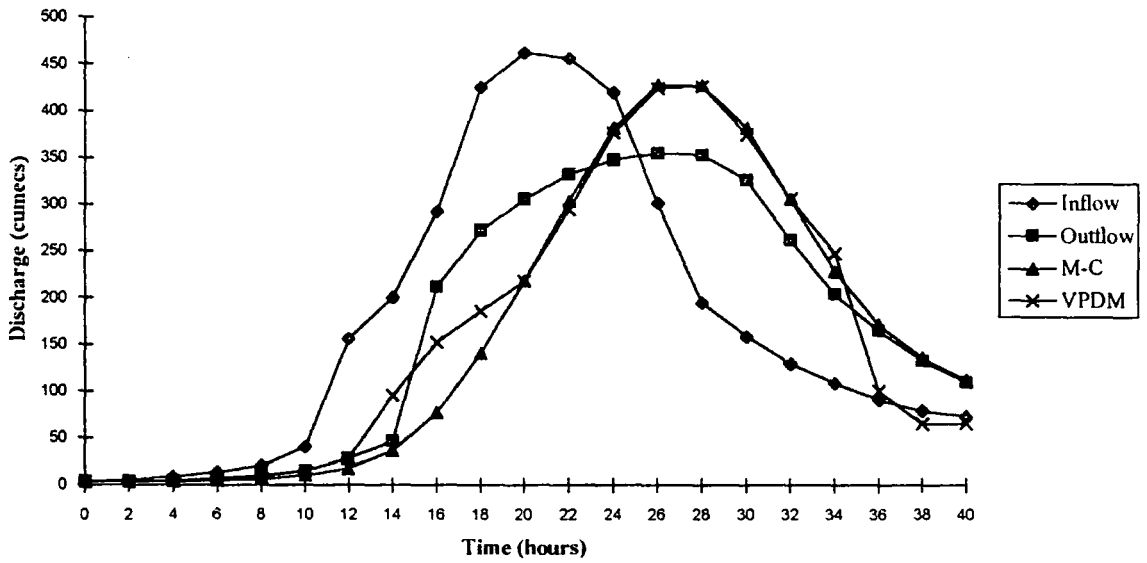
Fig. (5.4) Recorded And Predicted Hydrographs of Oct. 1981
Flood Event of Wear River Reach.
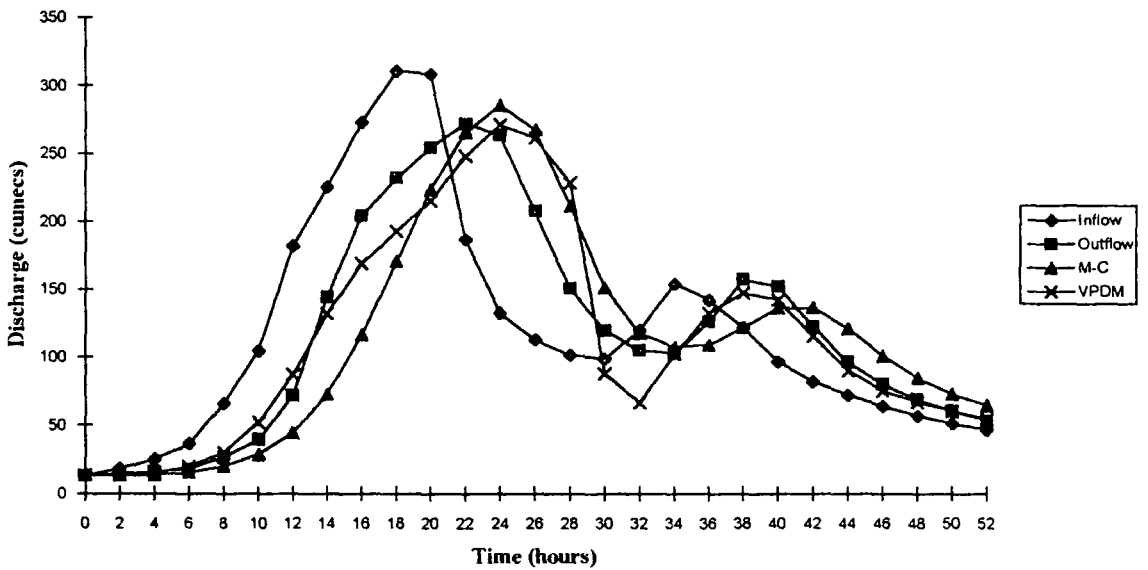
Fig. (5.5) Recorded And Predicted Hydrographs of April 1986 Flood Event of Wear River Reach.
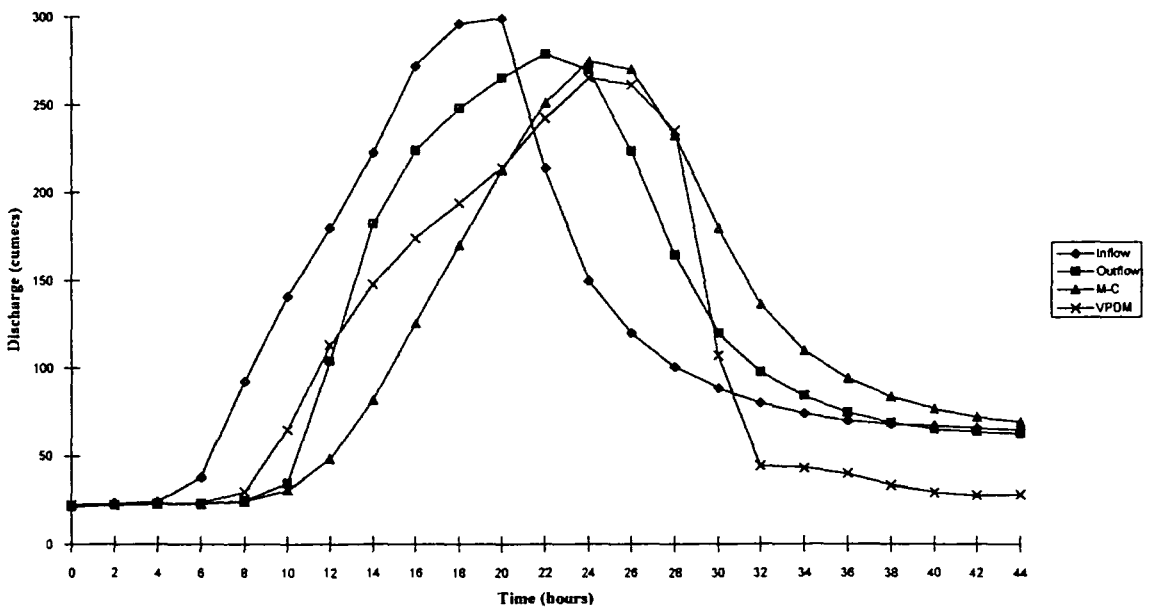
Fig. (5.6) Recorded And Predicted Hydrographs of Mar. 1986 Flood Event of Wear River Reach.
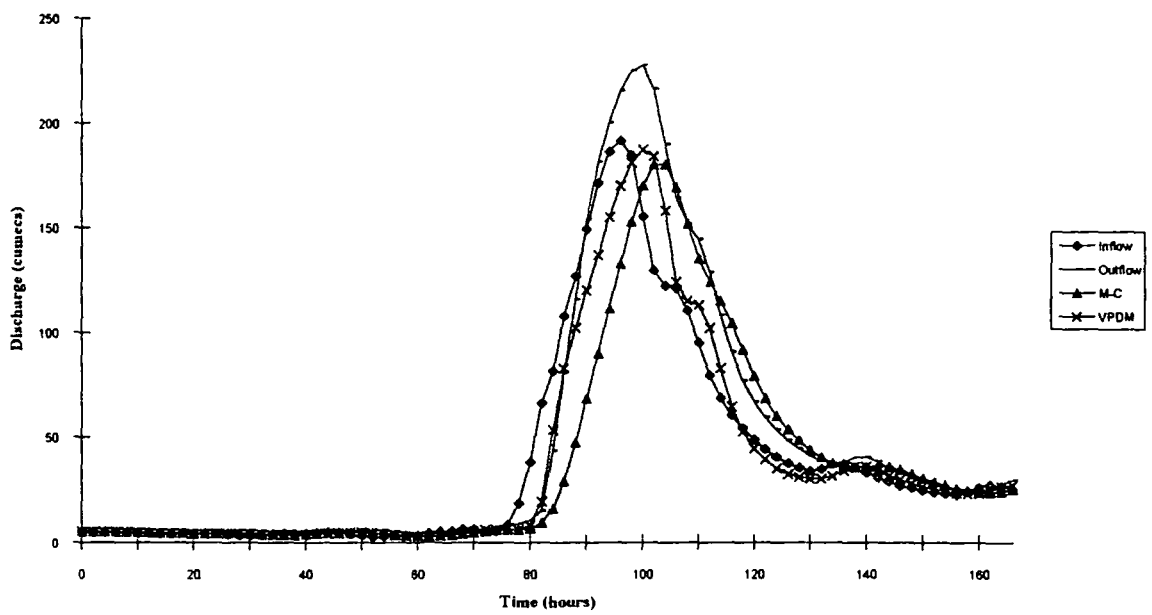
Fig. (5.7) Recorded And Predicted Hydrographs of Feb 1984 Flood Event of Wear River Reach.
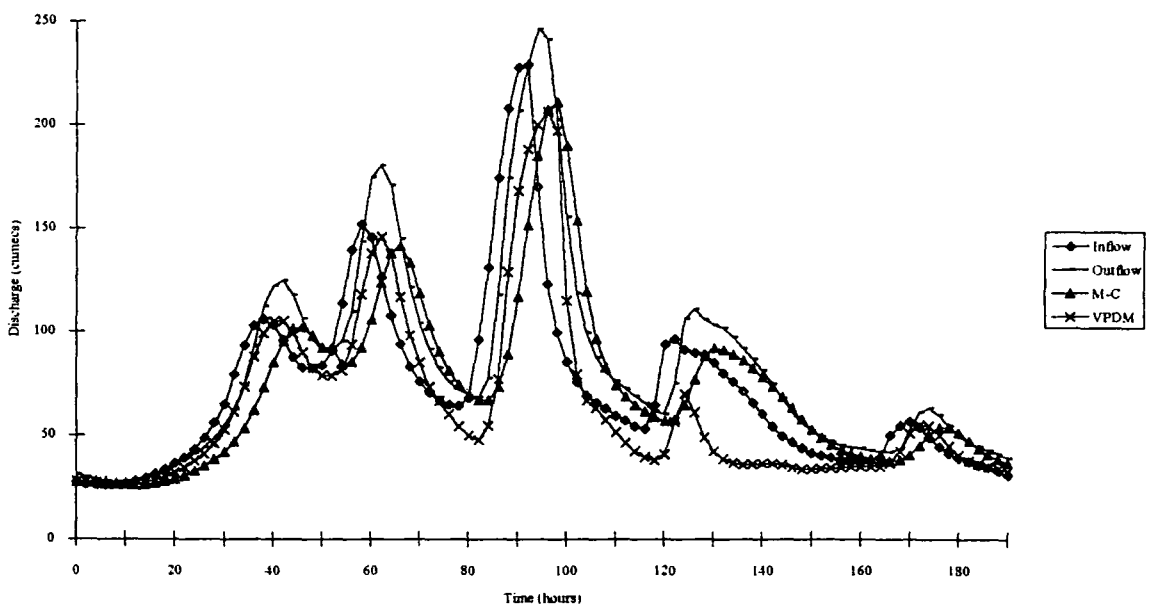
Fig. (5.8) Recorded And Predicted Hydrographs of Jan. 1984 Flood Event of Tees River Reach.
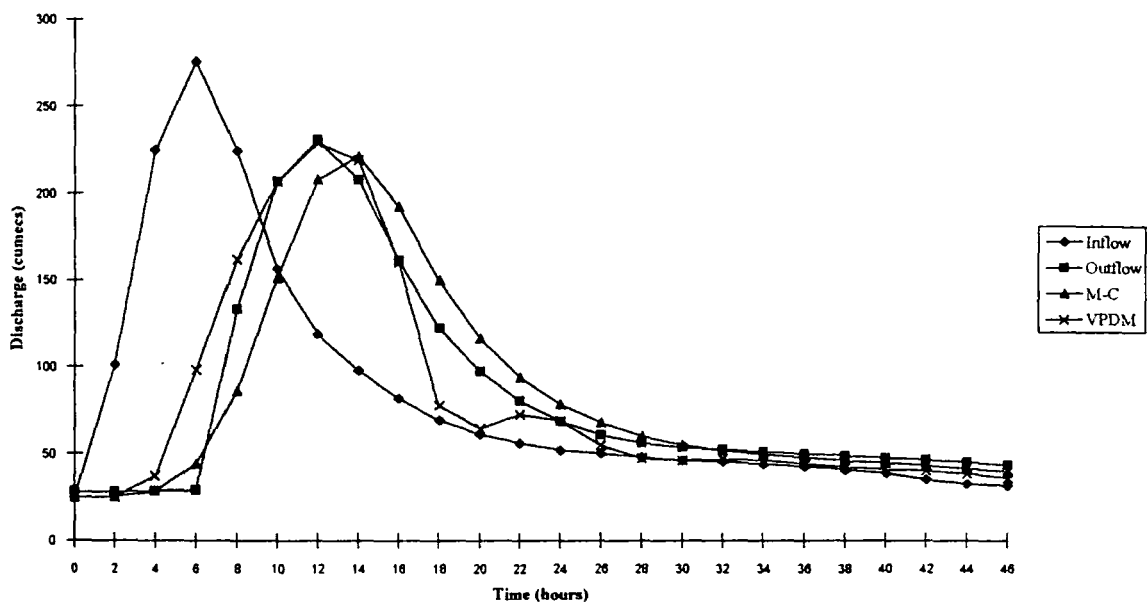
Fig. (5.9) Recorded And Predicted Hydrographs of Jan. 1982 Flood Event of Tees River.
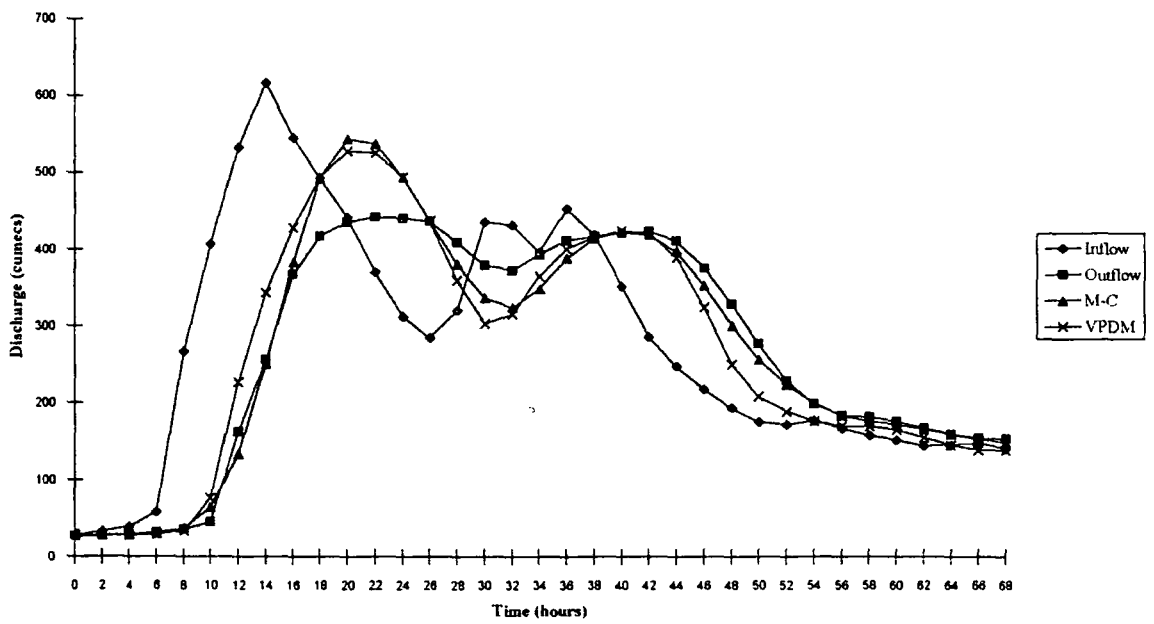
Fig. (5.10) Recorded And Predicted Hydrographs of Aug. 1986 Flood Event of Tees River Reach.
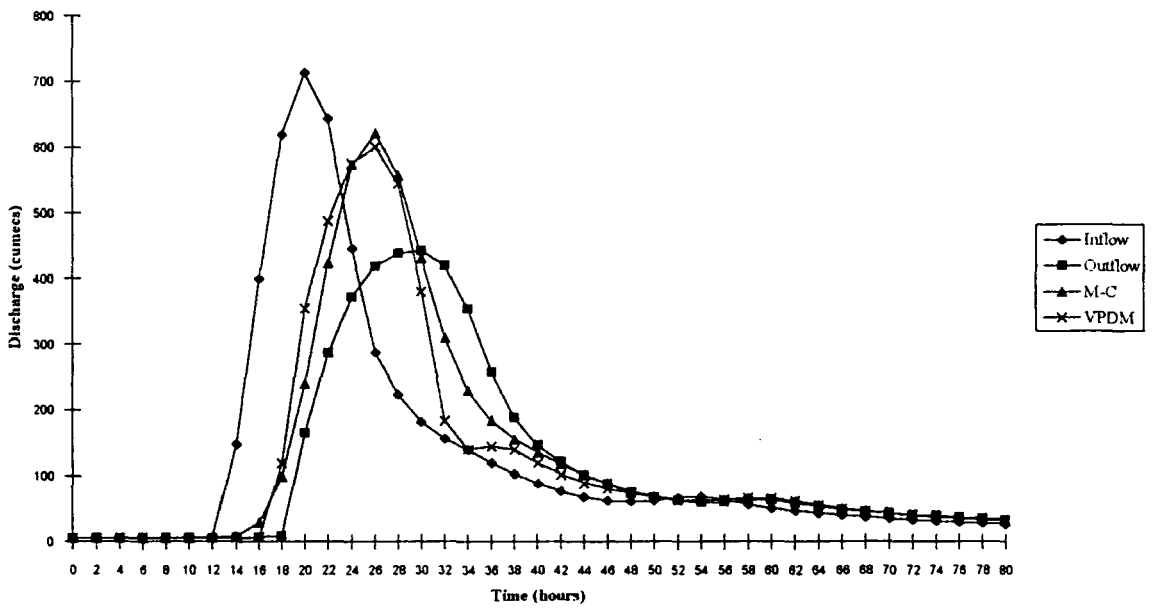
Table 5.3

The Muskingum-Cunge Simulation Of Peak

Attenuation And Time Lag

Flood events	Peak Flow Of	Routing Parameter		Peak Attenuation	Peak Attenuation	Time Lag	Time Lag
	Upstream			Recorded	Predicted	Recorded	Predicted
	(Cumecs)	k	ϵ	(Cumecs)	(Cumecs)	(Hours)	(Hours)
Wear River Reach							
1-10-1981	318.9	1.2	0.221	49	32	7	9.25
2-02-1981	181.7	1.002	0.335	1	18	4	6
26-8-1986	461.3	1.203	0.11	110	32	6	6
15-4-1986	302.4	1.303	0.21	21	25	2.2	4.1
-2-1984	232.6	1.403	0.233	?	10	?	6.8
-3-1986	191.29	1.401	0.272	?	16	?	7.9
Tees River Reach							
2-01-1982	616.35	1.214	0.179	177	71	8	6
13-1-1984	275.7	1.419	0.401	43	53	6	8
25-8-1986	713.8	1.111	0.300	275	95	10	6

predicts attenuation and time lag of both river reaches to a high degree of accuracy especially with those events of accurate inflow and outflow data. The Muskingum-Cunge method is therefore recommended for the analysis of flood wave propagation in rivers with large flood plains.

5.4 Variable Parameter Diffusion Method

Problems encountered in obtaining suitable data, such as the attenuation parameter $\propto$ and wave speed $\bar{c}$, for testing of the Muskingum-Cunge method, described in section 5.3, are compounded in the testing of the variable parameter diffusion method by the need to define functions of $\bar{c}$ (Q), and attenuation parameter $\propto$ (Q) accurately.

5.4.1 Attenuation Parameter $\propto$ Curve:

The attenuation parameter $\propto$ (Q) calculated for the Muskingum-Cunge method described in section 5.2 is also required for the variable parameter diffusion method.

Once the two values for the attenuation parameter $\propto$ for in-bank and over-bank flood have been determined they can be plotted and a curve drawn through these two points as shown in Figs. (5.11) and (5.12) for both Wear and Tees reaches. The value of $\propto$ for the over bank flood will always be considerably smaller than that for the inbank flood. The shape of the curve where it decreases with increasing Q should follow that for the corresponding wave speed curve, such that the steepest part of the $\propto$ curve will be at about bankfull discharge. One other important consideration is that as Q increases $\propto$ should decrease.

5.4.2 Calculation Of Convection Speed $\bar{c}$:

Price (1973) gives a further correction to the convection speed, suggesting $\bar{c}$ is defined by:

$$\bar{c} = \omega + Q^* \frac{d}{dQ}(\frac{L}{T_p})$$ 5.11

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$\bar{c}\,(\mathrm{Q})$ is properly defined as the average speed along a reach of the flood wave with peak discharge Q under the condition that there is no attenuation.

Equations (5.3) and (5.11) are given by Price (1973) and implemented in the variable parameter diffusion method (Price 1977b) where the attenuation parameter and the wave speed parameter are both functions of the input flow values.

Obviously the calculation of $\bar{c}$ for a natural river reach depends on the availability of a reasonable amount of data to construct the curve for $\frac{L}{T_p}$ as a function of discharge, which will be a mean curve in the sense that there will usually be some scatter of the data points. This scatter will arise from the variability of the attenuation of the peak discharge Q^* for different floods with the same average peak discharge along the reach.

Normally the propagation speed of flood waves increases with peak discharge up to bank-full condition, reduces rapidly for flood wave just inundating the flood plain, and then increases again for larger out of bank floods as the water starts to flow in the flood plain. This shows that small inbank floods will travel considerably faster than a flood which is just bankfull. The main reason for this effect is that the river channel generally has a more irregular surface width as the depth of water increases, and the irregularities increase the effective storage of the channel. This storage is magnified when water begins to pond up on the flood plain. So for some discharge greater than the bankfull discharge $\bar{c}$ will be a minimum. The curves for $\frac{L}{T_p}$ and $\bar{c}$ for both Wear and Tees reaches are shown in Figs. (5.11) and (5.12). These curves will generally have the following features:

1. c will increase rapidly with discharge to some maximum value, c_{max} when the flow is about two thirds bankfull;

2. c then decreases to a minimum value, c_{min}, for the flow above -bank and when there is little flow along the flood plain; and
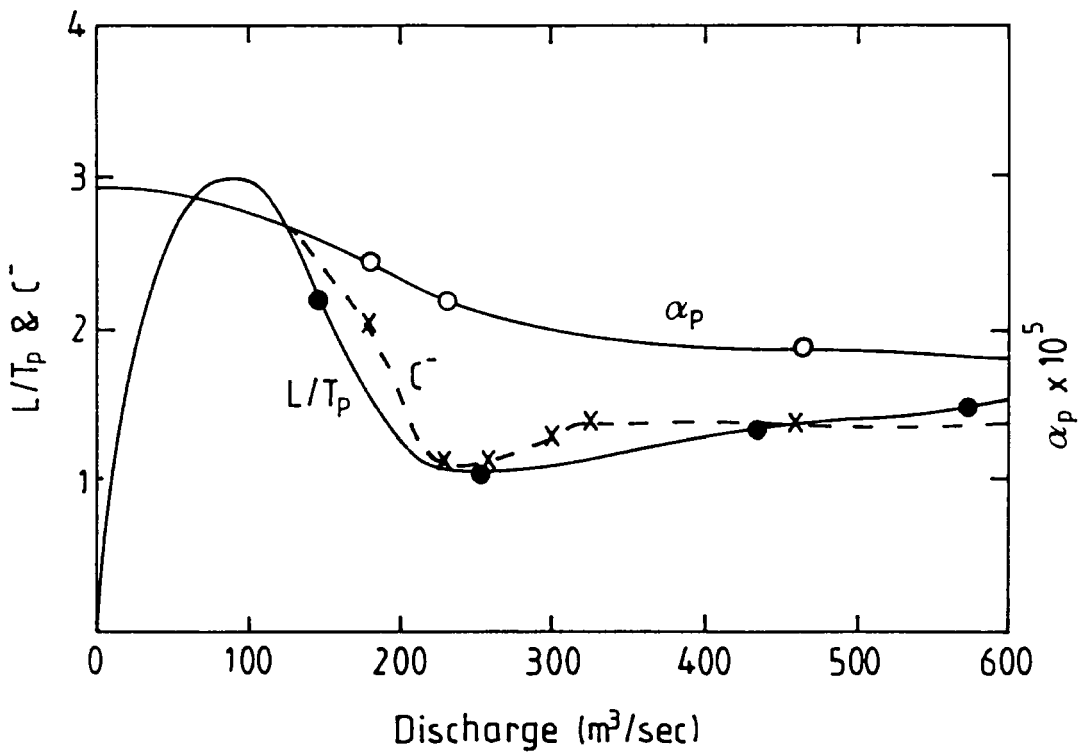
Fig. (5.11) Speed And Attenuation Parameter Curves For Wear River Reach.
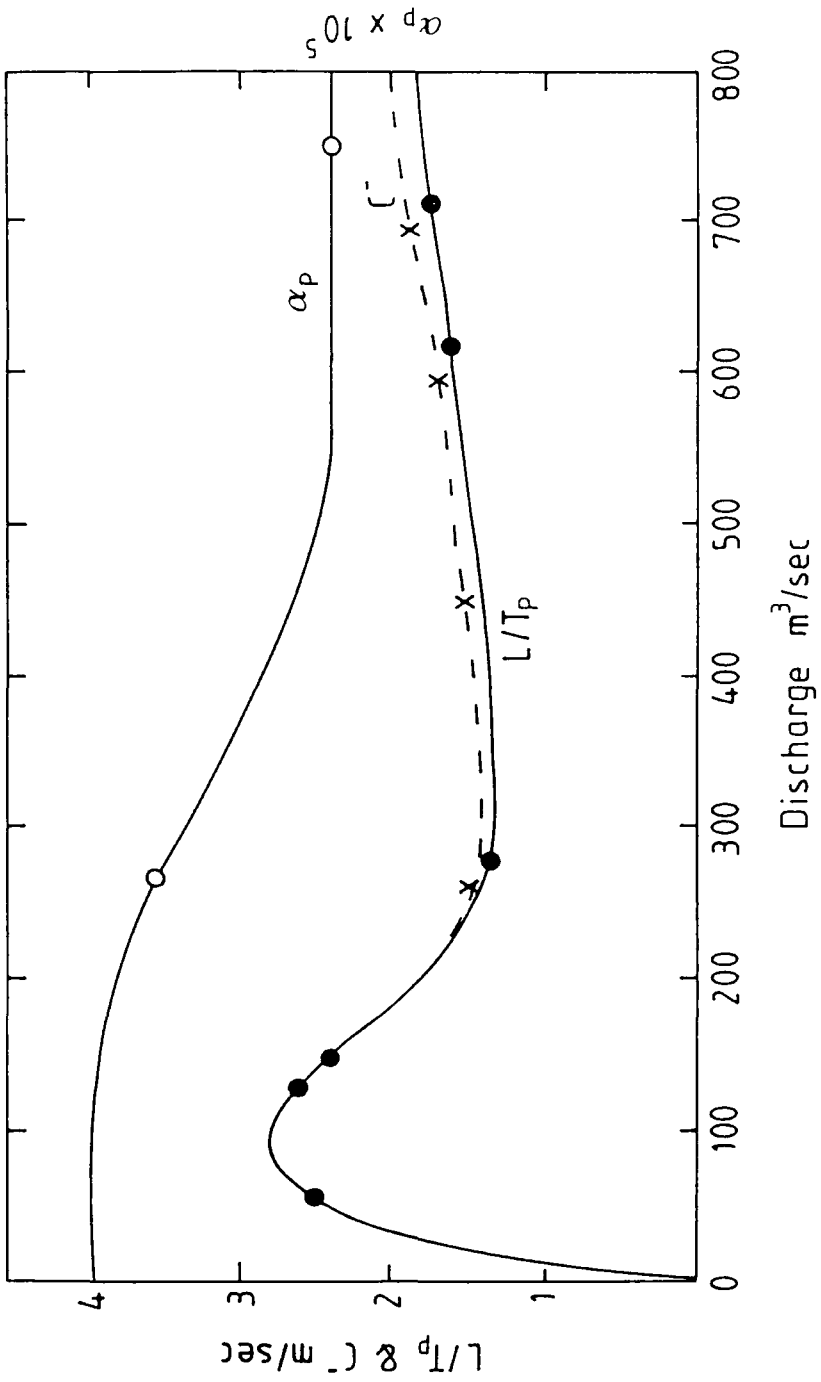
Fig. (5.12) Speed And Attenuation Parameter Curves For Tees River Reach.

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3. c increases slowly as the discharge increases and the flow along the flood plain becomes more important.

5.4.3 Application Of The Variable Parameter diffusion Method

5.4.3.1 Computer Model

The variable parameter diffusion method is included in a computer program VPDM1, a modified version of program FLOODS2, which is constructed by Price (1973), and included in volume III of Natural Environment Research Council Flood Studies Report (N.E.R.C. 1975). The computer program VPDM1 is written in Fortran 77; the listing of the program is in Appendix III-2. The program is based for solving equation (4.9).

Outputs from the model are a discharge hydrograph at each prescribed space node along the reach. Parameters $\propto$ and $\bar{c}$, representing conditions in the channel, are prescribed as average values for the whole reach, and hence all hydrographs at internal space nodes are meaningless. Significant output is restricted to the discharge hydrograph predicted at the downstream boundary. Samples of the output from VPDM1 are given in Appendix II. The symbol definitions of VPDM program are given in Appendix V-2.

5.4.3.2 Data Requirement

In the application of the variable parameter diffusion method as represented in the VPDM1 computer program, the following information is required:

1. the length of the river reach and the number of subreaches;

2. the number of time steps and the time step Δt which is calculated by $\Delta t = \frac{\Delta x}{\bar{c}_{ave}}$;

3. the curves derived for the wave speed and the attenuation parameter as shown in Figs. (5.11) and (5.12);

4. the functions digitalised for $\bar{c}$ and $\propto$ at 10 m^3sec^{-1} or 20 m^3sec^{-1} intervals;

5. the boundary condition upstream inflow hydrograph to be routed through the reach;

6. the boundary condition downstream outflow hydrograph to be compared with the predicted hydrograph;

7. the initial discharge along the reach of the river to be routed; and

8. the cut-off discharge to simulate drainage off the flood plain and to stablise the finite difference solution technique.

5.4.3.3 Test Application

The variable parameter diffusion method as represented in the computer program VPDM1 is also applied to the flood events used with the Muskingum-Cunge computer program M-C2.

Curves for the functions $\bar{c}$ (Q) and $\propto$ (Q) shown in Figs. (5.11) and (5.12) were digitalised at 10 m^3sec^{-1} or 20 m^3sec^{-1} intervals. A subreach length of Δx = 9.6 km was used for each test of flood event from River Wear, and the time step Δt set at 2.0 hours, this is in one hand. In the other hand Δx = 8.65 km was used for each test of flood event from River Tees, and the time step Δt also set at 2.0 hours. Δt is calculated by:

$$\Delta t = \frac{\Delta x}{\bar{c}_{ave}} \qquad 5.12$$

where $\bar{c}_{ave}$ is an average value for $\bar{c}$ over the range of discharge anticipated for the flood. Δt is choosen as a convenient fraction of an hour.

Figs. 5.2 - 5.10 presents the predicted hydrograph by the variable parameter diffusion method with the one of the 9 recorded events from both river reaches used in this study. The variable parameter diffusion method give almost identical

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results to the Muskingum-Cunge method and shows good reconstruction with the downstream hydrograph and also shows good estimation of attenuation and time lag, but some deviation in the hydrograph shape, especially in the recession limb.

Table (5.4) compares the recorded attenuation of peak discharge and time lag for the 9 flood events considered, with the predicted values by the variable parameter diffusion method.

The lateral inflow of both Wear and Tees rivers are also used in testing the VPDM1.

In conclusion the variable parameter diffusion method will give a better prediction of the shape of the downstream hydrograph, if the convection speed and the attenuation parameter can be accurately defined for the river reach. If not, the Muskingum-Cunge method is preferable by reason of its simplicity and ease of application.

5.5 Advantages And Disadvantages Of The Applied Numerical Methods

At this stage it is pertinent to list the advantages and disadvantages of employing the numerical routing models used in this chapter:

Advantages:

1. it is simpler in programming and cheap in cost when applied by computer;

2. topographical information does not have to be extensive or detailed;

3. the acceleration and momentum terms in flood routing are frequently small in comparison with the other terms, so that the simpler model can frequently be almost as accurate as the full solution;

4. both methods lend themselves more readily to adaptive modelling techniques; and

Table 5.4

The Variable Parameter Diffusion Method Simulation Of

Peak Attenuation And Time Lag

Flood events	Peak Flow Of Upstream (Cumecs)	Peak Attenuation Recorded (Cumecs)	Peak Attenuation Predicted (Cumecs)	Time Lag Recorded (Hours)	Time Lag Predicted (Hours)
Wear River Reach					
1-10-1981	.318.9	49	47	7	9.1
2-02-1981	181.7	1	15	4	3.9
26-8-1986	461.3	110	33	6	6.8
15-4-1986	302.4	21	35	2.2	4.0
-2-1984	232.6	?	5	?	4.0
-03-1986	191.29	?	20	?	6.0
Tees River Reach					
2-01-1982	616.35	177	83	8	6
13-1-1984	275.7	43	43	6	6
25-8-1986	713.8	275	115	10	6

5. it is easier to teach the simpler methods to the person who operates these models.

Disadvantages:

1. it is not usually possible to include backwater effects caused by tidal influences, hydraulic structures such as bridges;

2. a relatively large amount of measured data is required for the simple storage models to obtain useful estimates of coefficients and parameters; and

3. extrapolation of the simpler model outside the conditions under which the parameters or coefficients were derived may lead to a reduction in accuracy.

5.6 Conclusion

Chapter 5 covered the application of the Muskingum-Cunge and the variable parameter diffusion methods as represented in a computer programs M-C2 and VPDM1 respectively to predict the flood hydrograph for both River Wear and River Tees reaches. Both computer programs are suitable for the modelling of flood wave propagation in nontidal rivers and provide solutions of similar accuracy.

For the Muskingum-Cunge method, the routing parameters k and ϵ need to be calculated and information is required about the recorded flood hydrograph and the channel reach. The variable parameter diffusion method requires many accurate recorded flood discharge hydrographs for the definition of parameters $\bar{c}$ (Q) and $\propto$ (Q). If the parameters can be accurately defined, the variable parameter diffusion method gives a better prediction of the shape of the discharge hydrograph than the Muskingum-Cunge method, but if the parameters can not be defined accurately the Muskingum-Cunge method is preferred because of its simplicity and ease of application.

CHAPTER 6

MATHEMATICAL MODELLING AND APPLICATION OF STATE VARIABLE KINEMATIC WAVE MODEL

6.1 Mathematical Modelling

6.1.1 Introduction

A mathematical model represents the behaviour of the nature system by a set of equations.

Unsteady flow in rivers is caused by the motion of long waves such as flood waves. This wave motion may be adequately described by the one-dimensional Saint-Venant equation which has been discussed in chapter 2. Due to the complexity of the complete unsteady flow equations, many mathematical models which have been used in the past and those which are still being used in operational stream flow forecasting are based primarily on the equation for conservation of mass. The equation for conservation of momentum is either completely ignored or greatly simplified so as to include the effects of the friction forces only.

6.1.2 Governing Equations And Numerical Schemes

For the kinematic wave model, the continuity equation (2.18) and the momentum equation (2.19) are simplified to:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad 6.1$$

$$g(S - S_f) = 0 \qquad 6.2$$

where the lateral inflow, q_1 , has been ignored. Equation (6.2) implies that the energy slope is approximately equal to the channel bottom slope. Furthermore equation (6.1) can be approximated by finite difference expressions, and the con-

tinuous x-t region in which solutions of stage and discharge are sought is represented by a rectangular net of discrete points as shown in Fig. (6.1). The finite difference form of equation (6.1) can be represented as:

$$\frac{Q^{t+\Delta t}_{x+\Delta x} - Q^{t+\Delta t}_{x}}{\Delta x} + \frac{A^{t+\Delta t}_{x+\Delta x} - A^{t}_{x+\Delta x}}{\Delta t} = 0 \qquad 6.3$$

where the time derivatives are approximated by a forward difference quotient centred between the x-th and (x + Δx)-th points along the x-axis.

6.1.3 Discharge And Flow Area Relation

As mentioned by Li, Simons, and Stevens (1975), and Chang (1979), the flow cross-sectional area can be generally expressed as a power function of discharge:

$$A = \alpha Q^\beta \qquad 6.4$$

or

$$Q = \frac{1}{\alpha} A^{\frac{1}{\beta}} \qquad 6.5$$

in which α and β are coefficients values of which depend on the shape of the channel and the roughness of the wetted perimeter. The development of α and β depends on the shape of the cross-section. For example the coefficient α and β for a rectangular channel using Manning's equation are:

$$\alpha = (\frac{nP^{\frac{2}{3}}}{1.49S^{\frac{1}{2}}})^{\frac{3}{5}},$$

and

$$\beta = \frac{3}{5} \qquad 6.6$$

where n is Manning's roughness coefficient, P is the wetted perimeter and S is the channel slope.

The value of β for rivers is usually less than 1.0, and the average value of β for stable channels as deduced by Simons and Albertson (1960) is 0.87.

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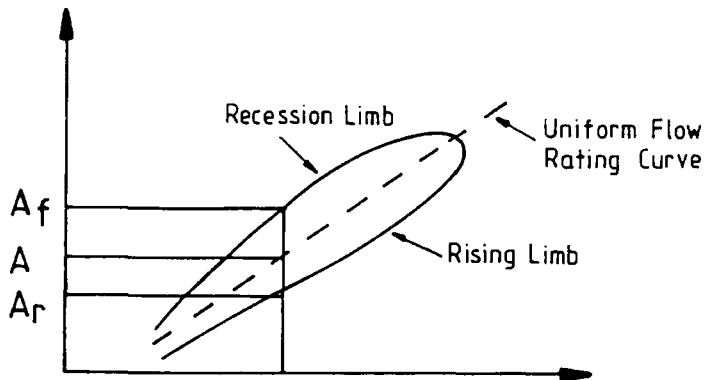
Fig.(6.1) Loop Rating Curve.

For a natural channel, α and β are derived directly from the observed discharge and cross-sectional area records by using the curvilinear regression equation.

$$Log A = Log \alpha + \beta Log Q \qquad\qquad 6.7$$

Flood flows in a natural channel show that the disharge for a particular wetted cross-sectional area, when the flood level is increasing, is larger than the discharge for the same cross-sectional area when the flood level is decreasing. This phenomenon can be shown graphically in the well-known loop rating curve, Fig. (6.1). Therefore, two sets of α and β coefficients should be defined; one for the rising limb, and another for the recession limb of the loop.

To account for the unsteady and nonuniform motion of flood flow over time, a channel is divided into n sucessive reaches. Although the surface profile of a flow is continuous, it may be approximated by assuming that the flow in each reach is uniform, as shown in Fig. (6.2).

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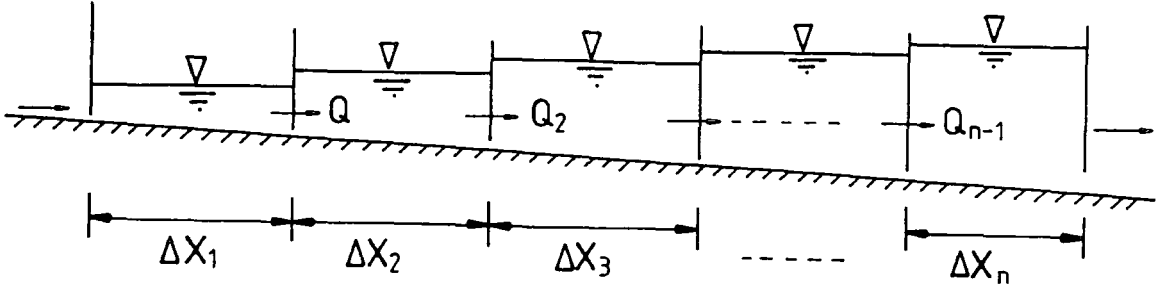
Fig. (6.2) Continuous Subreaches Each With Uniform Flow.

6.1.4 State Equation, "Cross-Sectional Area" as the state variable:

In this case the state variable model considers the cross-sectional area of the river as the state variable. From equation (6.5), discharge at any points x and x + Δx can be expressed respectively as equation (6.8) and (6.9).

$$Q_{x+\Delta x}^{t+\Delta t} = (\frac{1}{\alpha_{x+\Delta x}} A_{x+\Delta x}^{t+\Delta t})^{\frac{1}{\beta_{x+\Delta x}}} \qquad 6.8$$

and

$$Q_x^{t+\Delta t} = (\frac{1}{\alpha_x} A_x^{t+\Delta t})^{\frac{1}{\beta_x}} \qquad 6.9$$

At the most upstream boundary point x, the boundary condition is:

$$Q_x^{t+\Delta t} = (\frac{1}{\alpha_x} A_x^{t+\Delta t})^{\frac{1}{\beta_x}}$$

$$= I(t + \Delta t) \qquad 6.10$$

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in which I(t + Δt) is the inflow from the inflow hydrograph at time t + Δt . Equation (6.8) and (6.9) can then be substituted for equation (6.3) to express the continuity equation as:

$$\frac{(\frac{1}{\alpha_{x+\Delta x}}A_{x+\Delta x}^{t+\Delta t})^{\frac{1}{\beta_{x+\Delta x}}} - (\frac{1}{\alpha_x}A_x^{t+\Delta t})^{\frac{1}{\beta_x}}}{\Delta x} +$$

$$\frac{A_{x+\Delta x}^{t+\Delta t} - A_{x+\Delta x}^t}{\Delta t} = 0 \qquad 6.11$$

Equation (6.11) can then be rearranged to solve the change in channel cross-sectional area with respect to time at x + Δx for time t + Δt ,

$$\dot{A}_{x+\Delta x}^{t+\Delta t} = (\frac{\Delta A}{\Delta t})_{x+\Delta x}^{t+\Delta t} = \frac{A_{x+\Delta x}^{t+\Delta t} - A_{x+\Delta x}^t}{\Delta t}$$

$$= \frac{(\frac{1}{\alpha_x}A_x^{t+\Delta t})^{\frac{1}{\beta_x}} - (\frac{1}{\alpha_{x+\Delta x}}A_{x+\Delta x}^{t+\Delta t})^{\frac{1}{\beta_{x+\Delta x}}}}{\Delta x} \qquad 6.12$$

Equation (6.12) can be written for each of the n reaches of the channel as:

$$\dot{A}_1 = (\frac{\Delta A}{\Delta t})_1 = \frac{I(t + \Delta t) - (\frac{1}{\alpha_1}A_1)^{\frac{1}{\beta_1}}}{\Delta x_1}$$

$$\dot{A}_2 = (\frac{\Delta A}{\Delta t})_2 = \frac{(\frac{1}{\alpha_1}A_1)^{\frac{1}{\beta_1}} - (\frac{1}{\alpha_2}A_2)^{\frac{1}{\beta_2}}}{\Delta x_2}$$

$$\dot{A}_n = (\frac{\Delta A}{\Delta t})_n = \frac{(\frac{1}{\alpha_{n-1}}A_{n-1})^{\frac{1}{\beta_{n-1}}} - (\frac{1}{\alpha_n}A_n)^{\frac{1}{\beta_n}}}{\Delta x_n} \qquad 6.13$$

Equation (6.13) can be rearranged into a state variable form in which A is the state variable. The state equations can be written in a matrix form as:

$$\underline{\dot{A}}(t) = \underline{B}\underline{A}(t) + \underline{C}\underline{I}(t) \qquad 6.14$$

and

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$$\dot{A}_1 = \frac{-(\frac{1}{\alpha_1})^{\frac{1}{\beta_1}}}{\Delta x_1} A_1^{(\frac{1}{\beta_1}-1)}.A_1 + \frac{1}{\Delta x_1}I(t+\Delta t)$$

$$\dot{A}_2 = \frac{-(\frac{1}{\alpha_2})^{\frac{1}{\beta_2}}}{\Delta x_2} A_2^{(\frac{1}{\beta_2}-1)}.A_2 + \frac{(\frac{1}{\alpha_1})^{\frac{1}{\beta_1}}}{\Delta x_2}A_1^{(\frac{1}{\beta_1}-1)}.A_1$$

$$\dot{A}_n = \frac{-(\frac{1}{\alpha_n})^{\frac{1}{\beta_n}}}{\Delta x_n} A_n^{(\frac{1}{\beta_n}-1)}.A_n + \frac{(\frac{1}{\alpha_{n-1}})^{\frac{1}{\beta_{n-1}}}}{\Delta x_n}A_{n-1}^{(\frac{1}{\beta_{n-1}}-1)}.A_{n-1} \qquad 6.15$$

where α_i and A_i are the average values for i=1, 2, ... n at time t. Matrix representation of the state equation (6.15) is shown in equation (6.16).

$$
\begin{pmatrix} \dot{A}_1 \\ \dot{A}_2 \\ \vdots \\ \dot{A}_n \end{pmatrix} =
$$

$$
\begin{pmatrix}
\frac{-(\frac{1}{\alpha_1})^{\frac{1}{\beta_1}}}{\Delta x_1}A_1^{(\frac{1}{\beta_1}-1)} & & & \\
\frac{-(\frac{1}{\alpha_1})^{\frac{1}{\beta_1}}}{\Delta x_2}A_1^{(\frac{1}{\beta_1}-1)} & -\frac{(\frac{1}{\alpha_2})^{\frac{1}{\beta_2}}}{\Delta x_2}A_2^{(\frac{1}{\beta_2}-1)} & & \\
& & \ddots & \\
& & \frac{-(\frac{1}{\alpha_{n-1}})^{\frac{1}{\beta_{n-1}}}}{\Delta x_n}A_{n-1}^{(\frac{1}{\beta_{n-1}}-1)} & -\frac{(\frac{1}{\alpha_n})^{\frac{1}{\beta_n}}}{\Delta x_n}A_n^{(\frac{1}{\beta_n}-1)}
\end{pmatrix}
$$

$$
\begin{pmatrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{pmatrix} +
\begin{pmatrix} \frac{1}{\Delta x_1} & & & \\ & \frac{1}{\Delta x_2} & & \\ & & \ddots & \\ & & & \frac{1}{\Delta x_n} \end{pmatrix}
\begin{pmatrix} I(t+\Delta t) \\ 0 \\ \vdots \\ 0 \end{pmatrix} \qquad 6.16
$$

Solution of equation (6.16) provides the change in cross-sectional area of flow in each reach of the channel over a selected Δt time increment. The changes in cross-sectional area of flow in each reach over Δt can be used to compute the flow areas at time t + Δt using:

$$A(t+\Delta t) = A(t) + \dot{A}(t).\Delta t \qquad 6.17$$

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These areas are then used in the output equation to compute the flow rates in each reach at time t + Δt. The output equation is simply expressed as:

$$Q = (\frac{1}{\alpha}A)^{\frac{1}{\beta}} = (\frac{1}{\alpha})^{\frac{1}{\beta}}A^{\frac{1}{\beta}-1}.A \qquad 6.18$$

or

$$Q(t) = D(t)\underline{A}(t) \qquad 6.19$$

where the D matrix is a function of time. The output equation of the model in matrix representation is:

$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{pmatrix} = \begin{pmatrix} (\frac{1}{\alpha_1})^{\frac{1}{\beta_1}}A_1^{(\frac{1}{\beta_1}-1)} & & & \\ & (\frac{1}{\alpha_2})^{\frac{1}{\beta_2}}A_2^{(\frac{1}{\beta_2}-1)} & & \\ & & \ddots & \\ & & & -(\frac{1}{\alpha_n})^{\frac{1}{\beta_n}}A_n^{(\frac{1}{\beta_n}-1)} \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{pmatrix} \qquad 6.20$$

A flow chart of the procedures of this model is shown in Fig. (6.3).

6.1.5 State Equation, " Discharge" as the State Variable

In this case the state variable model consider the discharge, Q, as the state variable. From equation (6.4), cross-sectional areas at x and x + Δx points are:

$$A_{x+\Delta x}^{t+\Delta t} = \alpha_{x+\Delta x}(Q_{x+\Delta x}^{t+\Delta t})^{\beta_{x+\Delta x}} \qquad 6.21$$

$$A_{x+\Delta x}^{t} = \alpha_{x+\Delta x}(Q_{x+\Delta x}^{t})^{\beta_{x+\Delta x}} \qquad 6.22$$

Equation (6.21) and (6.22) are substituted for the continuity equation (6.3):

$$\frac{Q_{x+\Delta x}^{t+\Delta t} - Q_x^{t+\Delta t}}{\Delta x} + \frac{[\alpha_{x+\Delta x}(Q_{x+\Delta x}^{t+\Delta t})^{\beta_{x+\Delta x}}] - [\alpha_{x+\Delta x}(Q_{x+\Delta x}^{t})^{\beta_{x+\Delta x}}]}{\Delta t} = 0 \qquad 6.23$$

The rate of change of discharge at point x + Δx can be expressed as:

$$\dot{Q}_{x+\Delta x} = (\frac{\Delta Q}{\Delta t})_{x+\Delta x} = (\frac{\partial Q}{\partial A}.\frac{\partial A}{\partial t})_{x+\Delta x} \qquad 6.24$$

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$$A = \alpha.Q^\beta$$

$$Q = (\tfrac{1}{\alpha}A)^{\frac{1}{\beta}}$$

Initial Conditions

$A_o, Q_o, \Delta x$

Boundary Conditions

Upstream Inflow Hydrograph

State Equation (at time t)

$$\dot{A}(t) = [B][A(t)] + [C][I(t)]$$

Next Time Step

(at time t + Δt)

$$A(t + \Delta t) = A(t) + \dot{A}(t).\Delta t$$

Output Equation

(at time t + Δt)

$$Q(t + \Delta t) = [D][A(t + \Delta t)]$$
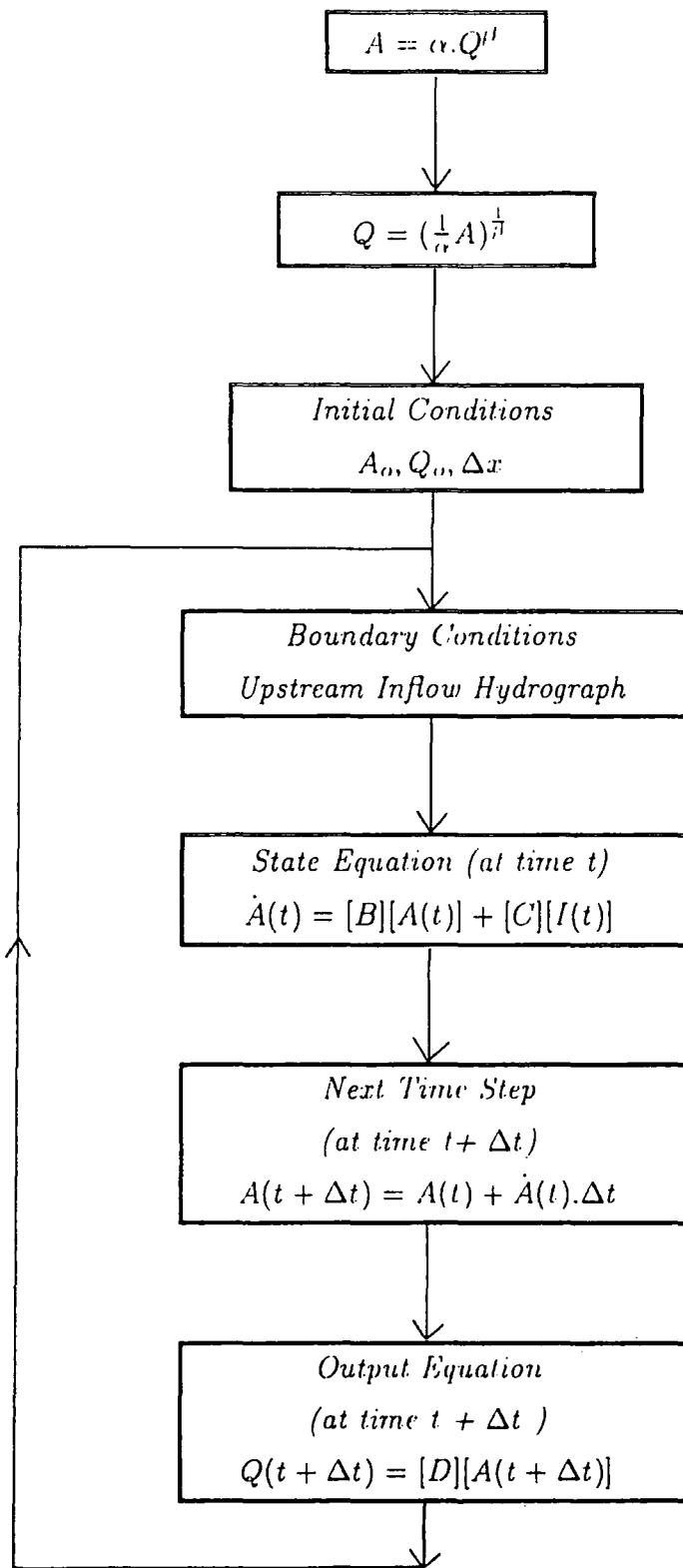
Fig. (6.3) Flow Chart for the Procedures of the State Variable Model With the Cross-Sectional Area as the State Variable

The rate of change of discharge with respect to the cross-sectional area of flow can be derived by differentiating equation (6.5) to obtain:

$$\frac{dQ}{dA} = \frac{1}{\alpha\beta}(\frac{1}{\alpha}A)^{\frac{1}{\beta}-1}$$

$$\frac{\Delta Q}{\Delta A} = \frac{1}{\alpha\beta}\frac{(\frac{1}{\alpha}A)^{\frac{1}{\beta}}}{(\frac{1}{\alpha}A)}$$

$$\frac{\Delta Q}{\Delta A} = \frac{1}{\alpha\beta}\frac{Q}{Q^{\beta}} = \frac{1}{\alpha\beta}Q^{1-\beta} \qquad\qquad 6.25$$

The state equation is derived by substituting equation (6.3) and (6.25) for equation (6.24) to obtain:

$$\dot{Q}_{x+\Delta x} = (\frac{\Delta Q}{\Delta t})_{x+\Delta x} = [(\frac{1}{\alpha\beta})_{x+\Delta x}(Q^{t+\Delta t}_{x+\Delta x})^{1-\beta_{x+\Delta x}}][\frac{Q^{t+\Delta t}_{x} - Q^{t+\Delta t}_{x+\Delta x}}{\Delta x}]$$

$$= \frac{(Q^{t+\Delta t}_{x+\Delta x})^{1-\beta_{x+\Delta x}}Q^{t+\Delta t}_{x} - (Q^{t+\Delta t}_{x+\Delta x})^{2-\beta_{x+\Delta x}}}{\alpha_{x+\Delta x}\beta_{x+\Delta x}}$$

$$= \frac{-(Q^{t+\Delta t}_{x+\Delta x})^{2-\beta_{x+\Delta x}}}{\alpha_{x+\Delta x}\beta_{x+\Delta x}\Delta x} + \frac{(Q^{t+\Delta t}_{x+\Delta x})^{1-\beta_{x+\Delta x}}}{\alpha_{x+\Delta x}\beta_{x+\Delta x}\Delta x}Q^{t+\Delta t}_{x} \qquad 6.26$$

The discharge at the most upstream point is obtained from the inflow hydrograph and is expressed as:

$$Q^{t+\Delta t}_{x} = I(t + \Delta t)$$

From equation (6.26), the rate of change of discharge, $\dot{Q}$, for various location along a channel at time $t + \Delta t$ can now be expressed in state variable form. The state equation in matrix form can be written as:

$$\underline{\dot{Q}}(t) = \underline{B}\underline{Q}(t) + \underline{C}\underline{I}(t) \qquad\qquad 6.27$$

and for each reach the state equations are:

$$\dot{Q}_1 = (\frac{\Delta Q}{\Delta t})_1 = -\frac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1}Q_1 + \frac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1}I(t+\Delta t)$$

$$\dot{Q}_2 = (\frac{\Delta Q}{\Delta t})_2 = -\frac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2}Q_2 + \frac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2}Q_1$$

$$\dot{Q}_n = (\frac{\Delta Q}{\Delta t})_n = -\frac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n}Q_n + \frac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n}Q_{n-1} \qquad 6.28$$

where α_i and Q_i are average values at time t for i=1, 2, ..., n. Matrix representation of the state equation (6.28) is expressed as shown in equation (6.29).

$$\begin{pmatrix} \dot{Q}_1 \\ \dot{Q}_2 \\ \vdots \\ \dot{Q}_n \end{pmatrix} = \begin{pmatrix} -\frac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1} & & & \\ \frac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2} & -\frac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2} & & \\ & & \ddots & \\ & & \frac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n} & -\frac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n} \end{pmatrix} \cdot$$

$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{pmatrix} + \begin{pmatrix} \frac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1} & & & \\ & \frac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2} & & \\ & & \ddots & \\ & & & \frac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n} \end{pmatrix} \begin{pmatrix} I(t+\Delta t) \\ 0 \\ \vdots \\ 0 \end{pmatrix} \qquad 6.29$$

Solution of equation (6.29) provides the rate of change in discharge for each reach of the channel over a selected Δt time increment. The changes in discharge in each reach over Δt can be used to compute the discharge at time t + Δt using:

$$Q(t+\Delta t) = Q(t) + \dot{Q}(t)\Delta t \qquad 6.30$$

A flow chart of the procedures of this model is shown in Fig.(6.4).

6.1.6 Lateral Inflow

A high proportion of research into the unsteady flow of water in open channels seems either to circumvent or ignore the problem of lateral inflow to the sides of

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$$A = \alpha . Q^{\mu}$$

Initial Conditions

$$Q_o, \Delta x$$

Boundary Conditions

Upstream Inflow Hydrograph

State Equation (at time t)

$$\dot{Q}(t) = [B][Q(t)] + [C][I(t)]$$

Output Equation

(at time t + Δt)

$$Q(t + \Delta t) = Q(t) + \dot{Q}(t).\Delta t$$
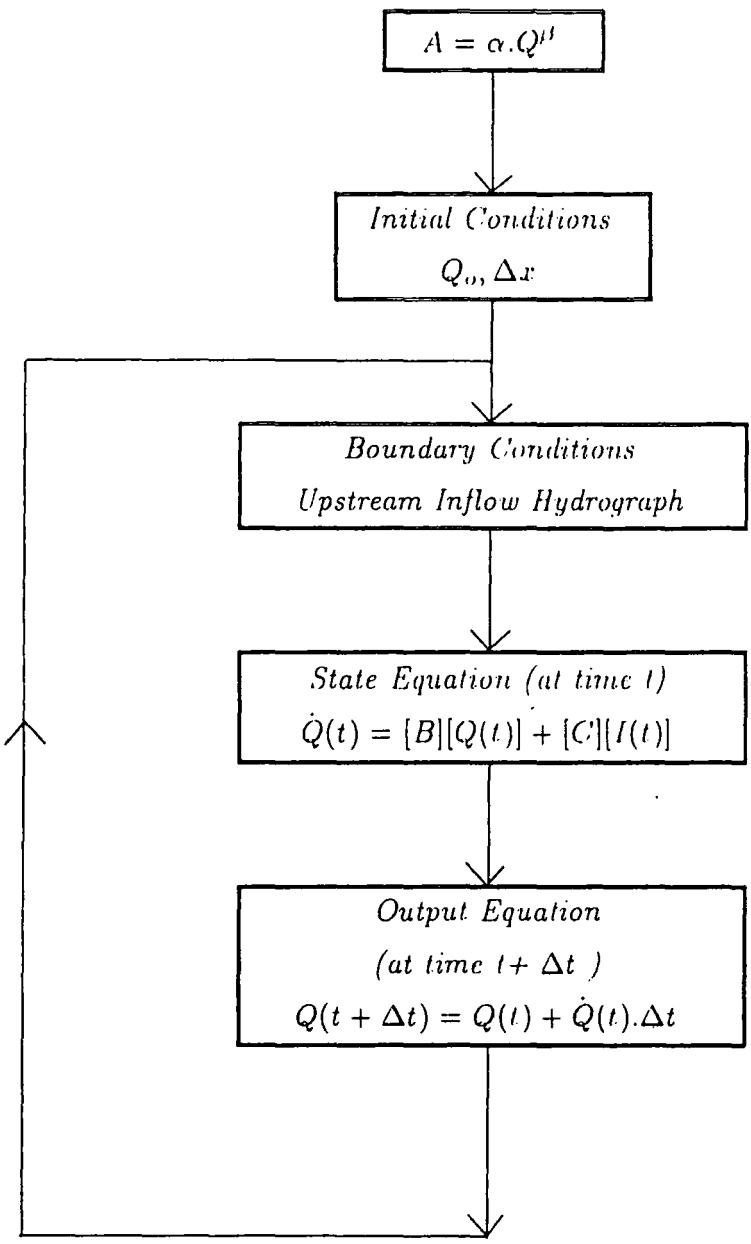
Fig. (6.4) Flow Chart for the Procedures of the State Variable Model With th
Discharge as the State Variable

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the channel. Frequently it is assumed that there is no lateral inflow. However, in natural channels, particularly when flood waters are caused by heavy rainfall, lateral inflow can be very significant.

The lateral inflow rate, q_1, can also be considered in the state variable model by modifying equation (6.3) to:

$$\left(\frac{\Delta A}{\Delta t}\right)_{x+\Delta x} = \frac{A_{x+\Delta x}^{t+\Delta t} - A_{x+\Delta x}^{t}}{\Delta t} = \frac{Q_x^{t+\Delta t} - Q_{x+\Delta x}^{t+\Delta t}}{\Delta x} + q_1 \qquad 6.31$$

The new state equation (Q as the state variable), including lateral inflow, can be developed by substituting equation (6.25) and (6.31) for equation (6.24)

$$\dot{Q}_{x+\Delta x}^{t+\Delta t} = \left(\frac{\Delta Q}{\Delta t}\right)_{x+\Delta x} = \left(\frac{\Delta Q}{\Delta A} \cdot \frac{\Delta A}{\Delta t}\right)_{x+\Delta x}$$

$$= \left\{\left(\frac{1}{\alpha\beta}\right)_{x+\Delta x}(Q_{x+\Delta x}^{t+\Delta t})^{1-\beta_{x+\Delta x}}\right\}\left\{q_1 + \frac{Q_x^{t+\Delta t} - Q_{x+\Delta x}^{t+\Delta t}}{\Delta x}\right\}$$

$$= \left\{\left(\frac{q}{\alpha\beta}\right)_{x+\Delta x}(Q_{x+\Delta x}^{t+\Delta t})^{1-\beta_{x+\Delta x}}\right\} + \left\{-\frac{(Q_{x+\Delta x}^{t+\Delta t})^{2-\beta_{x+\Delta x}}}{(\alpha\beta\Delta x)_{x+\Delta x}} + \right.$$

$$\left. \frac{(Q_{x+\Delta x}^{t+\Delta t})^{1-\beta_{x+\Delta x}}}{(\alpha\beta\Delta x)_{x+\Delta x}}Q_x^{t+\Delta t}\right\} \qquad 6.32$$

The state equation for each reach in the channel can be expressed as:

$$\dot{Q}_1 = \left(\frac{\Delta Q}{\Delta t}\right)_1 = \left(\frac{q_1}{\alpha_1\beta_1}Q_1^{1-\beta_1}\right) + \left(-\frac{Q_1^{2-\beta_1}}{\alpha_1\beta_1\Delta x_1} + \frac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1}I(t+\Delta t)\right)$$

$$= -\frac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1}Q_1 + \frac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1}(I(t+\Delta t) + q_{11}\Delta x_1)$$

$$\dot{Q}_2 = \left(\frac{\Delta Q}{\Delta t}\right)_2 = -\frac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2}Q_2 + \frac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2}(Q_1 + q_{12}\Delta x_2)$$

$$\dot{Q}_n = \left(\frac{\Delta Q}{\Delta t}\right)_n = -\frac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n}Q_n + \frac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n}(Q_{n-1} + q_{1n}\Delta x_n) \qquad 6.33$$

Matrix representation of the state equation (6.33), to include lateral inflow, is expressed as shown in equation (6.34) which is similar to equation (6.29) except that the lateral inflow terms are in the input matrix.

$$
\begin{pmatrix} \dot{Q}_1 \\ \dot{Q}_2 \\ \vdots \\ \dot{Q}_n \end{pmatrix} = \begin{pmatrix} -\dfrac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1} & & & \\ \dfrac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2} & -\dfrac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2} & & \\ & & \ddots & \\ & & \dfrac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n} & -\dfrac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n} \end{pmatrix} \cdot
$$
$$
\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{pmatrix} + \begin{pmatrix} \dfrac{Q_1^{1-\beta_1}}{\alpha_1\beta_1\Delta x_1} & & \\ & \dfrac{Q_2^{1-\beta_2}}{\alpha_2\beta_2\Delta x_2} & \\ & & \ddots \\ & & \dfrac{Q_n^{1-\beta_n}}{\alpha_n\beta_n\Delta x_n} \end{pmatrix} \begin{pmatrix} I + q_1\Delta x_1 \\ q_2\Delta x_2 \\ \vdots \\ q_n\Delta x_n \end{pmatrix} \qquad 6.34
$$

6.2 Application Of The State Variable Kinematic Wave Model

6.2.1 Computer Model

The computer program STROUT3, which is a modified version of the program STROUT (Chang, 1979), is written in Fortran 77; the listing of the program is in appendix III-3. This model is designed to simulate the flood routing in rivers and natural streams through the use of the state variable approach. It is based on the simplified one-dimensional Saint-Venant equations, and belongs to the category of kinematic wave flood routing models.

The major computations of this model are:

1. build a loop rating curve and compute the α and β coefficients for both rising and recession limbs for each subreach using curvilinear regression of the recorded flow Q and cross-sectional area A data;

2. compute the time increment which is constrained by the Courant criterion;

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

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3. rate the time steps from each reach, choosing the minimum time step of all the reaches as the step of the computation;

4. state equation computation to find the discharge increment at time t;

5. compute the output equation computation to find the output discharge at time t + Δt; and

6. use the previous output as an input for the next time step's computation until a simulation time is obtained that is equal to or greater than the simulation time for the simulated hydrograph.

The major computation procedure of the model is shown schematically in Fig. (6.5).

6.2.2 Data Requirement

In the application of the State Variable Kinematic Wave Model, the following information is required:

1. the number and length of the subreaches which can be scaled from a drainage map of the basin;

2. the simulation time for the simulated hydrograph;

3. the boundary condition upstream inflow hydrograph to be routed through the reach;

4. the water surface elevation and the corresponding top width of a certain cross-section for each subreach; and

5. the initial recorded-discharge and wetted cross-sectional area for each subreach which can be obtained from hydrographic surveys (field measurements).

A sample of the input data used in the computer model is shown in table (6.1). The arrangement of input data and its definitions are shown in Appendix
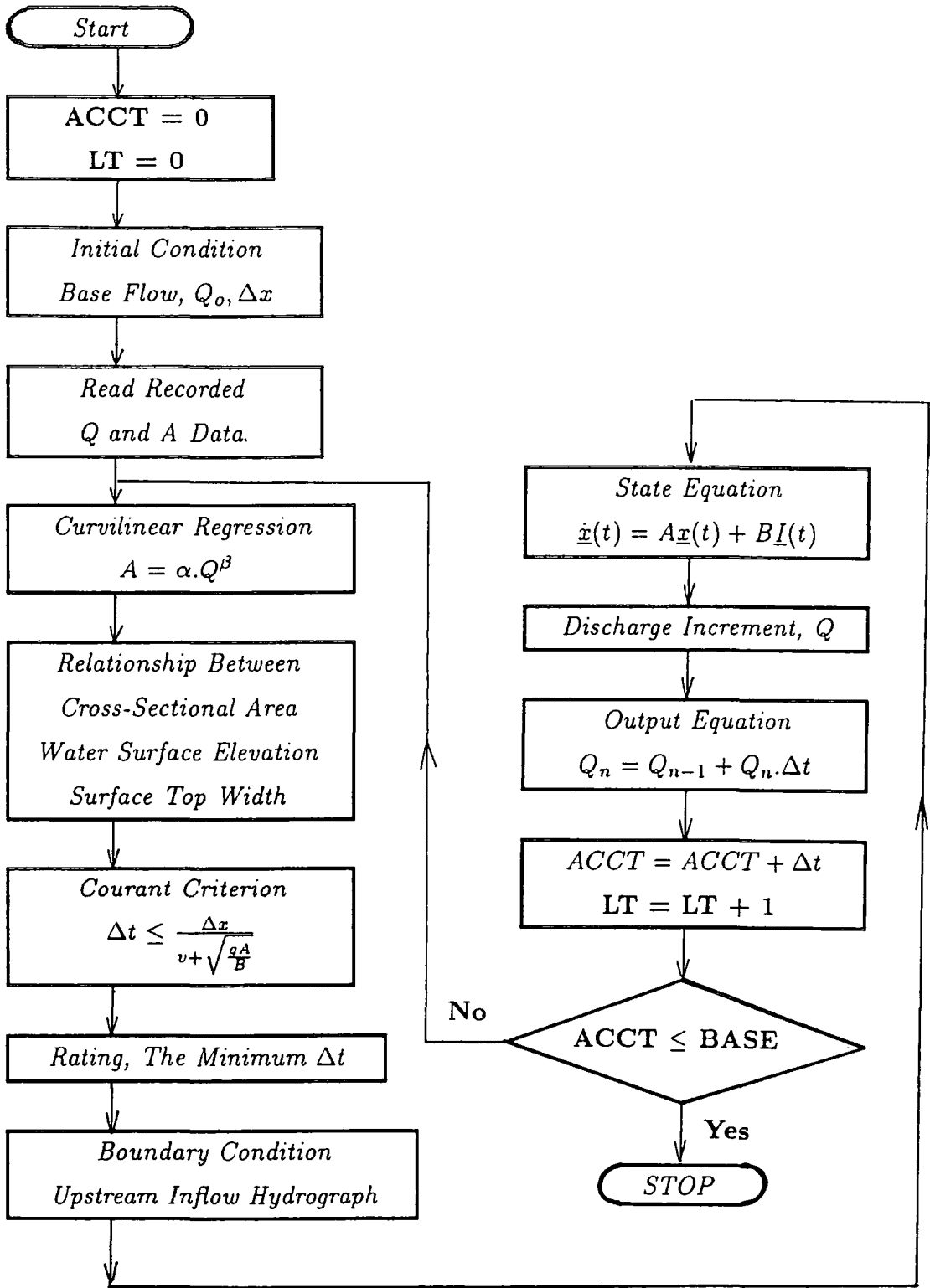
Fig. (6.5) Flow Chart of the Major Computation Procedures for "STROUT3'

Table 6.1

Input Data of the Computer Model STROUT3

5								
	94.6	18944.5	94.6	18944.5	94.6	18944.5	94.6	18944.5
	94.6	18944.4	0.0	0.0	0.0	0.0	0.0	0.0
	107.0							
10	10							
	0.0	94.6	2.	99.8	7.	116.62	12.	187.0
	17.	228.49	22.	194.73	27.	1012.12	32.	2880.5
	37.	4841.77	42.	6578.7	0.	0.	0.	0.
	62.	2135.37	67.	1634.0	72.	1321.37	77.	1200.6
	82.	1317.7	87.	1126.88	92.	951.28	97.	852.38
	102.	780.8	107.	600.	0.	0.	0.	0.
	44.	6754.62						
	0.	0.	0.	0.	0.			
	77.5	81.0	78.5	80.5	79.5			
3 3	3 3	3						
	2.95	89.24						
	4.92	93.83						
	6.56	97.77						
	2.62	102.36						
	4.26	109.58						
	5.90	119.42						
	1.64	136.48						
	2.95	144.36						
	4.26	152.89						
	2.62	111.55						
	3.93	118.11						
	4.92	122.05						
	1.96	91.86						
	3.28	91.86						
	4.59	109.58						
10								
10	1	1						
	112.6	8.7	158.8	12.5	317.7	30.0	564.0	41.4
	988.6	52.4	1765.5	77.3	2824.8	95.8	4060.0	110.0
	5296.5	124.5	6355.8	130.5	0.0	0.0	0.0	0.0
10								
10	1	1						
	123.5	6.8	176.5	12.37	285.0	22.3	400.0	23.6
	560.0	27.4	980.0	52.4	1800.0	81.6	3200.0	122.7
	4800.0	136.0	6200.0	140.0	0.0	0.0	0.0	0.0

10								
10	1	1						
107.69	5.9	155.36	10.98	210.0	14.19	320.0	17.65	
480.0	32.2	1050.0	65.9	2000.0	76.4	3150.0	125.68	
4800.0	136.0	6320.0	140.5	0.0	0.0	0.0	0.0	
10								
10	1	1						
109.8	6.2	161.71	14.1	240.5	16.5	340.7	23.8	
465.8	26.17	705.0	34.6	1300.0	61.1	2400.0	121.38	
4150.0	128.7	5900.0	138.5	0.0	0.0	0.0	0.0	
10								
10	1	1						
112.6	6.23	168.0	10.33	242.5	11.4	365.0	23.2	
620.7	33.3	1155.3	45.7	2020.5	80.0	3100.0	114.5	
4425.0	132.4	6000.2	140.1	0.0	0.0	0.0	0.0	
10								
10	1	1						
5264.0	97.48	4160.0	88.0	3185.0	81.66	2365.0	74.6	
1660.0	62.0	1040.0	56.9	540.0	37.89	290.0	24.56	
180.0	17.54	110.0	8.78	0.0	0.0	0.0	0.0	
10								
10	1	1						
5938.4	100.6	4615.6	95.16	3595.3	88.3	2748.1	66.6	
2028.3	64.9	1422.7	49.16	937.1	48.1	561.5	38.7	
317.0	37.1	130.0	14.2	0.0	0.0	0.0	0.0	
10								
10	1	1						
5709.9	108.48	4698.6	98.29	3603.1	94.6	2618.3	90.1	
1752.7	88.94	839.3	52.7	464.1	28.9	284.2	23.4	
184.3	16.2	109.4	6.1	0.0	0.0	0.0	0.0	
10								
10	1	1						
5516.8	104.7	4425.3	102.6	3415.6	96.9	2550.0	84.6	
1800.4	81.4	1200.0	48.6	850.0	46.9	480.0	34.9	
210.5	19.6	120.0	6.73	0.0	0.0	0.0	0.0	
10								
10	1	1						
5352.2	102.9	4405.7	100.4	3630.5	98.8	2870.0	90.7	
2150.6	82.0	1575.4	60.16	975.0	57.9	500.0	32.56	
280.0	28.9	110.0	7.81	0.0	0.0	0.0	0.0	

V.

6.2.3 Modelled Reach

A 28.87 km (115218 ft.) reach of the River Wear, from the Sunderland Bridge gauge station to the Chester-le-Street gauge station is modelled mathematically by using the State Variable Model. This reach with its five subreaches is shown schematically in Fig. (6.6). The intermediate stations were used to evaluate the simulation.

The river reach has irregular and complex geometrical features in the 28.87 km. Topographic maps and field surveying were used to determine the channel characteristics, namely the width and cross-section of each subreach as shown in Figs. (3.12-3.16).

The event of March 1986 was simulated by using the discharge hydrograph for the upstream boundary at Sunderland Bridge gauge station. Added to that, the discharge hydrographs calculated by the Muskingum-Cunge method for the intermediate stations (which are used for the estimation of cross-section area for different stages of the hydrograph for each intermediate station), were used by the author in this model as shown in Table (II.2). The rising limb of the computed discharge hydrographs at the intermediate stations and the downstream station of the reach agree quite well with the observed discharge hydrographs and better than the recession limb, as shown in Figs. (6.7-6.10). A sample of the output data of the computer program STROUT3 is shown in appendix II-19.

In this study the lateral inflows are considered as independent of flows occurring in the river to which they are added.
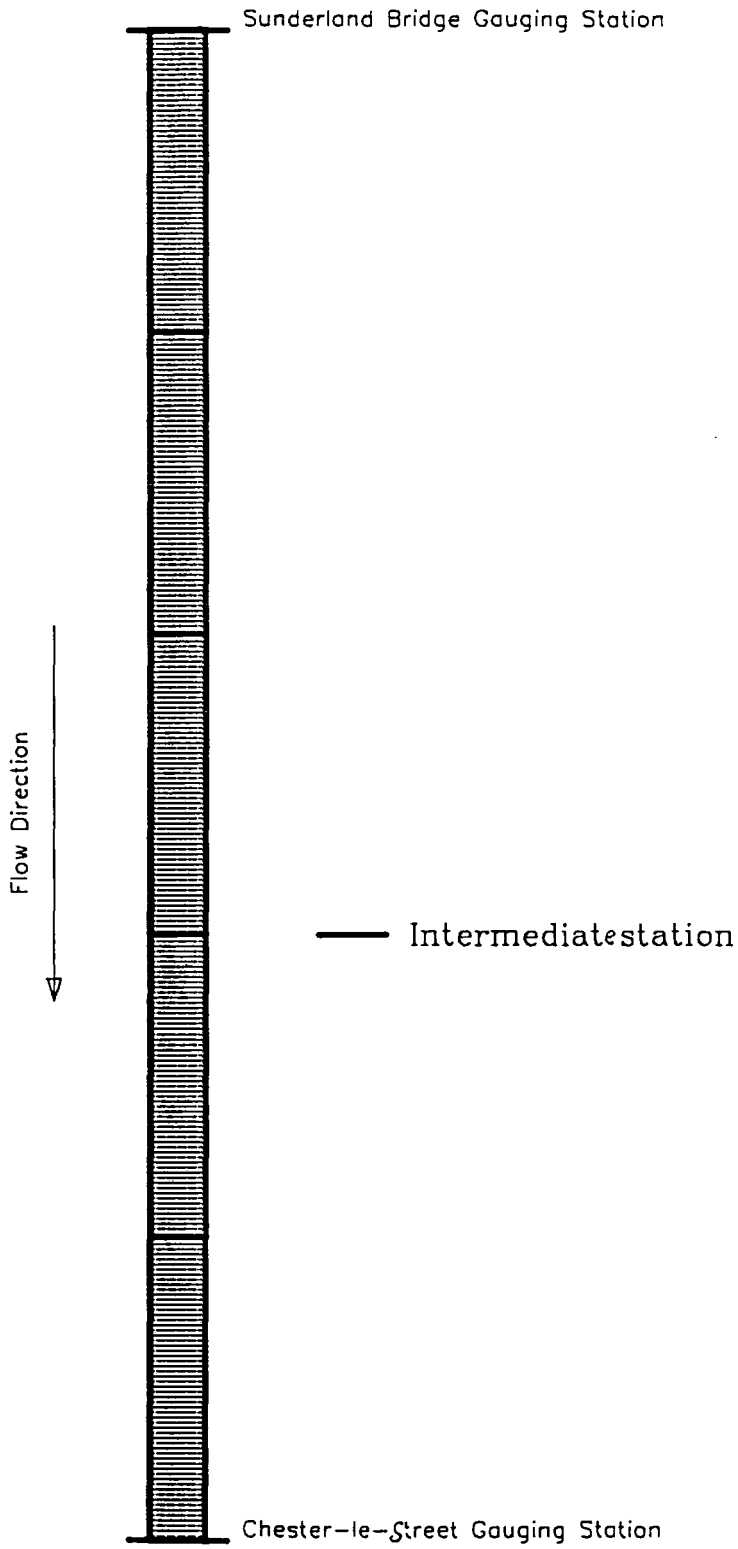
Fig.(6.6) Schematic River Reach.

6.3 Conclusion and Discussion

The state variable model is simple and easy to apply. The limitations of this model are inherited from the restriction resulting from the kinematic wave approximation. That is, local and convective acceleration must be negligible, and the water surface slope is nearly equal to the channel slope. The state variable model is based on the simplified one-dimensional Saint-Venant equations. The approach is based upon a lumped mathematical model to describe the temporally and spatially varied flood flow through natural stream channels. A channel is divided into several successive subreaches in which the flow condition is assumed to be uniform. An upstream inflow hydrograph is given and a state variable kinematic wave model is applied to route an inflow hydrograph through a river channel. Stage and discharge observations at the gauging stations were simulated implicitly by obtaining a numerical solution of state and output equations with the kinematic wave model subject to the initial and boundary conditions.

In conclusion, and by examining the fit of the hydrographs, Fig. 6.7 to Fig. 6.10 (M-C is the calculated Muskingum-Cunge hydrograph, and SVM is the calculated state variable model hydrograph), it can be analyzed that the rising limb of the calculated hydrographs coincide with the observed one and fit better than the recession hydrograph.

**Fig. (6.7) Calculated Outflow Hydrograph By STROUT3 Of Subreach 2 Of
Wear River For The Event Of Mar. 1986.**
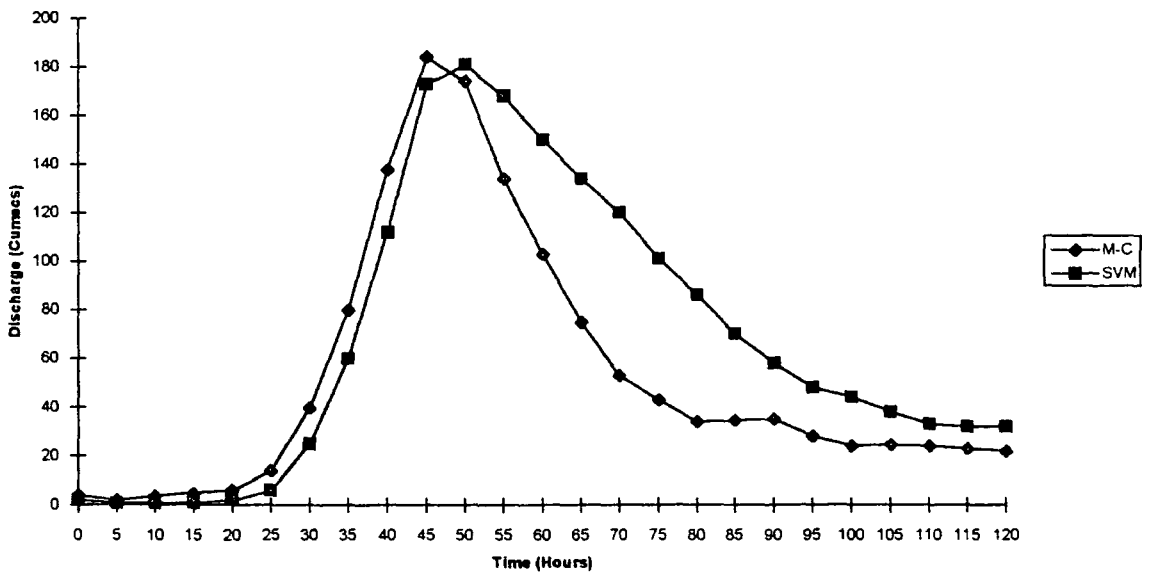
Fig. (6.8) Calculated Outflow Hydrograph By STROUT3 Of Subreach 3 Of Wear River For The Event Of Mar. 1986.
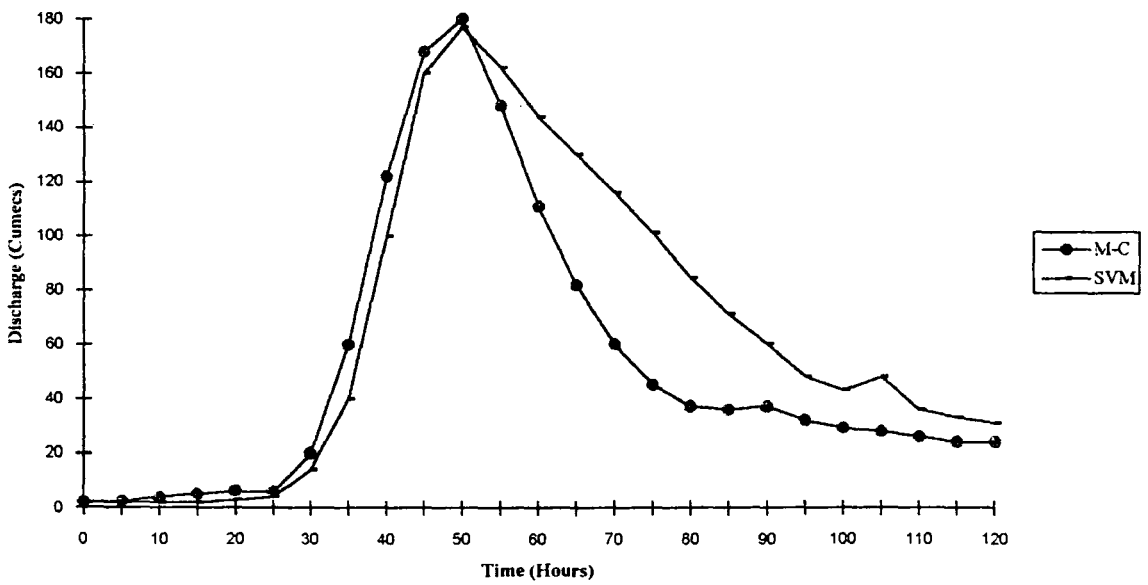
Fig. (6.9) Calculated Outflow Hydrograph By STROUT3 Of Subreach 4 Of Wear River For The Event Of Mar. 1986.
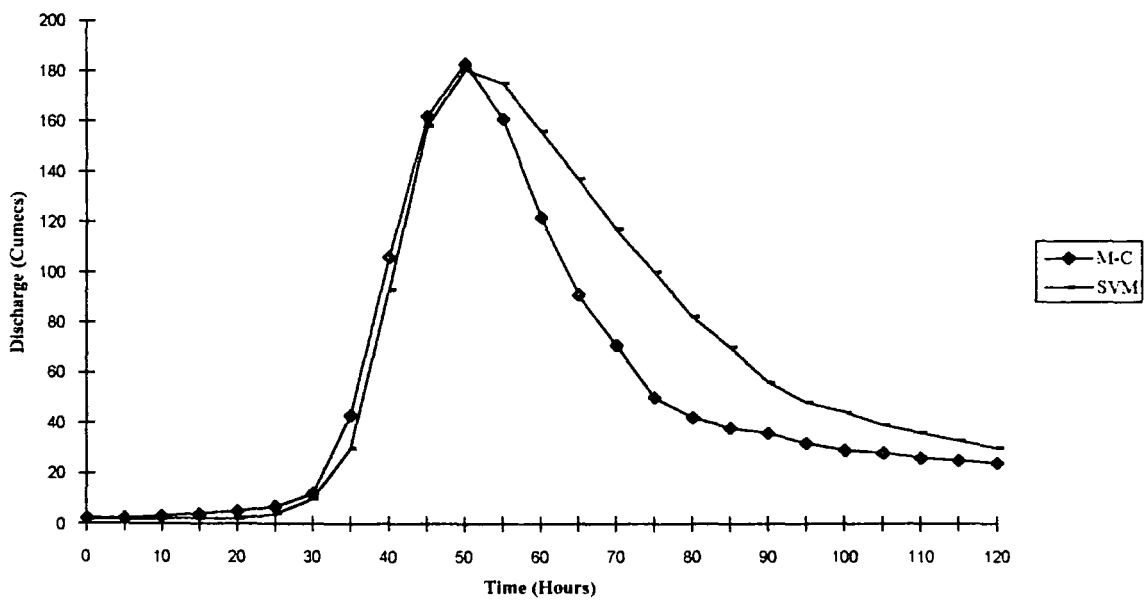
Fig. (6.10) Calculated Outflow Hydrograph By STROUT3 Of Subreach 5 Of Wear River For
The Event Of Mar. 1986.
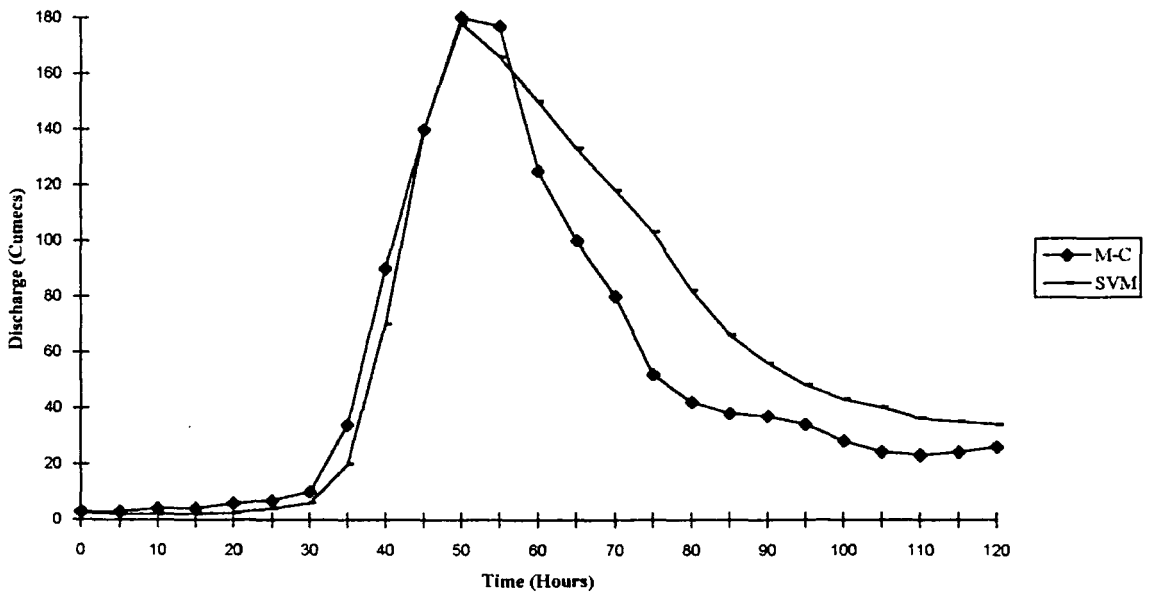
CHAPTER 7

THE APPLICATION OF THE NONLINEAR MUSKINGUM
METHOD USING THE STATE VARIABLE MODEL

7.1 Introduction

In this chapter, a nonlinear Muskingum model is solved using the state variable technique. Two curve fitting techniques are employed for the calibration of model parameters, namely Hooke-Jeeves and linear regression, and their performances are compared.

The Muskingum model which has been one of the most frequently used tools is:

$$S_t = k[xI_t + (1 - x)O_t]$$ 7.1

where S_t = the absolute channel storage at time t; I_t and O_t= the rates of inflow and outflow, respectively, at time t; k = the storage time constant for the river reach; and x = a weighting factor varying between 0-0.5.

The formulation of the linear Muskingum model has been modified by Tung, (1985) to account for nonlinearity by writing:

$$S_t = \alpha[xI_t + (1 - x)O_t]^m$$ 7.2

in which α and m = constants. Equation 7.2 has more degrees of freedom as compared with equation 7.1, which presumably would yield a closer fit to the nonlinear relation between storage and discharge(Tung, 1985). The calibration procedure of equation 7.2 becomes more complicated because of the presence of nonlinearity in the equation. Furthermore, the routing procedures for flood prediction will no longer be as straightforward as those for using the linear model.

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7.2 State Variable Modelling and Formulation for The Nonlinear Muskingum Model

The state variable model for continuous time has been formulated as shown by the state equation 4.19 and the output equation 4.20 and is described in section 4.3.3.1.

The output equation in the state variable model for the nonlinear Muskingum model can be derived by rearranging and manipulating equation 7.2 as follows:

$$S_t = \alpha[xI_t + (1-x)O_t]^m$$

$$\frac{S_t}{\alpha} = [xI_t + (1-x)O_t]^m$$

$$(\frac{S_t}{\alpha})^{\frac{1}{m}} = [xI_t + (1-x)O_t]$$

$$O_t = (\frac{1}{1-x})(\frac{S_t}{\alpha})^{\frac{1}{m}} - (\frac{x}{1-x})I_t \qquad 7.3$$

where O_t is the rate of outflow at time t; S_t is the channel storage; and I_t is the inflow rate.

The state equation in the state variable model for the nonlinear Muskingum model can be expressed by combining equation 7.3 and the continuity equation $(\dot{S}_t = \frac{ds}{dt} = I - O)$ as:

$$\dot{S}_t = -(\frac{1}{1-x})(\frac{S_t}{\alpha})^{\frac{1}{m}} + (\frac{1}{1-x})I_t \qquad 7.4$$

where the state variable for the system is the channel storage and the input is the inflow at the upstream end of the channel reach.

7.3 Calculation of the Parameters of the Nonlinear Muskingum Model

Two parameter estimation techniques are employed for the calculation of the parameters (α,x, and m) of the nonlinear Muskingum model, namely linear regression and the Hooke-Jeeves optimization technique.

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7.3.1 Linear Regression

In the linear regression model the nonlinear Muskingum model (equation 7.2) is simplified to:

$$Y = AX^B \qquad\qquad 7.5$$

where Y=S_t; A=α; X=$[x\ I_t + (1 - x)O_t]$ = weighted flow; and B=m. It is suggested that the value of x should be determined by trial and error, while α and m are calculated by using CURVEFIT program (version 2.10 December 31, 1986 by Thomas S. Cox). This program performs a least squares curve fit on X, and Y data. The weighted flow $(xI_t + (1 - x)O_t)$ and S_t are calculated by using historical flood data, and they are denoted X and Y respectively in equation 7.5 for simplification. The calculated values of α, x, and m of the flood events used in this study for both Rivers Wear and Tees by the linear regression model are shown in table (7.1).

7.3.2 The Hooke - Jeeves Optimization Technique

Optimization is the act of obtaining the best result under given circumstances, in design, construction and maintenance of any engineering system. In other words it can be defined as the process of finding the conditions that give a maximum value of a function. Without loss of generality, optimization can be taken to mean minimization since the maximum of a function can also be found by seeking the minimum of the negative of the function.

The Hooke - Jeeves method is a sequential technique, each step of which consists of two kinds of moves, one, called the exploratory move, explores the local behaviour of the objective function, and the other takes advantage of the pattern direction.

The procedure of Hooke - Jeeves is based on the direct search method and finds the minimum of a multivariable, unconstrained, nonlinear function:

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Minimize $\quad F\left(x_1, x_2, x_3, ...x_N\right)$

The Hooke - Jeeves method starts cautiously with short excursions from a starting point. Then, the step sizes grow with each repeated success (Tung, 1985). The algorithm of the Hooke - Jeeves method can be found in many text books (i.e Kuester and Mize (1973), and Ramamoorty (1988)). The Hooke - Jeeves computer program is listing in appendix III-5.

For the calculation of the three parameteres α, x, and m of the nonlinear Muskingum model, the Hooke - Jeeves optimization technique is employed to minimize the sum of the squares of deviations between the observed channel storage and the computed channel storage over the total data points, i.e.

$$\underset{\alpha,\, x,\, m}{\text{Minimize}}\, F = \sum_{t=1}^{n} \{\tilde{S}_t - \hat{S}_t\}^2 \qquad\qquad 7.6$$

or, equivalently

$$\underset{\alpha,\, x,\, m}{\text{Minimize}}\, F = \sum_{t=1}^{n} \{\tilde{S}_t - \alpha[xI_t + (1-x)O_t]^m\}^2 \qquad\qquad 7.7$$

in which $\tilde{S}_t =$ the observed channel storage at time t, which can be calculated from given historical inflow and outflow hydrographs selected for calibration; and $\hat{S}_t =$ the computed channel storage determined by the nonlinear Muskingum model. The calculated values of α, x, and m of the flood events used in this study for both Rivers Wear and Tees are shown in table (7.1).

Clearly optimization needs an index of agreement or disagreement between the observed and computed discharge hydrographs (Nash et al 1970). Linear regression analysis suggests a sum of squares criterion such as:

$$F^2 = \sum (Q - \hat{Q})^2 \qquad\qquad 7.8$$

where F^2 is the index of disagreement, Q is the observed discharge and $\hat{Q}$ is the computed discharge at corresponding times.

For n data points at intervals Δt equation (7.8) can be written:

$$F = \sqrt{\frac{1}{n} \sum (Q - \hat{Q})^2} \qquad\qquad 7.9$$

where F is the root mean sequare error.

$$E_{abs} = \frac{1}{n} \sum |Q - \hat{Q}| \qquad\qquad 7.10$$

E_{abs} is the mean absolute error

The difference between observed peak discharge and the predicted peak discharge $Q_{peak} - \hat{Q}_{peak}$ gives the error in predicting peak discharge. The difference between observed peak time and the predicted peak time $t_{peak} - \hat{t}_{peak}$ gives error in predicting time of peak discharge. Values of root mean sequare error, mean absolute error, error in predicting peak discharge and time of peak discharge are tabulated in table (7.1)

Table 7.1

Values of Parameters α, x, and m Estimated by Hooke-Jeeves (H-J) and Linear Regression Methods (LR) and Values of E_t, E_Q, F, and E_{abs}

Flood events	Methods	α	x	m	E_t	E_Q	F	E_{abs}
Wear River Reach								
1-10-1981	H-J	0.101	0.24	1.270	0.0	5	21.7	15.5
	LR	0.081	0.13	1.107	0.0	-8	25.6	18.1
2-02-1981	H-J	0.156	0.15	0.950	2.0	2	41	20.5
	LR	0.08	0.095	1.095	0.0	-8	36	18.5
26-8-1986	H-J	0.29	0.048	0.948	2	-140	44.5	33.8
	LR	0.25	0.05	0.950	3	-145	46	40.4
15-4-1986	H-J	0.113	0.24	1.27	0.0	15	31.5	27.2
	LR	0.13	0.1	1.45	-4	10	45.1	35.7
Tees River Reach								
2-01-1982	H-J	0.213	0.05	1.039	2	20	52	36.5
	LR	0.15	0.005	1.00	2	-10	55.34	38.76
25-8-1986	H-J	0.148	0.025	1.185	6	-65	48.54	34.5
	LR	0.6	0.0225	0.95	5	-115	50.45	32.87

7.4 The Application of the Non-Linear Muskingum Method Using the State Variable Model

7.4.1 Computer Program

The computer program for solving the nonlinear Muskingum model using the state variable model is written in Fortran 77 and listed in appendix III-4. A flow chart of the program is shown in Fig. (7.1).

Once the state variable model is formulated, the output from the system can be obtained by solving the state equation (equation 7.4) and the output equation (equation 7.3). The procedure for solving the discrete-time state variable nonlinear Muskingum model involves the following steps:

1. the upstream inflow hydrograph is discretized into several time stages where time intervals need not be equal;

2. the rate of change of storage, $\dot{S}_1$, can be evaluated by the state equation (equation 7.4), from the initial state of the system storage, S_1, and initial inflow I_1 to the channel reach;

3. the state of the system at the next time stage, S_2, is calculated by:

$$S_2 = S_1 + \dot{S}_1 \Delta t \qquad\qquad 7.11$$

4. the outflow rate at the current stage can then be calculated by solving the output equation (equation 7.3); and

5. using current information on the inflow rate and the channel storage, steps 2-4 are repeated recursively until the end of the simulation time.

7.4.2 Test Application

The nonlinear Muskingum model is applied to both the Rivers Wear and Tees, using the state variable modelling technique as a tool for performing flood routing.

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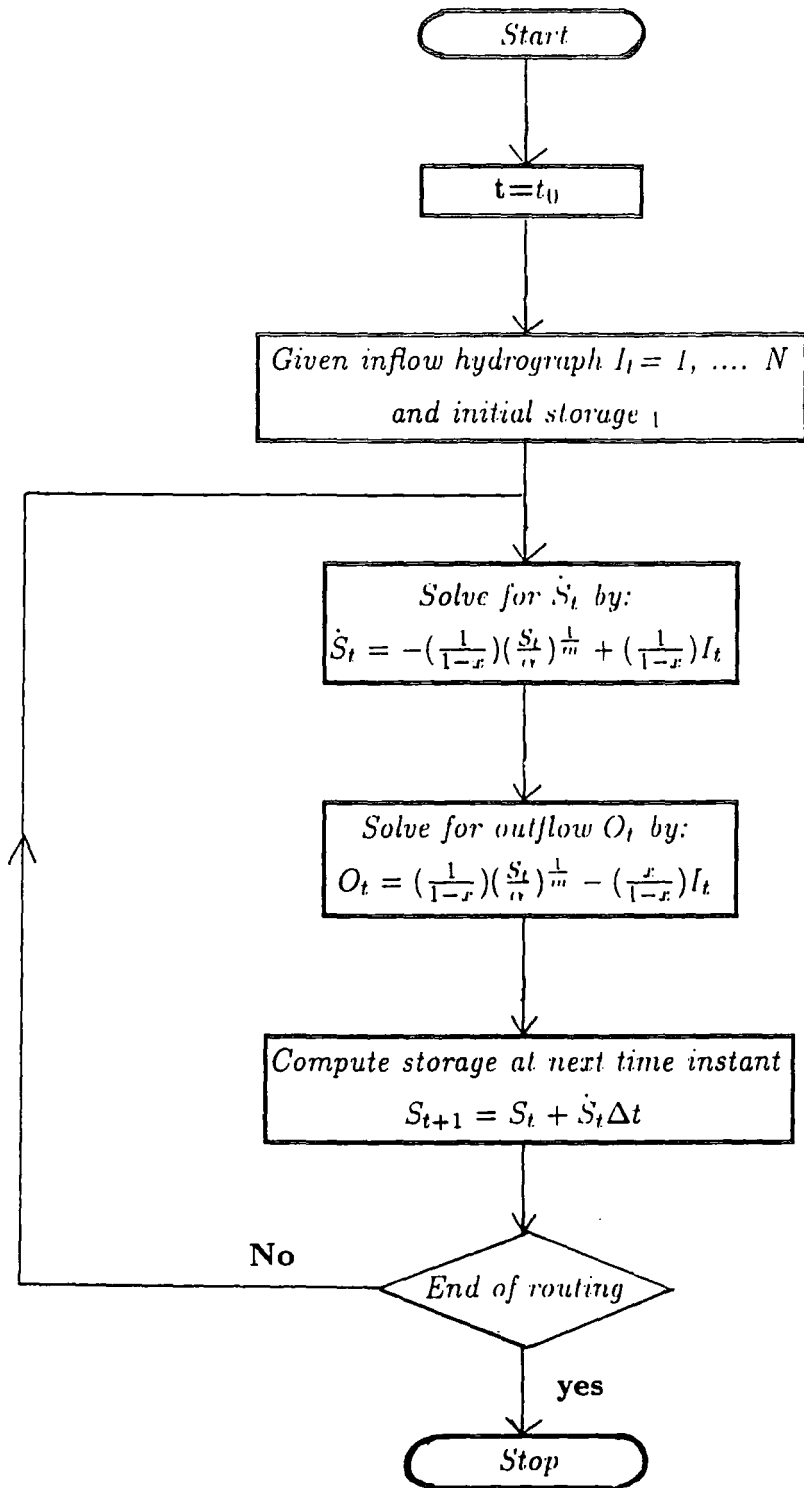
Fig. (7.1) Flow Chart for Discrete Time-State Variable Model for Nonlinea Muskingum Routing (Reproduced From Tung, 1985).

Hydrological data required for this model comprise discharge and lateral flow to the modelled reach. Values of discharge flow are expressed at regular time intervals.

Data from six flood events of both Wear and Tees Rivers are used to draw a comparison between the calculated hydrograph by computer program (SVMNM) and the recorded hydrograph. Events of Wear River are for Oct. 1981, Feb. 1981, Aug. 1986, and April 1986 and those of Tees River are for Jan. 1982, and Aug. 1986.

The inflow hydrograph for a given parameter set is routed to produce a computed outflow hydrograph. Then the computed and observed outflow hydrographs are compared. The computed outflow hydrograph obtained by the state variable modelling of the nonlinear Muskingum model of 6 flood events for both the Rivers Wear and Tees using two parameter estimation techniques, are tabulated in appendix (II-20 - II-31), and are plotted in Fig.(7.2-7.7). As can be observed the Hooke-Jeeves (H-J) method shows a good coincidence between the calculated and the observed outflow hydrographs, better than that produced by the linear regression (L-R) method.

7.5 Conclusion

This chapter covers the application of the nonlinear Muskingum model using the state variable modelling technique. An investigation was made of the utility of two parameter estimation techniques namely, Hooke-Jeeves and linear regression which are employed for the calibration of the Muskingum model parameters (α, x, and m) from the observed channel flow data. The result obtained by the method of Hooke-Jeeves is better than that produced by the linear regression method and shows a close similarity with the observed outflow hydrograph.

Fig. (7.2) Calculated And Observed Hydrographs For The Event 2-2-1981 Of Wear River.
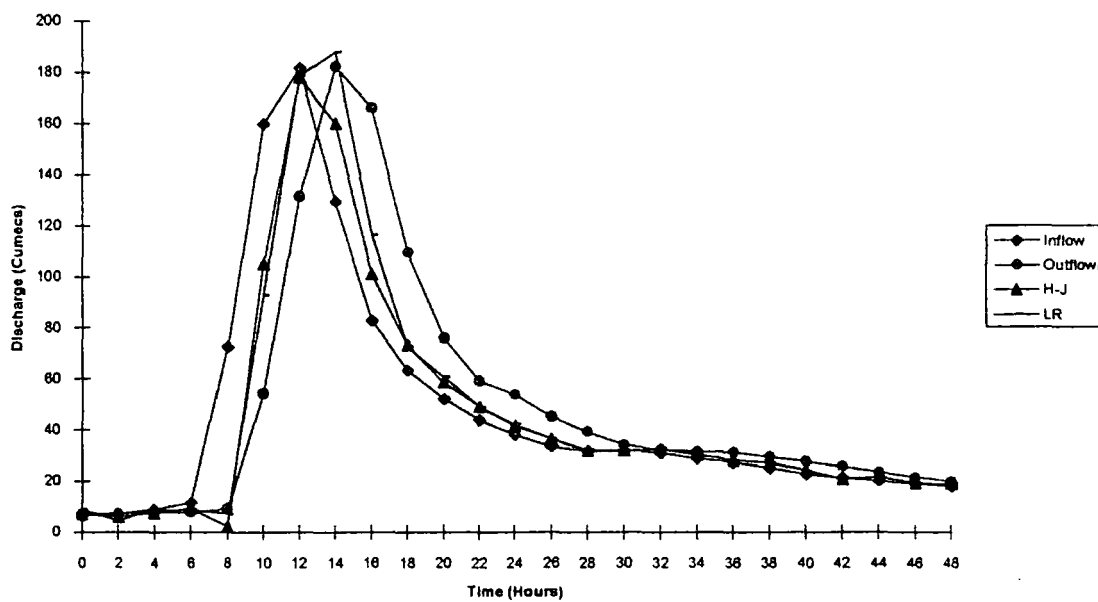
Fig.(7.3) Calculated And Observed Hydrographs For The Event 1-10-1981Of Wear River.
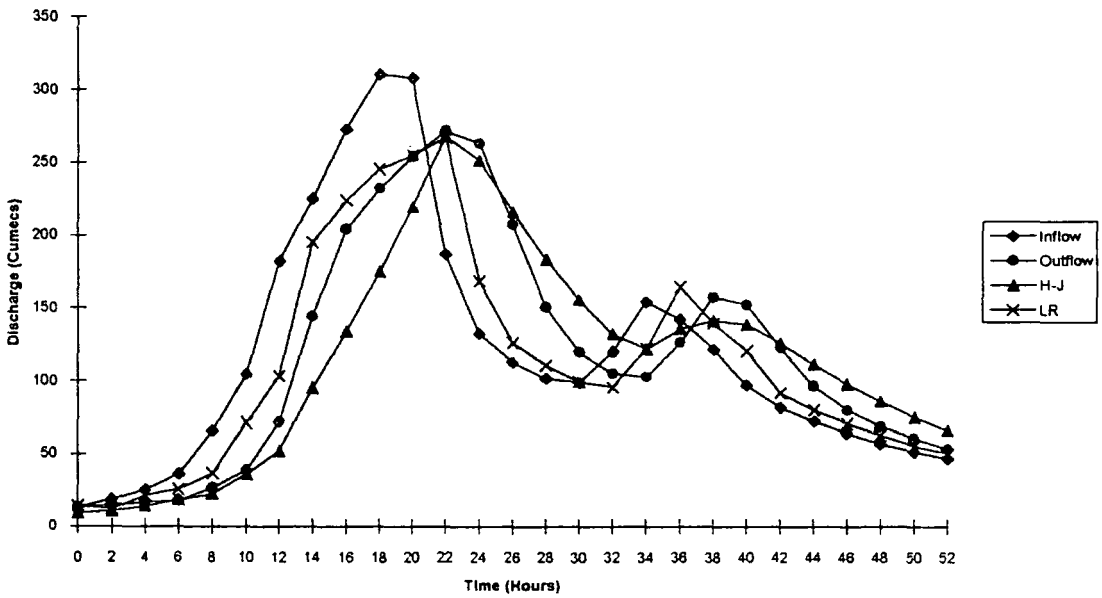
Fig. (7.4) Calculated And Observed Outflow Hydrographs For The Event 26-8-1986 Of Wear River.
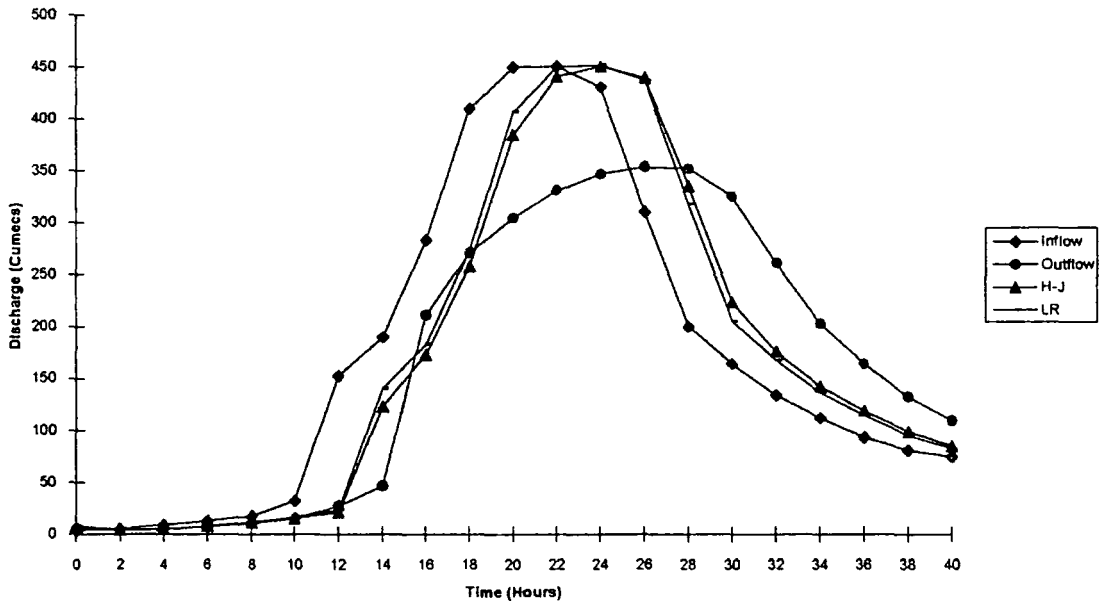
Fig. (7.5) Calculated And Observed Outflow Hydrographs For The Event 15-4-1986 Of Wear River.

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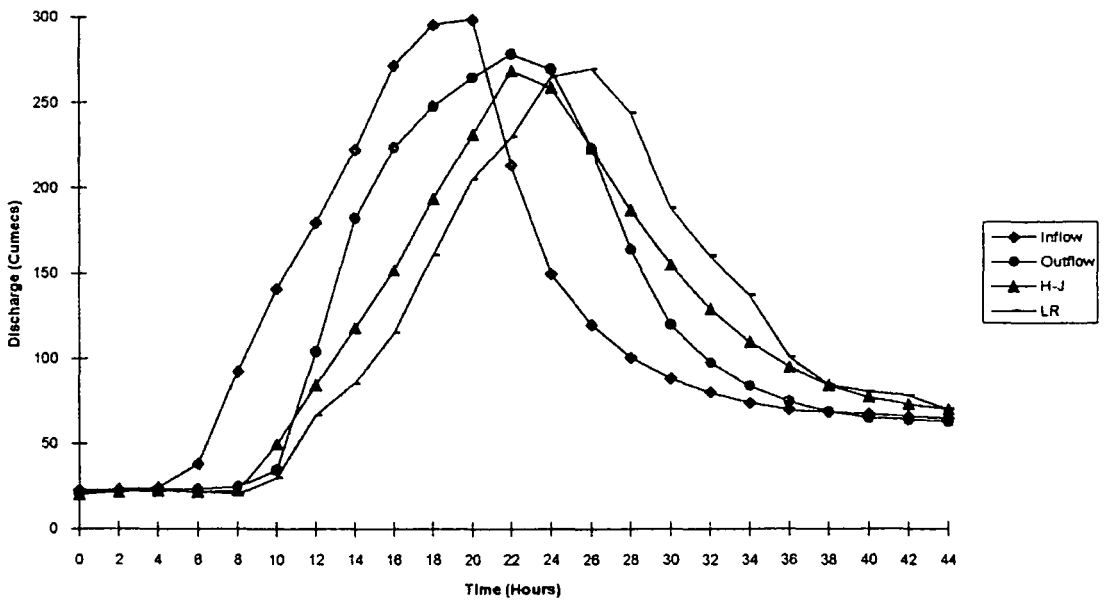
Fig. (7.6) Calculated And Observed Outflow Hydrographs For The Event 25-8-1986 Of Tees River.
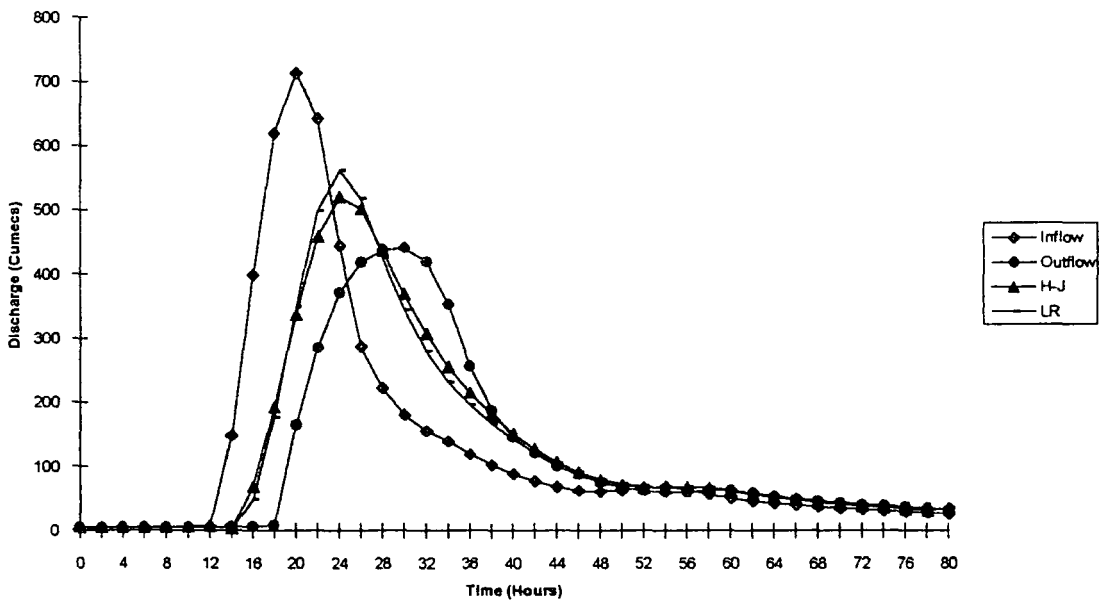
Fig. (7.7) Calculated And Observed Outflow Hydrographs For The Event 2-1-1982 Of Tees River.
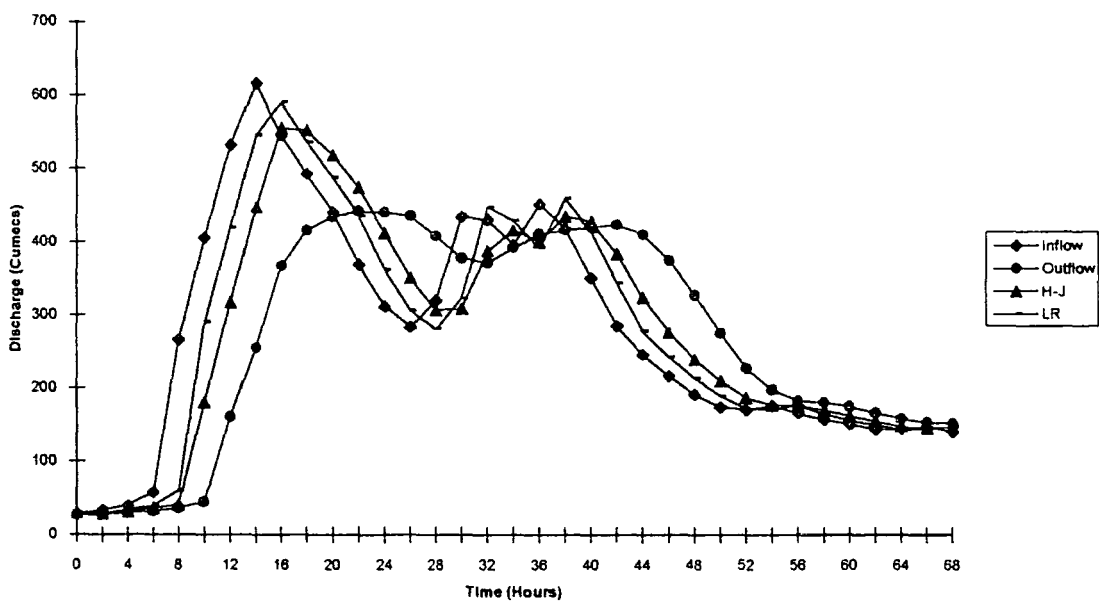
CHAPTER 8

CONCLUSION AND RECOMMENDATION FOR
FUTURE STUDIES

8.1 General Conclusion

Chapter 2, includes a review of the classification and characteristics of flood routing methods. The greater part of chapter 3 is concerned with details on the catchments and the hydrological data. These are further developed in the geological description of the catchments, and in the topographical data analysis.

The theory of the channel flow model and in particular, the Muskingum-Cunge method, the variable parameter diffusion method, and the state variable model is presented in chapter 4.

The main body of original work is found in chapter 5, 6, and 7. The application of Muskingum-Cunge and variable parameter diffusion is presented in chapter 5. Apart from the need to represent and calculate the attenuation parameter of the reach, the attenuation peak of discharge of the upstream inflow hydrograph, the peak value of the upstream discharge hydrograph, and the speed parameters all require calculation.

Chapter 6 covers the application of the state variable kinematic wave model and describes the unsteady non-uniform flow in terms of a set of first order ordinary differential equations and a set of arithmetic equations.

In chapter 7, a routing technique is applied for the nonlinear Muskingum model using the concept of state variable modelling. Two curve fitting techniques are employed for the calibration of model parameters.

The techniques applied and described in chapters 6 and 7 have not before

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been applied for rivers in the U. K. Therefore, the success demonstrated in this research points the way forward for the future development of flood routing in Britain.

8.2 Conclusions From the Study With Regard to the Muskingum-Cunge and Variable Parameter Diffusion Methods

For the Muskingum-Cunge and variable parameter diffusion methods a number of coefficients are calculated using past flood data which depend on the hydraulic characteristics of the reaches under investigation. The following are the important conclusions drawn during this study:

1. The Muskingum-Cunge and the variable parameter diffusion methods are used in this study according to the feasibility of the hydrological data such as flood wave celerity, attenuation and discharge records. The Muskingum-Cunge model became commonly used, as described by Price (1978) in relation to the River Soar, when it has been shown that firstly benefits of the model exceed its cost, and secondly that the model is better than existing techniques. The major advantage of the Muskingum-Cunge and the variable parameter diffusion methods is of course the reduced amount of data required for model calibration, and hence their conceptual simplicity.

2. The Muskingum-Cunge and the variable parameter diffusion methods eleminate the problem for complex data representation by combining all topographical channel and flood plain data to estimate model parameters.

3. An improved version of the Muskingum-Cunge method is recommended as the best hydrological flood routing method for inclusion in forecasting/warning systems rather than the conceptually more complex variable parameter diffusion method.

4. The Muskingum-Cunge and variable parameter diffusion methods are not generally suitable for application to streams with a proportionally large lateral inflow contribution because of the significant back water effects.

5. The representation of flood plain conditions in a numerical flood routing model is of primary importance as these conditions are the major cause of flood wave attenuation.

6. The Muskingum-Cunge method is considered to be only a suitable approximation for the diffusion method. However, with the coefficients considered as functions of flow, the Muskingum-Cunge can produce results as good as the variable parameter diffusion method.

7. It has been shown that the Muskingum-Cunge method is as good as the variable parameter diffusion method. However, it is obvious that, the greater the number of floods analysed during the calculation of the coefficients the greater would be the confidence with which they could be used for flood prediction. Therefore, here again an analysis of more flood events might help to establish the coefficient on a more firm basis.

8.3 Conclusion From the Study With Regard to the State Variable Modelling

State variable modelling is a relatively new technique and it appears to have considerable potential for application to water resource system. The state variable model is used in this study for solving the following models:

1. kinematic wave flood routing model; and

2. nonlinear Muskingum model.

For the kinematic wave model the state variable model is simple and easy to apply. The model is based on the simplified one-dimensional Saint-Venant equa-

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tions. The state variable model provides a basis for a lumped mathematical model to describe the temporally and spatially varied overland flow. The channel is divided into a series of interacting subreaches in which the flow condition is assumed to be uniform. The state variable kinematic wave model is applied to route an upstream inflow hydrograph through a river channel. Stage and discharge observations at the gauging stations are simulated implicitly by obtaining a numerical solution of state and output equations with the kinematic wave model subject to the initial and boundary conditions. The model is designed to accommodate irregular cross-sections located along the channel reach. The technique is simple in concept and computationally efficient in the state variable matrix forms for slowly varying floods and irregularly spaced cross-sections along the river. The comparison of the results of this simulation study with the observed discharge hydrograph shows a better agreement with the rising limb than the recession limb. Although, the state variable kinematic wave model is simple in application, it needs more hydrological and topographical data for each subreach than any other model, and it also needs flood events of long duration.

The nonlinear Muskingum model can also be solved by state variable modelling and used for flood routing. However, it has to be employed at a higher computing cost and is more complex than a linear equation. The main problem is formulated to calculate the parameters (α, x, and m) of the nonlinear Muskingum model by linear regression and the Hooke-Jeeves optimization technique. In general there is an important point to be noted from the studies made in this work. Whether the parameters are calculated by linear regression or the Hooke-Jeeves optimization technique, the latter with past flow records has emerged as suitable for the calculation of model parameters. Therefore, it is believed that such calculations should be useful for research with flood routing.

In conclusion both the Rivers Wear and Tees provide a valuable insight into the

hydraulic/hydrological system and analysis methods may, of course, be improved continuously with further data acquisition.

8.4 Recommendations

Although conclusions must apply strictly only to the specific applications, these results may provide an indication of future research and the following recommendations are made:

1. The Muskingum-Cunge and the variable parameter diffusion method are recommended in the Flood Studies Report (N.E.R.C., 1975) incorporating recent improvements and are considered to be useful methods. Following the acquisition of the hydrological data both rivers Wear and Tees provide excellent reaches for investigation.

2. In order to get an accurate result with the flood routing model, attention should be paid to incorporating more topographical and hydrological data in the calculation of the Muskingum equation.

3. The state variable kinematic wave model applied to the River Wear could be greatly improved if more high quality data were available and especially a discharge hydrograph at each successive subreach together with information on the geometrical analysis of the channel cross-section and water level at different stages.

4. It is believed that the derivation of nonlinear Muskingum parameters (α, x, and m) by the optimization technique is useful for research with flood routing.

5. An analysis of more flood events might help in the calculation of model parameters and establish them on a more firm basis.

6. Future research should be concentrated primarily on the improvement of data representation schemes, and on the analysis of various engineering applications

of numerical models to assist in engineering design.

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APPENDICES

Appendix I
Discharge Measurement of Rivers Wear and Tees
Table I.1
Discharge measurement of River Wear
Sunderland B. - Ch.Le St.Reach
of 26-8-1986

		Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
Day	Time	H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
25	0	0.294	2.80	0.125	0.402	3.59	0.328	4.11
	1	0.304	3.01	0.164	0.60	4.18	0.326	4.05
	2	0.343	3.91	0.185	0.72	5.32	0.332	4.23
	3	0.395	5.35	0.236	1.05	7.40	0.343	4.58
26	4	0.427	6.40	0.295	1.46	9.25	0.359	5.12
	5	0.460	7.60	0.379	2.18	11.9	0.384	6.04
	6	0.478	8.35	0.424	2.79	13.8	0.416	7.34
	7	0.484	8.62	0.464	3.51	15.5	0.447	8.74
	8	0.507	9.74	0.565	5.64	20.8	0.476	10.2
	9	0.535	11.2	0.642	7.71	26.3	0.510	12.1
	10	0.588	14.4	0.816	13.2	40.2	0.566	15.5
	11	1.286	71.2	0.969	18.9	108.9	0.642	21.1
	12	1.586	104.8	1.13	26.1	155.8	0.721	28.0
	13	1.618	108.6	1.261	32.8	172.7	0.804	35.2
	14	1.742	123.9	1.367	38.9	199.9	0.925	46.6
	15	1.988	157.0	1.444	43.6	242.2	1.680	139.6
	16	2.217	190.8	1.508	51.8	292.0	2.307	211.4
	17	2.540	243.4	1.723	63.1	366.7	2.698	248.4
	18	2.710	273.3	1.899	77.3	424.3	2.542	271.5
	19	2.823	294.1	1.942	81.0	452.4	3.134	289.8
	20	2.880	304.8	1.932	80.1	461.3	3.293	304.9
	21	2.936	315.5	1.815	70.3	452.9	3.440	318.9
	22	2.978	323.6	1.776	67.2	454.9	3.571	331.4
	23	2.981	324.2	1.694	60.9	443.2	3.667	340.6
	24	2.940	316.3	1.574	52.2	418.3	3.733	346.9
	25	2.797	289.2	1.448	43.9	375.0	3.781	351.5
	26	2.460	225.9	1.319	36.1	300.4	3.807	354.0
	27	2.116	175.5	1.191	29.2	232.6	3.809	354.2
27	28	1.918	147.2	1.086	24.0	194.1	3.785	351.9
	29	1.821	134.2	1.016	20.9	175.0	3.701	343.9
	30	1.724	121.6	0.965	18.8	158.3	3.505	325.1
	31	1.617	108.5	0.918	16.9	141.5	3.200	296.0
	32	1.536	98.9	0.877	15.4	129.0	2.831	261.0
	33	1.460	90.3	0.838	14.0	117.7	2.492	228.9
	34	1.389	82.6	0.806	12.9	107.8	2.214	202.6
	35	1.317	75.1	0.775	11.9	98.4	2.001	182.6
	36	1.251	68.5	0.748	11.0	90.0	1.843	163.9
	37	1.194	63.0	0.728	10.4	83.3	1.721	145.6
	38	1.151	59.0	0.722	10.2	78.9	1.627	132.0
	39	1.117	55.9	0.718	10.1	75.6	1.543	120.2
	40	1.092	53.7	0.715	9.9	73.0	1.461	109.0
	41	1.083	52.9	0.713	9.6	71.7	1.400	101.1

Table I.2
Discharge measurement of River Wear
Sunderland B.- Ch.Le St.Reach
of 2-2-1981

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
2	0	0.337	4.82	0.228	0.99	6.49	0.410	7.98
	1	0.337	4.82	0.228	0.99	6.49	0.406	6.91
	2	0.383	4.99	0.231	1.01	6.71	0.409	7.04
	3	0.394	5.32	0.255	1.18	7.27	0.414	7.25
	4	0.434	6.64	0.264	1.24	8.81	0.413	7.21
	5	0.442	6.92	0.266	1.25	9.13	0.418	7.42
	6	0.458	7.52	0.274	1.31	9.87	0.425	7.73
3	7	0.490	8.91	0.303	1.52	11.70	0.426	7.78
	8	0.514	10.10	0.342	1.83	13.30	0.427	7.82
	9	1.190	62.70	0.386	2.25	72.60	0.429	7.91
	10	1.727	122.00	0.462	3.44	140.20	0.441	8.46
	11	1.852	138.30	0.523	4.66	159.80	0.459	9.33
	12	1.943	150.70	0.598	6.48	175.70	0.476	10.20
	13	1.977	155.40	0.629	7.19	181.70	1.002	54.40
	14	1.895	144.10	0.604	6.64	168.50	1.623	131.40
	15	1.631	110.20	0.567	5.69	129.50	1.864	167.10
	16	1.415	85.40	0.529	4.80	100.80	1.998	182.30
	17	1.266	70.00	0.497	4.12	82.80	1.995	182.00
	18	1.163	60.10	0.473	3.65	71.30	1.857	166.00
	19	1.088	53.30	0.455	3.31	63.30	1.650	135.20
	20	1.026	48.00	0.437	3.00	57.00	1.464	109.50
	21	0.973	43.70	0.426	2.82	52.00	1.310	89.70
	22	0.927	40.10	0.417	2.68	47.80	1.196	75.90
	23	0.886	36.70	0.408	2.54	43.90	1.112	66.30
	24	0.855	33.80	0.400	2.42	40.50	1.047	59.20
	25	0.830	31.70	0.393	2.34	38.00	0.996	53.80
	26	0.803	29.40	0.384	2.23	35.30	0.949	48.90
	27	0.782	27.70	0.376	2.14	33.40	0.910	45.10
	28	0.770	26.70	0.369	2.05	32.10	0.877	41.90
	29	0.765	26.30	0.366	2.02	31.70	0.848	39.20
	30	0.767	26.50	0.375	2.13	32.00	0.821	36.70
4	31	0.767	26.50	0.378	2.16	32.00	0.800	34.80
	32	0.765	26.30	0.378	2.16	31.80	0.782	33.20
	33	0.753	25.40	0.375	2.13	30.80	0.770	32.20
	34	0.740	24.40	0.373	2.11	29.60	0.763	31.60
	35	0.730	23.60	0.370	2.06	28.70	0.762	31.50
	36	0.720	23.00	0.368	2.04	28.00	0.762	31.50
	37	0.710	22.30	0.364	2.01	27.20	0.757	31.10
	38	0.702	21.70	0.361	1.98	26.50	0.748	30.30
	39	0.685	20.50	0.357	1.95	25.10	0.736	29.30
	40	0.670	19.50	0.355	1.93	24.00	0.727	28.50

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...continued Table I.2

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	41	0.654	18.50	0.343	1.84	22.70	0.717	27.70
	42	0.646	18.00	0.327	1.71	22.00	0.707	26.70
	43	0.637	17.40	0.322	1.67	21.30	0.696	25.70
	44	0.628	16.90	0.319	1.64	20.70	0.684	24.70
	45	0.620	16.40	0.316	1.62	20.10	0.671	23.50
	46	0.612	15.90	0.313	1.60	19.60	0.656	22.30
	47	0.605	15.50	0.309	1.57	19.10	0.647	21.50
	48	0.598	15.10	0.308	1.56	18.61	0.636	20.60
	49	0.592	14.70	0.306	1.54	18.14	0.627	20.00

Table I.3
Discharge measurement of River Wear
Sunderland B. - Ch.Le St.Reach
of 1-10-1981

		Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
Day	Time	H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
1	0	0.494	9.1	0.317	1.63	13.4	0.527	13.1
	1	0.539	11.4	0.336	1.78	16.4	0.532	13.4
	2	0.559	12.0	0.390	2.30	18.6	0.555	14.8
	3	0.600	15.2	0.450	3.22	23.0	0.574	16.1
	4	0.623	16.6	0.481	3.80	25.4	0.578	16.4
	5	0.626	16.8	0.569	5.74	28.1	0.582	16.6
	6	0.682	20.3	0.671	8.79	36.3	0.601	18.0
	7	0.742	24.6	0.786	12.23	45.9	0.646	21.5
	8	0.896	37.6	0.875	15.30	66.0	0.704	26.5
	9	1.040	42.2	0.913	16.70	73.4	0.776	32.7
	10	1.230	66.5	0.930	17.40	104.6	0.847	39.1
	11	1.558	101.5	0.982	19.50	150.9	0.972	51.3
	12	1.736	123.2	1.064	23.00	182.3	1.163	72.1
	13	1.855	138.7	1.149	27.00	206.6	1.405	101.8
	14	1.940	150.3	1.215	30.40	225.3	1.713	144.4
	15	2.072	169.1	1.279	33.80	253.0	2.007	183.1
	16	2.177	184.7	1.288	34.30	273.1	2.231	204.2
	17	2.269	198.9	1.303	35.20	291.9	2.395	219.7
	18	2.360	213.4	1.310	35.60	310.5	2.526	232.1
	19	2.418	227.9	1.200	32.80	318.9	2.644	243.2
	20	2.393	218.8	1.173	28.20	308.0	2.758	254.0
	21	2.148	180.3	0.993	19.90	249.6	2.864	264.1
	22	1.821	134.2	0.882	15.60	186.8	2.943	271.7
	23	1.610	107.6	0.833	13.80	151.4	2.960	273.2
	24	1.489	93.6	0.797	12.60	132.4	2.859	263.0
	25	1.413	85.2	0.772	11.80	120.9	2.608	239.8
	26	1.357	79.3	0.750	11.10	112.7	2.265	207.4
	27	1.317	75.1	0.734	10.60	106.9	1.957	178.5
	28	1.279	71.3	0.720	10.20	101.6	1.754	150.4
	29	1.256	69.0	0.726	10.40	99.0	1.626	131.8
	30	1.253	68.7	0.729	10.50	98.8	1.538	119.5
	31	1.288	72.2	0.786	12.20	105.2	1.471	110.5
	32	1.375	81.1	0.867	15.00	119.8	1.428	104.8
	33	1.501	94.9	0.913	16.70	135.2	1.405	101.8
	34	1.607	107.3	0.903	16.30	154.1	1.410	102.4
	35	1.663	114.1	0.847	14.30	160.1	1.469	110.2
	36	1.633	101.4	0.787	12.30	141.8	1.586	126.2
	37	1.543	99.7	0.735	10.60	137.5	1.714	144.5
	38	1.438	87.9	0.696	9.50	121.5	1.799	157.2
	39	1.343	71.8	0.673	8.84	108.0	1.820	160.4
	40	1.262	69.6	0.647	7.86	96.6	1.763	151.8

		Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
Day	Time	H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	41	1.196	63.2	0.626	7.26	87.9	1.667	137.7
	42	1.149	58.8	0.607	6.72	81.7	1.558	122.3
	43	1.105	54.9	0.587	6.19	76.2	1.449	107.5
	44	1.071	51.9	0.576	5.91	72.1	1.361	96.1
	45	1.033	48.6	0.565	5.64	67.6	1.287	86.9
	46	1.001	46.0	0.552	5.32	64.0	1.228	79.7
	47	0.966	43.1	0.534	4.91	59.9	1.179	73.9
	48	0.935	40.7	0.528	4.77	56.7	1.133	68.7
	49	0.909	38.7	0.518	4.56	53.9	1.094	64.3
	50	0.887	36.8	0.506	4.30	51.3	1.058	60.4
	51	0.869	35.1	0.497	4.12	48.9	1.024	56.7
	52	0.852	33.6	0.489	3.96	46.8	0.991	53.3

Table I.4
Discharge measurement of River Wear
Sunderland B.G.S.- Ch.Le St.Reach
of 15-4-1986

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
Hours		*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
15	0	0.605	15.5	0.399	2.40	22.8	0.647	21.5
	1	0.605	15.5	0.409	2.55	23.0	0.653	22.0
	2	0.609	15.7	0.423	2.77	23.5	0.658	22.4
	3	0.613	16.0	0.433	2.94	24.1	0.663	22.5
	4	0.618	16.3	0.440	3.05	24.6	0.669	23.4
	5	0.628	16.9	0.585	6.14	29.3	0.669	23.4
	6	0.679	20.1	0.715	10.00	38.3	0.669	23.4
	7	0.955	42.2	0.874	15.30	73.2	0.669	23.4
	8	1.154	53.9	0.966	18.80	92.5	0.687	24.9
	9	1.292	72.6	1.058	22.80	121.4	0.718	27.8
	10	1.403	84.1	1.141	26.70	141.0	0.797	34.6
	11	1.517	96.9	1.206	29.90	161.2	1.070	61.7
	12	1.623	109.2	1.249	32.2	179.9	1.422	104.0
	13	1.736	123.2	1.291	34.50	200.6	1.719	145.3
	14	1.838	136.4	1.363	38.60	222.7	1.997	182.2
	15	1.973	154.9	1.433	42.90	251.7	2.249	205.9
	16	2.077	169.8	1.450	44.00	272.0	2.440	223.9
	17	2.134	178.2	1.479	45.80	285.0	2.578	237.0
	18	2.183	185.0	1.495	46.90	295.8	2.692	247.8
	19	2.214	190.4	1.501	47.30	302.4	2.788	256.9
	20	2.200	188.0	1.493	46.70	298.9	2.872	264.8
	21	2.019	161.4	1.410	45.50	258.2	2.944	271.7
	22	1.816	133.5	1.289	34.40	213.6	2.996	278.6
	23	1.655	113.1	1.098	24.60	175.2	3.001	277.1
	24	1.536	98.9	0.965	18.80	149.8	2.922	269.6
	25	1.436	87.7	0.900	16.20	132.2	2.734	251.8
	26	1.359	79.5	0.859	14.70	119.8	2.432	223.2
	27	1.288	72.2	0.821	13.40	108.9	2.101	192.0
	28	1.231	66.6	0.794	12.50	100.6	1.844	164.0
	29	1.183	62.0	0.771	11.70	93.9	1.665	137.4
	30	1.144	58.4	0.751	11.10	88.4	1.540	119.8
	31	1.112	55.5	0.734	10.60	84.1	1.445	107.8
	32	1.082	52.8	0.719	10.20	80.2	1.372	97.5
	33	1.055	50.5	0.709	9.90	76.8	1.312	89.9
	34	1.033	48.6	0.695	9.50	73.9	1.263	83.9
	35	1.016	47.2	0.683	9.10	71.6	1.222	79.0
	36	1.004	46.2	0.671	8.80	70.0	1.186	74.8
	37	0.998	45.7	0.661	8.50	69.0	1.157	71.4
	38	0.997	45.6	0.651	8.00	68.2	1.133	68.7
	39	0.997	45.6	0.643	7.70	67.8	1.113	66.4
	40	0.995	45.5	0.634	7.50	67.4	1.100	65.0

...continued Table I.4

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	41	0.990	45.1	0.625	7.20	66.5	1.091	64.0
	42	0.984	44.6	0.623	7.18	65.9	1.088	63.7
	43	0.981	44.3	0.622	7.10	65.4	1.084	63.2
	44	0.975	43.9	0.617	7.00	64.8	1.078	62.2
	45	0.967	43.2	0.617	7.00	63.9	1.070	61.7

Table I.5
Discharge measurement of River Wear
Sunderland B.G.S.- Ch.Le St.Reach
of 1-2-1984

Day	Time	Sunderland B. G.S. H	Sunderland B. G.S. Q	Burn Hall G.S. H	Burn Hall G.S. Q	Total inflow Q	Ch.Le St. G.S. (Outflow) H	Ch.Le St. G.S. (Outflow) Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
1	0	0.702	23.628	0.501	4.197	27.825	0.756	30.993
	1	0.695	23.089	0.491	3.994	27.083	0.748	30.310
	2	0.689	22.632	0.488	3.934	26.566	0.741	29.717
	3	0.686	22.405	0.485	3.875	26.280	0.735	29.212
	4	0.684	22.254	0.484	3.856	26.110	0.728	28.627
	5	0.682	22.104	0.485	3.875	25.979	0.720	27.963
	6	0.682	22.104	0.489	3.954	26.085	0.713	27.386
	7	0.684	22.254	0.493	4.034	26.288	0.710	27.141
	8	0.686	22.405	0.500	4.176	26.581	0.709	27.059
	9	0.688	22.556	0.507	4.321	26.877	0.709	27.059
	10	0.690	22.708	0.516	4.512	27.220	0.711	27.223
	11	0.693	22.936	0.524	4.685	27.621	0.719	27.880
	12	0.696	23.166	0.536	4.953	28.119	0.727	28.544
	13	0.700	23.473	0.549	5.253	28.726	0.738	29.464
	14	0.704	23.783	0.565	5.636	29.419	0.749	30.395
	15	0.711	24.328	0.582	6.061	30.389	0.758	31.165
2	16	0.720	25.038	0.590	6.268	31.306	0.765	31.768
	17	0.731	25.918	0.597	6.452	32.370	0.771	32.288
	18	0.743	26.894	0.600	6.532	33.426	0.779	32.986
	19	0.756	27.969	0.608	6.747	34.716	0.795	34.397
	20	0.770	29.147	0.620	7.079	36.226	0.811	35.829
	21	0.782	30.175	0.637	7.564	37.739	0.827	37.281
	22	0.793	31.131	0.656	8.130	39.261	0.842	38.661
	23	0.805	32.190	0.677	8.952	41.142	0.856	39.964
	24	0.822	33.716	0.691	9.343	43.059	0.868	41.093
	25	0.846	35.924	0.709	9.859	45.783	0.882	42.424
	26	0.874	38.580	0.722	10.241	48.821	0.899	44.061
	27	0.900	41.122	0.735	10.630	51.752	0.918	45.915
	28	0.935	44.589	0.761	11.431	56.020	0.945	48.595
	29	0.972	47.666	0.792	12.426	60.092	0.977	51.840
	30	1.010	50.915	0.839	14.017	64.932	1.009	55.158
	31	1.058	55.147	0.909	16.572	71.719	1.042	58.654
	32	1.113	60.168	0.976	19.228	79.396	1.077	62.442
	33	1.171	65.660	1.017	20.955	86.615	1.122	67.434
	34	1.238	72.252	1.024	21.257	93.509	1.179	73.947
	35	1.297	78.274	1.020	21.084	89.358	1.253	82.711
	36	1.336	82.365	1.006	20.484	102.849	1.337	93.067
	37	1.362	85.141	0.991	19.851	104.992	1.416	103.189
	38	1.376	86.651	0.976	19.228	105.879	1.486	112.459
	39	1.380	87.085	0.958	18.494	105.579	1.532	118.701
3	40	1.371	86.110	0.923	17.110	103.220	1.557	122.142

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Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	41	1.351	83.962	0.885	15.671	99.633	1.577	124.920
	42	1.323	80.992	0.860	14.760	95.752	1.576	124.781
	43	1.290	77.549	0.832	13.774	91.323	1.560	122.558
	44	1.258	74.271	0.813	13.124	87.395	1.526	117.880
	45	1.231	71.551	0.805	12.856	84.407	1.486	112.459
	46	1.213	69.762	0.808	12.956	82.718	1.440	106.336
	47	1.202	68.677	0.830	13.704	82.381	1.400	101.110
	48	1.195	67.991	0.845	14.227	82.218	1.363	96.358
	49	1.197	68.187	0.853	14.510	82.697	1.337	93.067
	50	1.209	69.367	0.847	14.298	83.665	1.322	91.186
	51	1.229	71.351	0.844	14.192	85.543	1.317	90.563
	52	1.269	75.391	0.874	15.267	90.658	1.322	91.186
	53	1.337	82.471	0.953	18.293	100.764	1.336	92.815
	54	1.429	92.469	1.024	21.257	113.726	1.355	95.341
	55	1.531	104.108	1.069	23.257	127.365	1.391	99.946
	56	1.622	114.975	1.103	24.829	139.804	1.465	109.649
	57	1.686	122.886	1.109	25.112	137.998	1.576	124.781
	58	1.720	127.178	1.107	25.018	152.196	1.706	143.354
	59	1.724	127.687	1.080	23.760	151.447	1.826	161.281
	60	1.698	124.393	1.026	21.344	145.737	1.914	174.418
	61	1.639	117.054	0.967	18.859	135.913	1.966	179.298
	62	1.576	109.425	0.921	17.033	126.458	1.978	180.425
	63	1.512	101.896	0.883	15.597	117.493	1.951	177.890
4	64	1.438	93.473	0.848	14.333	107.806	1.888	170.830
	65	1 381	87.193	0.820	13.362	100.555	1.806	158.242
	66	1.328	81.519	0.797	12.590	94.109	1.716	144.819
	67	1.277	76.210	0.775	11.875	88.085	1.629	132.244
	68	1.233	71.751	0.755	11.243	82.994	1.551	121.313
	69	1.199	68.383	0.738	10.721	79.104	1.482	111.922
	70	1.170	65.564	0.725	10.330	75.894	1.422	103.973
	71	1.145	63.173	0.713	9.976	73.149	1.371	97.378
	72	1.119	60.727	0.708	9.830	70.557	1.325	91.561
	73	1.096	58.597	0.708	9.830	68.427	1.283	86.360
	74	1.078	56.952	0.708	9.830	66.782	1.252	82.590
	75	1.064	55.686	0.709	9.859	65.545	1.221	78.879
	76	1.053	54.699	0.717	10.093	64.792	1.195	75.813
	77	1.044	53.898	0.727	10.390	64.288	1.175	73.484
	78	1.039	53.455	0.733	10.570	64.025	1.160	71.753
	79	1.037	53.278	0.755	11.243	64.521	1.147	70.265
	80	1.055	54.878	0.816	13.226	68.104	1.138	69.241

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	81	1.143	62.984	0.907	16.496	79.480	1.132	68.562
	82	1.285	77.033	0.973	19.105	96.138	1.130	68.336
	83	1.412	90.586	1.024	21.257	111.843	1.143	69.809
	84	1.567	108.353	1.056	22.669	131.022	1.208	77.341
	85	1.734	128.963	1.073	23.439	152.402	1.347	94.328
	86	1.894	150.098	1.092	24.315	174.413	1.525	117.743
	87	2.028	168.820	1.108	25.065	193.885	1.719	145.260
5	88	2.119	182.055	1.123	25.780	207.835	1.913	174.324
	89	2.200	194.185	1.109	25.112	219.297	2.094	191.326
	90	2.265	204.185	1.077	23.622	227.777	2.256	206.580
	91	2.312	211.494	1.022	21.171	232.665	2.382	218.466
	92	2.313	211.651	0.922	17.072	228.723	2.493	228.953
	93	2.176	190.557	0.845	14.227	204.784	2.596	238.697
	94	1.984	157.532	0.793	12.459	169.991	2.674	246.082
	95	1.743	130.116	0.758	11.337	141.453	2.695	248.072
	96	1.602	112.548	0.728	10.419	122.967	2.622	241.158
	96	1.496	100.049	0.698	9.542	109.591	2.450	224.889
	97	1.413	90.696	0.672	8.814	99.510	2.208	202.057
	98	1.348	83.641	0.654	8.069	91.710	1.979	180.519
	99	1.291	77.653	0.638	7.594	85.247	1.787	155.374
	100	1.241	72.554	0.619	7.051	79.605	1.640	133.812
	101	1.205	68.972	0.600	6.532	75.504	1.530	118.427
	102	1.175	66.046	0.574	5.859	71.905	1.449	107.524
	103	1.149	63.553	0.562	5.563	69.116	1.387	99.431
	104	1.130	61.757	0.551	5.300	67.057	1.334	92.689
	105	1.115	60.354	0.552	5.323	65.677	1.292	87.466
	106	1.101	59.057	0.546	5.183	64.240	1.260	83.557
	107	1.090	58.046	0.531	4.840	62.886	1.233	80.309
	108	1.077	56.861	0.515	4.490	61.351	1.214	78.049
	109	1.059	55.236	0.496	4.095	59.331	1.197	76.047
	110	1.044	53.898	0.504	4.259	58.157	1.181	74.180
6	111	1.031	52.749	0.514	4.469	57.218	1.166	72.444
	112	1.014	51.262	0.515	4.490	55.752	1.151	70.722
	113	0.998	49.879	0.513	4.448	54.327	1.134	68.788
	114	0.987	48.938	0.509	4.363	53.301	1.118	66.985
	115	0.985	48.768	0.506	4.300	53.068	1.103	65.310
	116	1.008	50.742	0.506	4.300	55.042	1.087	63.540
	117	1.111	59.982	0.511	4.405	64.387	1.070	61.678
	118	1.290	77.549	0.525	4.707	82.256	1.058	60.375
	119	1.394	88.609	0.540	5.044	93.653	1.055	60.051
	120	1.432	92.803	0.539	5.021	97.834	1.088	63.650

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	121	1.423	91.803	0.531	4.840	96.643	1.188	74.995
	122	1.395	88.719	0.523	4.663	93.382	1.332	92.438
	123	1.374	86.434	0.529	4.796	91.230	1.439	106.204
	124	1.358	84.711	0.570	5.759	90.470	1.479	111.520
	125	1.347	83.535	0.593	6.346	89.881	1.475	110.984
	126	1.340	82.790	0.600	6.532	89.322	1.454	108.187
	127	1.336	82.365	0.598	6.478	88.843	1.435	105.678
	128	1.325	81.202	0.592	6.320	87.522	1.423	104.104
	129	1.303	78.898	0.582	6.061	84.959	1.417	103.319
	130	1.279	76.416	0.573	5.834	82.250	1.414	102.928
	131	1.257	74.170	0.568	5.710	79.880	1.405	101.758
	132	1.238	72.252	0.567	5.685	77.937	1.390	99.817
	133	1.216	70.059	0.569	5.735	75.794	1.371	97.378
	134	1.194	67.893	0.567	5.685	73.578	1.347	94.328
7	135	1.172	65.757	0.560	5.515	71.272	1.327	91.812
	136	1.147	63.363	0.548	5.229	68.592	1.306	89.195
	137	1.119	60.727	0.539	5.021	65.748	1.286	86.728
	138	1.090	58.046	0.526	4.729	62.775	1.264	84.043
	139	1.066	55.866	0.512	4.426	60.292	1.241	81.267
	140	1.037	53.278	0.497	4.115	57.393	1.216	78.286
	141	1.002	50.224	0.484	3.856	54.080	1.186	74.762
	142	0.975	47.919	0.470	3.588	51.507	1.155	71.180
	143	0.955	46.242	0.458	3.367	49.609	1.124	67.659
	144	0.938	44.835	0.449	3.207	48.042	1.096	64.534
	145	0.924	43.533	0.440	3.052	46.585	1.066	61.243
	146	0.911	42.219	0.433	2.934	45.153	1.039	58.333
	147	0.898	40.924	0.427	2.835	43.759	1.016	55.893
	148	0.887	39.842	0.423	2.771	42.613	0.997	53.905
	149	0.875	38.677	0.417	2.675	41.352	0.981	52.251
	150	0.868	38.004	0.412	2.597	40.601	0.966	50.716
	151	0.862	37.432	0.406	2.505	39.937	0.952	49.299
	152	0.857	36.958	0.399	2.401	39.359	0.940	48.095
	153	0.855	36.769	0.395	2.342	39.111	0.928	46.901
	154	0.849	36.205	0.395	2.342	38.547	0.918	45.915
	155	0.844	35.738	0.396	2.357	38.095	0.910	45.131
	156	0.840	35.366	0.395	2.342	37.708	0.904	44.546
	157	0.835	34.904	0.394	2.328	37.232	0.900	44.157
	158	0.832	34.628	0.400	2.416	37.044	0.898	43.964
8	159	0.829	34.353	0.403	2.460	36.813	0.893	43.481
	160	0.822	33.716	0.404	2.475	36.191	0.887	42.903

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	161	0.830	34.445	0.405	2.490	36.935	0.882	42.424
	162	0.841	35.459	0.401	2.430	37.889	0.878	42.042
	163	0.851	36.892	0.400	2.416	39.308	0.878	42.042
	164	0.883	39.452	0.412	2.597	42.049	0.877	41.947
	165	0.963	46.910	0.441	3.069	49.979	0.875	41.757
	166	1.003	50.310	0.460	3.404	53.714	0.886	42.807
	167	1.012	51.089	0.462	3.440	54.529	0.894	43.577
	168	1.024	52.135	0.475	3.682	55.817	0.924	46.506
	169	1.028	52.486	0.503	4.238	56.724	0.982	52.354
	170	1.018	51.611	0.506	4.300	55.911	1.036	58.012
	171	0.998	49.879	0.496	4.095	53.974	1.065	61.134
	172	0.973	47.750	0.481	3.797	51.547	1.079	62.662
	173	0.947	45.578	0.464	3.477	49.055	1.084	63.210
	174	0.924	43.533	0.449	3.207	46.740	1.071	61.787
	175	0.904	41.520	0.436	2.984	44.504	1.051	59.620
	176	0.886	39.744	0.425	2.803	42.547	1.025	56.843
	177	0.872	38.388	0.417	2.675	41.063	1.000	54.217
	178	0.861	37.337	0.411	2.582	39.919	0.977	51.840
	179	0.852	36.486	0.405	2.490	38.976	0.956	49.702
	180	0.844	35.738	0.398	2.386	38.124	0.940	48.095
	181	0.837	35.089	0.392	2.299	37.388	0.925	46.605
	182	0.828	34.262	0.389	2.256	36.518	0.913	45.424
9	183	0.817	33.264	0.387	2.227	35.491	0.902	44.352
	184	0.810	32.635	0.383	2.171	34.806	0.893	43.481
	185	0.806	32.278	0.378	2.102	34.380	0.884	42.616
	186	0.796	31.394	0.372	2.022	33.416	0.875	41.757
	187	0.787	30.608	0.366	1.942	32.550	0.865	40.810
	188	0.778	29.831	0.360	1.865	31.696	0.855	39.870
	189	0.770	29.147	0.354	1.790	30.937	0.847	39.124
	190	0.761	28.387	0.348	1.716	30.103	0.838	38.291

		Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
Day	Time	H	Q	H	Q	Q	H	Q
Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*	
1	0	0.363	4.246	0.265	0.879	5.125	0.400	6.438
	1	0.363	4.246	0.258	0.824	5.070	0.397	6.290
	2	0.363	4.246	0.228	0.608	4.854	0.397	6.290
	3	0.363	4.246	0.215	0.526	4.772	0.398	6.339
	4	0.364	4.282	0.213	0.514	4.796	0.400	6.438
	5	0.363	4.246	0.211	0.503	4.749	0.402	6.537
	6	0.362	4.210	0.213	0.514	4.724	0.402	6.537
	7	0.361	4.174	0.216	0.532	4.706	0.401	6.487
	8	0.361	4.174	0.214	0.520	4.694	0.399	6.388
	9	0.360	4.139	0.211	0.503	4.350	0.396	6.241
	10	0.357	4.033	0.211	0.503	4.536	0.394	6.143
	11	0.350	3.792	0.216	0.532	4.324	0.392	6.046
	12	0.346	3.656	0.218	0.545	4.201	0.390	5.950
	13	0.344	3.590	0.220	0.557	4.147	0.389	5.902
	14	0.343	3.557	0.220	0.557	4.114	0.393	6.095
	15	0.343	3.557	0.220	0.557	4.114	0.394	6.143
2	16	0.344	3.590	0.219	0.551	4.141	0.394	6.143
	17	0.346	3.656	0.218	0.545	4.201	0.393	6.095
	18	0.348	3.724	0.248	0.747	4.471	0.391	5.988
	19	0.349	3.758	0.258	0.824	4.582	0.388	5.854
	20	0.350	3.792	0.257	0.816	4.508	0.386	5.758
	21	0.352	3.860	0.255	0.800	4.660	0.384	5.663
	22	0.350	3.792	0.254	0.793	4.585	0.384	5.663
	23	0.347	3.690	0.253	0.785	4.475	0.384	5.663
	24	0.343	3.557	0.248	0.747	4.304	0.382	5.569
	25	0.338	3.393	0.245	0.725	4.118	0.381	5.522
	26	0.334	3.265	0.218	0.545	3.810	0.381	5.522
	27	0.330	3.138	0.200	0.441	3.579	0.385	5.711
	28	0.327	3.045	0.196	0.419	3.464	0.388	5.854
	29	0.325	2.984	0.197	0.425	3.409	0.389	5.902
	30	0.325	2.984	0.206	0.474	3.458	0.389	5.902
	31	0.328	3.076	0.211	0.503	3.579	0.387	5.806
	32	0.331	3.170	0.224	0.582	3.752	0.384	5.663
	33	0.335	3.296	0.249	0.755	4.051	0.381	5.522
	34	0.339	3.425	0.241	0.697	4.122	0.376	5.289
	35	0.345	3.623	0.236	0.662	4.285	0.372	5.106
	36	0.351	3.826	0.238	0.676	4.502	0.368	4.924
	37	0.355	3.963	0.238	0.676	4.639	0.366	4.835
	38	0.354	3.929	0.235	0.655	4.584	0.369	4.970
	39	0.352	3.860	0.232	0.635	4.495	0.373	5.151
3	40	0.355	3.963	0.229	0.615	4.578	0.376	5.289

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	41	0.356	3.998	0.226	0.595	4.593	0.379	5.429
	42	0.357	4.033	0.253	0.785	4.818	0.383	5.616
	43	0.358	4.068	0.260	0.839	4.907	0.387	5.806
	44	0.365	4.318	0.256	0.808	5.126	0.389	5.902
	45	0.369	4.463	0.250	0.762	5.225	0.389	5.902
	46	0.363	4.246	0.246	0.733	4.979	0.389	5.902
	47	0.353	3.894	0.242	0.704	4.598	0.391	5.998
	48	0.337	3.361	0.236	0.662	4.023	0.388	5.854
	49	0.331	3.170	0.226	0.595	3.765	0.386	5.758
	50	0.324	2.953	0.201	0.446	3.399	0.386	5.758
	51	0.314	2.656	0.180	0.340	2.996	0.388	5.854
	52	0.307	2.456	0.167	0.283	2.739	0.392	6.046
	53	0.306	2.428	0.161	0.259	2.687	0.393	6.095
	54	0.311	2.569	0.161	0.259	2.828	0.389	5.902
	55	0.316	2.714	0.174	0.313	3.027	0.385	5.711
	56	0.316	2.714	0.196	0.419	3.133	0.376	5.289
	57	0.313	2.627	0.221	0.563	3.190	0.371	5.060
	58	0.313	2.627	0.228	0.608	3.235	0.367	4.879
	59	0.313	2.627	0.238	0.676	3.303	0.360	4.569
	60	0.320	2.833	0.242	0.704	3.537	0.351	4.180
	61	0.333	3.233	0.244	0.718	3.951	0.349	4.095
	62	0.359	4.103	0.242	0.704	4.807	0.349	4.095
	63	0.371	4.536	0.238	0.676	5.212	0.353	4.265
4	64	0.374	4.648	0.234	0.648	5.296	0.359	4.525
	65	0.376	4.723	0.228	0.608	5.331	0.361	4.613
	66	0.385	5.066	0.252	0.777	5.843	0.364	4.745
	67	0.401	5.703	0.260	0.839	6.542	0.366	4.835
	68	0.405	5.868	0.257	0.816	6.684	0.372	5.106
	69	0.400	5.663	0.256	0.808	6.471	0.379	5.429
	70	0.396	5.501	0.254	0.793	6.294	0.388	5.854
	71	0.391	5.301	0.254	0.793	6.094	0.397	6.290
	72	0.378	4.798	0.255	0.800	5.598	0.402	6.537
	73	0.374	4.648	0.261	0.847	5.495	0.403	6.587
	74	0.378	4.798	0.244	0.718	5.516	0.413	7.092
	75	0.396	5.501	0.255	0.800	6.301	0.423	7.610
	76	0.435	7.169	0.305	1.242	8.411	0.432	8.088
	77	0.477	9.184	0.435	2.967	12.151	0.441	8.575
	78	0.536	12.368	0.602	6.585	18.971	0.451	9.128
	79	0.601	16.402	0.787	12.262	28.664	0.462	9.750
	80	0.669	21.137	0.916	16.840	37.977	0.475	10.503

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	81	0.766	28.808	0.998	20.145	48.953	0.496	11.761
	82	0.937	44.753	1.030	21.519	66.272	0.548	15.083
	83	1.031	52.749	1.032	21.606	74.355	0.701	26.408
	84	1.109	59.797	1.036	21.781	81.578	0.892	43.384
	85	1.240	72.453	1.047	22.268	94.721	1.079	62.662
	86	1.356	84.497	1.073	23.439	107.936	1.238	80.907
	87	1.422	91.692	1.073	23.439	115.131	1.368	96.995
5	88	1.525	103.407	1.071	23.348	126.755	1.509	115.565
	89	1.611	113.637	1.074	23.485	137.122	1.652	135.530
	90	1.714	126.416	1.061	22.894	149.310	1.778	154.022
	91	1.800	137.518	1.036	21.781	159.299	1.884	170.208
	92	1.898	150.643	1.006	20.484	171.127	1.987	181.270
	93	1.968	160.323	0.978	19.311	179.634	2.092	191.138
	94	2.021	167.819	0.958	18.494	186.313	2.185	199.890
	95	2.045	171.260	0.980	19.393	190.653	2.275	208.371
	96	2.054	172.558	0.964	18.737	191.295	2.350	215.446
	97	2.048	171.693	0.944	17.934	189.527	2.404	220.544
	98	2.016	167.106	0.931	17.422	184.528	2.449	224.795
	99	1.936	155.867	0.890	15.857	171.724	2.477	227.441
	100	1.829	141.350	0.841	14.087	155.437	2.476	227.346
	101	1.725	127.814	0.804	12.823	140.637	2.440	223.944
	102	1.642	117.423	0.786	12.230	129.653	2.355	215.918
	103	1.594	111.583	0.789	12.328	123.911	2.224	203.564
	104	1.576	109.425	0.804	12.823	122.248	2.076	189.633
	105	1.572	108.948	0.807	12.923	121.871	1.941	176.951
	106	1.565	108.115	0.802	12.756	120.871	1.843	163.880
	107	1.539	105.045	0.776	11.907	116.952	1.786	155.224
	108	1.491	99.475	0.742	10.843	110.318	1.762	151.628
	109	1.432	92.803	0.705	9.743	102.546	1.744	148.951
	110	1.371	86.110	0.671	8.787	94.897	1.713	144.379
	111	1.305	79.106	0.642	7.711	86.817	1.665	137.399
6	112	1.241	72.554	0.618	7.023	79.577	1.603	128.564
	113	1.189	67.405	0.598	6.478	73.883	1.531	118.564
	114	1.141	62.794	0.577	5.934	68.728	1.454	108.187
	115	1.098	58.780	0.554	5.371	64.151	1.382	98.788
	116	1.057	55.057	0.556	5.418	60.475	1.316	90.438
	117	1.022	51.960	0.551	5.300	57.260	1.257	83.194
	118	0.990	49.194	0.538	4.998	54.192	1.204	76.870
	119	0.960	46.659	0.524	4.685	51.344	1.157	71.409
	120	0.933	44.425	0.519	4.576	49.001	1.116	66.761

Day	Time	Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
		H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	121	0.909	42.019	0.504	4.259	46.278	1.081	62.881
	122	0.889	40.038	0.496	4.095	44.133	1.050	59.512
	123	0.872	38.388	0.490	3.974	42.362	1.022	56.526
	124	0.855	36.769	0.483	3.836	40.605	0.993	53.490
	125	0.840	35.366	0.473	3.644	39.010	0.968	50.920
	126	0.824	33.879	0.472	3.625	37.422	0.943	48.395
	127	0.811	32.725	0.478	3.740	36.465	0.923	46.407
	128	0.798	31.570	0.477	3.720	35.290	0.903	44.449
	129	0.788	30.695	0.476	3.701	34.396	0.885	42.711
	130	0.783	30.262	0.477	3.720	33.982	0.870	41.282
	131	0.783	30.262	0.478	3.740	34.002	0.856	39.964
	132	0.792	31.044	0.480	3.778	34.822	0.843	38.753
	133	0.806	32.278	0.478	3.740	36.018	0.832	37.739
	134	0.820	33.535	0.474	3.663	37.198	0.828	37.372
	135	0.826	34.080	0.468	3.551	37.631	0.829	37.464
7	136	0.824	33.897	0.461	3.422	37.319	0.837	38.199
	137	0.815	33.083	0.463	3.458	36.541	0.849	39.310
	138	0.802	31.923	0.460	3.404	35.327	0.859	40.245
	139	0.788	30.695	0.455	3.313	34.008	0.863	40.621
	140	0.775	29.574	0.450	3.225	32.799	0.861	40.433
	141	0.765	28.724	0.448	3.190	31.914	0.852	39.590
	142	0.753	27.719	0.445	3.138	30.857	0.840	38.476
	143	0.741	26.730	0.440	3.052	29.782	0.824	37.007
	144	0.730	25.838	0.436	2.984	28.822	0.808	35.559
	145	0.719	24.959	0.426	2.819	27.778	0.795	34.397
	146	0.710	24.250	0.418	2.691	26.941	0.783	33.336
	147	0.702	23.628	0.413	2.613	26.241	0.770	32.201
	148	0.694	23.013	0.423	2.771	25.784	0.758	31.165
	149	0.686	22.405	0.424	2.787	25.192	0.746	30.141
	150	0.679	21.879	0.421	2.739	24.618	0.734	29.128
	151	0.673	21.433	0.419	2.707	24.140	0.724	28.294
	152	0.668	21.064	0.416	2.660	23.724	0.714	27.469
	153	0.664	20.771	0.414	2.628	23.399	0.705	26.733
	154	0.659	20.407	0.413	2.613	23.020	0.697	26.085
	155	0.657	20.263	0.413	2.613	22.876	0.690	25.522
	156	0.657	20.263	0.414	2.628	22.891	0.684	25.043
	157	0.664	20.771	0.414	2.628	23.399	0.680	24.726
	158	0.678	21.804	0.414	2.628	24.432	0.677	24.489
	159	0.693	22.936	0.413	2.613	25.549	0.675	24.331
8	160	0.703	23.705	0.411	2.582	26.287	0.675	24.331

		Sunderland B. G.S.		Burn Hall G.S.		Total inflow	Ch.Le St. G.S. (Outflow)	
Day	Time	H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
	161	0.711	24.328	0.418	2.691	27.019	0.676	24.410
	162	0.714	24.564	0.421	2.739	27.303	0.685	25.123
	163	0.712	24.407	0.418	2.691	27.098	0.700	26.327
	164	0.706	23.938	0.415	2.644	26.582	0.717	27.715
	165	0.699	23.396	0.412	2.597	25.993	0.732	28.961
	166	0.691	22.784	0.410	2.566	25.350	0.739	29.549
	167	0.683	22.179	0.407	2.521	24.700	0.740	29.633

Table I.7
Discharge measurement of River Tees
Broken Scar - Low Morr Reach
of 13-1-1984

		Broken Scar G.S.		South Park G.S.		Total inflow	Low Morr G.S. (Outflow)	
Day	Time	H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
13	0	0.457	25.7	0.389	2.01	24.9	0.702	28.3
	2	1.506	110.9	0.389	2.01	101.3	0.694	27.7
	4	2.065	248.2	0.444	2.79	225.1	0.704	28.5
	6	2.249	304.2	0.466	3.14	275.7	0.710	28.9
	8	2.054	245.0	0.577	5.33	224.5	2.574	133.3
	11	1.766	168.5	0.606	6.05	156.6	3.686	206.9
	12	1.579	125.9	0.627	6.61	118.8	4.027	231.0
	14	1.463	102.4	0.627	6.61	97.8	3.700	207.9
	16	1.365	84.3	0.628	6.64	81.6	3.013	161.4
	18	1.284	70.5	0.628	6.64	69.2	2.396	122.4
14	20	1.227	61.5	0.624	6.53	61.0	1.970	97.1
	22	1.191	56.1	0.608	6.10	55.8	1.670	80.3
	24	1.163	52.1	0.590	5.63	51.8	1.447	68.3
	26	1.150	50.3	0.572	5.21	49.8	1.297	60.6
	28	1.136	48.3	0.569	5.15	47.9	1.205	55.9
	30	1.122	46.4	0.560	4.95	46.1	1.152	53.3
	32	1.114	45.4	0.556	4.86	45.1	1.128	52.1
	34	1.102	43.7	0.561	4.97	43.6	1.101	50.8
	36	1.091	42.2	0.561	4.97	42.3	1.077	49.6
	38	1.074	39.8	0.573	5.23	40.4	1.055	48.6
	40	1.056	37.4	0.584	5.49	38.5	1.032	47.5
	42	1.023	33.2	0.583	5.47	34.7	1.007	46.3
15	44	1.004	30.9	0.569	5.15	32.3	0.979	44.9
	46	0.998	30.2	0.551	4.75	31.3	0.937	43.0

Table I.8
Discharge measurement of River Tees
Broken Scar - Low Morr Reach
of 2-1-1982

		Broken Scar G.S.		South Park G.S.		Total inflow	Low Morr G.S. (Outflow)	
Day	Time	H	Q	H	Q	Q	H	Q
	Hours	*m*	*Cumecs*	*m*	*Cumecs*	*Cumecs*	*m*	*Cumecs*
2	0	0.904	20.37	0.557	4.88	27.45	0.675	26.24
	2	0.928	22.68	0.650	7.27	33.22	0.693	27.64
	4	0.959	25.86	0.714	9.31	39.36	0.714	29.20
	6	1.090	42.03	0.765	11.16	58.21	0.749	31.69
	8	2.067	248.78	0.795	12.35	266.69	0.813	35.91
	10	2.492	380.04	0.830	13.84	406.11	0.970	44.81
	12	2.817	509.35	0.879	16.09	532.68	3.224	161.33
	14	3.012	590.80	0.914	17.62	616.35	4.314	256.05
	16	2.839	518.26	0.933	18.48	545.06	5.418	367.51
	18	2.706	465.48	0.940	18.80	492.74	5.880	416.18
	20	2.568	413.47	0.939	18.75	440.66	6.022	434.58
	22	2.366	342.48	0.935	18.57	369.41	6.081	441.35
	24	2.186	284.43	0.943	18.93	311.88	6.071	440.20
	26	2.087	254.62	0.971	20.24	283.97	6.030	435.50
	28	2.199	288.45	0.999	21.59	319.76	5.787	408.00
	30	2.533	400.73	1.034	23.32	434.54	5.515	378.00
	32	2.511	392.82	1.084	25.90	430.38	5.460	372.00
	34	2.404	355.37	1.121	27.88	395.80	5.643	392.00
	36	2.560	410.54	1.132	28.49	451.85	5.812	410.80
	38	2.466	376.86	1.128	28.27	417.85	5.858	415.90
	40	2.271	311.22	1.105	27.02	350.40	5.893	419.90
	42	2.062	247.33	1.084	25.90	284.88	5.915	422.40
	44	1.930	210.47	1.060	24.65	246.21	5.805	410.00
	46	1.823	182.61	1.036	23.42	216.57	5.483	374.50
	48	1.728	159.40	1.017	22.47	191.98	5.035	327.20
	50	1.657	143.00	0.994	21.34	173.94	4.516	275.30
	52	1.648	140.98	0.982	20.76	171.08	3.970	227.30
	54	1.669	145.71	0.983	20.81	175.88	3.553	197.70
	56	1.619	134.56	0.996	21.44	165.65	3.334	182.70
	58	1.572	124.45	1.015	22.37	156.88	3.301	180.50
	60	1.538	117.36	1.024	22.82	150.45	3.218	174.90
	62	1.507	110.07	1.026	22.92	143.39	3.090	166.40
	64	1.510	111.67	1.022	22.72	144.61	2.965	158.30
	66	1.523	114.30	1.017	22.47	146.88	2.888	153.30
	68	1.488	107.29	1.016	22.42	139.80	2.868	152.00

Table I.9
Discharge measurement of River Tees
Broken Scar - Low Morr Reach
of 25-8-1986

Day	Time	Broken Scar G.S.		South Park G.S.		Total inflow	Low Morr G.S. (Outflow)	
	Time	H	Q	H	Q	Q	H	Q
	Hours	m	Cumecs	m	Cumecs	Cumecs	m	Cumecs
25	0	0.588	4.90	0.143	0.4	5.3	0.368	5.4
	2	0.588	4.90	0.138	0.4	5.3	0.370	5.5
	4	0.594	5.00	0.138	0.4	5.4	0.376	5.7
	6	0.609	5.25	0.178	0.5	5.8	0.380	5.9
26	8	0.615	5.30	0.276	1.06	6.4	0.381	5.9
	10	0.629	5.60	0.384	1.60	7.2	0.379	5.9
	12	0.656	6.10	0.340	1.46	7.6	0.378	5.8
	14	1.670	147.3	0.315	1.29	148.6	0.388	6.2
	16	2.523	397.1	0.423	2.48	399.6	0.409	7.2
	18	3.071	616.5	0.471	3.23	619.7	0.440	8.7
	20	3.276	709.8	0.516	4.04	713.8	3.064	164.7
	22	3.114	635.6	0.658	7.31	642.9	4.626	286.0
	24	2.626	435.0	0.750	10.60	445.6	5.458	371.8
	26	2.159	276.1	0.773	11.47	287.6	5.888	419.3
	28	1.929	210.2	0.803	12.68	222.9	6.030	438.5
	30	1.764	168.0	0.820	13.40	181.4	6.085	441.8
27	32	1.653	142.1	0.828	13.75	155.8	5.895	420.1
	34	1.575	125.1	0.847	14 60	139.7	5.283	353.1
	36	1.482	106.1	0.828	13.75	119.9	4.322	256.8
	38	1.398	90.2	0.804	12.73	102.9	3.411	187.9
	40	1.322	76.8	0.781	11.79	88.6	2.770	145.7
	42	1.258	66.4	0.752	10.67	77.1	2.380	121.4
	44	1.209	58.8	0.728	9.80	68.6	2.025	100.3
	46	1.178	54.3	0.692	8.57	62.5	1.804	87.7
	48	1.170	53.1	0.679	8.16	61.3	1.571	74.9
	50	1.185	55.3	0.665	7.72	63.0	1.423	67.1
	52	1.220	60.5	0.637	6.89	67.4	1.329	62.2
	54	1.234	62.6	0.637	6.89	69.5	1.284	59.9
28	56	1.200	57.5	0.637	6.89	64.4	1.299	60.7
	58	1.149	50.1	0.631	6.72	56.8	1.347	63.1
	60	1.108	44.6	0.631	6.72	51.3	1.354	63.5
	62	1.076	40.1	0.629	6.68	46.8	1.269	59.1
	64	1.055	37.28	0.623	6.50	43.8	1.160	53.7
	66	1.031	34.2	0.608	6.10	40.3	1.067	49.2
	68	1.016	32.4	0.583	5.47	37.9	1.007	46.3
	70	1.000	30.5	0.563	5.01	35.5	0.958	44.0
	72	0.986	28.8	0.541	4.54	33.3	0.904	41.4
	74	0.977	27.4	0.520	4.12	31.5	0.886	40.3
	76	0.960	26.0	0.500	3.74	29.7	0.842	37.7
	78	0.950	24.9	0.480	3.38	28.3	0.800	35.5
29	80	0.937	23.6	0.464	3.11	26.7	0.778	33.6

Appendix II
Outputs of Computer Programs.
Table II.1
Output of M-C2 Computer Program of the Event
2-2-1981 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	6.50	
0.00	5774.0	6.50	
0.00	11548.0	6.50	
0.00	17322.0	6.50	
0.00	23096.0	6.50	
0.00	28870.0	6.50	6.50
2.00	0.0	7.27	
2.00	5774.0	6.87	
2.00	11548.0	6.70	
2.00	17322.0	6.68	
2.00	23096.0	6.59	
2.00	28870.0	6.51	7.25
4.00	0.0	9.13	
4.00	5774.0	8.22	
4.00	11548.0	7.40	
4.00	17322.0	6.96	
4.00	23096.0	6.84	
4.00	28870.0	6.72	7.42
6.00	0.0	11.70	
6.00	5774.0	10.45	
6.00	11548.0	9.55	
6.00	17322.0	8.40	
6.00	23096.0	7.52	
6.00	28870.0	7.13	7.78
8.00	0.0	72.60	
8.00	5774.0	37.34	
8.00	11548.0	21.12	
8.00	17322.0	14.65	
8.00	23096.0	11.23	
8.00	28870.0	9.17	

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Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	159.80	
10.00	5774.0	116.83	
10.00	11548.0	72.48	
10.00	17322.0	44.12	
10.00	23096.0	26.97	
10.00	28870.0	18.26	9.33
12.00	0.0	181.70	
12.00	5774.0	177.96	
12.00	11548.0	149.35	
12.00	17322.0	110.22	
12.00	23096.0	74.39	
12.00	28870.0	47.31	54.40
14.00	0.0	129.50	
14.00	5774.0	161.76	
14.00	11548.0	177.14	
14.00	17322.0	168.27	
14.00	23096.0	139.22	
14.00	28870.0	104.41	167.10
16.00	0.0	82.80	
16.00	5774.0	104.55	
16.00	11548.0	136.45	
16.00	17322.0	162.78	
16.00	23096.0	171.96	
16.00	28870.0	159.37	182.00
18.00	0.0	63.30	
18.00	5774.0	70.69	
18.00	11548.0	84.69	
18.00	17322.0	110.09	
18.00	23096.0	139.66	
18.00	28870.0	161.50	135.20

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	52.00	
20.00	5774.0	57.40	
20.00	11548.0	62.76	
20.00	17322.0	71.14	
20.00	23096.0	90.24	
20.00	28870.0	115.56	89.70
22.00	0.0	43.90	
22.00	5774.0	47.71	
22.00	11548.0	52.43	
22.00	17322.0	56.87	
22.00	23096.0	61.68	
22.00	28870.0	72.51	66.30
24.00	0.0	38.00	
24.00	5774.0	40.78	
24.00	11548.0	44.00	
24.00	17322.0	48.18	
24.00	23096.0	52.44	
24.00	28870.0	55.83	53.80
26.00	0.0	33.40	
26.00	5774.0	35.61	
26.00	11548.0	38.08	
26.00	17322.0	40.80	
26.00	23096.0	44.38	
26.00	28870.0	48.55	45.10
28.00	0.0	31.70	
28.00	5774.0	32.28	
28.00	11548.0	33.79	
28.00	17322.0	35.82	
28.00	23096.0	38.10	
28.00	28870.0	41.04	39.20

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	32.00	
30.00	5774.0	31.70	
30.00	11548.0	31.75	
30.00	17322.0	32.57	
30.00	23096.0	34.07	
30.00	28870.0	35.90	34.80
32.00	0.0	30.80	
32.00	5774.0	31.58	
32.00	11548.0	31.65	
32.00	17322.0	31.54	
32.00	23096.0	31.86	
32.00	28870.0	32.82	32.20
34.00	0.0	28.70	
34.00	5774.0	29.81	
34.00	11548.0	30.86	
34.00	17322.0	31.35	
34.00	23096.0	31.40	
34.00	28870.0	31.48	31.50
36.00	0.0	27.20	
36.00	5774.0	27.88	
36.00	11548.0	28.83	
36.00	17322.0	29.95	
36.00	23096.0	30.78	
36.00	28870.0	31.14	31.10
38.00	0.0	25.10	
38.00	5774.0	26.23	
38.00	11548.0	27.03	
38.00	17322.0	27.89	
38.00	23096.0	28.96	
38.00	28870.0	29.98	29.30

....continued Table II.1

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	22.70	
40.00	5774.0	23.92	
40.00	11548.0	25.14	
40.00	17322.0	26.11	
40.00	23096.0	26.96	
40.00	28870.0	27.96	27.70
42.00	0.0	21.30	
42.00	5774.0	21.90	
42.00	11548.0	22.87	
42.00	17322.0	24.04	
42.00	23096.0	25.11	
42.00	28870.0	26.02	25.70
44.00	0.0	20.10	
44.00	5774.0	20.70	
44.00	11548.0	21.23	
44.00	17322.0	21.98	
44.00	23096.0	23.00	
44.00	28870.0	24.09	23.50
46.00	0.0	19.10	
46.00	5774.0	19.58	
46.00	11548.0	20.15	
46.00	17322.0	20.65	
46.00	23096.0	21.24	
46.00	28870.0	22.08	21.50
48.00	0.0	18.14	
48.00	5774.0	18.62	
48.00	11548.0	19.08	
48.00	17322.0	19.62	
48.00	23096.0	20.12	
48.00	28870.0	20.62	20.00

AVERAGE RECORDED DISCHARGE = 31.03
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE=-9.21%
STANDARD DEVIATION = 4.01 %

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	5.13	
0.00	5774.0	5.12	
0.00	11548.0	5.12	
0.00	17322.0	5.12	
0.00	23096.0	5.12	
0.00	28870.0	5.12	6.44
2.00	0.0	4.85	
2.00	5774.0	5.04	
2.00	11548.0	5.10	
2.00	17322.0	5.12	
2.00	23096.0	5.12	
2.00	28870.0	5.12	6.29
4.00	0.0	4.80	
4.00	5774.0	4.85	
4.00	11548.0	4.99	
4.00	17322.0	5.06	
4.00	23096.0	5.10	
4.00	28870.0	5.12	6.44
6.00	0.0	4.72	
6.00	5774.0	4.78	
6.00	11548.0	4.84	
6.00	17322.0	4.95	
6.00	23096.0	5.03	
6.00	28870.0	5.08	6.54
8.00	0.0	4.69	
8.00	5774.0	4.72	
8.00	11548.0	4.76	
8.00	17322.0	4.83	
8.00	23096.0	4.92	
8.00	28870.0	5.00	6.39

continued Table II.2

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	4.54	
10.00	5774.0	4.65	
10.00	11548.0	4.70	
10.00	17322.0	4.75	
10.00	23096.0	4.81	
10.00	28870.0	4.89	6.14
12.00	0.0	4.20	
12.00	5774.0	4.44	
12.00	11548.0	4.59	
12.00	17322.0	4.67	
12.00	23096.0	4.73	
12.00	28870.0	4.79	5.95
14.00	0.0	4.11	
14.00	5774.0	4.19	
14.00	11548.0	4.38	
14.00	17322.0	4.53	
14.00	23096.0	4.63	
14.00	28870.0	4.70	6.10
16.00	0.0	4.14	
16.00	5774.0	4.13	
16.00	11548.0	4.19	
16.00	17322.0	4.33	
16.00	23096.0	4.47	
16.00	28870.0	4.59	6.14
18.00	0.0	4.47	
18.00	5774.0	4.24	
18.00	11548.0	4.17	
18.00	17322.0	4.20	
18.00	23096.0	4.30	
18.00	28870.0	4.43	6.00

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	4.51	
20.00	5774.0	4.46	
20.00	11548.0	4.31	
20.00	17322.0	4.21	
20.00	23096.0	4.21	
20.00	28870.0	4.28	5.76
22.00	0.0	4.59	
22.00	5774.0	4.53	
22.00	11548.0	4.47	
22.00	17322.0	4.35	
22.00	23096.0	4.26	
22.00	28870.0	4.23	5.66
24.00	0.0	4.30	
24.00	5774.0	4.49	
24.00	11548.0	4.51	
24.00	17322.0	4.47	
24.00	23096.0	4.38	
24.00	28870.0	4.29	5.57
26.00	0.0	3.81	
26.00	5774.0	4.17	
26.00	11548.0	4.39	
26.00	17322.0	4.47	
26.00	23096.0	4.46	
26.00	28870.0	4.40	5.52
28.00	0.0	3.46	
28.00	5774.0	3.73	
28.00	11548.0	4.05	
28.00	17322.0	4.29	
28.00	23096.0	4.41	
28.00	28870.0	4.44	5.85

continued Table II.2

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	3.46	
30.00	5774.0	3.48	
30.00	11548.0	3.68	
30.00	17322.0	3.95	
30.00	23096.0	4.20	
30.00	28870.0	4.35	5.90
32.00	0.0	3.75	
32.00	5774.0	3.55	
32.00	11548.0	3.52	
32.00	17322.0	3.66	
32.00	23096.0	3.88	
32.00	28870.0	4.11	5.66
34.00	0.0	4.12	
34.00	5774.0	3.85	
34.00	11548.0	3.64	
34.00	17322.0	3.57	
34.00	23096.0	3.65	
34.00	28870.0	3.83	5.29
36.00	0.0	4.50	
36.00	5774.0	4.22	
36.00	11548.0	3.95	
36.00	17322.0	3.73	
36.00	23096.0	3.63	
36.00	28870.0	3.66	4.92
38.00	0.0	4.58	
38.00	5774.0	4.50	
38.00	11548.0	4.28	
38.00	17322.0	4.03	
38.00	23096.0	3.82	
38.00	28870.0	3.69	4.97

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	4.58	
40.00	5774.0	4.58	
40.00	11548.0	4.51	
40.00	17322.0	4.33	
40.00	23096.0	4.11	
40.00	28870.0	3.90	5.29
42.00	0.0	4.82	
42.00	5774.0	4.65	
42.00	11548.0	4.59	
42.00	17322.0	4.52	
42.00	23096.0	4.37	
42.00	28870.0	4.17	5.62
44.00	0.0	5.13	
44.00	5774.0	4.90	
44.00	11548.0	4.73	
44.00	17322.0	4.63	
44.00	23096.0	4.54	
44.00	28870.0	4.41	5.90
46.00	0.0	4.98	
46.00	5774.0	5.06	
46.00	11548.0	4.94	
46.00	17322.0	4.78	
46.00	23096.0	4.67	
46.00	28870.0	4.57	5.90
48.00	0.0	4.02	
48.00	5774.0	4.69	
48.00	11548.0	4.93	
48.00	17322.0	4.92	
48.00	23096.0	4.82	
48.00	28870.0	4.71	5.85

continued Table II.2

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
50.00	0.0	3.40	
50.00	5774.0	3.88	
50.00	11548.0	4.46	
50.00	17322.0	4.78	
50.00	23096.0	4.87	
50.00	28870.0	4.82	5.76
52.00	0.0	2.74	
52.00	5774.0	3.23	
52.00	11548.0	3.73	
52.00	17322.0	4.26	
52.00	23096.0	4.63	
52.00	28870.0	4.79	6.05
54.00	0.0	2.83	
54.00	5774.0	2.81	
54.00	11548.0	3.14	
54.00	17322.0	3.59	
54.00	23096.0	4.08	
54.00	28870.0	4.47	5.90
56.00	0.0	3.13	
56.00	5774.0	2.92	
56.00	11548.0	2.87	
56.00	17322.0	3.10	
56.00	23096.0	3.48	
56.00	28870.0	3.92	5.29
58.00	0.0	3.23	
58.00	5774.0	3.15	
58.00	11548.0	2.99	
58.00	17322.0	2.93	
58.00	23096.0	3.08	
58.00	28870.0	3.39	4.88

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	3.54	
60.00	5774.0	3.32	
60.00	11548.0	3.19	
60.00	17322.0	3.05	
60.00	23096.0	2.98	
60.00	28870.0	3.07	4.18
62.00	0.0	4.81	
62.00	5774.0	3.92	
62.00	11548.0	3.50	
62.00	17322.0	3.27	
62.00	23096.0	3.11	
62.00	28870.0	3.03	4.10
64.00	0.0	5.30	
64.00	5774.0	4.88	
64.00	11548.0	4.18	
64.00	17322.0	3.69	
64.00	23096.0	3.39	
64.00	28870.0	3.19	4.52
66.00	0.0	5.84	
66.00	5774.0	5.43	
66.00	11548.0	5.00	
66.00	17322.0	4.40	
66.00	23096.0	3.89	
66.00	28870.0	3.53	4.74
68.00	0.0	6.68	
68.00	5774.0	6.07	
68.00	11548.0	5.60	
68.00	17322.0	5.13	
68.00	23096.0	4.58	
68.00	28870.0	4.07	5.11

continued Table II.2

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
70.00	0.0	6.29	
70.00	5774.0	6.51	
70.00	11548.0	6.17	
70.00	17322.0	5.74	
70.00	23096.0	5.27	
70.00	28870.0	4.76	5.85
72.00	0.0	5.60	
72.00	5774.0	6.09	
72.00	11548.0	6.35	
72.00	17322.0	6.19	
72.00	23096.0	5.84	
72.00	28870.0	5.41	6.54
74.00	0.0	5.52	
74.00	5774.0	5.61	
74.00	11548.0	5.97	
74.00	17322.0	6.22	
74.00	23096.0	6.17	
74.00	28870.0	5.90	7.09
76.00	0.0	8.41	
76.00	5774.0	6.43	
76.00	11548.0	5.90	
76.00	17322.0	5.97	
76.00	23096.0	6.13	
76.00	28870.0	6.13	8.09
78.00	0.0	18.97	
78.00	5774.0	11.55	
78.00	11548.0	7.99	
78.00	17322.0	6.56	
78.00	23096.0	6.17	
78.00	28870.0	6.14	9.13

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
80.00	0.0	37.98	
80.00	5774.0	24.29	
80.00	11548.0	15.23	
80.00	17322.0	10.13	
80.00	23096.0	7.64	
80.00	28870.0	6.63	10.50
82.00	0.0	66.27	
82.00	5774.0	45.67	
82.00	11548.0	30.21	
82.00	17322.0	19.49	
82.00	23096.0	12.85	
82.00	28870.0	9.19	15.08
84.00	0.0	81.58	
84.00	5774.0	69.31	
84.00	11548.0	51.75	
84.00	17322.0	36.04	
84.00	23096.0	24.10	
84.00	28870.0	16.06	43.38
86.00	0.0	107.94	
86.00	5774.0	88.78	
86.00	11548.0	73.91	
86.00	17322.0	57.35	
86.00	23096.0	41.69	
86.00	28870.0	28.92	80.91
88.00	0.0	126.76	
88.00	5774.0	112.20	
88.00	11548.0	94.85	
88.00	17322.0	79.06	
88.00	23096.0	62.81	
88.00	28870.0	47.22	115.57

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
90.00	0.0	149.31	
90.00	5774.0	132.58	
90.00	11548.0	117.10	
90.00	17322.0	100.47	
90.00	23096.0	84.38	
90.00	28870.0	68.24	154.02
92.00	0.0	171.13	
92.00	5774.0	154.71	
92.00	11548.0	138.19	
92.00	17322.0	122.29	
92.00	23096.0	105.93	
92.00	28870.0	89.75	181.27
94.00	0.0	186.31	
94.00	5774.0	174.48	
94.00	11548.0	159:50	
94.00	17322.0	143.50	
94.00	23096.0	127.54	
94.00	28870.0	111.31	199.89
96.00	0.0	191.29	
96.00	5774.0	186.87	
96.00	11548.0	177.08	
96.00	17322.0	163.64	
96.00	23096.0	148.45	
96.00	28870.0	132.70	215.45
98.00	0.0	184.53	
98.00	5774.0	188.80	
98.00	11548.0	186.64	
98.00	17322.0	178.93	
98.00	23096.0	167.13	
98.00	28870.0	152.96	224.79

continued Table II.2

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
100.00	0.0	155.44	
100.00	5774.0	175.79	
100.00	11548.0	184.54	
100.00	17322.0	185.33	
100.00	23096.0	179.93	
100.00	28870.0	169.93	227.35
102.00	0.0	129.65	
102.00	5774.0	149.10	
102.00	11548.0	168.18	
102.00	17322.0	179.49	
102.00	23096.0	183.04	
102.00	28870.0	180.05	215.92
104.00	0.0	122.25	
104.00	5774.0	128.99	
104.00	11548.0	144.43	
104.00	17322.0	161.71	
104.00	23096.0	174.22	
104.00	28870.0	180.03	189.63
106.00	0.0	120.87	
106.00	5774.0	122.39	
106.00	11548.0	128.24	
106.00	17322.0	140.83	
106.00	23096.0	156.24	
106.00	28870.0	169.09	163.88
108.00	0.0	110.32	
108.00	5774.0	117.70	
108.00	11548.0	121.42	
108.00	17322.0	127.17	
108.00	23096.0	137.87	
108.00	28870.0	151.58	151.63

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
110.00	0.0	94.90	
110.00	5774.0	106.12	
110.00	11548.0	114.39	
110.00	17322.0	119.71	
110.00	23096.0	125.75	
110.00	28870.0	135.24	144.38
112.00	0.0	79.58	
112.00	5774.0	91.06	
112.00	11548.0	102.11	
112.00	17322.0	111.00	
112.00	23096.0	117.50	
112.00	28870.0	123.97	128.56
114.00	0.0	68.73	
114.00	5774.0	77.16	
114.00	11548.0	87.65	
114.00	17322.0	98.34	
114.00	23096.0	107.59	
114.00	28870.0	114.95	108.19
116.00	0.0	60.48	
116.00	5774.0	66.86	
116.00	11548.0	74.83	
116.00	17322.0	84.54	
116.00	23096.0	94.81	
116.00	28870.0	104.21	90.44
118.00	0.0	54.19	
118.00	5774.0	59.05	
118.00	11548.0	65.09	
118.00	17322.0	72.61	
118.00	23096.0	81.68	
118.00	28870.0	91.50	76.87

continued Table II.2

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
120.00	0.0	49.00	
120.00	5774.0	52.98	
120.00	11548.0	57.67	
120.00	17322.0	63.41	
120.00	23096.0	70.50	
120.00	28870.0	79.02	66.76
122.00	0.0	44.13	
122.00	5774.0	47.82	
122.00	11548.0	51.76	
122.00	17322.0	56.31	
122.00	23096.0	61.79	
122.00	28870.0	68.50	59.51
124.00	0.0	40.60	
124.00	5774.0	43.34	
124.00	11548.0	46.75	
124.00	17322.0	50.58	
124.00	23096.0	54.98	
124.00	28870.0	60.23	53.49
126.00	0.0	37.42	
126.00	5774.0	39.84	
126.00	11548.0	42.54	
126.00	17322.0	45.76	
126.00	23096.0	49.45	
126.00	28870.0	53.69	48.40
128.00	0.0	35.29	
128.00	5774.0	36.96	
128.00	11548.0	39.17	
128.00	17322.0	41.76	
128.00	23096.0	44.82	
128.00	28870.0	48.36	44.45

continued Table II.2

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
130.00	0.0	33.98	
130.00	5774.0	35.02	
130.00	11548.0	36.54	
130.00	17322.0	38.57	
130.00	23096.0	41.02	
130.00	28870.0	43.93	41.28
132.00	0.0	34.82	
132.00	5774.0	34.33	
132.00	11548.0	34.90	
132.00	17322.0	36.21	
132.00	23096.0	38.04	
132.00	28870.0	40.33	38.75
134.00	0.0	37.20	
134.00	5774.0	35.52	
134.00	11548.0	34.76	
134.00	17322.0	34.99	
134.00	23096.0	35.98	
134.00	28870.0	37.59	37.37
136.00	0.0	37.32	
136.00	5774.0	37.09	
136.00	11548.0	35.95	
136.00	17322.0	35.15	
136.00	23096.0	35.12	
136.00	28870.0	35.85	38.20
138.00	0.0	35.33	
138.00	5774.0	36.68	
138.00	11548.0	36.87	
138.00	17322.0	36.17	
138.00	23096.0	35.47	
138.00	28870.0	35.29	40.24

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Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
140.00	0.0	32.80	
140.00	5774.0	34.65	
140.00	11548.0	36.06	
140.00	17322.0	36.55	
140.00	23096.0	36.23	
140.00	28870.0	35.69	40.43
142.00	0.0	30.86	
142.00	5774.0	32.35	
142.00	11548.0	34.05	
142.00	17322.0	35.47	
142.00	23096.0	36.19	
142.00	28870.0	36.17	38.48
144.00	0.0	28.82	
144.00	5774.0	30.35	
144.00	11548.0	31.87	
144.00	17322.0	33.49	
144.00	23096.0	34.91	
144.00	28870.0	35.79	35.56
146.00	0.0	26.94	
146.00	5774.0	28.36	
146.00	11548.0	29.86	
146.00	17322.0	31.37	
146.00	23096.0	32.95	
146.00	28870.0	34.37	33.34
148.00	0.0	25.78	
148.00	5774.0	26.70	
148.00	11548.0	27.97	
148.00	17322.0	29.39	
148.00	23096.0	30.89	
148.00	28870.0	32.42	31.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
150.00	0.0	24.62	
150.00	5774.0	25.50	
150.00	11548.0	26.43	
150.00	17322.0	27.61	
150.00	23096.0	28.96	
150.00	28870.0	30.42	29.13
152.00	0.0	23.72	
152.00	5774.0	24.41	
152.00	11548.0	25.24	
152.00	17322.0	26.16	
152.00	23096.0	27.27	
152.00	28870.0	28.56	27.47
154.00	0.0	23.02	
154.00	5774.0	23.56	
154.00	11548.0	24.22	
154.00	17322.0	25.00	
154.00	23096.0	25.89	
154.00	28870.0	26.95	26.09
156.00	0.0	22.89	
156.00	5774.0	23.03	
156.00	11548.0	23.45	
156.00	17322.0	24.04	
156.00	23096.0	24.77	
156.00	28870.0	25.63	25.04
158.00	0.0	24.43	
158.00	5774.0	23.38	
158.00	11548.0	23.17	
158.00	17322.0	23.41	
158.00	23096.0	23.91	
158.00	28870.0	24.58	24.49

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
160.00	0.0	26.29	
160.00	5774.0	24.92	
160.00	11548.0	23.85	
160.00	17322.0	23.41	
160.00	23096.0	23.45	
160.00	28870.0	23.82	24.33
162.00	0.0	27.30	
162.00	5774.0	26.49	
162.00	11548.0	25.32	
162.00	17322.0	24.27	
162.00	23096.0	23.68	
162.00	28870.0	23.56	25.12
164.00	0.0	26.58	
164.00	5774.0	27.01	
164.00	11548.0	26.55	
164.00	17322.0	25.62	
164.00	23096.0	24.64	
164.00	28870.0	23.97	27.71
166.00	0.0	25.35	
166.00	5774.0	26.23	
166.00	11548.0	26.73	
166.00	17322.0	26.53	
166.00	23096.0	25.82	
166.00	28870.0	24.95	29.55

AVERAGE RECORDED DISCHARGE = 87.81
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE=17.53%
STANDARD DEVIATION = 39.06 %

Table II.3
Output of M-C2 Computer Program of the Event
1-10-1981 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	13.40	
0.00	5574.0	13.40	
0.00	11148.0	13.40	
0.00	16722.0	13.40	
0.00	22296.0	13.40	
0.00	27870.0	13.40	13.10
2.00	0.0	18.60	
2.00	5574.0	15.47	
2.00	11148.0	14.22	
2.00	16722.0	13.73	
2.00	22296.0	13.53	
2.00	27870.0	13.45	14.80
4.00	0.0	25.40	
4.00	5574.0	21.42	
4.00	11148.0	17.88	
4.00	16722.0	15.69	
4.00	22296.0	14.51	
4.00	27870.0	13.92	16.40
6.00	0.0	36.30	
6.00	5574.0	29.88	
6.00	11148.0	24.91	
6.00	16722.0	20.75	
6.00	22296.0	17.75	
6.00	27870.0	15.82	18.00
8.00	0.0	66.00	
8.00	5574.0	48.34	
8.00	11148.0	37.40	
8.00	16722.0	30.02	
8.00	22296.0	24.55	
8.00	27870.0	20.52	26.50

continued Table II.3

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	104.60	
10.00	5574.0	81.99	
10.00	11148.0	62.11	
10.00	16722.0	47.49	
10.00	22296.0	37.17	
10.00	27870.0	29.71	39.10
12.00	0.0	182.30	
12.00	5574.0	136.31	
12.00	11148.0	104.30	
12.00	16722.0	79.42	
12.00	22296.0	60.55	
12.00	27870.0	46.73	72.10
14.00	0.0	225.30	
14.00	5574.0	201.08	
14.00	11148.0	163.23	
14.00	16722.0	128.63	
14.00	22296.0	99.67	
14.00	27870.0	76.61	144.40
16.00	0.0	273.10	
16.00	5574.0	245.19	
16.00	11148.0	220.01	
16.00	16722.0	187.06	
16.00	22296.0	152.92	
16.00	27870.0	121.68	204.20
18.00	0.0	310.50	
18.00	5574.0	288.99	
18.00	11148.0	263.52	
18.00	16722.0	238.51	
18.00	22296.0	208.77	
18.00	27870.0	176.26	232.10

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	308.00	
20.00	5574.0	310.30	
20.00	11148.0	298.40	
20.00	16722.0	278.30	
20.00	22296.0	255.42	
20.00	27870.0	228.50	254.00
22.00	0.0	186.80	
22.00	5574.0	259.76	
22.00	11148.0	290.66	
22.00	16722.0	296.07	
22.00	22296.0	286.21	
22.00	27870.0	268.65	271.70
24.00	0.0	132.40	
24.00	5574.0	162.49	
24.00	11148.0	219.97	
24.00	16722.0	262.38	
24.00	22296.0	283.05	
24.00	27870.0	285.60	263.00
26.00	0.0	112.70	
26.00	5574.0	123.46	
26.00	11148.0	144.86	
26.00	16722.0	188.56	
26.00	22296.0	232.28	
26.00	27870.0	262.78	207.40
28.00	0.0	101.60	
28.00	5574.0	107.89	
28.00	11148.0	116.48	
28.00	16722.0	131.97	
28.00	22296.0	164.46	
28.00	27870.0	204.21	150.40

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	98.80	
30.00	5574.0	100.25	
30.00	11148.0	104.54	
30.00	16722.0	111.17	
30.00	22296.0	122.50	
30.00	27870.0	146.32	119.50
32.00	0.0	119.80	
32.00	5574.0	107.09	
32.00	11148.0	102.81	
32.00	16722.0	103.61	
32.00	22296.0	107.74	
32.00	27870.0	115.76	104.80
34.00	0.0	154.10	
34.00	5574.0	133.90	
34.00	11148.0	117.90	
34.00	16722.0	108.78	
34.00	22296.0	105.51	
34.00	27870.0	106.56	102.40
36.00	0.0	141.80	
36.00	5574.0	149.96	
36.00	11148.0	140.87	
36.00	16722.0	127.36	
36.00	22296.0	116.28	
36.00	27870.0	109.75	126.20
38.00	0.0	121.50	
38.00	5574.0	133.43	
38.00	11148.0	143.73	
38.00	16722.0	142.51	
38.00	22296.0	133.79	
38.00	27870.0	123.48	157.20

continued Table II.3

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	96.60	
40.00	5574.0	111.17	
40.00	11148.0	124.21	
40.00	16722.0	136.02	
40.00	22296.0	140.25	
40.00	27870.0	136.74	151.80
42.00	0.0	81.70	
42.00	5574.0	90.14	
42.00	11148.0	102.33	
42.00	16722.0	115.08	
42.00	22296.0	127.54	
42.00	27870.0	135.33	122.30
44.00	0.0	72.10	
44.00	5574.0	77.57	
44.00	11148.0	84.70	
44.00	16722.0	94.85	
44.00	22296.0	106.58	
44.00	27870.0	118.93	96.10
46.00	0.0	64.00	
46.00	5574.0	68.68	
46.00	11148.0	73.78	
46.00	16722.0	79.98	
46.00	22296.0	88.51	
46.00	27870.0	98.95	79.70
48.00	0.0	56.70	
48.00	5574.0	60.93	
48.00	11148.0	65.41	
48.00	16722.0	70.22	
48.00	22296.0	75.79	
48.00	27870.0	83.07	68.70

continued Table II.3

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
50.00	0.0	51.30	
50.00	5574.0	54.40	
50.00	11148.0	58.17	
50.00	16722.0	62.35	
50.00	22296.0	66.89	
50.00	27870.0	71.99	60.40
52.00	0.0	46.80	
52.00	5574.0	49.40	
52.00	11148.0	52.27	
52.00	16722.0	55.67	
52.00	22296.0	59.53	
52.00	27870.0	63.78	53.30

AVERAGE RECORDED DISCHARGE = 105.65
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE=-17.34 %
STANDARD DEVIATION = 21.80 %

Table II.4
Output of M-C2 Computer Program of the Event
1-2-1984 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	27.80	
0.00	5574.0	27.80	
0.00	11148.0	27.80	
0.00	16722.0	27.80	
0.00	22296.0	27.80	
0.00	27870.0	27.80	30.99
2.00	0.0	26.56	
2.00	5574.0	27.37	
2.00	11148.0	27.65	
2.00	16722.0	27.75	
2.00	22296.0	27.78	
2.00	27870.0	27.79	29.71
4.00	0.0	26.11	
4.00	5574.0	26.43	
4.00	11148.0	27.06	
4.00	16722.0	27.45	
4.00	22296.0	27.65	
4.00	27870.0	27.74	28.62
6.00	0.0	26.08	
6.00	5574.0	26.11	
6.00	11148.0	26.34	
6.00	16722.0	26.82	
6.00	22296.0	27.24	
6.00	27870.0	27.51	27.38
8.00	0.0	26.58	
8.00	5574.0	26.25	
8.00	11148.0	26.17	
8.00	16722.0	26.30	
8.00	22296.0	26.66	
8.00	27870.0	27.05	27.05

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	27.22	
10.00	5574.0	26.79	
10.00	11148.0	26.43	
10.00	16722.0	26.26	
10.00	22296.0	26.30	
10.00	27870.0	26.54	27.22
12.00	0.0	28.11	
12.00	5574.0	27.51	
12.00	11148.0	27.03	
12.00	16722.0	26.63	
12.00	22296.0	26.39	
12.00	27870.0	26.34	28.54
14.00	0.0	29.41	
14.00	5574.0	28.54	
14.00	11148.0	27.85	
14.00	16722.0	27.30	
14.00	22296.0	26.85	
14.00	27870.0	26.55	30.39
16.00	0.0	31.30	
16.00	5574.0	30.03	
16.00	11148.0	29.03	
16.00	16722.0	28.24	
16.00	22296.0	27.61	
16.00	27870.0	27.10	31.76
18.00	0.0	33.42	
18.00	5574.0	31.99	
18.00	11148.0	30.67	
18.00	16722.0	29.57	
18.00	22296.0	28.67	
18.00	27870.0	27.96	32.98

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continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	36.22	
20.00	5574.0	34.34	
20.00	11148.0	32.75	
20.00	16722.0	31.35	
20.00	22296.0	30.15	
20.00	27870.0	29.16	35.82
22.00	0.0	39.26	
22.00	5574.0	37.20	
22.00	11148.0	35.27	
22.00	16722.0	33.57	
22.00	22296.0	32.08	
22.00	27870.0	30.78	38.66
24.00	0.0	43.06	
24.00	5574.0	40.50	
24.00	11148.0	38.28	
24.00	16722.0	36.25	
24.00	22296.0	34.45	
24.00	27870.0	32.85	41.09
26.00	0.0	48.82	
26.00	5574.0	44.96	
26.00	11148.0	41.96	
26.00	16722.0	39.48	
26.00	22296.0	37.30	
26.00	27870.0	35.38	44.06
28.00	0.0	56.02	
28.00	5574.0	51.17	
28.00	11148.0	47.00	
28.00	16722.0	43.61	
28.00	22296.0	40.83	
28.00	27870.0	38.45	48.59

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	64.93	
30.00	5574.0	58.93	
30.00	11148.0	53.70	
30.00	16722.0	49.20	
30.00	22296.0	45.44	
30.00	27870.0	42.34	55.15
32.00	0.0	79.39	
32.00	5574.0	69.71	
32.00	11148.0	62.47	
32.00	16722.0	56.57	
32.00	22296.0	51.61	
32.00	27870.0	47.46	62.44
34.00	0:0	93.51	
34.00	5574.0	83.93	
34.00	11148.0	74.37	
34.00	16722.0	66.37	
34.00	22296.0	59.78	
34.00	27870.0	54.29	73.94
36.00	0.0	102.85	
36.00	5574.0	96.41	
36.00	11148.0	87.92	
36.00	16722.0	78.77	
36.00	22296.0	70.42	
36.00	27870.0	63.26	93.06
38.00	0.0	105.88	
38.00	5574.0	103.69	
38.00	11148.0	98.64	
38.00	16722.0	91.31	
38.00	22296.0	82.82	
38.00	27870.0	74.45	112.45

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	103.22	
40.00	5574.0	104.90	
40.00	11148.0	103.94	
40.00	16722.0	100.23	
40.00	22296.0	94.11	
40.00	27870.0	86.43	122.14
42.00	0.0	95.75	
42.00	5574.0	100.71	
42.00	11148.0	103.43	
42.00	16722.0	103.65	
42.00	22296.0	101.21	
42.00	27870.0	96.30	124.78
44.00	0.0	87.39	
44.00	5574.0	93.03	
44.00	11148.0	98.16	
44.00	16722.0	101.62	
44.00	22296.0	102.87	
44.00	27870.0	101.62	117.88
46.00	0.0	82.71	
46.00	5574.0	85.96	
46.00	11148.0	90.77	
46.00	16722.0	95.73	
46.00	22296.0	99.63	
46.00	27870.0	101.72	106.33
48.00	0.0	82.21	
48.00	5574.0	82.64	
48.00	11148.0	84.97	
48.00	16722.0	88.93	
48.00	22296.0	93.52	
48.00	27870.0	97.60	96.35

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
50.00	0.0	83.66	
50.00	5574.0	82.72	
50.00	11148.0	82.74	
50.00	16722.0	84.33	
50.00	22296.0	87.50	
50.00	27870.0	91.58	91.18
52.00	0.0	90.65	
52.00	5574.0	86.03	
52.00	11148.0	83.86	
52.00	16722.0	83.18	
52.00	22296.0	84.04	
52.00	27870.0	86.44	91.18
54.00	0.0	113.72	
54.00	5574.0	98.43	
54.00	11148.0	90.23	
54.00	16722.0	86.03	
54.00	22296.0	84.18	
54.00	27870.0	84.16	95.34
56.00	0.0	139.80	
56.00	5574.0	122.20	
56.00	11148.0	106.34	
56.00	16722.0	95.63	
56.00	22296.0	89.27	
56.00	27870.0	85.93	109.64
58.00	0.0	152.19	
58.00	5574.0	143.50	
58.00	11148.0	129.01	
58.00	16722.0	113.79	
58.00	22296.0	101.67	
58.00	27870.0	93.42	143.35

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	145.73	
60.00	5574.0	149.69	
60.00	11148.0	145.16	
60.00	16722.0	134.08	
60.00	22296.0	120.38	
60.00	27870.0	107.84	174.41
62.00	0.0	126.45	
62.00	5574.0	139.23	
62.00	11148.0	145.95	
62.00	16722.0	145.08	
62.00	22296.0	137.42	
62.00	27870.0	125.84	180.42
64.00	0.0	107.80	
64.00	5574.0	120.45	
64.00	11148.0	132.99	
64.00	16722.0	141.47	
64.00	22296.0	143.60	
64.00	27870.0	139.18	170.83
66.00	0.0	94.11	
66.00	5574.0	103.50	
66.00	11148.0	115.02	
66.00	16722.0	127.08	
66.00	22296.0	136.59	
66.00	27870.0	141.05	144.81
68.00	0.0	82.99	
68.00	5574.0	90.59	
68.00	11148.0	99.43	
68.00	16722.0	110.05	
68.00	22296.0	121.53	
68.00	27870.0	131.56	121.31

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
70.00	0.0	75.89	
70.00	5574.0	80.79	
70.00	11148.0	87.50	
70.00	16722.0	95.67	
70.00	22296.0	105.47	
70.00	27870.0	116.33	103.97
72.00	0.0	70.55	
72.00	5574.0	74.21	
72.00	11148.0	78.74	
72.00	16722.0	84.75	
72.00	22296.0	92.23	
72.00	27870.0	101.26	91.56
74.00	0.0	66.78	
74.00	5574.0	69.37	
74.00	11148.0	72.69	
74.00	16722.0	76.86	
74.00	22296.0	82.28	
74.00	27870.0	89.10	82.59
76.00	0.0	64.79	
76.00	5574.0	66.18	
76.00	11148.0	68.38	
76.00	16722.0	71.34	
76.00	22296.0	75.13	
76.00	27870.0	80.04	75.81
78.00	0.0	64.02	
78.00	5574.0	64.57	
78.00	11148.0	65.70	
78.00	16722.0	67.55	
78.00	22296.0	70.16	
78.00	27870.0	73.58	71.75

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
80.00	0.0	68.10	
80.00	5574.0	65.44	
80.00	11148.0	64.90	
80.00	16722.0	65.48	
80.00	22296.0	66.92	
80.00	27870.0	69.16	69.24
82.00	0.0	96.13	
82.00	5574.0	77.65	
82.00	11148.0	69.62	
82.00	16722.0	66.54	
82.00	22296.0	65.89	
82.00	27870.0	66.64	68.33
84.00	0.0	131.02	
84.00	5574.0	107.53	
84.00	11148.0	87.66	
84.00	16722.0	75.72	
84.00	22296.0	69.68	
84.00	27870.0	67.22	77.34
86.00	0.0	174.41	
86.00	5574.0	145.18	
86.00	11148.0	119.84	
86.00	16722.0	98.34	
86.00	22296.0	83.31	
86.00	27870.0	74.28	117.74
88.00	0:0	207.83	
88.00	5574.0	184.96	
88.00	11148.0	158.05	
88.00	16722.0	132.29	
88.00	22296.0	109.53	
88.00	27870.0	92.03	174.32

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
90.00	0.0	227.77	
90.00	5574.0	213.95	
90.00	11148.0	194.07	
90.00	16722.0	169.61	
90.00	22296.0	144.39	
90.00	27870.0	120.95	206.58
92.00	0.0	228.72	
92.00	5574.0	227.66	
92.00	11148.0	218.03	
92.00	16722.0	201.53	
92.00	22296.0	179.77	
92.00	27870.0	155.80	228.95
94.00	0.0	169.99	
94.00	5574.0	208.50	
94.00	11148.0	220.76	
94.00	16722.0	218.44	
94.00	22296.0	206.65	
94.00	27870.0	188.25	246.08
96.00	0.0	122.96	
96.00	5574.0	155.05	
96.00	11148.0	190.52	
96.00	16722.0	210.30	
96.00	22296.0	215.27	
96.00	27870.0	209.02	241.15
98.00	0.0	99.51	
98.00	5574.0	115.92	
98.00	11148.0	142.73	
98.00	16722.0	174.73	
98.00	22296.0	198.23	
98.00	27870.0	209.21	202.05

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continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
100.00	0.0	85.24	
100.00	5574.0	95.13	
100.00	11148.0	109.63	
100.00	16722.0	132.38	
100.00	22296.0	160.92	
100.00	27870.0	185.76	155.37
102.00	0.0	75.50	
102.00	5574.0	82.21	
102.00	11148.0	91.15	
102.00	16722.0	104.00	
102.00	22296.0	123.53	
102.00	27870.0	148.86	118.42
104.00	0.0	69.11	
104.00	5574.0	73.52	
104.00	11148.0	79.51	
104.00	16722.0	87.56	
104.00	22296.0	98.97	
104.00	27870.0	115.90	99.43
106.00	0.0	65.67	
106.00	5574.0	68.07	
106.00	11148.0	71.84	
106.00	16722.0	77.13	
106.00	22296.0	84.34	
106.00	27870.0	94.48	87.46
108.00	0.0	62.88	
108.00	5574.0	64.79	
108.00	11148.0	67.06	
108.00	16722.0	70.36	
108.00	22296.0	75.03	
108.00	27870.0	81.46	80.30

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
110.00	0.0	59.33	
110.00	5574.0	61.72	
110.00	11148.0	63.81	
110.00	16722.0	66.05	
110.00	22296.0	69.03	
110.00	27870.0	73.17	76.04
112.00	0.0	57.21	
112.00	5574.0	58.68	
112.00	11148.0	60.74	
112.00	16722.0	62.82	
112.00	22296.0	65.03	
112.00	27870.0	67.79	72.44
114.00	0.0	54.32	
114.00	5574.0	56.26	
114.00	11148.0	57.91	
114.00	16722.0	59.84	
114.00	22296.0	61.87	
114.00	27870.0	64.03	68.78
116.00	0.0	53.06	
116.00	5574.0	53.95	
116.00	11148.0	55.52	
116.00	16722.0	57.15	
116.00	22296.0	58.98	
116.00	27870.0	60.94	65.31
118.00	0.0	64.38	
118.00	5574.0	56.98	
118.00	11148.0	55.04	
118.00	16722.0	55.41	
118.00	22296.0	56.61	
118.00	27870.0	58.23	61.67

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
120.00	0.0	93.65	
120.00	5574.0	74.20	
120.00	11148.0	62.84	
120.00	16722.0	57.73	
120.00	22296.0	56.24	
120.00	27870.0	56.54	60.05
122.00	0.0	96.64	
122.00	5574.0	94.06	
122.00	11148.0	80.67	
122.00	16722.0	68.80	
122.00	22296.0	61.49	
122.00	27870.0	58.06	74.99
124.00	0.0	91.23	
124.00	5574.0	94.70	
124.00	11148.0	93.85	
124.00	16722.0	84.82	
124.00	22296.0	74.07	
124.00	27870.0	65.71	106.20
126.00	0.0	89.88	
126.00	5574.0	90.88	
126.00	11148.0	93.36	
126.00	16722.0	93.39	
126.00	22296.0	87.42	
126.00	27870.0	78.40	110.98
128.00	0.0	88.84	
128.00	5574.0	89.55	
128.00	11148.0	90.50	
128.00	16722.0	92.38	
128.00	22296.0	92.85	
128.00	27870.0	89.00	105.67

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
130.00	0.0	84.95	
130.00	5574.0	87.53	
130.00	11148.0	88.89	
130.00	16722.0	90.01	
130.00	22296.0	91.58	
130.00	27870.0	92.29	103.31
132.00	0.0	79.88	
132.00	5574.0	83.29	
132.00	11148.0	86.11	
132.00	16722.0	87.97	
132.00	22296.0	89.36	
132.00	27870.0	90.84	101.75
134.00	0.0	75.79	
134.00	5574.0	78.58	
134.00	11148.0	81.76	
134.00	16722.0	84.68	
134.00	22296.0	86.88	
134.00	27870.0	88.55	97.37
136.00	0.0	71.27	
136.00	5574.0	74.33	
136.00	11148.0	77.22	
136.00	16722.0	80.29	
136.00	22296.0	83.24	
136.00	27870.0	85.68	91.81
138.00	0.0	65.74	
138.00	5574.0	69.47	
138.00	11148.0	72.75	
138.00	16722.0	75.78	
138.00	22296.0	78.84	
138.00	27870.0	81.80	86.72

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
140.00	0.0	60.29	
140.00	5574.0	63.99	
140.00	11148.0	67.69	
140.00	16722.0	71.11	
140.00	22296.0	74.27	
140.00	27870.0	77.36	81.26
142.00	0.0	54.08	
142.00	5574.0	58.27	
142.00	11148.0	62.14	
142.00	16722.0	65.89	
142.00	22296.0	69.41	
142.00	27870.0	72.70	74.76
144.00	0.0	49.60	
144.00	5574.0	52.67	
144.00	11148.0	56.47	
144.00	16722.0	60.31	
144.00	22296.0	64.08	
144.00	27870.0	67.69	67.65
146.00	0.0	46.58	
146.00	5574.0	48.66	
146.00	11148.0	51.42	
146.00	16722.0	54.86	
146.00	22296.0	58.56	
146.00	27870.0	62.30	61.24
148.00	0.0	43.75	
148.00	5574.0	45.67	
148.00	11148.0	47.72	
148.00	16722.0	50.26	
148.00	22296.0	53.39	
148.00	27870.0	56.90	55.89

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
150.00	0.0	41.35	
150.00	5574.0	42.99	
150.00	11148.0	44.82	
150.00	16722.0	46.80	
150.00	22296.0	49.17	
150.00	27870.0	52.05	52.25
152.00	0.0	39.93	
152.00	5574.0	40.91	
152.00	11148.0	42.33	
152.00	16722.0	44.03	
152.00	22296.0	45.92	
152.00	27870.0	48.15	49.29
154.00	0.0	39.11	
154.00	5574.0	39.68	
154.00	11148.0	40.53	
154.00	16722.0	41.77	
154.00	22296.0	43.31	
154.00	27870.0	45.10	46.90
156.00	0.0	38.09	
156.00	5574.0	38.78	
156.00	11148.0	39.40	
156.00	16722.0	40.18	
156.00	22296.0	41.27	
156.00	27870.0	42.67	45.13
158.00	0.0	37.23	
158.00	5574.0	37.82	
158.00	11148.0	38.47	
158.00	16722.0	39.10	
158.00	22296.0	39.85	
158.00	27870.0	40.83	44.15

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
160.00	0.0	36.81	
160.00	5574.0	37.10	
160.00	11148.0	37.59	
160.00	16722.0	38.19	
160.00	22296.0	38.81	
160.00	27870.0	39.52	43.48
162.00	0.0	36.93	
162.00	5574.0	36.86	
162.00	11148.0	37.04	
162.00	16722.0	37.42	
162.00	22296.0	37.94	
162.00	27870.0	38.54	42.42
164.00	0.0	39.30	
164.00	5574.0	37.74	
164.00	11148.0	37.17	
164.00	16722.0	37.09	
164.00	22296.0	37.32	
164.00	27870.0	37.75	42.04
166.00	0.0	49.97	
166.00	5574.0	42.92	
166.00	11148.0	39.50	
166.00	16722.0	37.97	
166.00	22296.0	37.40	
166.00	27870.0	37.36	41.75
168.00	0.0	54.52	
168.00	5574.0	51.31	
168.00	11148.0	45.69	
168.00	16722.0	41.58	
168.00	22296.0	39.19	
168.00	27870.0	38.02	43.57

continued Table II.4

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
170.00	0.0	56.72	
170.00	5574.0	55.17	
170.00	11148.0	52.46	
170.00	16722.0	47.89	
170.00	22296.0	43.67	
170.00	27870.0	40.69	52.35
172.00	0.0	53.97	
172.00	5574.0	55.73	
172.00	11148.0	55.28	
172.00	16722.0	53.28	
172.00	22296.0	49.61	
172.00	27870.0	45.62	61.13
174.00	0.0	49.05	
174.00	5574.0	52.33	
174.00	11148.0	54.55	
174.00	16722.0	54.96	
174.00	22296.0	53.74	
174.00	27870.0	50.90	63.21
176.00	0.0	44.50	
176.00	5574.0	47.59	
176.00	11148.0	50.77	
176.00	16722.0	53.26	
176.00	22296.0	54.34	
176.00	27870.0	53.86	59.62
178.00	0.0	41.06	
178.00	5574.0	43.42	
178.00	11148.0	46.26	
178.00	16722.0	49.30	
178.00	22296.0	51.94	
178.00	27870.0	53.50	54.21

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
180.00	0.0	38.97	
180.00	5574.0	40.42	
180.00	11148.0	42.48	
180.00	16722.0	45.05	
180.00	22296.0	47.93	
180.00	27870.0	50.61	49.70
182.00	0.0	37.38	
182.00	5574.0	38.47	
182.00	11148.0	39.81	
182.00	16722.0	41.64	
182.00	22296.0	43.97	
182.00	27870.0	46.65	46.60
184.00	0.0	35.49	
184.00	5574.0	36.77	
184.00	11148.0	37.93	
184.00	16722.0	39.22	
184.00	22296.0	40.89	
184.00	27870.0	43.00	44.35
186.00	0.0	34.38	
186.00	5574.0	35.15	
186.00	11148.0	36.25	
186.00	16722.0	37.39	
186.00	22296.0	38.65	
186.00	27870.0	40.18	42.61
188.00	0.0	32.55	
188.00	5574.0	33.78	
188.00	11148.0	34.71	
188.00	16722.0	35.76	
188.00	22296.0	36.87	
188.00	27870.0	38.08	40.81

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
190.00	0.0	30.93	
190.00	5574.0	32.03	
190.00	11148.0	33.21	
190.00	16722.0	34.23	
190.00	22296.0	35.27	
190.00	27870.0	36.36	39.12

AVERAGE RECORDED DISCHARGE = 76.06
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE=2.50%
STANDARD DEVIATION = 16.68 %

Table II.5
Output of M-C2 Computer Program of the Event
15-4-1986 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	23.00	
0.00	5774.0	23.00	
0.00	11548.0	23.00	
0.00	17322.0	23.00	
0.00	23096.0	23.00	
0.00	28870.0	23.00	22.00
2.00	0.0	24.10	
2.00	5774.0	23.39	
2.00	11548.0	23.14	
2.00	17322.0	23.05	
2.00	23096.0	23.02	
2.00	28870.0	23.01	22.50
4.00	0.0	29.30	
4.00	5774.0	25.95	
4.00	11548.0	24.31	
4.00	17322.0	23.56	
4.00	23096.0	23.23	
4.00	28870.0	23.09	23.40
6.00	0.0	73.20	
6.00	5774.0	44.97	
6.00	11548.0	32.74	
6.00	17322.0	27.31	
6.00	23096.0	24.90	
6.00	28870.0	23.83	23.40
8.00	0.0	121.40	
8.00	5774.0	90.05	
8.00	11548.0	60.93	
8.00	17322.0	42.75	
8.00	23096.0	32.81	
8.00	28870.0	27.71	27.80

continued Table II.5

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	161.20	
10.00	5774.0	135.19	
10.00	11548.0	105.79	
10.00	17322.0	76.73	
10.00	23096.0	54.77	
10.00	28870.0	40.60	61.70
12.00	0.0	200.60	
12.00	5774.0	174.93	
12.00	11548.0	148.99	
12.00	17322.0	120.83	
12.00	23096.0	92.20	
12.00	28870.0	67.96	145.30
14.00	0.0	251.70	
14.00	5774.0	218.52	
14.00	11548.0	190.16	
14.00	17322.0	163.32	
14.00	23096.0	135.63	
14.00	28870.0	107.39	205.90
16.00	0.0	285.00	
16.00	5774.0	263.14	
16.00	11548.0	234.08	
16.00	17322.0	205.49	
16.00	23096.0	178.02	
16.00	28870.0	150.39	237.00
18.00	0.0	302.40	
18.00	5774.0	290.91	
18.00	11548.0	272.66	
18.00	17322.0	247.48	
18.00	23096.0	220.12	
18.00	28870.0	192.69	256.90

continued Table II.5

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	258.20	
20.00	5774.0	286.41	
20.00	11548.0	289.03	
20.00	17322.0	278.15	
20.00	23096.0	258.06	
20.00	28870.0	233.31	271.70
22.00	0.0	175.20	
22.00	5774.0	228.89	
22.00	11548.0	265.85	
22.00	17322.0	280.57	
22.00	23096.0	278.73	
22.00	28870.0	265.10	277.10
24.00	0.0	132.20	
24.00	5774.0	160.59	
24.00	11548.0	204.98	
24.00	17322.0	244.27	
24.00	23096.0	267.55	
24.00	28870.0	274.52	251.80
26.00	0.0	108.90	
26.00	5774.0	124.27	
26.00	11548.0	148.23	
26.00	17322.0	185.23	
26.00	23096.0	223.47	
26.00	28870.0	251.87	192.00
28.00	0.0	93.90	
28.00	5774.0	103.75	
28.00	11548.0	117.27	
28.00	17322.0	137.69	
28.00	23096.0	168.77	
28.00	28870.0	204.30	137.40

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	84.10	
30.00	5774.0	90.53	
30.00	11548.0	99.22	
30.00	17322.0	111.11	
30.00	23096.0	128.62	
30.00	28870.0	154.91	107.80
32.00	0.0	76.80	
32.00	5774.0	81.58	
32.00	11548.0	87.46	
32.00	17322.0	95.18	
32.00	23096.0	105.66	
32.00	28870.0	120.78	89.90
34.00	0.0	71.60	
34.00	5774.0	75.01	
34.00	11548.0	79.31	
34.00	17322.0	84.65	
34.00	23096.0	91.56	
34.00	28870.0	100.83	79.00
36.00	0.0	69.00	
36.00	5774.0	70.72	
36.00	11548.0	73.53	
36.00	17322.0	77.32	
36.00	23096.0	82.13	
36.00	28870.0	88.32	71.40
38.00	0.0	67.80	
38.00	5774.0	68.60	
38.00	11548.0	70.00	
38.00	17322.0	72.32	
38.00	23096.0	75.60	
38.00	28870.0	79.88	66.40

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	66.50	
40.00	5774.0	67.35	
40.00	11548.0	68.17	
40.00	17322.0	69.38	
40.00	23096.0	71.32	
40.00	28870.0	74.13	64.00
42.00	0.0	65.40	
42.00	5774.0	66.12	
42.00	11548.0	66.92	
42.00	17322.0	67.74	
42.00	23096.0	68.82	
42.00	28870.0	70.46	63.20
44.00	0.0	63.90	
44.00	5774.0	64.87	
44.00	11548.0	65.68	
44.00	17322.0	66.49	
44.00	23096.0	67.31	
44.00	28870.0	68.30	61.70

AVERAGE RECORDED DISCHARGE = 103.57
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = -39.31 %
STANDARD DEVIATION = 33.05 %

Table II.6
Output of M-C2 Computer Program of the Event
26-8-1986 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	3.59	
0.00	5774.0	3.59	
0.00	11548.0	3.59	
0.00	17322.0	3.59	
0.00	23096.0	3.59	
0.00	28870.0	3.59	4.11
2.00	0.0	5.32	
2.00	5774.0	4.31	
2.00	11548.0	3.89	
2.00	17322.0	3.72	
2.00	23096.0	3.64	
2.00	28870.0	3.61	4.23
4.00	0.0	9.25	
4.00	5774.0	6.93	
4.00	11548.0	5.39	
4.00	17322.0	4.51	
4.00	23096.0	4.05	
4.00	28870.0	3.81	5.12
6.00	0.0	13.80	
6.00	5774.0	11.08	
6.00	11548.0	8.61	
6.00	17322.0	6.71	
6.00	23096.0	5.42	
6.00	28870.0	4.61	7.34
8.00	0.0	20.80	
8.00	5774.0	16.64	
8.00	11548.0	13.32	
8.00	17322.0	10.52	
8.00	23096.0	8.26	
8.00	28870.0	6.58	10.20

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	40.20	
10.00	5774.0	28.77	
10.00	11548.0	21.60	
10.00	17322.0	16.69	
10.00	23096.0	13.03	
10.00	28870.0	10.20	15.50
12.00	0.0	155.80	
12.00	5774.0	88.15	
12.00	11548.0	53.36	
12.00	17322.0	34.72	
12.00	23096.0	24.11	
12.00	28870.0	17.57	28.00
14.00	0.0	199.90	
14.00	5774.0	172.03	
14.00	11548.0	122.08	
14.00	17322.0	81.48	
14.00	23096.0	53.92	
14.00	28870.0	36.36	46.60
16.00	0.0	292.00	
16.00	5774.0	237.49	
16.00	11548.0	197.76	
16.00	17322.0	152.39	
16.00	23096.0	110.22	
16.00	28870.0	76.88	211.40
18.00	0.0	424.30	
18.00	5774.0	345.53	
18.00	11548.0	281.36	
18.00	17322.0	231.23	
18.00	23096.0	183.97	
18.00	28870.0	139.96	271.50

continued Table II.6

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	461.30	
20.00	5774.0	437.20	
20.00	11548.0	381.75	
20.00	17322.0	321.69	
20.00	23096.0	267.50	
20.00	28870.0	217.45	304.90
22.00	0.0	454.90	
22.00	5774.0	457.84	
22.00	11548.0	444.01	
22.00	17322.0	405.82	
22.00	23096.0	355.09	
22.00	28870.0	302.48	331.40
24.00	0.0	418.30	
24.00	5774.0	439.70	
24.00	11548.0	449.80	
24.00	17322.0	445.19	
24.00	23096.0	420.62	
24.00	28870.0	380.76	346.90
26.00	0.0	300.40	
26.00	5774.0	369.71	
26.00	11548.0	410.77	
26.00	17322.0	433.33	
26.00	23096.0	439.43	
26.00	28870.0	427.18	354.00
28.00	0.0	194.10	
28.00	5774.0	258.23	
28.00	11548.0	324.45	
28.00	17322.0	375.42	
28.00	23096.0	409.32	
28.00	28870.0	426.44	351.90

continued Table II.6

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	158.30	
30.00	5774.0	181.23	
30.00	11548.0	228.20	
30.00	17322.0	285.88	
30.00	23096.0	339.10	
30.00	28870.0	380.53	325.10
32.00	0.0	129.00	
32.00	5774.0	146.80	
32.00	11548.0	168.37	
32.00	17322.0	205.07	
32.00	23096.0	253.84	
32.00	28870.0	304.81	261.00
34.00	0.0	107.80	
34.00	5774.0	120.72	
34.00	11548.0	136.60	
34.00	17322.0	156.29	
34.00	23096.0	186.27	
34.00	28870.0	227.26	202.60
36.00	0.0	90.00	
36.00	5774.0	100.78	
36.00	11548.0	112.90	
36.00	17322.0	127.34	
36.00	23096.0	145.16	
36.00	28870.0	170.43	163.90
38.00	0.0	78.90	
38.00	5774.0	85.71	
38.00	11548.0	94.88	
38.00	17322.0	105.84	
38.00	23096.0	118.93	
38.00	28870.0	135.02	132.00

continued Table II.6

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	73.00	
40.00	5774.0	76.66	
40.00	11548.0	82.23	
40.00	17322.0	89.95	
40.00	23096.0	99.62	
40.00	28870.0	111.39	109.10

AVERAGE RECORDED DISCHARGE = 267.42
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = -14.58%
STANDARD DEVIATION = 16.11 %

Table II.7
Output of M-C2 Computer Program of the Event
13-1-1984 of River Tees

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	24.90	
0.00	6920.0	24.90	
0.00	13840.0	24.90	
0.00	20760.0	24.90	
0.00	27680.0	24.90	
0.00	34600.0	24.90	28.30
2.00	0.0	101.30	
2.00	6920.0	49.86	
2.00	13840.0	33.05	
2.00	20760.0	27.56	
2.00	27680.0	25.77	
2.00	34600.0	25.18	27.70
4.00	0.0	225.10	
4.00	6920.0	139.10	
4.00	13840.0	78.15	
4.00	20760.0	47.50	
4.00	27680.0	33.99	
4.00	34600.0	28.42	28.50
6.00	0.0	275.70	
6.00	6920.0	237.21	
6.00	13840.0	168.01	
6.00	20760.0	105.93	
6.00	27680.0	65.89	
6.00	34600.0	44.12	28.90
8.00	0.0	224.50	
8.00	6920.0	256.99	
8.00	13840.0	240.11	
8.00	20760.0	188.37	
8.00	27680.0	130.80	
8.00	34600.0	85.98	133.30

Continued Table II.7

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	156.60	
10.00	6920.0	203.99	
10.00	13840.0	238.81	
10.00	20760.0	237.02	
10.00	27680.0	201.30	
10.00	34600.0	151.53	206.90
12.00	0.0	118.80	
12.00	6920.0	146.69	
12.00	13840.0	187.06	
12.00	20760.0	221.81	
12.00	27680.0	230.22	
12.00	34600.0	208.19	231.00
14.00	0.0	97.80	
14.00	6920.0	113.37	
14.00	13840.0	137.88	
14.00	20760.0	172.78	
14.00	27680.0	206.23	
14.00	34600.0	221.25	207.90
16.00	0.0	81.60	
16.00	6920.0	93.31	
16.00	13840.0	108.08	
16.00	20760.0	129.94	
16.00	27680.0	160.51	
16.00	34600.0	192.06	161.40
18.00	0.0	69.20	
18.00	6920.0	78.15	
18.00	13840.0	89.12	
18.00	20760.0	103.01	
18.00	27680.0	122.72	
18.00	34600.0	149.79	122.40

Continued Table II.7

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	61.00	
20.00	6920.0	66.98	
20.00	13840.0	75.07	
20.00	20760.0	85.24	
20.00	27680.0	98.22	
20.00	34600.0	116.11	97.10
22.00	0.0	55.80	
22.00	6920.0	59.61	
22.00	13840.0	64.99	
22.00	20760.0	72.30	
22.00	27680.0	81.68	
22.00	34600.0	93.74	80.30
24.00	0.0	51.80	
24.00	6920.0	54.69	
24.00	13840.0	58.28	
24.00	20760.0	63.17	
24.00	27680.0	69.80	
24.00	34600.0	78.42	68.30
26.00	0.0	49.80	
26.00	6920.0	51.30	
26.00	13840.0	53.77	
26.00	20760.0	57.06	
26.00	27680.0	61.52	
26.00	34600.0	67.54	60.60
28.00	0.0	47.90	
28.00	6920.0	49.26	
28.00	13840.0	50.76	
28.00	20760.0	52.95	
28.00	27680.0	55.94	
28.00	34600.0	60.01	55.90

Continued Table II.7

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	46.10	
30.00	6920.0	47.38	
30.00	13840.0	48.72	
30.00	20760.0	50.20	
30.00	27680.0	52.21	
30.00	34600.0	54.93	53.30
32.00	0.0	45.10	
32.00	6920.0	45.84	
32.00	13840.0	46.95	
32.00	20760.0	48.22	
32.00	27680.0	49.66	
32.00	34600.0	51.52	52.10
34.00	0.0	43.60	
34.00	6920.0	44.65	
34.00	13840.0	45.51	
34.00	20760.0	46.54	
34.00	27680.0	47.74	
34.00	34600.0	49.13	50.80
36.00	0.0	42.30	
36.00	6920.0	43.23	
36.00	13840.0	44.23	
36.00	20760.0	45.14	
36.00	27680.0	46.15	
36.00	34600.0	47.29	49.60
38.00	0.0	40.40	
38.00	6920.0	41.73	
38.00	13840.0	42.79	
38.00	20760.0	43.81	
38.00	27680.0	44.76	
38.00	34600.0	45.75	48.60

Continued Table II.7

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	38.50	
40.00	6920.0	39.85	
40.00	13840.0	41.17	
40.00	20760.0	42.31	
40.00	27680.0	43.37	
40.00	34600.0	44.35	47.50
42.00	0.0	34.70	
42.00	6920.0	37.33	
42.00	13840.0	39.09	
42.00	20760.0	40.55	
42.00	27680.0	41.79	
42.00	34600.0	42.90	46.30
44.00	0.0	32.30	
44.00	6920.0	34.05	
44.00	13840.0	36.35	
44.00	20760.0	38.27	
44.00	27680.0	39.87	
44.00	34600.0	41.22	44.90
46.00	0.0	31.30	
46.00	6920.0	32.06	
46.00	13840.0	33.52	
46.00	20760.0	35.52	
46.00	27680.0	37.46	
46.00	34600.0	39.15	43.02

AVERAGE RECORDED DISCHARGE = 55.97
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE=-5.70%
STANDARD DEVIATION = 7.93 %

Table II.8
Output of M-C2 Computer Program of the Event
2-1-1982 of River Tees

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	27.45	
0.00	6920.0	27.45	
0.00	13840.0	27.45	
0.00	20760.0	27.45	
0.00	27680.0	27.45	
0.00	34600.0	27.45	26.24
2.00	0.0	33.22	
2.00	6920.0	29.83	
2.00	13840.0	28.43	
2.00	20760.0	27.85	
2.00	27680.0	27.62	
2.00	34600.0	27.52	27.64
4.00	0.0	39.36	
4.00	6920.0	35.64	
4.00	13840.0	32.18	
4.00	20760.0	29.96	
4.00	27680.0	28.71	
4.00	34600.0	28.07	29.20
6.00	0.0	58.21	
6.00	6920.0	47.01	
6.00	13840.0	40.21	
6.00	20760.0	35.42	
6.00	27680.0	32.17	
6.00	34600.0	30.12	31.69
8.00	0.0	266.69	
8.00	6920.0	143.78	
8.00	13840.0	86.67	
8.00	20760.0	59.21	
8.00	27680.0	45.12	
8.00	34600.0	37.44	35.91

Continued Table II.8

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	406.11	
10.00	6920.0	320.17	
10.00	13840.0	214.63	
10.00	20760.0	138.52	
10.00	27680.0	91.44	
10.00	34600.0	63.96	44.81
12.00	0.0	532.68	
12.00	6920.0	455.49	
12.00	13840.0	372.52	
12.00	20760.0	277.24	
12.00	27680.0	194.17	
12.00	34600.0	132.89	161.33
14.00	0.0	616.35	
14.00	6920.0	564.66	
14.00	13840.0	497.80	
14.00	20760.0	421.07	
14.00	27680.0	333.83	
14.00	34600.0	249.75	256.05
16.00	0.0	545.06	
16.00	6920.0	585.29	
16.00	13840.0	570.99	
16.00	20760.0	525.48	
16.00	27680.0	461.27	
16.00	34600.0	383.63	367.51
18.00	0.0	492.74	
18.00	6920.0	524.80	
18.00	13840.0	559.89	
18.00	20760.0	564.94	
18.00	27680.0	539.66	
18.00	34600.0	491.06	416.18

Continued Table II.8

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	440.66	
20.00	6920.0	472.31	
20.00	13840.0	504.30	
20.00	20760.0	537.14	
20.00	27680.0	552.66	
20.00	34600.0	543.44	434.58
22.00	0.0	369.41	
22.00	6920.0	412.32	
22.00	13840.0	448.62	
22.00	20760.0	482.42	
22.00	27680.0	515.09	
22.00	34600.0	536.88	441.35
24.00	0.0	311.88	
24.00	6920.0	347.09	
24.00	13840.0	386.61	
24.00	20760.0	424.16	
24.00	27680.0	459.46	
24.00	34600.0	492.87	440.20
26.00	0.0	283.97	
26.00	6920.0	301.52	
26.00	13840.0	329.59	
26.00	20760.0	364.32	
26.00	27680.0	400.64	
26.00	34600.0	436.30	435.50
28.00	0.0	319.76	
28.00	6920.0	299.29	
28.00	13840.0	301.51	
28.00	20760.0	319.14	
28.00	27680.0	346.88	
28.00	34600.0	379.64	408.00

Continued Table II.8

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	434.54	
30.00	6920.0	366.41	
30.00	13840.0	327.03	
30.00	20760.0	312.60	
30.00	27680.0	317.34	
30.00	34600.0	335.77	378.00
32.00	0.0	430.38	
32.00	6920.0	430.61	
32.00	13840.0	391.59	
32.00	20760.0	353.17	
32.00	27680.0	329.48	
32.00	34600.0	322.94	372.00
34.00	0.0	395.80	
34.00	6920.0	416.13	
34.00	13840.0	423.38	
34.00	20760.0	403.45	
34.00	27680.0	373.13	
34.00	34600.0	347.25	392.00
36.00	0.0	451.85	
36.00	6920.0	419.56	
36.00	13840.0	417.78	
36.00	20760.0	420.43	
36.00	27680.0	409.46	
36.00	34600.0	387.26	410.00
38.00	0.0	417.85	
38.00	6920.0	436.79	
38.00	13840.0	426.60	
38.00	20760.0	421.50	
38.00	27680.0	420.51	
38.00	34600.0	413.30	415.90

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	350.40	
40.00	6920.0	390.66	
40.00	13840.0	417.45	
40.00	20760.0	422.66	
40.00	27680.0	421.95	
40.00	34600.0	420.87	419.90
42.00	0.0	284.88	
42.00	6920.0	324.70	
42.00	13840.0	364.34	
42.00	20760.0	395.73	
42.00	27680.0	411.54	
42.00	34600.0	417.62	422.40
44.00	0.0	246.21	
44.00	6920.0	270.23	
44.00	13840.0	303.53	
44.00	20760.0	340.30	
44.00	27680.0	373.39	
44.00	34600.0	396.01	410.00
46.00	0.0	216.57	
46.00	6920.0	234.77	
46.00	13840.0	256.70	
46.00	20760.0	285.42	
46.00	27680.0	318.75	
46.00	34600.0	351.60	374.50
48.00	0.0	191.98	
48.00	6920.0	207.02	
48.00	13840.0	224.05	
48.00	20760.0	244.17	
48.00	27680.0	269.50	
48.00	34600.0	299.52	327.20

Continued Table II.8

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
50.00	0.0	173.94	
50.00	6920.0	185.03	
50.00	13840.0	198.51	
50.00	20760.0	214.17	
50.00	27680.0	232.63	
50.00	34600.0	255.28	275.30
52.00	0.0	171.08	
52.00	6920.0	173.12	
52.00	13840.0	180.56	
52.00	20760.0	191.62	
52.00	27680.0	205.48	
52.00	34600.0	222.17	227.30
54.00	0.0	175.88	
54.00	6920.0	173.12	
54.00	13840.0	173.36	
54.00	20760.0	177.95	
54.00	27680.0	186.44	
54.00	34600.0	198.17	197.70
56.00	0.0	165.65	
56.00	6920.0	171.57	
56.00	13840.0	172.49	
56.00	20760.0	173.15	
56.00	27680.0	176.25	
56.00	34600.0	182.62	182.70
58.00	0.0	156.88	
58.00	6920.0	162.23	
58.00	13840.0	167.75	
58.00	20760.0	170.56	
58.00	27680.0	172.18	
58.00	34600.0	174.78	180.50

Continued Table II.8

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	150.45	
60.00	6920.0	154.40	
60.00	13840.0	159.18	
60.00	20760.0	164.31	
60.00	27680.0	168.04	
60.00	34600.0	170.56	174.90
62.00	0.0	143.39	
62.00	6920.0	147.67	
62.00	13840.0	151.78	
62.00	20760.0	156.30	
62.00	27680.0	161.13	
62.00	34600.0	165.27	166.40
64.00	0.0	144.61	
64.00	6920.0	144.03	
64.00	13840.0	146.30	
64.00	20760.0	149.67	
64.00	27680.0	153.72	
64.00	34600.0	158.21	158.30
66.00	0.0	146.88	
66.00	6920.0	145.53	
66.00	13840.0	144.72	
66.00	20760.0	145.76	
66.00	27680.0	148.19	
66.00	34600.0	151.59	153.30
68.00	0.0	139.80	
68.00	6920.0	143.92	
68.00	13840.0	144.84	
68.00	20760.0	144.80	
68.00	27680.0	145.44	
68.00	34600.0	147.17	152.00

AVERAGE RECORDED DISCHARGE = 269.99
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE=-0.09%
STANDARD DEVIATION = 4.53 %

Table II.9
Output of M-C2 Computer Program of the Event
25-8-1986 of River Tees

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	5.30	
0.00	6920.0	5.30	
0.00	13840.0	5.30	
0.00	20760.0	5.30	
0.00	27680.0	5.30	
0.00	34600.0	5.30	5.40
2.00	0.0	5.30	
2.00	6920.0	5.30	
2.00	13840.0	5.30	
2.00	20760.0	5.30	
2.00	27680.0	5.30	
2.00	34600.0	5.30	5.50
4.00	0.0	5.40	
4.00	6920.0	5.34	
4.00	13840.0	5.32	
4.00	20760.0	5.31	
4.00	27680.0	5.30	
4.00	34600.0	5.30	5.70
6.00	0.0	5.80	
6.00	6920.0	5.58	
6.00	13840.0	5.45	
6.00	20760.0	5.38	
6.00	27680.0	5.34	
6.00	34600.0	5.32	5.90
8.00	0.0	6.40	
8.00	6920.0	6.07	
8.00	13840.0	5.80	
8.00	20760.0	5.60	
8.00	27680.0	5.48	
8.00	34600.0	5.40	5.90

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	7.20	
10.00	6920.0	6.76	
10.00	13840.0	6.37	
10.00	20760.0	6.05	
10.00	27680.0	5.80	
10.00	34600.0	5.62	5.90
12.00	0.0	7.60	
12.00	6920.0	7.38	
12.00	13840.0	7.03	
12.00	20760.0	6.67	
12.00	27680.0	6.32	
12.00	34600.0	6.03	5.80
14.00	0.0	148.60	
14.00	6920.0	70.29	
14.00	13840.0	35.35	
14.00	20760.0	19.62	
14.00	27680.0	12.43	
14.00	34600.0	9.04	6.20
16.00	0.0	399.60	
16.00	6920.0	260.13	
16.00	13840.0	154.67	
16.00	20760.0	88.39	
16.00	27680.0	50.19	
16.00	34600.0	29.22	7.20
18.00	0.0	619.70	
18.00	6920.0	497.34	
18.00	13840.0	365.50	
18.00	20760.0	248.35	
18.00	27680.0	159.48	
18.00	34600.0	98.77	8.70

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	713.80	
20.00	6920.0	661.43	
20.00	13840.0	570.17	
20.00	20760.0	456.40	
20.00	27680.0	340.78	
20.00	34600.0	240.03	164.70
22.00	0.0	642.90	
22.00	6920.0	682.23	
22.00	13840.0	670.59	
22.00	20760.0	614.72	
22.00	27680.0	526.69	
22.00	34600.0	423.34	286.00
24.00	0.0	445.60	
24.00	6920.0	555.21	
24.00	13840.0	625.74	
24.00	20760.0	650.60	
24.00	27680.0	630.59	
24.00	34600.0	572.79	371.80
26.00	0.0	287.60	
26.00	6920.0	375.45	
26.00	13840.0	475.35	
26.00	20760.0	558.89	
26.00	27680.0	609.80	
26.00	34600.0	621.29	419.30
28.00	0.0	222.90	
28.00	6920.0	258.91	
28.00	13840.0	323.72	
28.00	20760.0	408.01	
28.00	27680.0	491.85	
28.00	34600.0	557.37	438.50

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	181.40	
30.00	6920.0	204.48	
30.00	13840.0	234.77	
30.00	20760.0	284.25	
30.00	27680.0	353.06	
30.00	34600.0	430.20	441.80
32.00	0.0	155.80	
32.00	6920.0	170.04	
32.00	13840.0	189.19	
32.00	20760.0	214.55	
32.00	27680.0	253.32	
32.00	34600.0	308.78	420.10
34.00	0.0	139.70	
34.00	6920.0	148.65	
34.00	13840.0	160.55	
34.00	20760.0	176.48	
34.00	27680.0	197.66	
34.00	34600.0	228.62	353.10
36.00	0.0	119.90	
36.00	6920.0	130.90	
36.00	13840.0	140.77	
36.00	20760.0	151.77	
36.00	27680.0	165.51	
36.00	34600.0	183.39	256.80
38.00	0.0	102.90	
38.00	6920.0	112.35	
38.00	13840.0	122.66	
38.00	20760.0	132.73	
38.00	27680.0	143.32	
38.00	34600.0	155.66	187.90

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	88.60	
40.00	6920.0	96.55	
40.00	13840.0	105.34	
40.00	20760.0	114.97	
40.00	27680.0	124.84	
40.00	34600.0	135.11	145.70
42.00	0.0	77.10	
42.00	6920.0	83.49	
42.00	13840.0	90.75	
42.00	20760.0	98.86	
42.00	27680.0	107.82	
42.00	34600.0	117.28	121.40
44.00	0.0	68.60	
44.00	6920.0	73.33	
44.00	13840.0	78.98	
44.00	20760.0	85.53	
44.00	27680.0	92.94	
44.00	34600.0	101.21	100.30
46.00	0.0	62.50	
46.00	6920.0	65.89	
46.00	13840.0	70.03	
46.00	20760.0	75.00	
46.00	27680.0	80.85	
46.00	34600.0	87.57	87.70
48.00	0.0	61.30	
48.00	6920.0	61.97	
48.00	13840.0	64.15	
48.00	20760.0	67.42	
48.00	27680.0	71.64	
48.00	34600.0	76.76	74.90

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
50.00	0.0	63.00	
50.00	6920.0	62.06	
50.00	13840.0	62.01	
50.00	20760.0	63.20	
50.00	27680.0	65.55	
50.00	34600.0	68.93	67.10
52.00	0.0	67.40	
52.00	6920.0	64.96	
52.00	13840.0	63.35	
52.00	20760.0	62.60	
52.00	27680.0	62.94	
52.00	34600.0	64.39	62.20
54.00	0.0	69.50	
54.00	6920.0	68.33	
54.00	13840.0	66.46	
54.00	20760.0	64.73	
54.00	27680.0	63.55	
54.00	34600.0	63.21	59.90
56.00	0.0	64.40	
56.00	6920.0	67.23	
56.00	13840.0	67.84	
56.00	20760.0	67.07	
56.00	27680.0	65.77	
56.00	34600.0	64.54	60.70
58.00	0.0	56.80	
58.00	6920.0	61.02	
58.00	13840.0	64.47	
58.00	20760.0	66.34	
58.00	27680.0	66.74	
58.00	34600.0	66.20	63.10

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	51.30	
60.00	6920.0	54.36	
60.00	13840.0	58.06	
60.00	20760.0	61.62	
60.00	27680.0	64.24	
60.00	34600.0	65.63	63.50
62.00	0.0	46.80	
62.00	6920.0	49.30	
62.00	13840.0	52.11	
62.00	20760.0	55.42	
62.00	27680.0	58.87	
62.00	34600.0	61.86	59.10
64.00	0.0	43.80	
64.00	6920.0	45.47	
64.00	13840.0	47.60	
64.00	20760.0	50.11	
64.00	27680.0	53.06	
64.00	34600.0	56.29	53.70
66.00	0.0	40.30	
66.00	6920.0	42.25	
66.00	13840.0	44.04	
66.00	20760.0	46.02	
66.00	27680.0	48.29	
66.00	34600.0	50.94	49.20
68.00	0.0	37.90	
68.00	6920.0	39.23	
68.00	13840.0	40.91	
68.00	20760.0	42.65	
68.00	27680.0	44.52	
68.00	34600.0	46.62	46.30

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
70.00	0.0	35.50	
70.00	6920.0	36.83	
70.00	13840.0	38.17	
70.00	20760.0	39.69	
70.00	27680.0	41.34	
70.00	34600.0	43.11	44.00
72.00	0.0	33.30	
72.00	6920.0	34.52	
72.00	13840.0	35.81	
72.00	20760.0	37.12	
72.00	27680.0	38.55	
72.00	34600.0	40.10	41.40
74.00	0.0	31.50	
74.00	6920.0	32.50	
74.00	13840.0	33.63	
74.00	20760.0	34.84	
74.00	27680.0	36.11	
74.00	34600.0	37.47	40.30
76.00	0.0	29.70	
76.00	6920.0	30.70	
76.00	13840.0	31.70	
76.00	20760.0	32.77	
76.00	27680.0	33.92	
76.00	34600.0	35.14	37.70
78.00	0.0	28.30	
78.00	6920.0	29.08	
78.00	13840.0	29.98	
78.00	20760.0	30.94	
78.00	27680.0	31.96	
78.00	34600.0	33.05	35.50

Continued Table II.9

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
80.00	0.0	26.70	
80.00	6920.0	27.59	
80.00	13840.0	28.42	
80.00	20760.0	29.29	
80.00	27680.0	30.20	
80.00	34600.0	31.18	33.60

AVERAGE RECORDED DISCHARGE = 55.95
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE=-6.90%
STANDARD DEVIATION = 4.07 %

Table II.10
Output of VPDM1 Computer Program of the Event
13-1-1984 of River Tees

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.249E+02	
0.00	8650.0	0.249E+02	
0.00	17300.0	0.249E+02	
0.00	25950.0	0.249E+02	
0.00	34600.0	0.249E+02	
0.00	34600.0	0.249E+02	0.283E+02
2.00	0.0	0.101E+03	
2.00	8650.0	0.572E+02	
2.00	17300.0	0.375E+02	
2.00	25950.0	0.306E+02	
2.00	34600.0	0.249E+02	
2.00	34600.0	0.249E+02	0.277E+02
4.00	0.0	0.225E+03	
4.00	8650.0	0.154E+03	
4.00	17300.0	0.979E+02	
4.00	25950.0	0.685E+02	
4.00	34600.0	0.370E+02	
4.00	34600.0	0.370E+02	0.285E+02
6.00	0.0	0.276E+03	
6.00	8650.0	0.232E+03	
6.00	17300.0	0.179E+03	
6.00	25950.0	0.139E+03	
6.00	34600.0	0.981E+02	
6.00	34600.0	0.981E+02	0.289E+02
8.00	0.0	0.225E+03	
8.00	8650.0	0.253E+03	
8.00	17300.0	0.229E+03	
8.00	25950.0	0.196E+03	
8.00	34600.0	0.162E+03	
8.00	34600.0	0.162E+03	0.133E+03

Continued Table II.10

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	0.157E+03	
10.00	8650.0	0.216E+03	
10.00	17300.0	0.239E+03	
10.00	25950.0	0.227E+03	
10.00	34600.0	0.207E+03	
10.00	34600.0	0.207E+03	0.207E+03
12.00	0.0	0.119E+03	
12.00	8650.0	0.154E+03	
12.00	17300.0	0.205E+03	
12.00	25950.0	0.227E+03	
12.00	34600.0	0.229E+03	
12.00	34600.0	0.229E+03	0.231E+03
14.00	0.0	0.978E+02	
14.00	8650.0	0.980E+02	
14.00	17300.0	0.141E+03	
14.00	25950.0	0.190E+03	
14.00	34600.0	0.219E+03	
14.00	34600.0	0.219E+03	0.208E+03
16.00	0.0	0.816E+02	
16.00	8650.0	0.801E+02	
16.00	17300.0	0.786E+02	
16.00	25950.0	0.122E+03	
16.00	34600.0	0.160E+03	
16.00	34600.0	0.160E+03	0.161E+03
18.00	0.0	0.692E+02	
18.00	8650.0	0.826E+02	
18.00	17300.0	0.646E+02	
18.00	25950.0	0.739E+02	
18.00	34600.0	0.778E+02	
18.00	34600.0	0.778E+02	0.122E+03

Continued Table II.10

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	0.610E+02	
20.00	8650.0	0.765E+02	
20.00	17300.0	0.730E+02	
20.00	25950.0	0.713E+02	
20.00	34600.0	0.642E+02	
20.00	34600.0	0.642E+02	0.971E+02
22.00	0.0	0.558E+02	
22.00	8650.0	0.623E+02	
22.00	17300.0	0.696E+02	
22.00	25950.0	0.740E+02	
22.00	34600.0	0.725E+02	
22.00	34600.0	0.725E+02	0.803E+02
24.00	0.0	0.518E+02	
24.00	8650.0	0.526E+02	
24.00	17300.0	0.565E+02	
24.00	25950.0	0.658E+02	
24.00	34600.0	0.683E+02	
24.00	34600.0	0.683E+02	0.683E+02
26.00	0.0	0.498E+02	
26.00	8650.0	0.511E+02	
26.00	17300.0	0.479E+02	
26.00	25950.0	0.554E+02	
26.00	34600.0	0.548E+02	
26.00	34600.0	0.548E+02	0.606E+02
28.00	0.0	0.479E+02	
28.00	8650.0	0.523E+02	
28.00	17300.0	0.468E+02	
28.00	25950.0	0.512E+02	
28.00	34600.0	0.469E+02	
28.00	34600.0	0.469E+02	0.559E+02

Continued Table II.10

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	0.461E+02	
30.00	8650.0	0.514E+02	
30.00	17300.0	0.477E+02	
30.00	25950.0	0.515E+02	
30.00	34600.0	0.460E+02	
30.00	34600.0	0.460E+02	0.533E+02
32.00	0.0	0.451E+02	
32.00	8650.0	0.493E+02	
32.00	17300.0	0.468E+02	
32.00	25950.0	0.519E+02	
32.00	34600.0	0.468E+02	
32.00	34600.0	0.468E+02	0.521E+02
34.00	0.0	0.436E+02	
34.00	8650.0	0.476E+02	
34.00	17300.0	0.444E+02	
34.00	25950.0	0.505E+02	
34.00	34600.0	0.458E+02	
34.00	34600.0	0.458E+02	0.508E+02
36.00	0.0	0.423E+02	
36.00	8650.0	0.467E+02	
36.00	17300.0	0.425E+02	
36.00	25950.0	0.486E+02	
36.00	34600.0	0.437E+02	
36.00	34600.0	0.437E+02	0.496E+02
38.00	0.0	0.404E+02	
38.00	8650.0	0.457E+02	
38.00	17300.0	0.413E+02	
38.00	25950.0	0.471E+02	
38.00	34600.0	0.420E+02	
38.00	34600.0	0.420E+02	0.486E+02

Continued Table II.10

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	0.385E+02	
40.00	8650.0	0.439E+02	
40.00	17300.0	0.401E+02	
40.00	25950.0	0.458E+02	
40.00	34600.0	0.409E+02	
40.00	34600.0	0.409E+02	0.475E+02
42.00	0.0	0.347E+02	
42.00	8650.0	0.410E+02	
42.00	17300.0	0.381E+02	
42.00	25950.0	0.440E+02	
42.00	34600.0	0.399E+02	
42.00	34600.0	0.399E+02	0.463E+02
44.00	0.0	0.323E+02	
44.00	8650.0	0.375E+02	
44.00	17300.0	0.352E+02	
44.00	25950.0	0.412E+02	
44.00	34600.0	0.381E+02	
44.00	34600.0	0.381E+02	0.449E+02
46.00	0.0	0.313E+02	
46.00	8650.0	0.353E+02	
46.00	17300.0	0.325E+02	
46.00	25950.0	0.379E+02	
46.00	34600.0	0.356E+02	
46.00	34600.0	0.356E+02	0.430E+02

AVERAGE RECORDED DISCHARGE = 55.97 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE =7.98%
STANDARD DEVIATION = 11.35 %

Table II.11
Output of VPDM1 Computer Program of the Event
25-8-1986 of River Tees

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.530E+01	
0.00	8650.0	0.530E+01	
0.00	17300.0	0.530E+01	
0.00	25950.0	0.530E+01	
0.00	34600.0	0.530E+01	
0.00	34600.0	0.530E+01	0.540E+01
2.00	0.0	0.530E+01	
2.00	8650.0	0.530E+01	
2.00	17300.0	0.530E+01	
2.00	25950.0	0.530E+01	
2.00	34600.0	0.530E+01	
2.00	34600.0	0.530E+01	0.550E+01
4.00	0.0	0.540E+01	
4.00	8650.0	0.532E+01	
4.00	17300.0	0.530E+01	
4.00	25950.0	0.530E+01	
4.00	34600.0	0.530E+01	
4.00	34600.0	0.530E+01	0.570E+01
6.00	0.0	0.580E+01	
6.00	8650.0	0.543E+01	
6.00	17300.0	0.533E+01	
6.00	25950.0	0.531E+01	
6.00	34600.0	0.530E+01	
6.00	34600.0	0.530E+01	0.590E+01
8.00	0.0	0.640E+01	
8.00	8650.0	0.573E+01	
8.00	17300.0	0.544E+01	
8.00	25950.0	0.534E+01	
8.00	34600.0	0.531E+01	
8.00	34600.0	0.531E+01	0.590E+01

Continued Table II.11

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	0.720E+01	
10.00	8650.0	0.624E+01	
10.00	17300.0	0.568E+01	
10.00	25950.0	0.544E+01	
10.00	34600.0	0.533E+01	
10.00	34600.0	0.533E+01	0.590E+01
12.00	0.0	0.760E+01	
12.00	8650.0	0.687E+01	
12.00	17300.0	0.609E+01	
12.00	25950.0	0.565E+01	
12.00	34600.0	0.541E+01	
12.00	34600.0	0.541E+01	0.580E+01
14.00	0.0	0.149E+03	
14.00	8650.0	0.469E+02	
14.00	17300.0	0.153E+02	
14.00	25950.0	0.784E+01	
14.00	34600.0	0.559E+01	
14.00	34600.0	0.559E+01	0.620E+01
16.00	0.0	0.400E+03	
16.00	8650.0	0.263E+03	
16.00	17300.0	0.123E+03	
16.00	25950.0	0.446E+02	
16.00	34600.0	0.716E+01	
16.00	34600.0	0.716E+01	0.720E+01
18.00	0.0	0.620E+03	
18.00	8650.0	0.492E+03	
18.00	17300.0	0.373E+03	
18.00	25950.0	0.235E+03	
18.00	34600.0	0.119E+03	
18.00	34600.0	0.119E+03	0.870E+01

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	0.714E+03	
20.00	8650.0	0.630E+03	
20.00	17300.0	0.537E+03	
20.00	25950.0	0.442E+03	
20.00	34600.0	0.355E+03	
20.00	34600.0	0.355E+03	0.165E+03
22.00	0.0	0.643E+03	
22.00	8650.0	0.666E+03	
22.00	17300.0	0.624E+03	
22.00	25950.0	0.556E+03	
22.00	34600.0	0.488E+03	
22.00	34600.0	0.488E+03	0.286E+03
24.00	0.0	0.446E+03	
24.00	8650.0	0.575E+03	
24.00	17300.0	0.622E+03	
24.00	25950.0	0.608E+03	
24.00	34600.0	0.575E+03	
24.00	34600.0	0.575E+03	0.372E+03
26.00	0.0	0.288E+03	
26.00	8650.0	0.406E+03	
26.00	17300.0	0.522E+03	
26.00	25950.0	0.581E+03	
26.00	34600.0	0.601E+03	
26.00	34600.0	0.601E+03	0.419E+03
28.00	0.0	0.223E+03	
28.00	8650.0	0.248E+03	
28.00	17300.0	0.356E+03	
28.00	25950.0	0.470E+03	
28.00	34600.0	0.544E+03	
28.00	34600.0	0.544E+03	0.439E+03

Continued Table II.11

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	0.181E+03	
30.00	8650.0	0.181E+03	
30.00	17300.0	0.200E+03	
30.00	25950.0	0.300E+03	
30.00	34600.0	0.380E+03	
30.00	34600.0	0.380E+03	0.442E+03
32.00	0.0	0.156E+03	
32.00	8650.0	0.173E+03	
32.00	17300.0	0.147E+03	
32.00	25950.0	0.181E+03	
32.00	34600.0	0.183E+03	
32.00	34600.0	0.183E+03	0.420E+03
34.00	0.0	0.140E+03	
34.00	8650.0	0.165E+03	
34.00	17300.0	0.151E+03	
34.00	25950.0	0.162E+03	
34.00	34600.0	0.140E+03	
34.00	34600.0	0.140E+03	0.353E+03
36.00	0.0	0.120E+03	
36.00	8650.0	0.141E+03	
36.00	17300.0	0.145E+03	
36.00	25950.0	0.162E+03	
36.00	34600.0	0.144E+03	
36.00	34600.0	0.144E+03	0.257E+03
38.00	0.0	0.103E+03	
38.00	8650.0	0.118E+03	
38.00	17300.0	0.122E+03	
38.00	25950.0	0.148E+03	
38.00	34600.0	0.139E+03	
38.00	34600.0	0.139E+03	0.188E+03

300

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	0.886E+02	
40.00	8650.0	0.102E+03	
40.00	17300.0	0.998E+02	
40.00	25950.0	0.125E+03	
40.00	34600.0	0.119E+03	
40.00	34600.0	0.119E+03	0.146E+03
42.00	0.0	0.771E+02	
42.00	8650.0	0.910E+02	
42.00	17300.0	0.856E+02	
42.00	25950.0	0.105E+03	
42.00	34600.0	0.102E+03	
42.00	34600.0	0.102E+03	0.121E+03
44.00	0.0	0.686E+02	
44.00	8650.0	0.814E+02	
44.00	17300.0	0.773E+02	
44.00	25950.0	0.899E+02	
44.00	34600.0	0.894E+02	
44.00	34600.0	0.894E+02	0.100E+03
46.00	0.0	0.625E+02	
46.00	8650.0	0.722E+02	
46.00	17300.0	0.713E+02	
46.00	25950.0	0.791E+02	
46.00	34600.0	0.810E+02	
46.00	34600.0	0.810E+02	0.778E+02
48.00	0.0	0.613E+02	
48.00	8650.0	0.654E+02	
48.00	17300.0	0.662E+02	
48.00	25950.0	0.707E+02	
48.00	34600.0	0.741E+02	
48.00	34600.0	0.741E+02	0.749E+02

Continued Table II.11

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
50.00	0.0	0.630E+02	
50.00	8650.0	0.630E+02	
50.00	17300.0	0.631E+02	
50.00	25950.0	0.649E+02	
50.00	34600.0	0.680E+02	
50.00	34600.0	0.680E+02	0.671E+02
52.00	0.0	0.674E+02	
52.00	8650.0	0.648E+02	
52.00	17300.0	0.634E+02	
52.00	25950.0	0.626E+02	
52.00	34600.0	0.638E+02	
52.00	34600.0	0.638E+02	0.622E+02
54.00	0.0	0.695E+02	
54.00	8650.0	0.679E+02	
54.00	17300.0	0.659E+02	
54.00	25950.0	0.638E+02	
54.00	34600.0	0.629E+02	
54.00	34600.0	0.629E+02	0.599E+02
56.00	0.0	0.644E+02	
56.00	8650.0	0.678E+02	
56.00	17300.0	0.680E+02	
56.00	25950.0	0.663E+02	
56.00	34600.0	0.650E+02	
56.00	34600.0	0.650E+02	0.607E+02
58.00	0.0	0.568E+02	
58.00	8650.0	0.623E+02	
58.00	17300.0	0.665E+02	
58.00	25950.0	0.672E+02	
58.00	34600.0	0.673E+02	
58.00	34600.0	0.673E+02	0.631E+02

Continued Table II.11

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	0.513E+02	
60.00	8650.0	0.550E+02	
60.00	17300.0	0.607E+02	
60.00	25950.0	0.643E+02	
60.00	34600.0	0.668E+02	
60.00	34600.0	0.668E+02	0.635E+02
62.00	0.0	0.468E+02	
62.00	8650.0	0.492E+02	
62.00	17300.0	0.536E+02	
62.00	25950.0	0.585E+02	
62.00	34600.0	0.623E+02	
62.00	34600.0	0.623E+02	0.591E+02
64.00	0.0	0.438E+02	
64.00	8650.0	0.454E+02	
64.00	17300.0	0.478E+02	
64.00	25950.0	0.521E+02	
64.00	34600.0	0.560E+02	
64.00	34600.0	0.560E+02	0.537E+02
66.00	0.0	0.403E+02	
66.00	8650.0	0.427E+02	
66.00	17300.0	0.441E+02	
66.00	25950.0	0.469E+02	
66.00	34600.0	0.502E+02	
66.00	34600.0	0.502E+02	0.492E+02
68.00	0.0	0.379E+02	
68.00	8650.0	0.401E+02	
68.00	17300.0	0.416E+02	
68.00	25950.0	0.434E+02	
68.00	34600.0	0.458E+02	
68.00	34600.0	0.458E+02	0.463E+02

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Continued Table II.11

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
70.00	0.0	0.355E+02	
70.00	8650.0	0.376E+02	
70.00	17300.0	0.394E+02	
70.00	25950.0	0.409E+02	
70.00	34600.0	0.427E+02	
70.00	34600.0	0.427E+02	0.440E+02
72.00	0.0	0.333E+02	
72.00	8650.0	0.351E+02	
72.00	17300.0	0.371E+02	
72.00	25950.0	0.387E+02	
72.00	34600.0	0.404E+02	
72.00	34600.0	0.404E+02	0.414E+02
74.00	0.0	0.315E+02	
74.00	8650.0	0.329E+02	
74.00	17300.0	0.348E+02	
74.00	25950.0	0.365E+02	
74.00	34600.0	0.382E+02	
74.00	34600.0	0.382E+02	0.403E+02
76.00	0.0	0.297E+02	
76.00	8650.0	0.310E+02	
76.00	17300.0	0.326E+02	
76.00	25950.0	0.343E+02	
76.00	34600.0	0.361E+02	
76.00	34600.0	0.361E+02	0.377E+02
78.00	0.0	0.283E+02	
78.00	8650.0	0.294E+02	
78.00	17300.0	0.307E+02	
78.00	25950.0	0.323E+02	
78.00	34600.0	0.339E+02	
78.00	34600.0	0.339E+02	0.355E+02

Continued Table II.11

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
80.00	0.0	0.267E+02	
80.00	8650.0	0.280E+02	
80.00	17300.0	0.291E+02	
80.00	25950.0	0.304E+02	
80.00	34600.0	0.319E+02	
80.00	34600.0	0.319E+02	0.336E+02

AVERAGE RECORDED DISCHARGE = 60.71 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = -3.27 %
STANDARD DEVIATION = 9.38 %

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.274E+02	
0.00	8650.0	0.274E+02	
0.00	17300.0	0.274E+02	
0.00	25950.0	0.274E+02	
0.00	34600.0	0.274E+02	
0.00	34600.0	0.274E+02	0.262E+02
2.00	0.0	0.332E+02	
2.00	8650.0	0.291E+02	
2.00	17300.0	0.279E+02	
2.00	25950.0	0.276E+02	
2.00	34600.0	0.274E+02	
2.00	34600.0	0.274E+02	0.276E+02
4.00	0.0	0.394E+02	
4.00	8650.0	0.340E+02	
4.00	17300.0	0.302E+02	
4.00	25950.0	0.286E+02	
4.00	34600.0	0.276E+02	
4.00	34600.0	0.276E+02	0.292E+02
6.00	0.0	0.582E+02	
6.00	8650.0	0.452E+02	
6.00	17300.0	0.367E+02	
6.00	25950.0	0.320E+02	
6.00	34600.0	0.290E+02	
6.00	34600.0	0.290E+02	0.317E+02
8.00	0.0	0.267E+03	
8.00	8650.0	0.148E+03	
8.00	17300.0	0.827E+02	
8.00	25950.0	0.533E+02	
8.00	34600.0	0.335E+02	
8.00	34600.0	0.335E+02	0.359E+02

Continued Table II.12

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
10.00	0.0	0.406E+03	
10.00	8650.0	0.327E+03	
10.00	17300.0	0.230E+03	
10.00	25950.0	0.153E+03	
10.00	34600.0	0.770E+02	
10.00	34600.0	0.770E+02	0.448E+02
12.00	0.0	0.533E+03	
12.00	8650.0	0.448E+03	
12.00	17300.0	0.373E+03	
12.00	25950.0	0.300E+03	
12.00	34600.0	0.227E+03	
12.00	34600.0	0.227E+03	0.161E+03
14.00	0.0	0.616E+03	
14.00	8650.0	0.543E+03	
14.00	17300.0	0.470E+03	
14.00	25950.0	0.407E+03	
14.00	34600.0	0.343E+03	
14.00	34600.0	0.343E+03	0.256E+03
16.00	0.0	0.545E+03	
16.00	8650.0	0.573E+03	
16.00	17300.0	0.536E+03	
16.00	25950.0	0.483E+03	
16.00	34600.0	0.428E+03	
16.00	34600.0	0.428E+03	0.368E+03
18.00	0.0	0.493E+03	
18.00	8650.0	0.536E+03	
18.00	17300.0	0.551E+03	
18.00	25950.0	0.529E+03	
18.00	34600.0	0.493E+03	
18.00	34600.0	0.493E+03	0.416E+03

Continued Table II.12

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
20.00	0.0	0.441E+03	
20.00	8650.0	0.486E+03	
20.00	17300.0	0.523E+03	
20.00	25950.0	0.536E+03	
20.00	34600.0	0.527E+03	
20.00	34600.0	0.527E+03	0.435E+03
22.00	0.0	0.369E+03	
22.00	8650.0	0.423E+03	
22.00	17300.0	0.473E+03	
22.00	25950.0	0.509E+03	
22.00	34600.0	0.525E+03	
22.00	34600.0	0.525E+03	0.441E+03
24.00	0.0	0.312E+03	
24.00	8650.0	0.353E+03	
24.00	17300.0	0.407E+03	
24.00	25950.0	0.458E+03	
24.00	34600.0	0.493E+03	
24.00	34600.0	0.493E+03	0.440E+03
26.00	0.0	0.284E+03	
26.00	8650.0	0.299E+03	
26.00	17300.0	0.336E+03	
26.00	25950.0	0.390E+03	
26.00	34600.0	0.436E+03	
26.00	34600.0	0.436E+03	0.436E+03
28.00	0.0	0.320E+03	
28.00	8650.0	0.295E+03	
28.00	17300.0	0.293E+03	
28.00	25950.0	0.325E+03	
28.00	34600.0	0.359E+03	
28.00	34600.0	0.359E+03	0.408E+03

Continued Table II.12

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
30.00	0.0	0.435E+03	
30.00	8650.0	0.363E+03	
30.00	17300.0	0.316E+03	
30.00	25950.0	0.305E+03	
30.00	34600.0	0.302E+03	
30.00	34600.0	0.302E+03	0.378E+03
32.00	0.0	0.430E+03	
32.00	8650.0	0.422E+03	
32.00	17300.0	0.378E+03	
32.00	25950.0	0.341E+03	
32.00	34600.0	0.315E+03	
32.00	34600.0	0.315E+03	0.372E+03
34.00	0.0	0.396E+03	
34.00	8650.0	0.420E+03	
34.00	17300.0	0.415E+03	
34.00	25950.0	0.388E+03	
34.00	34600.0	0.364E+03	
34.00	34600.0	0.364E+03	0.392E+03
36.00	0.0	0.452E+03	
36.00	8650.0	0.423E+03	
36.00	17300.0	0.422E+03	
36.00	25950.0	0.413E+03	
36.00	34600.0	0.400E+03	
36.00	34600.0	0.400E+03	0.410E+03
38.00	0.0	0.418E+03	
38.00	8650.0	0.432E+03	
38.00	17300.0	0.427E+03	
38.00	25950.0	0.423E+03	
38.00	34600.0	0.415E+03	
38.00	34600.0	0.415E+03	0.416E+03

Continued Table II.12

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
40.00	0.0	0.350E+03	
40.00	8650.0	0.397E+03	
40.00	17300.0	0.418E+03	
40.00	25950.0	0.423E+03	
40.00	34600.0	0.423E+03	
40.00	34600.0	0.423E+03	0.420E+03
42.00	0.0	0.285E+03	
42.00	8650.0	0.331E+03	
42.00	17300.0	0.376E+03	
42.00	25950.0	0.403E+03	
42.00	34600.0	0.420E+03	
42.00	34600.0	0.420E+03	0.422E+03
44.00	0.0	0.246E+03	
44.00	8650.0	0.267E+03	
44.00	17300.0	0.310E+03	
44.00	25950.0	0.354E+03	
44.00	34600.0	0.388E+03	
44.00	34600.0	0.388E+03	0.410E+03
46.00	0.0	0.217E+03	
46.00	8650.0	0.227E+03	
46.00	17300.0	0.246E+03	
46.00	25950.0	0.287E+03	
46.00	34600.0	0.323E+03	
46.00	34600.0	0.323E+03	0.375E+03
48.00	0.0	0.192E+03	
48.00	8650.0	0.204E+03	
48.00	17300.0	0.208E+03	
48.00	25950.0	0.230E+03	
48.00	34600.0	0.249E+03	
48.00	34600.0	0.249E+03	0.327E+03

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Continued Table II.12

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
50.00	0.0	0.174E+03	
50.00	8650.0	0.186E+03	
50.00	17300.0	0.190E+03	
50.00	25950.0	0.200E+03	
50.00	34600.0	0.207E+03	
50.00	34600.0	0.207E+03	0.275E+03
52.00	0.0	0.171E+03	
52.00	8650.0	0.174E+03	
52.00	17300.0	0.177E+03	
52.00	25950.0	0.185E+03	
52.00	34600.0	0.188E+03	
52.00	34600.0	0.188E+03	0.227E+03
54.00	0.0	0.176E+03	
54.00	8650.0	0.173E+03	
54.00	17300.0	0.171E+03	
54.00	25950.0	0.176E+03	
54.00	34600.0	0.175E+03	
54.00	34600.0	0.175E+03	0.198E+03
56.00	0.0	0.166E+03	
56.00	8650.0	0.173E+03	
56.00	17300.0	0.170E+03	
56.00	25950.0	0.173E+03	
56.00	34600.0	0.169E+03	
56.00	34600.0	0.169E+03	0.183E+03
58.00	0.0	0.157E+03	
58.00	8650.0	0.164E+03	
58.00	17300.0	0.166E+03	
58.00	25950.0	0.172E+03	
58.00	34600.0	0.168E+03	
58.00	34600.0	0.168E+03	0.181E+03

Continued Table II.12

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	0.150E+03	
60.00	8650.0	0.155E+03	
60.00	17300.0	0.157E+03	
60.00	25950.0	0.166E+03	
60.00	34600.0	0.164E+03	
60.00	34600.0	0.164E+03	0.175E+03
62.00	0.0	0.143E+03	
62.00	8650.0	0.148E+03	
62.00	17300.0	0.148E+03	
62.00	25950.0	0.157E+03	
62.00	34600.0	0.154E+03	
62.00	34600.0	0.154E+03	0.166E+03
64.00	0.0	0.145E+03	
64.00	8650.0	0.146E+03	
64.00	17300.0	0.142E+03	
64.00	25950.0	0.151E+03	
64.00	34600.0	0.144E+03	
64.00	34600.0	0.144E+03	0.158E+03
66.00	0.0	0.147E+03	
66.00	8650.0	0.149E+03	
66.00	17300.0	0.142E+03	
66.00	25950.0	0.149E+03	
66.00	34600.0	0.138E+03	
66.00	34600.0	0.138E+03	0.153E+03
68.00	0.0	0.140E+03	
68.00	8650.0	0.148E+03	
68.00	17300.0	0.143E+03	
68.00	25950.0	0.150E+03	
68.00	34600.0	0.137E+03	
68.00	34600.0	0.137E+03	0.152E+03

AVERAGE RECORDED DISCHARGE = 269.99 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = 4.96%
STANDARD DEVIATION = 11.85 %

Table II.13
Output of VPDM1 Computer Program of the Event
1-10-1981 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.134E+02	
0.00	9623.3	0.134E+02	
0.00	19246.7	0.134E+02	
0.00	28870.0	0.134E+02	
0.00	28870.0	0.134E+02	0.131E+02
2.00	0.0	0.186E+02	
2.00	9623.3	0.153E+02	
2.00	19246.7	0.142E+02	
2.00	28870.0	0.134E+02	
2.00	28870.0	0.134E+02	0.148E+02
4.00	0.0	0.254E+02	
4.00	9623.3	0.207E+02	
4.00	19246.7	0.174E+02	
4.00	28870.0	0.149E+02	
4.00	28870.0	0.149E+02	0.164E+02
6.00	0.0	0.363E+02	
6.00	9623.3	0.300E+02	
6.00	19246.7	0.246E+02	
6.00	28870.0	0.200E+02	
6.00	28870.0	0.200E+02	0.180E+02
8.00	0.0	0.660E+02	
8.00	9623.3	0.500E+02	
8.00	19246.7	0.398E+02	
8.00	28870.0	0.298E+02	
8.00	28870.0	0.298E+02	0.265E+02
10.00	0.0	0.105E+03	
10.00	9623.3	0.848E+02	
10.00	19246.7	0.691E+02	
10.00	28870.0	0.522E+02	
10.00	28870.0	0.522E+02	0.391E+02

Continued Table II.13

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
12.00	0.0	0.182E+03	
12.00	9623.3	0.137E+03	
12.00	19246.7	0.113E+03	
12.00	28870.0	0.873E+02	
12.00	28870.0	0.873E+02	0.721E+02
14.00	0.0	0.225E+03	
14.00	9623.3	0.188E+03	
14.00	19246.7	0.159E+03	
14.00	28870.0	0.132E+03	
14.00	28870.0	0.132E+03	0.144E+03
16.00	0.0	0.273E+03	
16.00	9623.3	0.221E+03	
16.00	19246.7	0.193E+03	
16.00	28870.0	0.169E+03	
16.00	28870.0	0.169E+03	0.204E+03
18.00	0.0	0.311E+03	
18.00	9623.3	0.261E+03	
18.00	19246.7	0.220E+03	
18.00	28870.0	0.193E+03	
18.00	28870.0	0.193E+03	0.232E+03
20.00	0.0	0.308E+03	
20.00	9623.3	0.295E+03	
20.00	19246.7	0.252E+03	
20.00	28870.0	0.215E+03	
20.00	28870.0	0.215E+03	0.254E+03
22.00	0.0	0.187E+03	
22.00	9623.3	0.277E+03	
22.00	19246.7	0.275E+03	
22.00	28870.0	0.248E+03	
22.00	28870.0	0.248E+03	0.272E+03

Continued Table II.13

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
24.00	0.0	0.132E+03	
24.00	9623.3	0.219E+03	
24.00	19246.7	0.265E+03	
24.00	28870.0	0.271E+03	
24.00	28870.0	0.271E+03	0.263E+03
26.00	0.0	0.113E+03	
26.00	9623.3	0.154E+03	
26.00	19246.7	0.225E+03	
26.00	28870.0	0.261E+03	
26.00	28870.0	0.261E+03	0.207E+03
28.00	0.0	0.102E+03	
28.00	9623.3	0.776E+02	
28.00	19246.7	0.159E+03	
28.00	28870.0	0.228E+03	
28.00	28870.0	0.228E+03	0.150E+03
30.00	0.0	0.988E+02	
30.00	9623.3	0.653E+02	
30.00	19246.7	0.760E+02	
30.00	28870.0	0.880E+02	
30.00	28870.0	0.880E+02	0.120E+03
32.00	0.0	0.120E+03	
32.00	9623.3	0.100E+03	
32.00	19246.7	0.812E+02	
32.00	28870.0	0.667E+02	
32.00	28870.0	0.667E+02	0.105E+03
34.00	0.0	0.154E+03	
34.00	9623.3	0.136E+03	
34.00	19246.7	0.117E+03	
34.00	28870.0	0.102E+03	
34.00	28870.0	0.102E+03	0.102E+03

Continued Table II.13

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
36.00	0.0	0.142E+03	
36.00	9623.3	0.151E+03	
36.00	19246.7	0.141E+03	
36.00	28870.0	0.132E+03	
36.00	28870.0	0.132E+03	0.126E+03
38.00	0.0	0.122E+03	
38.00	9623.3	0.140E+03	
38.00	19246.7	0.146E+03	
38.00	28870.0	0.147E+03	
38.00	28870.0	0.147E+03	0.157E+03
40.00	0.0	0.966E+02	
40.00	9623.3	0.113E+03	
40.00	19246.7	0.130E+03	
40.00	28870.0	0.142E+03	
40.00	28870.0	0.142E+03	0.152E+03
42.00	0.0	0.817E+02	
42.00	9623.3	0.881E+02	
42.00	19246.7	0.103E+03	
42.00	28870.0	0.115E+03	
42.00	28870.0	0.115E+03	0.122E+03
44.00	0.0	0.721E+02	
44.00	9623.3	0.739E+02	
44.00	19246.7	0.824E+02	
44.00	28870.0	0.900E+02	
44.00	28870.0	0.900E+02	0.961E+02
46.00	0.0	0.640E+02	
46.00	9623.3	0.661E+02	
46.00	19246.7	0.707E+02	
46.00	28870.0	0.750E+02	
46.00	28870.0	0.750E+02	0.797E+02

Continued Table II.13

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
48.00	0.0	0.567E+02	
48.00	9623.3	0.599E+02	
48.00	19246.7	0.634E+02	
48.00	28870.0	0.667E+02	
48.00	28870.0	0.667E+02	0.687E+02
50.00	0.0	0.513E+02	
50.00	9623.3	0.540E+02	
50.00	19246.7	0.572E+02	
50.00	28870.0	0.604E+02	
50.00	28870.0	0.604E+02	0.604E+02
52.00	0.0	0.468E+02	
52.00	9623.3	0.490E+02	
52.00	19246.7	0.517E+02	
52.00	28870.0	0.544E+02	
52.00	28870.0	0.544E+02	0.533E+02

AVERAGE RECORDED DISCHARGE = 105.65 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE =-6.07%
STANDARD DEVIATION = 24.62 %

Table II.14
Output of VPDM1 Computer Program of the Event
26-8-1986 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.359E+01	
0.00	9623.3	0.359E+01	
0.00	19246.7	0.359E+01	
0.00	28870.0	0.359E+01	
0.00	28870.0	0.359E+01	0.411E+01
2.00	0.0	0.532E+01	
2.00	9623.3	0.414E+01	
2.00	19246.7	0.378E+01	
2.00	28870.0	0.359E+01	
2.00	28870.0	0.359E+01	0.423E+01
4.00	0.0	0.925E+01	
4.00	9623.3	0.630E+01	
4.00	19246.7	0.483E+01	
4.00	28870.0	0.391E+01	
4.00	28870.0	0.391E+01	0.512E+01
6.00	0.0	0.138E+02	
6.00	9623.3	0.104E+02	
6.00	19246.7	0.754E+01	
6.00	28870.0	0.544E+01	
6.00	28870.0	0.544E+01	0.734E+01
8.00	0.0	0.208E+02	
8.00	9623.3	0.164E+02	
8.00	19246.7	0.124E+02	
8.00	28870.0	0.901E+01	
8.00	28870.0	0.901E+01	0.102E+02
10.00	0.0	0.402E+02	
10.00	9623.3	0.289E+02	
10.00	19246.7	0.216E+02	
10.00	28870.0	0.151E+02	
10.00	28870.0	0.151E+02	0.155E+02

Continued Table II.14

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
12.00	0.0	0.156E+03	
12.00	9623.3	0.924E+02	
12.00	19246.7	0.628E+02	
12.00	28870.0	0.285E+02	
12.00	28870.0	0.285E+02	0.280E+02
14.00	0.0	0.200E+03	
14.00	9623.3	0.166E+03	
14.00	19246.7	0.133E+03	
14.00	28870.0	0.951E+02	
14.00	28870.0	0.951E+02	0.466E+02
16.00	0.0	0.292E+03	
16.00	9623.3	0.214E+03	
16.00	19246.7	0.183E+03	
16.00	28870.0	0.152E+03	
16.00	28870.0	0.152E+03	0.211E+03
18.00	0.0	0.424E+03	
18.00	9623.3	0.291E+03	
18.00	19246.7	0.222E+03	
18.00	28870.0	0.185E+03	
18.00	28870.0	0.185E+03	0.272E+03
20.00	0.0	0.461E+03	
20.00	9623.3	0.390E+03	
20.00	19246.7	0.289E+03	
20.00	28870.0	0.217E+03	
20.00	28870.0	0.217E+03	0.305E+03
22.00	0.0	0.455E+03	
22.00	9623.3	0.445E+03	
22.00	19246.7	0.374E+03	
22.00	28870.0	0.294E+03	
22.00	28870.0	0.294E+03	0.331E+03

Continued Table II.14

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
24.00	0.0	0.418E+03	
24.00	9623.3	0.451E+03	
24.00	19246.7	0.429E+03	
24.00	28870.0	0.376E+03	
24.00	28870.0	0.376E+03	0.347E+03
26.00	0.0	0.300E+03	
26.00	9623.3	0.401E+03	
26.00	19246.7	0.434E+03	
26.00	28870.0	0.423E+03	
26.00	28870.0	0.423E+03	0.354E+03
28.00	0.0	0.194E+03	
28.00	9623.3	0.307E+03	
28.00	19246.7	0.389E+03	
28.00	28870.0	0.425E+03	
28.00	28870.0	0.425E+03	0.352E+03
30.00	0.0	0.158E+03	
30.00	9623.3	0.225E+03	
30.00	19246.7	0.314E+03	
30.00	28870.0	0.374E+03	
30.00	28870.0	0.374E+03	0.325E+03
32.00	0.0	0.129E+03	
32.00	9623.3	0.165E+03	
32.00	19246.7	0.241E+03	
32.00	28870.0	0.305E+03	
32.00	28870.0	0.305E+03	0.261E+03
34.00	0.0	0.108E+03	
34.00	9623.3	0.890E+02	
34.00	19246.7	0.177E+03	
34.00	28870.0	0.247E+03	
34.00	28870.0	0.247E+03	0.203E+03

Continued Table II.14

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
36.00	0.0	0.900E+02	
36.00	9623.3	0.616E+02	
36.00	19246.7	0.884E+02	
36.00	28870.0	0.100E+03	
36.00	28870.0	0.100E+03	0.164E+03
38.00	0.0	0.787E+02	
38.00	9623.3	0.684E+02	
38.00	19246.7	0.712E+02	
38.00	28870.0	0.652E+02	
38.00	28870.0	0.652E+02	0.132E+03
40.00	0.0	0.730E+02	
40.00	9623.3	0.716E+02	
40.00	19246.7	0.755E+02	
40.00	28870.0	0.659E+02	
40.00	28870.0	0.659E+02	0.109E+03

AVERAGE RECORDED DISCHARGE = 267.42 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = -7.52 %
STANDARD DEVIATION = 20.13 %

Table II.15
Output of VPDM1 Computer Program of the Event
15-4-1986 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.228E+02	
0.00	9623.3	0.228E+02	
0.00	19246.7	0.228E+02	
0.00	28870.0	0.228E+02	
0.00	28870.0	0.228E+02	0.215E+02
2.00	0.0	0.235E+02	
2.00	9623.3	0.231E+02	
2.00	19246.7	0.229E+02	
2.00	28870.0	0.228E+02	
2.00	28870.0	0.228E+02	0.224E+02
4.00	0.0	0.246E+02	
4.00	9623.3	0.239E+02	
4.00	19246.7	0.234E+02	
4.00	28870.0	0.230E+02	
4.00	28870.0	0.230E+02	0.234E+02
6.00	0.0	0.383E+02	
6.00	9623.3	0.300E+02	
6.00	19246.7	0.268E+02	
6.00	28870.0	0.238E+02	
6.00	28870.0	0.238E+02	0.234E+02
8.00	0.0	0.925E+02	
8.00	9623.3	0.616E+02	
8.00	19246.7	0.462E+02	
8.00	28870.0	0.299E+02	
8.00	28870.0	0.299E+02	0.249E+02
10.00	0.0	0.141E+03	
10.00	9623.3	0.114E+03	
10.00	19246.7	0.913E+02	
10.00	28870.0	0.651E+02	
10.00	28870.0	0.651E+02	0.346E+02

Continued Table II.15

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
12.00	0.0	0.180E+03	
12.00	9623.3	0.156E+03	
12.00	19246.7	0.136E+03	
12.00	28870.0	0.113E+03	
12.00	28870.0	0.113E+03	0.104E+03
14.00	0.0	0.223E+03	
14.00	9623.3	0.189E+03	
14.00	19246.7	0.168E+03	
14.00	28870.0	0.148E+03	
14.00	28870.0	0.148E+03	0.182E+03
16.00	0.0	0.272E+03	
16.00	9623.3	0.220E+03	
16.00	19246.7	0.193E+03	
16.00	28870.0	0.174E+03	
16.00	28870.0	0.174E+03	0.224E+03
18.00	0.0	0.296E+03	
18.00	9623.3	0.255E+03	
18.00	19246.7	0.218E+03	
18.00	28870.0	0.194E+03	
18.00	28870.0	0.194E+03	0.248E+03
20.00	0.0	0.299E+03	
20.00	9623.3	0.284E+03	
20.00	19246.7	0.246E+03	
20.00	28870.0	0.214E+03	
20.00	28870.0	0.214E+03	0.265E+03
22.00	0.0	0.214E+03	
22.00	9623.3	0.277E+03	
22.00	19246.7	0.269E+03	
22.00	28870.0	0.242E+03	
22.00	28870.0	0.242E+03	0.279E+03

Continued Table II.15

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
24.00	0.0	0.150E+03	
24.00	9623.3	0.230E+03	
24.00	19246.7	0.265E+03	
24.00	28870.0	0.265E+03	
24.00	28870.0	0.265E+03	0.270E+03
26.00	0.0	0.120E+03	
26.00	9623.3	0.178E+03	
26.00	19246.7	0.234E+03	
26.00	28870.0	0.261E+03	
26.00	28870.0	0.261E+03	0.223E+03
28.00	0.0	0.101E+03	
28.00	9623.3	0.960E+02	
28.00	19246.7	0.184E+03	
28.00	28870.0	0.235E+03	
28.00	28870.0	0.235E+03	0.164E+03
30.00	0.0	0.884E+02	
30.00	9623.3	0.562E+02	
30.00	19246.7	0.100E+03	
30.00	28870.0	0.107E+03	
30.00	28870.0	0.107E+03	0.120E+03
32.00	0.0	0.802E+02	
32.00	9623.3	0.541E+02	
32.00	19246.7	0.782E+02	
32.00	28870.0	0.444E+02	
32.00	28870.0	0.444E+02	0.975E+02
34.00	0.0	0.739E+02	
34.00	9623.3	0.516E+02	
34.00	19246.7	0.842E+02	
34.00	28870.0	0.432E+02	
34.00	28870.0	0.432E+02	0.839E+02

Continued Table II.15

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
36.00	0.0	0.700E+02	
36.00	9623.3	0.407E+02	
36.00	19246.7	0.841E+02	
36.00	28870.0	0.399E+02	
36.00	28870.0	0.399E+02	0.748E+02
38.00	0.0	0.682E+02	
38.00	9623.3	0.307E+02	
38.00	19246.7	0.776E+02	
38.00	28870.0	0.336E+02	
38.00	28870.0	0.336E+02	0.687E+02
40.00	0.0	0.674E+02	
40.00	9623.3	0.268E+02	
40.00	19246.7	0.698E+02	
40.00	28870.0	0.294E+02	
40.00	28870.0	0.294E+02	0.650E+02
42.00	0.0	0.659E+02	
42.00	9623.3	0.280E+02	
42.00	19246.7	0.645E+02	
42.00	28870.0	0.279E+02	
42.00	28870.0	0.279E+02	0.637E+02
44.00	0.0	0.648E+02	
44.00	9623.3	0.313E+02	
44.00	19246.7	0.628E+02	
44.00	28870.0	0.285E+02	
44.00	28870.0	0.285E+02	0.626E+02

AVERAGE RECORDED DISCHARGE = 113.62 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = 0.95%
STANDARD DEVIATION = 34.85 %

Table II.16
Output of VPDM1 Computer Program of the Event
1-3-1986 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.513E+01	
0.00	9623.3	0.513E+01	
0.00	19246.7	0.513E+01	
0.00	28870.0	0.513E+01	
0.00	28870.0	0.513E+01	0.644E+01
2.00	0.0	0.485E+01	
2.00	9623.3	0.505E+01	
2.00	19246.7	0.510E+01	
2.00	28870.0	0.513E+01	
2.00	28870.0	0.513E+01	0.629E+01
4.00	0.0	0.480E+01	
4.00	9623.3	0.492E+01	
4.00	19246.7	0.503E+01	
4.00	28870.0	0.510E+01	
4.00	28870.0	0.510E+01	0.644E+01
6.00	0.0	0.472E+01	
6.00	9623.3	0.480E+01	
6.00	19246.7	0.492E+01	
6.00	28870.0	0.502E+01	
6.00	28870.0	0.502E+01	0.654E+01
8.00	0.0	0.469E+01	
8.00	9623.3	0.471E+01	
8.00	19246.7	0.480E+01	
8.00	28870.0	0.490E+01	
8.00	28870.0	0.490E+01	0.639E+01
10.00	0.0	0.454E+01	
10.00	9623.3	0.464E+01	
10.00	19246.7	0.470E+01	
10.00	28870.0	0.479E+01	
10.00	28870.0	0.479E+01	0.614E+01

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
12.00	0.0	0.420E+01	
12.00	9623.3	0.448E+01	
12.00	19246.7	0.460E+01	
12.00	28870.0	0.469E+01	
12.00	28870.0	0.469E+01	0.595E+01
14.00	0.0	0.411E+01	
14.00	9623.3	0.427E+01	
14.00	19246.7	0.445E+01	
14.00	28870.0	0.459E+01	
14.00	28870.0	0.459E+01	0.610E+01
16.00	0.0	0.414E+01	
16.00	9623.3	0.414E+01	
16.00	19246.7	0.428E+01	
16.00	28870.0	0.443E+01	
16.00	28870.0	0.443E+01	0.614E+01
18.00	0.0	0.447E+01	
18.00	9623.3	0.418E+01	
18.00	19246.7	0.418E+01	
18.00	28870.0	0.427E+01	
18.00	28870.0	0.427E+01	0.600E+01
20.00	0.0	0.451E+01	
20.00	9623.3	0.435E+01	
20.00	19246.7	0.420E+01	
20.00	28870.0	0.418E+01	
20.00	28870.0	0.418E+01	0.576E+01
22.00	0.0	0.459E+01	
22.00	9623.3	0.450E+01	
22.00	19246.7	0.433E+01	
22.00	28870.0	0.421E+01	
22.00	28870.0	0.421E+01	0.566E+01

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
24.00	0.0	0.430E+01	
24.00	9623.3	0.453E+01	
24.00	19246.7	0.446E+01	
24.00	28870.0	0.435E+01	
24.00	28870.0	0.435E+01	0.557E+01
26.00	0.0	0.381E+01	
26.00	9623.3	0.430E+01	
26.00	19246.7	0.446E+01	
26.00	28870.0	0.447E+01	
26.00	28870.0	0.447E+01	0.552E+01
28.00	0.0	0.346E+01	
28.00	9623.3	0.390E+01	
28.00	19246.7	0.427E+01	
28.00	28870.0	0.445E+01	
28.00	28870.0	0.445E+01	0.585E+01
30.00	0.0	0.346E+01	
30.00	9623.3	0.356E+01	
30.00	19246.7	0.393E+01	
30.00	28870.0	0.424E+01	
30.00	28870.0	0.424E+01	0.590E+01
32.00	0.0	0.375E+01	
32.00	9623.3	0.347E+01	
32.00	19246.7	0.363E+01	
32.00	28870.0	0.390E+01	
32.00	28870.0	0.390E+01	0.566E+01
34.00	0.0	0.412E+01	
34.00	9623.3	0.366E+01	
34.00	19246.7	0.353E+01	
34.00	28870.0	0.361E+01	
34.00	28870.0	0.361E+01	0.529E+01

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
36.00	0.0	0.450E+01	
36.00	9623.3	0.405E+01	
36.00	19246.7	0.368E+01	
36.00	28870.0	0.353E+01	
36.00	28870.0	0.353E+01	0.492E+01
38.00	0.0	0.458E+01	
38.00	9623.3	0.443E+01	
38.00	19246.7	0.402E+01	
38.00	28870.0	0.370E+01	
38.00	28870.0	0.370E+01	0.497E+01
40.00	0.0	0.458E+01	
40.00	9623.3	0.464E+01	
40.00	19246.7	0.438E+01	
40.00	28870.0	0.406E+01	
40.00	28870.0	0.406E+01	0.529E+01
42.00	0.0	0.482E+01	
42.00	9623.3	0.475E+01	
42.00	19246.7	0.464E+01	
42.00	28870.0	0.441E+01	
42.00	28870.0	0.441E+01	0.562E+01
44.00	0.0	0.513E+01	
44.00	9623.3	0.489E+01	
44.00	19246.7	0.480E+01	
44.00	28870.0	0.465E+01	
44.00	28870.0	0.465E+01	0.590E+01
46.00	0.0	0.498E+01	
46.00	9623.3	0.500E+01	
46.00	19246.7	0.492E+01	
46.00	28870.0	0.481E+01	
46.00	28870.0	0.481E+01	0.590E+01

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
48.00	0.0	0.402E+01	
48.00	9623.3	0.476E+01	
48.00	19246.7	0.492E+01	
48.00	28870.0	0.493E+01	
48.00	28870.0	0.493E+01	0.585E+01
50.00	0.0	0.340E+01	
50.00	9623.3	0.416E+01	
50.00	19246.7	0.467E+01	
50.00	28870.0	0.491E+01	
50.00	28870.0	0.491E+01	0.576E+01
52.00	0.0	0.274E+01	
52.00	9623.3	0.344E+01	
52.00	19246.7	0.413E+01	
52.00	28870.0	0.462E+01	
52.00	28870.0	0.462E+01	0.605E+01
54.00	0.0	0.283E+01	
54.00	9623.3	0.289E+01	
54.00	19246.7	0.349E+01	
54.00	28870.0	0.407E+01	
54.00	28870.0	0.407E+01	0.590E+01
56.00	0.0	0.313E+01	
56.00	9623.3	0.276E+01	
56.00	19246.7	0.299E+01	
56.00	28870.0	0.345E+01	
56.00	28870.0	0.345E+01	0.529E+01
58.00	0.0	0.323E+01	
58.00	9623.3	0.291E+01	
58.00	19246.7	0.280E+01	
58.00	28870.0	0.297E+01	
58.00	28870.0	0.297E+01	0.488E+01

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	0.354E+01	
60.00	9623.3	0.320E+01	
60.00	19246.7	0.289E+01	
60.00	28870.0	0.279E+01	
60.00	28870.0	0.279E+01	0.418E+01
62.00	0.0	0.481E+01	
62.00	9623.3	0.380E+01	
62.00	19246.7	0.323E+01	
62.00	28870.0	0.290E+01	
62.00	28870.0	0.290E+01	0.410E+01
64.00	0.0	0.530E+01	
64.00	9623.3	0.463E+01	
64.00	19246.7	0.384E+01	
64.00	28870.0	0.326E+01	
64.00	28870.0	0.326E+01	0.452E+01
66.00	0.0	0.584E+01	
66.00	9623.3	0.538E+01	
66.00	19246.7	0.463E+01	
66.00	28870.0	0.391E+01	
66.00	28870.0	0.391E+01	0.474E+01
68.00	0.0	0.668E+01	
68.00	9623.3	0.610E+01	
68.00	19246.7	0.544E+01	
68.00	28870.0	0.472E+01	
68.00	28870.0	0.472E+01	0.511E+01
70.00	0.0	0.629E+01	
70.00	9623.3	0.651E+01	
70.00	19246.7	0.612E+01	
70.00	28870.0	0.554E+01	
70.00	28870.0	0.554E+01	0.585E+01

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
72.00	0.0	0.560E+01	
72.00	9623.3	0.632E+01	
72.00	19246.7	0.644E+01	
72.00	28870.0	0.620E+01	
72.00	28870.0	0.620E+01	0.654E+01
74.00	0.0	0.552E+01	
74.00	9623.3	0.584E+01	
74.00	19246.7	0.629E+01	
74.00	28870.0	0.644E+01	
74.00	28870.0	0.644E+01	0.709E+01
76.00	0.0	0.841E+01	
76.00	9623.3	0.629E+01	
76.00	19246.7	0.613E+01	
76.00	28870.0	0.624E+01	
76.00	28870.0	0.624E+01	0.809E+01
78.00	0.0	0.190E+02	
78.00	9623.3	0.106E+02	
78.00	19246.7	0.748E+01	
78.00	28870.0	0.614E+01	
78.00	28870.0	0.614E+01	0.913E+01
80.00	0.0	0.380E+02	
80.00	9623.3	0.240E+02	
80.00	19246.7	0.143E+02	
80.00	28870.0	0.807E+01	
80.00	28870.0	0.807E+01	0.105E+02
82.00	0.0	0.663E+02	
82.00	9623.3	0.509E+02	
82.00	19246.7	0.343E+02	
82.00	28870.0	0.194E+02	
82.00	28870.0	0.194E+02	0.151E+02

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
84.00	0.0	0.816E+02	
84.00	9623.3	0.782E+02	
84.00	19246.7	0.639E+02	
84.00	28870.0	0.535E+02	
84.00	28870.0	0.535E+02	0.434E+02
86.00	0.0	0.108E+03	
86.00	9623.3	0.991E+02	
86.00	19246.7	0.874E+02	
86.00	28870.0	0.826E+02	
86.00	28870.0	0.826E+02	0.809E+02
88.00	0.0	0.127E+03	
88.00	9623.3	0.120E+03	
88.00	19246.7	0.107E+03	
88.00	28870.0	0.102E+03	
88.00	28870.0	0.102E+03	0.116E+03
90.00	0.0	0.149E+03	
90.00	9623.3	0.140E+03	
90.00	19246.7	0.126E+03	
90.00	28870.0	0.120E+03	
90.00	28870.0	0.120E+03	0.154E+03
92.00	0.0	0.171E+03	
92.00	9623.3	0.160E+03	
92.00	19246.7	0.146E+03	
92.00	28870.0	0.137E+03	
92.00	28870.0	0.137E+03	0.181E+03
94.00	0.0	0.186E+03	
94.00	9623.3	0.177E+03	
94.00	19246.7	0.165E+03	
94.00	28870.0	0.155E+03	
94.00	28870.0	0.155E+03	0.200E+03

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
96.00	0.0	0.191E+03	
96.00	9623.3	0.187E+03	
96.00	19246.7	0.179E+03	
96.00	28870.0	0.170E+03	
96.00	28870.0	0.170E+03	0.215E+03
98.00	0.0	0.185E+03	
98.00	9623.3	0.190E+03	
98.00	19246.7	0.187E+03	
98.00	28870.0	0.181E+03	
98.00	28870.0	0.181E+03	0.225E+03
100.00	0.0	0.155E+03	
100.00	9623.3	0.178E+03	
100.00	19246.7	0.186E+03	
100.00	28870.0	0.187E+03	
100.00	28870.0	0.187E+03	0.227E+03
102.00	0.0	0.130E+03	
102.00	9623.3	0.150E+03	
102.00	19246.7	0.171E+03	
102.00	28870.0	0.184E+03	
102.00	28870.0	0.184E+03	0.216E+03
104.00	0.0	0.122E+03	
104.00	9623.3	0.123E+03	
104.00	19246.7	0.142E+03	
104.00	28870.0	0.158E+03	
104.00	28870.0	0.158E+03	0.190E+03
106.00	0.0	0.121E+03	
106.00	9623.3	0.115E+03	
106.00	19246.7	0.121E+03	
106.00	28870.0	0.124E+03	
106.00	28870.0	0.124E+03	0.164E+03

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Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
108.00	0.0	0.110E+03	
108.00	9623.3	0.113E+03	
108.00	19246.7	0.115E+03	
108.00	28870.0	0.115E+03	
108.00	28870.0	0.115E+03	0.152E+03
110.00	0.0	0.949E+02	
110.00	9623.3	0.103E+03	
110.00	19246.7	0.109E+03	
110.00	28870.0	0.113E+03	
110.00	28870.0	0.113E+03	0.144E+03
112.00	0.0	0.796E+02	
112.00	9623.3	0.861E+02	
112.00	19246.7	0.964E+02	
112.00	28870.0	0.102E+03	
112.00	28870.0	0.102E+03	0.129E+03
114.00	0.0	0.687E+02	
114.00	9623.3	0.697E+02	
114.00	19246.7	0.819E+02	
114.00	28870.0	0.826E+02	
114.00	28870.0	0.826E+02	0.108E+03
116.00	0.0	0.605E+02	
116.00	9623.3	0.572E+02	
116.00	19246.7	0.711E+02	
116.00	28870.0	0.648E+02	
116.00	28870.0	0.648E+02	0.904E+02
118.00	0.0	0.542E+02	
118.00	9623.3	0.473E+02	
118.00	19246.7	0.636E+02	
118.00	28870.0	0.528E+02	
118.00	28870.0	0.528E+02	0.769E+02

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
120.00	0.0	0.490E+02	
120.00	9623.3	0.393E+02	
120.00	19246.7	0.571E+02	
120.00	28870.0	0.447E+02	
120.00	28870.0	0.447E+02	0.668E+02
122.00	0.0	0.441E+02	
122.00	9623.3	0.332E+02	
122.00	19246.7	0.504E+02	
122.00	28870.0	0.392E+02	
122.00	28870.0	0.392E+02	0.595E+02
124.00	0.0	0.406E+02	
124.00	9623.3	0.295E+02	
124.00	19246.7	0.439E+02	
124.00	28870.0	0.352E+02	
124.00	28870.0	0.352E+02	0.535E+02
126.00	0.0	0.374E+02	
126.00	9623.3	0.281E+02	
126.00	19246.7	0.384E+02	
126.00	28870.0	0.325E+02	
126.00	28870.0	0.325E+02	0.484E+02
128.00	0.0	0.353E+02	
128.00	9623.3	0.283E+02	
128.00	19246.7	0.347E+02	
128.00	28870.0	0.308E+02	
128.00	28870.0	0.308E+02	0.444E+02
130.00	0.0	0.340E+02	
130.00	9623.3	0.293E+02	
130.00	19246.7	0.329E+02	
130.00	28870.0	0.301E+02	
130.00	28870.0	0.301E+02	0.413E+02

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
132.00	0.0	0.348E+02	
132.00	9623.3	0.309E+02	
132.00	19246.7	0.326E+02	
132.00	28870.0	0.303E+02	
132.00	28870.0	0.303E+02	0.388E+02
134.00	0.0	0.372E+02	
134.00	9623.3	0.336E+02	
134.00	19246.7	0.338E+02	
134.00	28870.0	0.314E+02	
134.00	28870.0	0.314E+02	0.374E+02
136.00	0.0	0.373E+02	
136.00	9623.3	0.359E+02	
136.00	19246.7	0.358E+02	
136.00	28870.0	0.337E+02	
136.00	28870.0	0.337E+02	0.382E+02
138.00	0.0	0.353E+02	
138.00	9623.3	0.359E+02	
138.00	19246.7	0.369E+02	
138.00	28870.0	0.360E+02	
138.00	28870.0	0.360E+02	0.402E+02
140.00	0.0	0.328E+02	
140.00	9623.3	0.338E+02	
140.00	19246.7	0.357E+02	
140.00	28870.0	0.360E+02	
140.00	28870.0	0.360E+02	0.404E+02
142.00	0.0	0.309E+02	
142.00	9623.3	0.314E+02	
142.00	19246.7	0.334E+02	
142.00	28870.0	0.341E+02	
142.00	28870.0	0.341E+02	0.385E+02

Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
144.00	0.0	0.288E+02	
144.00	9623.3	0.293E+02	
144.00	19246.7	0.309E+02	
144.00	28870.0	0.318E+02	
144.00	28870.0	0.318E+02	0.356E+02
146.00	0.0	0.269E+02	
146.00	9623.3	0.275E+02	
146.00	19246.7	0.289E+02	
146.00	28870.0	0.297E+02	
146.00	28870.0	0.297E+02	0.333E+02
148.00	0.0	0.258E+02	
148.00	9623.3	0.261E+02	
148.00	19246.7	0.271E+02	
148.00	28870.0	0.279E+02	
148.00	28870.0	0.279E+02	0.312E+02
150.00	0.0	0.246E+02	
150.00	9623.3	0.251E+02	
150.00	19246.7	0.258E+02	
150.00	28870.0	0.264E+02	
150.00	28870.0	0.264E+02	0.291E+02
152.00	0.0	0.237E+02	
152.00	9623.3	0.242E+02	
152.00	19246.7	0.247E+02	
152.00	28870.0	0.253E+02	
152.00	28870.0	0.253E+02	0.275E+02
154.00	0.0	0.230E+02	
154.00	9623.3	0.234E+02	
154.00	19246.7	0.239E+02	
154.00	28870.0	0.243E+02	
154.00	28870.0	0.243E+02	0.261E+02

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
156.00	0.0	0.229E+02	
156.00	9623.3	0.229E+02	
156.00	19246.7	0.232E+02	
156.00	28870.0	0.235E+02	
156.00	28870.0	0.235E+02	0.250E+02
158.00	0.0	0.244E+02	
158.00	9623.3	0.234E+02	
158.00	19246.7	0.231E+02	
158.00	28870.0	0.230E+02	
158.00	28870.0	0.230E+02	0.245E+02
160.00	0.0	0.263E+02	
160.00	9623.3	0.249E+02	
160.00	19246.7	0.239E+02	
160.00	28870.0	0.232E+02	
160.00	28870.0	0.232E+02	0.243E+02
162.00	0.0	0.273E+02	
162.00	9623.3	0.267E+02	
162.00	19246.7	0.255E+02	
162.00	28870.0	0.246E+02	
162.00	28870.0	0.246E+02	0.251E+02
164.00	0.0	0.266E+02	
164.00	9623.3	0.273E+02	
164.00	19246.7	0.269E+02	
164.00	28870.0	0.264E+02	
164.00	28870.0	0.264E+02	0.277E+02

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Continued Table II.16

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
166.00	0.0	0.254E+02	
166.00	9623.3	0.265E+02	
166.00	19246.7	0.270E+02	
166.00	28870.0	0.272E+02	
166.00	28870.0	0.272E+02	0.295E+02

AVERAGE RECORDED DISCHARGE = 87.81 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE =19.30 %
STANDARD DEVIATION = 25.79 %

Table II.17
Output of VPDM1 Computer Program of the Event
1-2-1986 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.278E+02	
0.00	9623.3	0.278E+02	
0.00	19246.7	0.278E+02	
0.00	28870.0	0.278E+02	
0.00	28870.0	0.278E+02	0.310E+02
2.00	0.0	0.266E+02	
2.00	9623.3	0.273E+02	
2.00	19246.7	0.276E+02	
2.00	28870.0	0.278E+02	
2.00	28870.0	0.278E+02	0.297E+02
4.00	0.0	0.261E+02	
4.00	9623.3	0.265E+02	
4.00	19246.7	0.270E+02	
4.00	28870.0	0.274E+02	
4.00	28870.0	0.274E+02	0.286E+02
6.00	0.0	0.261E+02	
6.00	9623.3	0.260E+02	
6.00	19246.7	0.263E+02	
6.00	28870.0	0.266E+02	
6.00	28870.0	0.266E+02	0.274E+02
8.00	0.0	0.266E+02	
8.00	9623.3	0.261E+02	
8.00	19246.7	0.261E+02	
8.00	28870.0	0.261E+02	
8.00	28870.0	0.261E+02	0.271E+02
10.00	0.0	0.272E+02	
10.00	9623.3	0.267E+02	
10.00	19246.7	0.264E+02	
10.00	28870.0	0.261E+02	
10.00	28870.0	0.261E+02	0.272E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
12.00	0.0	0.281E+02	
12.00	9623.3	0.276E+02	
12.00	19246.7	0.270E+02	
12.00	28870.0	0.266E+02	
12.00	28870.0	0.266E+02	0.285E+02
14.00	0.0	0.294E+02	
14.00	9623.3	0.287E+02	
14.00	19246.7	0.280E+02	
14.00	28870.0	0.274E+02	
14.00	28870.0	0.274E+02	0.304E+02
16.00	0.0	0.313E+02	
16.00	9623.3	0.302E+02	
16.00	19246.7	0.293E+02	
16.00	28870.0	0.285E+02	
16.00	28870.0	0.285E+02	0.318E+02
18.00	0.0	0.334E+02	
18.00	9623.3	0.322E+02	
18.00	19246.7	0.310E+02	
18.00	28870.0	0.300E+02	
18.00	28870.0	0.300E+02	0.330E+02
20.00	0.0	0.362E+02	
20.00	9623.3	0.347E+02	
20.00	19246.7	0.333E+02	
20.00	28870.0	0.320E+02	
20.00	28870.0	0.320E+02	0.358E+02
22.00	0.0	0.393E+02	
22.00	9623.3	0.376E+02	
22.00	19246.7	0.360E+02	
22.00	28870.0	0.345E+02	
22.00	28870.0	0.345E+02	0.387E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
24.00	0.0	0.431E+02	
24.00	9623.3	0.411E+02	
24.00	19246.7	0.393E+02	
24.00	28870.0	0.375E+02	
24.00	28870.0	0.375E+02	0.411E+02
26.00	0.0	0.488E+02	
26.00	9623.3	0.458E+02	
26.00	19246.7	0.434E+02	
26.00	28870.0	0.411E+02	
26.00	28870.0	0.411E+02	0.441E+02
28.00	0.0	0.560E+02	
28.00	9623.3	0.523E+02	
28.00	19246.7	0.491E+02	
28.00	28870.0	0.459E+02	
28.00	28870.0	0.459E+02	0.486E+02
30.00	0.0	0.649E+02	
30.00	9623.3	0.605E+02	
30.00	19246.7	0.567E+02	
30.00	28870.0	0.527E+02	
30.00	28870.0	0.527E+02	0.551E+02
32.00	0.0	0.794E+02	
32.00	9623.3	0.721E+02	
32.00	19246.7	0.669E+02	
32.00	28870.0	0.613E+02	
32.00	28870.0	0.613E+02	0.624E+02
34.00	0.0	0.935E+02	
34.00	9623.3	0.866E+02	
34.00	19246.7	0.804E+02	
34.00	28870.0	0.733E+02	
34.00	28870.0	0.733E+02	0.739E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
36.00	0.0	0.103E+03	
36.00	9623.3	0.988E+02	
36.00	19246.7	0.939E+02	
36.00	28870.0	0.878E+02	
36.00	28870.0	0.878E+02	0.931E+02
38.00	0.0	0.106E+03	
38.00	9623.3	0.105E+03	
38.00	19246.7	0.103E+03	
38.00	28870.0	0.994E+02	
38.00	28870.0	0.994E+02	0.112E+03
40.00	0.0	0.103E+03	
40.00	9623.3	0.105E+03	
40.00	19246.7	0.106E+03	
40.00	28870.0	0.105E+03	
40.00	28870.0	0.105E+03	0.122E+03
42.00	0.0	0.958E+02	
42.00	9623.3	0.999E+02	
42.00	19246.7	0.103E+03	
42.00	28870.0	0.105E+03	
42.00	28870.0	0.105E+03	0.125E+03
44.00	0.0	0.874E+02	
44.00	9623.3	0.913E+02	
44.00	19246.7	0.959E+02	
44.00	28870.0	0.992E+02	
44.00	28870.0	0.992E+02	0.118E+03
46.00	0.0	0.827E+02	
46.00	9623.3	0.837E+02	
46.00	19246.7	0.879E+02	
46.00	28870.0	0.900E+02	
46.00	28870.0	0.900E+02	0.106E+03

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Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
48.00	0.0	0.822E+02	
48.00	9623.3	0.805E+02	
48.00	19246.7	0.832E+02	
48.00	28870.0	0.823E+02	
48.00	28870.0	0.823E+02	0.964E+02
50.00	0.0	0.837E+02	
50.00	9623.3	0.806E+02	
50.00	19246.7	0.829E+02	
50.00	28870.0	0.790E+02	
50.00	28870.0	0.790E+02	0.912E+02
52.00	0.0	0.906E+02	
52.00	9623.3	0.840E+02	
52.00	19246.7	0.862E+02	
52.00	28870.0	0.787E+02	
52.00	28870.0	0.787E+02	0.912E+02
54.00	0.0	0.114E+03	
54.00	9623.3	0.967E+02	
54.00	19246.7	0.968E+02	
54.00	28870.0	0.813E+02	
54.00	28870.0	0.813E+02	0.953E+02
56.00	0.0	0.140E+03	
56.00	9623.3	0.119E+03	
56.00	19246.7	0.117E+03	
56.00	28870.0	0.938E+02	
56.00	28870.0	0.938E+02	0.110E+03
58.00	0.0	0.152E+03	
58.00	9623.3	0.138E+03	
58.00	19246.7	0.137E+03	
58.00	28870.0	0.118E+03	
58.00	28870.0	0.118E+03	0.143E+03

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
60.00	0.0	0.146E+03	
60.00	9623.3	0.145E+03	
60.00	19246.7	0.148E+03	
60.00	28870.0	0.138E+03	
60.00	28870.0	0.138E+03	0.174E+03
62.00	0.0	0.126E+03	
62.00	9623.3	0.136E+03	
62.00	19246.7	0.145E+03	
62.00	28870.0	0.146E+03	
62.00	28870.0	0.146E+03	0.180E+03
64.00	0.0	0.108E+03	
64.00	9623.3	0.116E+03	
64.00	19246.7	0.131E+03	
64.00	28870.0	0.138E+03	
64.00	28870.0	0.138E+03	0.171E+03
66.00	0.0	0.941E+02	
66.00	9623.3	0.978E+02	
66.00	19246.7	0.110E+03	
66.00	28870.0	0.117E+03	
66.00	28870.0	0.117E+03	0.145E+03
68.00	0.0	0.830E+02	
68.00	9623.3	0.849E+02	
68.00	19246.7	0.944E+02	
68.00	28870.0	0.982E+02	
68.00	28870.0	0.982E+02	0.121E+03
70.00	0.0	0.759E+02	
70.00	9623.3	0.762E+02	
70.00	19246.7	0.832E+02	
70.00	28870.0	0.852E+02	
70.00	28870.0	0.852E+02	0.104E+03

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
72.00	0.0	0.706E+02	
72.00	9623.3	0.700E+02	
72.00	19246.7	0.767E+02	
72.00	28870.0	0.734E+02	
72.00	28870.0	0.734E+02	0.916E+02
74.00	0.0	0.668E+02	
74.00	9623.3	0.643E+02	
74.00	19246.7	0.733E+02	
74.00	28870.0	0.666E+02	
74.00	28870.0	0.666E+02	0.826E+02
76.00	0.0	0.648E+02	
76.00	9623.3	0.589E+02	
76.00	19246.7	0.707E+02	
76.00	28870.0	0.600E+02	
76.00	28870.0	0.600E+02	0.758E+02
78.00	0.0	0.640E+02	
78.00	9623.3	0.545E+02	
78.00	19246.7	0.690E+02	
78.00	28870.0	0.542E+02	
78.00	28870.0	0.542E+02	0.718E+02
80.00	0.0	0.681E+02	
80.00	9623.3	0.526E+02	
80.00	19246.7	0.691E+02	
80.00	28870.0	0.498E+02	
80.00	28870.0	0.498E+02	0.692E+02
82.00	0.0	0.961E+02	
82.00	9623.3	0.630E+02	
82.00	19246.7	0.771E+02	
82.00	28870.0	0.478E+02	
82.00	28870.0	0.478E+02	0.683E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
84.00	0.0	0.131E+03	
84.00	9623.3	0.923E+02	
84.00	19246.7	0.103E+03	
84.00	28870.0	0.546E+02	
84.00	28870.0	0.546E+02	0.773E+02
86.00	0.0	0.174E+03	
86.00	9623.3	0.129E+03	
86.00	19246.7	0.140E+03	
86.00	28870.0	0.769E+02	
86.00	28870.0	0.769E+02	0.118E+03
88.00	0.0	0.208E+03	
88.00	9623.3	0.165E+03	
88.00	19246.7	0.170E+03	
88.00	28870.0	0.129E+03	
88.00	28870.0	0.129E+03	0.174E+03
90.00	0.0	0.228E+03	
90.00	9623.3	0.195E+03	
90.00	19246.7	0.187E+03	
90.00	28870.0	0.168E+03	
90.00	28870.0	0.168E+03	0.207E+03
92.00	0.0	0.229E+03	
92.00	9623.3	0.213E+03	
92.00	19246.7	0.201E+03	
92.00	28870.0	0.188E+03	
92.00	28870.0	0.188E+03	0.229E+03
94.00	0.0	0.170E+03	
94.00	9623.3	0.208E+03	
94.00	19246.7	0.208E+03	
94.00	28870.0	0.200E+03	
94.00	28870.0	0.200E+03	0.246E+03

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
96.00	0.0	0.123E+03	
96.00	9623.3	0.172E+03	
96.00	19246.7	0.200E+03	
96.00	28870.0	0.206E+03	
96.00	28870.0	0.206E+03	0.241E+03
98.00	0.0	0.995E+02	
98.00	9623.3	0.113E+03	
98.00	19246.7	0.159E+03	
98.00	28870.0	0.197E+03	
98.00	28870.0	0.197E+03	0.202E+03
100.00	0.0	0.852E+02	
100.00	9623.3	0.781E+02	
100.00	19246.7	0.101E+03	
100.00	28870.0	0.115E+03	
100.00	28870.0	0.115E+03	0.155E+03
102.00	0.0	0.755E+02	
102.00	9623.3	0.701E+02	
102.00	19246.7	0.785E+02	
102.00	28870.0	0.791E+02	
102.00	28870.0	0.791E+02	0.118E+03
104.00	0.0	0.691E+02	
104.00	9623.3	0.670E+02	
104.00	19246.7	0.737E+02	
104.00	28870.0	0.667E+02	
104.00	28870.0	0.667E+02	0.994E+02
106.00	0.0	0.657E+02	
106.00	9623.3	0.621E+02	
106.00	19246.7	0.723E+02	
106.00	28870.0	0.632E+02	
106.00	28870.0	0.632E+02	0.875E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
108.00	0.0	0.629E+02	
108.00	9623.3	0.562E+02	
108.00	19246.7	0.699E+02	
108.00	28870.0	0.573E+02	
108.00	28870.0	0.573E+02	0.803E+02
110.00	0.0	0.593E+02	
110.00	9623.3	0.500E+02	
110.00	19246.7	0.669E+02	
110.00	28870.0	0.514E+02	
110.00	28870.0	0.514E+02	0.760E+02
112.00	0.0	0.572E+02	
112.00	9623.3	0.443E+02	
112.00	19246.7	0.634E+02	
112.00	28870.0	0.462E+02	
112.00	28870.0	0.462E+02	0.724E+02
114.00	0.0	0.543E+02	
114.00	9623.3	0.399E+02	
114.00	19246.7	0.593E+02	
114.00	28870.0	0.422E+02	
114.00	28870.0	0.422E+02	0.688E+02
116.00	0.0	0.531E+02	
116.00	9623.3	0.373E+02	
116.00	19246.7	0.553E+02	
116.00	28870.0	0.394E+02	
116.00	28870.0	0.394E+02	0.653E+02
118.00	0.0	0.644E+02	
118.00	9623.3	0.417E+02	
118.00	19246.7	0.549E+02	
118.00	28870.0	0.378E+02	
118.00	28870.0	0.378E+02	0.617E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
120.00	0.0	0.936E+02	
120.00	9623.3	0.622E+02	
120.00	19246.7	0.674E+02	
120.00	28870.0	0.408E+02	
120.00	28870.0	0.408E+02	0.601E+02
122.00	0.0	0.966E+02	
122.00	9623.3	0.816E+02	
122.00	19246.7	0.913E+02	
122.00	28870.0	0.565E+02	
122.00	28870.0	0.565E+02	0.750E+02
124.00	0.0	0.912E+02	
124.00	9623.3	0.784E+02	
124.00	19246.7	0.106E+03	
124.00	28870.0	0.700E+02	
124.00	28870.0	0.700E+02	0.106E+03
126.00	0.0	0.899E+02	
126.00	9623.3	0.643E+02	
126.00	19246.7	0.106E+03	
126.00	28870.0	0.612E+02	
126.00	28870.0	0.612E+02	0.111E+03
128.00	0.0	0.888E+02	
128.00	9623.3	0.519E+02	
128.00	19246.7	0.102E+03	
128.00	28870.0	0.490E+02	
128.00	28870.0	0.490E+02	0.106E+03
130.00	0.0	0.849E+02	
130.00	9623.3	0.427E+02	
130.00	19246.7	0.960E+02	
130.00	28870.0	0.423E+02	
130.00	28870.0	0.423E+02	0.103E+03

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
132.00	0.0	0.799E+02	
132.00	9623.3	0.363E+02	
132.00	19246.7	0.878E+02	
132.00	28870.0	0.387E+02	
132.00	28870.0	0.387E+02	0.102E+03
134.00	0.0	0.758E+02	
134.00	9623.3	0.335E+02	
134.00	19246.7	0.789E+02	
134.00	28870.0	0.366E+02	
134.00	28870.0	0.366E+02	0.974E+02
136.00	0.0	0.713E+02	
136.00	9623.3	0.340E+02	
136.00	19246.7	0.717E+02	
136.00	28870.0	0.357E+02	
136.00	28870.0	0.357E+02	0.918E+02
138.00	0.0	0.657E+02	
138.00	9623.3	0.351E+02	
138.00	19246.7	0.668E+02	
138.00	28870.0	0.360E+02	
138.00	28870.0	0.360E+02	0.867E+02
140.00	0.0	0.603E+02	
140.00	9623.3	0.351E+02	
140.00	19246.7	0.627E+02	
140.00	28870.0	0.365E+02	
140.00	28870.0	0.365E+02	0.813E+02
142.00	0.0	0.541E+02	
142.00	9623.3	0.335E+02	
142.00	19246.7	0.579E+02	
142.00	28870.0	0.365E+02	
142.00	28870.0	0.365E+02	0.748E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
144.00	0.0	0.496E+02	
144.00	9623.3	0.315E+02	
144.00	19246.7	0.523E+02	
144.00	28870.0	0.357E+02	
144.00	28870.0	0.357E+02	0.676E+02
146.00	0.0	0.466E+02	
146.00	9623.3	0.309E+02	
146.00	19246.7	0.470E+02	
146.00	28870.0	0.344E+02	
146.00	28870.0	0.344E+02	0.612E+02
148.00	0.0	0.438E+02	
148.00	9623.3	0.316E+02	
148.00	19246.7	0.434E+02	
148.00	28870.0	0.336E+02	
148.00	28870.0	0.336E+02	0.559E+02
150.00	0.0	0.414E+02	
150.00	9623.3	0.324E+02	
150.00	19246.7	0.411E+02	
150.00	28870.0	0.336E+02	
150.00	28870.0	0.336E+02	0.523E+02
152.00	0.0	0.399E+02	
152.00	9623.3	0.331E+02	
152.00	19246.7	0.396E+02	
152.00	28870.0	0.339E+02	
152.00	28870.0	0.339E+02	0.493E+02
154.00	0.0	0.391E+02	
154.00	9623.3	0.337E+02	
154.00	19246.7	0.387E+02	
154.00	28870.0	0.342E+02	
154.00	28870.0	0.342E+02	0.469E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
156.00	0.0	0.381E+02	
156.00	9623.3	0.342E+02	
156.00	19246.7	0.380E+02	
156.00	28870.0	0.345E+02	
156.00	28870.0	0.345E+02	0.451E+02
158.00	0.0	0.372E+02	
158.00	9623.3	0.343E+02	
158.00	19246.7	0.375E+02	
158.00	28870.0	0.348E+02	
158.00	28870.0	0.348E+02	0.441E+02
160.00	0.0	0.368E+02	
160.00	9623.3	0.343E+02	
160.00	19246.7	0.368E+02	
160.00	28870.0	0.348E+02	
160.00	28870.0	0.348E+02	0.435E+02
162.00	0.0	0.369E+02	
162.00	9623.3	0.346E+02	
162.00	19246.7	0.365E+02	
162.00	28870.0	0.347E+02	
162.00	28870.0	0.347E+02	0.424E+02
164.00	0.0	0.393E+02	
164.00	9623.3	0.361E+02	
164.00	19246.7	0.369E+02	
164.00	28870.0	0.349E+02	
164.00	28870.0	0.349E+02	0.420E+02
166.00	0.0	0.500E+02	
166.00	9623.3	0.421E+02	
166.00	19246.7	0.403E+02	
166.00	28870.0	0.362E+02	
166.00	28870.0	0.362E+02	0.418E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
168.00	0.0	0.545E+02	
168.00	9623.3	0.508E+02	
168.00	19246.7	0.477E+02	
168.00	28870.0	0.421E+02	
168.00	28870.0	0.421E+02	0.436E+02
170.00	0.0	0.567E+02	
170.00	9623.3	0.556E+02	
170.00	19246.7	0.547E+02	
170.00	28870.0	0.509E+02	
170.00	28870.0	0.509E+02	0.524E+02
172.00	0.0	0.540E+02	
172.00	9623.3	0.551E+02	
172.00	19246.7	0.569E+02	
172.00	28870.0	0.553E+02	
172.00	28870.0	0.553E+02	0.611E+02
174.00	0.0	0.491E+02	
174.00	9623.3	0.506E+02	
174.00	19246.7	0.546E+02	
174.00	28870.0	0.544E+02	
174.00	28870.0	0.544E+02	0.632E+02
176.00	0.0	0.445E+02	
176.00	9623.3	0.451E+02	
176.00	19246.7	0.499E+02	
176.00	28870.0	0.498E+02	
176.00	28870.0	0.498E+02	0.596E+02
178.00	0.0	0.411E+02	
178.00	9623.3	0.405E+02	
178.00	19246.7	0.451E+02	
178.00	28870.0	0.446E+02	
178.00	28870.0	0.446E+02	0.542E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
180.00	0.0	0.390E+02	
180.00	9623.3	0.375E+02	
180.00	19246.7	0.414E+02	
180.00	28870.0	0.404E+02	
180.00	28870.0	0.404E+02	0.497E+02
182.00	0.0	0.374E+02	
182.00	9623.3	0.358E+02	
182.00	19246.7	0.388E+02	
182.00	28870.0	0.377E+02	
182.00	28870.0	0.377E+02	0.466E+02
184.00	0.0	0.355E+02	
184.00	9623.3	0.345E+02	
184.00	19246.7	0.370E+02	
184.00	28870.0	0.361E+02	
184.00	28870.0	0.361E+02	0.444E+02
186.00	0.0	0.344E+02	
186.00	9623.3	0.334E+02	
186.00	19246.7	0.354E+02	
186.00	28870.0	0.349E+02	
186.00	28870.0	0.349E+02	0.426E+02
188.00	0.0	0.326E+02	
188.00	9623.3	0.323E+02	
188.00	19246.7	0.340E+02	
188.00	28870.0	0.337E+02	
188.00	28870.0	0.337E+02	0.408E+02

Continued Table II.17

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
190.00	0.0	0.309E+02	
190.00	9623.3	0.309E+02	
190.00	19246.7	0.325E+02	
190.00	28870.0	0.326E+02	
190.00	28870.0	0.326E+02	0.391E+02

AVERAGE RECORDED DISCHARGE = 76.06 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = 28.38 %
STANDARD DEVIATION = 39.00 %

Table II.18
Output of VPDM1 Computer Program of the Event
2-2-1981 of River Wear

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
0.00	0.0	0.650E+01	
0.00	9623.3	0.650E+01	
0.00	19246.7	0.650E+01	
0.00	28870.0	0.650E+01	
0.00	28870.0	0.650E+01	0.650E+01
2.00	0.0	0.727E+01	
2.00	9623.3	0.675E+01	
2.00	19246.7	0.659E+01	
2.00	28870.0	0.650E+01	
2.00	28870.0	0.650E+01	0.725E+01
4.00	0.0	0.913E+01	
4.00	9623.3	0.777E+01	
4.00	19246.7	0.710E+01	
4.00	28870.0	0.666E+01	
4.00	28870.0	0.666E+01	0.742E+01
6.00	0.0	0.117E+02	
6.00	9623.3	0.982E+01	
6.00	19246.7	0.843E+01	
6.00	28870.0	0.741E+01	
6.00	28870.0	0.741E+01	0.778E+01
8.00	0.0	0.726E+02	
8.00	9623.3	0.355E+02	
8.00	19246.7	0.205E+02	
8.00	28870.0	0.915E+01	
8.00	28870.0	0.915E+01	0.791E+01
10.00	0.0	0.160E+03	
10.00	9623.3	0.112E+03	
10.00	19246.7	0.760E+02	
10.00	28870.0	0.366E+02	
10.00	28870.0	0.366E+02	0.933E+01

Continued Table II.18

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
12.00	0.0	0.182E+03	
12.00	9623.3	0.166E+03	
12.00	19246.7	0.141E+03	
12.00	28870.0	0.111E+03	
12.00	28870.0	0.111E+03	0.544E+02
14.00	0.0	0.130E+03	
14.00	9623.3	0.165E+03	
14.00	19246.7	0.166E+03	
14.00	28870.0	0.154E+03	
14.00	28870.0	0.154E+03	0.167E+03
16.00	0.0	0.828E+02	
16.00	9623.3	0.119E+03	
16.00	19246.7	0.151E+03	
16.00	28870.0	0.165E+03	
16.00	28870.0	0.165E+03	0.182E+03
18.00	0.0	0.633E+02	
18.00	9623.3	0.694E+02	
18.00	19246.7	0.103E+03	
18.00	28870.0	0.124E+03	
18.00	28870.0	0.124E+03	0.135E+03
20.00	0.0	0.520E+02	
20.00	9623.3	0.460E+02	
20.00	19246.7	0.642E+02	
20.00	28870.0	0.739E+02	
20.00	28870.0	0.739E+02	0.897E+02
22.00	0.0	0.439E+02	
22.00	9623.3	0.396E+02	
22.00	19246.7	0.467E+02	
22.00	28870.0	0.486E+02	
22.00	28870.0	0.486E+02	0.663E+02

Continued Table II.18

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
24.00	0.0	0.380E+02	
24.00	9623.3	0.369E+02	
24.00	19246.7	0.415E+02	
24.00	28870.0	0.386E+02	
24.00	28870.0	0.386E+02	0.538E+02
26.00	0.0	0.334E+02	
26.00	9623.3	0.328E+02	
26.00	19246.7	0.389E+02	
26.00	28870.0	0.362E+02	
26.00	28870.0	0.362E+02	0.451E+02
28.00	0.0	0.317E+02	
28.00	9623.3	0.288E+02	
28.00	19246.7	0.353E+02	
28.00	28870.0	0.325E+02	
28.00	28870.0	0.325E+02	0.392E+02
30.00	0.0	0.320E+02	
30.00	9623.3	0.271E+02	
30.00	19246.7	0.324E+02	
30.00	28870.0	0.290E+02	
30.00	28870.0	0.290E+02	0.348E+02
32.00	0.0	0.308E+02	
32.00	9623.3	0.269E+02	
32.00	19246.7	0.310E+02	
32.00	28870.0	0.275E+02	
32.00	28870.0	0.275E+02	0.322E+02
34.00	0.0	0.287E+02	
34.00	9623.3	0.263E+02	
34.00	19246.7	0.301E+02	
34.00	28870.0	0.273E+02	
34.00	28870.0	0.273E+02	0.315E+02

Continued Table II.18

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
36.00	0.0	0.272E+02	
36.00	9623.3	0.251E+02	
36.00	19246.7	0.287E+02	
36.00	28870.0	0.268E+02	
36.00	28870.0	0.268E+02	0.311E+02
38.00	0.0	0.251E+02	
38.00	9623.3	0.236E+02	
38.00	19246.7	0.269E+02	
38.00	28870.0	0.256E+02	
38.00	28870.0	0.256E+02	0.293E+02
40.00	0.0	0.227E+02	
40.00	9623.3	0.219E+02	
40.00	19246.7	0.248E+02	
40.00	28870.0	0.242E+02	
40.00	28870.0	0.242E+02	0.277E+02
42.00	0.0	0.213E+02	
42.00	9623.3	0.203E+02	
42.00	19246.7	0.226E+02	
42.00	28870.0	0.225E+02	
42.00	28870.0	0.225E+02	0.257E+02
44.00	0.0	0.201E+02	
44.00	9623.3	0.194E+02	
44.00	19246.7	0.209E+02	
44.00	28870.0	0.209E+02	
44.00	28870.0	0.209E+02	0.235E+02
46.00	0.0	0.191E+02	
46.00	9623.3	0.188E+02	
46.00	19246.7	0.197E+02	
46.00	28870.0	0.198E+02	
46.00	28870.0	0.198E+02	0.215E+02

Continued Table II.18

Time (HRS)	Distance (M)	Calculated Discharge (Cumecs)	Prototype Discharge (Cumecs)
48.00	0.0	0.181E+02	
48.00	9623.3	0.182E+02	
48.00	19246.7	0.188E+02	
48.00	28870.0	0.190E+02	
48.00	28870.0	0.190E+02	0.200E+02

AVERAGE RECORDED DISCHARGE = 31.03 CUMECS
DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE DISCHARGE = 9.95 %
STANDARD DEVIATION = 15.03 %

		1	STATION
			ARF=0.56276417E+00
			BET=0.64179468E+00
		2	STATION
			ARF=0.24838185E+00
			BET=0.75359601E+00
		3	STATION
			ARF=0.22176588E+00
			BET=0.76948106E+00
		4	STATION
			ARF=0.25297320E+00
			BET=0.75564873E+00
		5	STATION
			ARF=0.16953522E+00
			BET=0.79695326E+00
		1	STATION
			ARF=0.86006832E+00
			BET=0.57024807E+00
		2	STATION
			ARF=0.19770927E+01
			BET=0.45744610E+00
		3	STATION
			ARF=0.46871758E+00
			BET=0.65826982E+00
		4	STATION
			ARF=0.47094536E+00
			BET=0.65677088E+00
		5	STATION
			ARF=0.66938651E+00
			BET=0.61201638E+00

ACCT	EINF	2 STATION	3 STATION	4 STATION	5 STATION	DOWN BOUND
23.82	0.9460E+02	0.9460E+024	0.9460E+02	0.9460E+02	0.9460E+02	0.9460E+02
24.14	0.9460E+02	0.9460E+02	0.9460E+02	0.9460E+02	0.9460E+02	0.9460E+02
47.84	0.6388E+04	0.6260E+04	0.5840E+04	0.6206E+04	0.6417E+04	0.6443E+04
47.92	0.6380E+04	0.6538E+04	0.6170E+04	0.6077E+04	0.6223E+04	0.6181E+04

48.03	0.6371E+04	0.6665E+04	0.6433E+04	0.6208E+04	0.6240E+04	0.6264E+04
48.13	0.6361E+04	0.6618E+04	0.6626E+04	0.6380E+04	0.6292E+04	0.6289E+04
71.83	0.4046E+04	0.4065E+04	0.4036E+04	0.4028E+04	0.4049E+04	0.4046E+04
71.95	0.4036E+04	0.4065E+04	0.4054E+04	0.4031E+04	0.4039E+04	0.4037E+04
72.06	0.4024E+04	0.4042E+04	0.4059E+04	0.4039E+04	0.4041E+04	0.4042E+04
72.17	0.4014E+04	0.4007E+04	0.4045E+04	0.4041E+04	0.4040E+04	0.4041E+04
95.88	0.1702E+04	0.1691E+04	0.1705E+04	0.1719E+04	0.1727E+04	0.1727E+04
96.04	0.1687E+04	0.1678E+04	0.1665E+04	0.1680E+04	0.1698E+04	0.1688E+04
96.20	0.1671E+04	0.1682E+04	0.1667E+04	0.1661E+04	0.1681E+04	0.1679E+04

Table II.20
Output of STVNLM-HJ Computer Program of The
Event 2-1-1982 of River Tees

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	27.45	7.23	29.76
2	33.22	6.84	27.85
4	39.36	7.73	31.24
6	58.21	9.09	35.83
8	266.69	12.82	40.10
10	406.11	50.58	181.28
12	532.68	88.05	317.31
14	616.35	123.94	475.35
16	545.60	152.11	555.49
18	472.94	150.46	552.18
20	440.66	140.55	518.27
22	369.41	127.62	474.01
24	311.88	110.18	412.04
26	283.97	93.49	350.89
28	319.76	82.34	306.94
30	434.54	84.47	308.97
32	430.38	105.40	387.90
34	395.80	112.48	416.20
36	451.85	109.08	400.54
38	417.85	117.63	434.27
40	350.4	114.89	427.60
42	284.88	102.02	382.91
44	246.21	85.69	323.47
46	216.57	72.81	276.26
48	191.98	62.86	239.65
50	173.94	54.91	210.17
52	171.08	48.87	187.08
54	175.88	46.21	176.52
56	165.65	46.10	176.64
58	156.88	44.27	170.01
60	150.45	42.08	161.86
62	143.39	40.17	154.85
64	144.61	38.26	147.35
66	146.88	37.81	145.45
68	139.80	38.04	146.75

Table II.21
Output of STVNLM-HJ Computer Program of The
Event 25-8-1986 of River Tees

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	5.3	1.038	5.155
2	5.3	1.063	5.259
4	5.4	1.069	5.286
6	5.8	1.089	5.357
8	6.4	1.162	5.655
10	7.2	1.287	6.155
12	7.6	1.461	6.862
14	148.6	1.584	3.745
16	399.6	25.72	69.169
18	619.7	80.79	192.72
20	713.8	151.96	337.19
22	642.9	214.72	459.45
24	445.6	245.30	521.09
26	287.6	232.71	502.0
28	222.8	196.98	436.81
30	181.4	161.31	369.22
32	155.8	130.01	307.65
34	139.7	104.7	256.02
36	119.9	85.31	215.33
38	102.9	69.40	180.86
40	88.60	56.41	151.78
42	77.1	45.88	127.42
44	68.6	37.49	107.37
46	62.5	31.03	91.42
48	61.3	26.21	79.01
50	63.0	23.24	71.28
52	67.4	21.86	67.49
54	69.5	21.84	67.40
56	64.4	22.19	68.46
58	56.8	21.51	66.85
60	51.3	19.84	62.47
62	46.8	17.98	57.50
64	43.8	16.19	52.62
66	40.3	14.72	48.56
68	37.9	13.35	44.68
70	35.5	12.21	41.45

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
72	33.3	11.22	38.59
74	31.5	10.34	36.00
76	29.7	9.59	33.78
78	38.3	8.91	31.48
80	26.7	10.04	35.24

Table II.22
Output of STVNLM-HJ Computer Program of The
Event 2-2-1981 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	6.5	0.89	7.34
2	7.27	0.84	5.93
4	9.13	1.06	7.63
6	11.7	1.31	9.47
8	72.6	1.68	2.18
10	159.8	13.42	105.13
12	181.7	22.53	182.98
14	129.5	19.81	178.12
16	82.8	11.71	100.93
18	63.3	8.69	73.22
20	52.0	7.03	58.40
22	43.9	5.97	49.09
24	38.0	5.10	41.49
26	33.4	4.52	36.53
28	31.7	3.99	31.69
30	32.0	4.00	31.65
32	30.8	4.05	32.43
34	28.7	3.78	30.13
36	27.2	3.54	28.06
38	25.1	3.40	27.03
40	22.1	3.08	24.43
42	21.3	2.69	20.82
44	20.1	2.77	21.8
46	19.1	2.48	19.25
48	18.1	2.46	19.18

Table II.23
Output of STVNLM-HJ Computer Program of The Event 1-10-1981 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	13.4	2.1	10.23
2	18.6	2.62	11.38
4	25.4	3.83	15.19
6	36.3	5.53	19.54
8	66.0	8.32	21.93
10	104.6	15.67	37.34
12	182.3	26.87	50.06
14	225.3	48.91	101.31
16	273.1	69.58	141.35
18	310.5	91.54	184.4
20	308.0	112.55	235.1
22	186.8	124.7	301.3
24	132.4	105.6	274.3
26	112.7	81.96	223.33
28	101.6	63.52	179.77
30	98.8	50.5	145.6
32	119.8	42.69	117.1
34	154.1	43.14	107.55
36	41.8	50.90	133.15
38	121.5	52.34	143.52
40	96.6	48.67	141.26
42	81.7	41.22	124.92
44	72.1	34.02	106.8
46	64.0	28.23	91.68
48	56.7	23.62	79.32
50	51.3	19.85	68.59
52	46.8	16.97	60.16

Table II.24
Output of STVNLM-HJ Computer Program of The
Event 26-8-1986 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	3.74	1.77	6.8
2	5.41	1.24	4.6
4	9.19	1.38	4.9
6	13.0	2.08	7.7
8	18.0	2.96	11.2
10	32.3	4.09	15.3
12	153.0	6.91	21.6
14	190.3	28.81	123.2
16	283.6	39.99	173.22
18	409.8	58.39	258.64
20	450.0	83.58	385.0
22	450.9	94.40	440.9
24	430.9	96.07	450.5
26	311.0	92.78	439.89
28	200.2	71.30	335.26
30	164.1	48.79	223.3
32	133.6	38.92	175.8
34	111.7	31.88	142.3
36	92.9	26.77	118.45
38	80.9	22.52	98.52
40	74.4	19.58	84.80

Table II.25
Output of STVNLM-HJ Computer Program of The
Event 15-4-1986 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	22.8	5.78	20.3
2	23.5	6.18	21.6
4	24.6	6.49	22.5
6	38.3	6.83	21.6
8	92.5	9.61	22.4
10	141.0	21.29	49.79
12	179.9	36.49	84.74
14	222.7	52.35	117.9
16	272.0	69.81	152.0
18	296.8	89.81	193.8
20	298.9	106.9	231.4
22	213.6	118.2	268.8
24	149.8	109.0	258.7
26	119.8	90.84	223.3
28	100.6	73.58	187.0
30	88.4	59.17	155.0
32	80.2	48.06	129.2
34	73.9	39.88	109.7
36	70.0	33.91	94.8
38	68.2	29.77	84.2
40	67.4	27.10	77.1
42	65.9	25.48	72.9
44	64.8	24.30	69.8

Table II.26
Output of STVNLM-LR Computer Program of The
Event 15-4-1986 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	22.8	12.00	22.6
2	23.5	12.02	22.6
4	24.6	12.17	22.7
6	38.3	12.48	21.8
8	92.5	15.23	20.2
10	141.0	27.28	29.9
12	179.9	45.79	44.9
14	222.7	68.28	60.5
16	272.0	95.30	115.3
18	296.8	127.7	160.7
20	298.9	160.6	200.0
22	213.6	190.3	230
24	149.8	201.5	265
26	119.8	199.9	270
28	100.6	192.9	244.3
30	88.4	183.2	190.5
32	80.2	172.2	165.4
34	73.9	160.8	141
36	70.0	149.5	134.9
38	68.2	138.6	84.4
40	67.4	128.7	80.2
42	65.9	119.7	78
44	64.8	111.5	72

Table II.27
Output of STVNLM-LR Computer Program of The
Event 26-8-1986 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	3.74	1.77	8.0
2	5.4	1.o5	4.4
4	9.19	1.20	5.0
6	13.0	1.89	8.2
8	18.0	2.69	11.9
10	32.3	3.71	16.3
12	153.0	6.37	23.7
14	190.3	27.91	140.6
16	283.6	36.19	183.0
18	409.8	52.94	273.9
20	450.0	75.58	406.1
22	450.9	82.88	449.9
24	430.9	83.04	451.9
26	311.0	79.53	437.1
28	200.2	58.50	317.7
30	164.1	38.91	205.0
32	133.6	32.08	167.3
34	111.7	26.45	136.4
36	92.9	22.32	114.1
38	80.9	18.77	94.9
40	74.4	16.43	82.3

Table II.28
Output of STVNLM-LR Computer Program of The
Event 1-10-1981 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	13.4	1.55	14.5
2	18.6	1.36	11.9
4	25.4	2.47	21.4
6	36.3	3.13	25.8
8	66.0	4.88	36.7
10	104.6	9.75	71.5
12	182.3	15.27	103.3
14	225.3	28.42	195.2
16	273.1	33.43	224.2
18	310.5	41.57	248.3
20	308.0	47.26	260.3
22	186.8	45.87	275.8
24	132.4	22.87	168.3
26	112.7	16.88	126.1
28	101.6	14.64	110.5
30	98.8	13.15	99.3
32	119.8	13.06	95.4
34	154.1	17.11	121.7
36	141.8	22.51	164.2
38	121.5	18.77	139.2
40	96.6	15.82	120.3
42	81.7	11.85	91.6
44	72.1	10.19	79.8
46	64.0	8.89	70.6
48	56.7	7.79	62.6
50	51.3	6.80	55.2
52	46.8	6.14	50.4

Table II.29
Output of STVNLM-LR Computer Program of The
Event 2-2-1981 of River Wear

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	6.5	0.86	8.9
2	7.27	0.44	4.5
4	9.13	0.90	9.1
6	11.7	0.90	8.8
8	72.6	1.37	7.2
10	159.8	12.27	92.7
12	181.7	23.44	178.7
14	129.5	23.93	188.0
16	82.8	14.18	116.3
18	63.3	8.59	72.48
20	52.0	7.06	60.6
22	43.9	5.61	49.0
24	38.0	4.76	42.1
26	33.4	4.07	36.4
28	31.7	3.55	32.0
30	32.0	3.50	31.5
32	30.8	3.58	32.3
34	28.7	3.32	30.2
36	27.2	3.07	28.0
38	25.1	2.92	26.9
40	22.1	2.61	24.4
42	21.3	2.23	20.8
44	20.1	2.30	21.6
46	19.1	2.04	19.3
48	18.1	2.01	19.0

Table II.30
Output of STVNLM-LR Computer Program of The
Event 25-8-1986 of River Tees

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	5.3	2.38	4.2
2	5.3	2.55	4.5
4	5.4	2.67	4.8
6	5.8	2.77	4.9
8	6.4	2.90	5.2
10	7.2	3.10	5.6
12	7.6	3.36	6.1
14	148.6	3.61	3.3
16	399.6	27.82	48.8
18	619.7	86.28	176.8
20	713.8	160.0	349.8
22	642.9	220.7	498.8
24	445.6	244.7	562.3
26	287.6	225.2	518.1
28	222.8	186.8	425.8
30	181.4	153.0	345.0
32	155.8	125.7	280.4
34	139.7	104.9	231.6
36	119.9	89.63	196.1
38	102.9	76.93	166.9
40	88.6	66.25	142.6
42	77.1	57.24	122.2
44	68.6	49.71	105.3
46	62.5	43.58	91.6
48	61.3	38.72	80.8
50	63.0	35.47	73.5
52	67.4	33.71	69.5
54	69.5	33.36	68.6
56	64.4	33.50	69.1
58	56.8	32.7	67.5
60	51.3	30.92	63.7
62	46.8	28.85	59.2
64	43.8	26.78	54.7
66	40.3	24.95	50.8

...Continued Table II.30

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
68	37.9	23.19	47.0
70	35.5	21.66	43.8
72	33.3	20.28	40.8
74	31.5	19.02	38.1
76	29.7	17.91	35.8
78	38.3 .	16.88	33.4
80	26.7	17.69	35.4

Table II.31
Output of STVNLM-LR Computer Program of The
Event 2-1-1982 of River Tees

Time (Hours)	Inflow (Cumecs)	Storage	Outflow (Cumecs)
0	27.4	4.30	28.6
2	33.2	4.09	27.2
4	39.3	5.08	33.8
6	58.2	5.99	39.9
8	266.6	9.05	59.2
10	406.1	43.61	290.1
12	532.6	62.93	419.0
14	616.3	81.88	545.5
16	545.6	93.68	585.9
18	492.7	80.45	536.6
20	440.6	73.14	487.8
22	369.4	65.27	435.5
24	311.8	54.26	361.9
26	283.9	45.90	306.1
28	319.7	42.20	281.1
30	434.5	48.63	323.6
32	430.3	67.11	447.4
34	395.8	64.25	428.5
36	451.8	58.79	391.6
38	417.8	68.82	459.0
40	350.4	61.96	413.3
42	284.8	51.46	343.3
44	246.2	41.71	278.2
46	216.5	36.37	242.6
48	191.9	32.03	213.6
50	173.9	28.42	189.5
52	171.0	25.81	172.1
54	175.8	25.64	170.9
56	165.6	26.46	176.5
58	156.8	24.65	164.4
60	150.4	23.40	156.0
62	143.3	22.47	149.8
64	144.6	21.39	142.6
66	146.8	21.72	144.8
68	139.8	22.06	147.1

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APPENDIX III
Computer Programmes Used in This Study

III-1 M-C2 Program


```
C    Q1 - ARRAY FOR THE DISCHARGE ALONG THE REACH AT THE NEW TIME LEVEL.

C    Q2 - ARRAY FOR THE DISCHARGE ALONG THE REACH AT THE OLD TIME LEVEL.

C    DX - SPACE INCREMENT.

C    DXLR - LENGTH OF THE REACH.

C    JX - NUMBER OF SPACE GRID POINTS.

C    X - ARRAY FOR THE DISTANCES OF THE GRID POINTS ALONG THE CHANNEL.

C    DT - TIME INCREMENT.

C    T - TIME IN SECONDS.

C    TH - TIME IN HOURS.

C    LEND - NUMBER OF TIME STEPS.

C    TITLE - ARRAY WHICH STORES DATA FOR THE HEADING OF THE OUTPUT.

C    J1, L1 AND L2 REFER TO WHEN AND HOW THE RESULTS ARE WRITTEN.

C    WSP - WAVE SPEED.

C    AP - ATTENUATION PARAMETER.

C    QCON - DISCHARGE CONSTANT.

C    C1, C2, C3 AND C4 ARE PARAMETERS IN THE MUSKINGUM METHOD.

C    DTQHYDRO - TIME INTERVAL IN HOURS BETWEEN THE DATA POINTS OF THE
             INPUT AND OTHER DISCHARGE HYDROGRAPHS.

C    QHYDRO - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE
             HYDROGRAPH AT THE UPSTREAM SECTION.

C    IQH - NUMBER OF DATA POINTS FOR THE UPSTREAM HYDROGRAPH.

C    QTRIB1 - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE
             HYDROGRAPH AT THE FIRST TRIBUTARY.

C    ITR1 - NUMBER OF DATA POINTS FOR THE HYDROGRAPH AT THE FIRST TRIBUTARY.

C    JT1 - POSITION OF THE INPUT DISCHARGE FROM THE FIRST TRIBUTARY.

C    QTRIB2 - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE
             HYDROGRAPH AT THE SECOND TRIBUTARY.

C    ITR2 - NUMBER OF DATA POINTS FOR THE HYDROGRAPH AT THE SECOND TRIBUTARY.

C    JT2 - POSITION OF THE INPUT DISCHARGE FROM THE SECOND TRIBUTARY.

C    QINIT - INITIAL DISCHARGE FOR THE FLOW THROUGHOUT THE REACH.

C    QINB - BASE VALUE FOR THE LATERAL INFLOW.

C    QINA - AMPLITUDE OF THE FUNCTION FOR THE LATERAL INFLOW.

C    TQIN - TIME WHEN THE LATERAL INFLOW TAKES ITS MAXIMUM VALUE.

C    TSCQIN - TIME SCALE FOR THE LATERAL INFLOW FUNCTION.

C    QDNS - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE HYDROGRAPH
             AT THE DOWNSTREAM END OF THE REACH.

C    IQDNS - NUMBER OF DATA POINTS FOR THE DOWNSTREAM HYDROGRAPH.

C    TDEVN - TIME IN HOURS WHEN THE CALCULATIONS OF THE ERROR
             PARAMETERS ARE BEGUN.

C    TOTDIS - AVERAGE RECORDED DISCHARGE AFTER THE TIME TDEVN.

C    DISDIF - DIFFERENCE BETWEEN THE AVERAGE RECORDED AND PREDICTED
             DISCHARGES AS A PERCENTAGE OF THE RECORDED DISCHARGES.

C    DEVN - ULTIMATELY RECORDS THE STANDARD DEVIATION OF THE PREDICTED
             DISCHARGE AS A PERCENTAGE OF THE AVERAGE RECORDED DISCHARGE.
```

```
C ********************************************************************
      REAL Q1(50), Q2(50), X(50)
      COMMON DX, DT, JX, DXLR, LEND, TH, J1, L1, L2, QHYDRO(200),
     1    DTQHYD, QINIT, AP, WSP, QCON, QDNS(200), TDEVN
C FIRST READ IN THE APPRPRIATE DATA AND WRITE IT OUT
C FOR EASY REFERENCE.
      CALL DATIN
C NEXT CALCULATE VARIOUS CONSTANTS AND PARAMETERS
C FOR USE BELOW.
      DX = DXLR / FLOAT(JX - 1)
      DK = DX / WSP
      EPSILO=0.5-(QCON*AP/(DX*WSP*DXLR))
C     EPSILO = 0.5 - (QCON*AP/(WSP*DXLR**2))
      CC = (DK * (1.0 - EPSILO)) + DT * 0.5
      C1 = (DK * EPSILO + DT * 0.5) / CC
      C2 = (DT * 0.5 - DK * EPSILO) / CC
      C3 = (DK * (1.0 - EPSILO) - DT * 0.5) / CC
      PRINT *, ' C1 C2 C3 EPS'
      WRITE (6,10) C1, C2, C3, EPSILO
   10 FORMAT (4F10.5)
      JXM1 = JX - 1
      T = 0.0
C THE FOLLOWING VARIABLES ARE ONLY USED WHEN A RECORDED DOWNSTREAM
C DOWNSTREAM HYDROGRAPH IS AVAILABLE FOR COMPARISON. ALL SUCCEEDIND
C STATEMENTS BEGINNING IN COLUMN 13 REFER TO THIS CASE ONLY, AND
C SHOULD NOT BE INCLUDED OTHERWISE.
      DEVN = 0.0
      TOTDIS = 0.0
      TOTD = 0.0
      QP1 = QINIT
      QP2 = QINIT
      QDNP2 = QINIT
      QDNP1 = QINIT
      JCOUNT = 0
      ICOUNT = 0
C DEFINE X AND THE INITIAL VALUES OF Q1 AND Q2
      DO 20 J = 1, JX
      X(J) = DX * FLOAT(J - 1)
      Q1(J) = QINIT
      Q2(J) = QINIT
   20 CONTINUE
C BEGIN THE MAIN TIME LOOP
      DO 110 L = 1, LEND
      TH = T / 3600.0
      QP2 = QP1
      QP1 = Q1(JX)
      QDNP2 = QDNP1
```

```
        QDN = FF(QDNS,TH,DTQHYD)
        QDNP1 = QDN
C       QDN=FF(QDNS,TH,DTQHYD)
C   UPDATE THE VALUES FOR THE DISCHARGE
        DO 30 J = 1, JX
        Q2(J) = Q1(J)
   30 CONTINUE
C   FIND THE VALUE OF Q1(1) FROM THE INPUT HYDROGRAPH AND ADD THE
C   CONTRIBUTION FROM THE TRIBUTARY, IF ANY
C       QTOT=0.0
C       IF(JT1.EQ.1) QTOT=FF(QTRIB1,TH,DTQHYD)
        Q1(1) = FF(QHYDRO,TH,DTQHYD)
C   THE MAIN CALCULATIONS FOR Q1 ARE PERFORMED IN THE FOLLOWING LOOP
        DO 40 J = 2, JX
C   QTOT REFERS TO THE INFLOW DISCHARGE FROM TRIBUTARIES AND LATERAL
C   RUNOFF. UNDER SNOW-MELT CONDITIONS IT MAY BE PREFERABLE TO TAKE
C   THE LATERAL INFLOW AS PROPORTIONAL TO THE DISCHARGE AT THE
C   UPSTREAM BOUNDARY
C       TX=(TH-TQIN)/TSCQIN
C       QTOT=QINA*EXP(-TX*TX)+QINB
C       QTOT=Q1(1)*CONST/DXLR
C       IF(J.EQ.JT1) QTOT=QTOT+FF(QTRIB1,TH,DTQHYD)/DX
C       IF(J.EQ.JT2) QTOT=QTOT+FF(QTRIB2,TH,DTQHYD)/DX
        Q1(J) = C1 * Q1(J - 1) + C2 * Q2(J - 1) + C3 * Q2(J)
   40 CONTINUE
C   PERFORM VARIOUS SUMS ON THE ERROR PARAMETERS
        IF (TH .LT. TDEVN) GO TO 50
        DEVN = DEVN + (Q1(JX) - QDN) * (Q1(JX) - QDN)
        ICOUNT = ICOUNT + 1
        JCOUNT = JCOUNT + 1
        IF (JCOUNT .NE. 2) GO TO 50
        TOTD = TOTD + 2.0 * DT * (Q1(JX) + QP1 + QP2) / 3.0
        TOTDIS = TOTDIS + 2.0 * DT * (QDN + QDNP1 + QDNP2) / 3.0
        JCOUNT = 0
C   NOW WRITE OUT THE RESULTS - IF IT IS TIME
   50 IF (L .NE. L1*(L/L1)) GO TO 100
        WRITE (6,60) (TH,X(J),Q1(J),J=1,JXM1,J1)
   60 FORMAT ((20X,F6.2,9X,F8.1,8X,F7.2))
   70 WRITE (6,80) TH, X(JX), Q1(JX), QDN
   80 FORMAT ((20X,F6.2,9X,F8.1,2(8X,F7.2)))
        WRITE (6,90)
   90 FORMAT (' ', /)
        T = T + DT
        GO TO 110
  100 IF (L .EQ. L2*(L/L2)) GO TO 70
  110 CONTINUE
```

```
C   FINALLY, WORK OUT THE ERROR PARAMETERS
      TOTDIS = TOTDIS / ((TH - TDEVN)*3600.0)
      TOTD = TOTD / ((TH - TDEVN)*3600.0)
      DISDIF = (1.0 - TOTD/TOTDIS) * 100.0
      DEVN = SQRT(DEVN/FLOAT(ICOUNT)) * 100.0 / TOTDIS
      WRITE (6,120) TOTDIS, DISDIF, DEVN
  120 FORMAT (' AVERAGE RECORDED DISCHARGE = ', F7.2,
     1 ' DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE D',
     2 'ISCHARGE = ', F6.2, '
     3 F6.2, '
      STOP
      END
C   ***************************************************************
      SUBROUTINE DATIN
C   THIS SUBROUTINE READS IN THE RELEVANT DATA, WRITES IT OUT FOR EASY
C   REFERENCE, AND PROVIDES A HEADING FOR THE RESULTS
      COMMON DX, DT, JX, DXLR, LEND, TH, J1, L1, L2, QHYDRO(200),
     1 DTQHYD, QINIT, AP, WSP, QCON, QDNS(200), TDEVN
C      READ(1,100) (TITLE(I),I=1,60)
C      READ(1,*) (TITLE(I),I=1,60)
C 100 FORMAT(10A8/5A8)
      READ (5,10) JX, LEND, IQH, IQDNS, J1, L1, L2
   10 FORMAT (7I3)
      READ (5,20) DXLR, DT, DTQHYD, QINIT, WSP, AP, QCON, TDEVN
   20 FORMAT (8E10.2)
C      WRITE(3,300) (TITLE(I),I=1,60)
C 300 FORMAT(1H ,(15A8))
C 301 FORMAT - FOR WRITE STATEMENT
C      WRITE(3,*) DXLR,DT,DTQHYD,QINIT,QINB,QINA,TQIN,TSCQIN, WSP,AP,
C      QCON, TDEVN
C 302 FORMAT - FOR WRITE STATEMENT
C   READ IN THE DISCHARGE HYDROGRAPHS
      READ (5,30) (QHYDRO(I),I=1,IQH)
C      IF(ITR1.NE.0) READ(2,200) (QTRIB1(I),I=1,ITR1)
C      IF(ITR2.NE.0) READ(2,200) (QTRIB2(I),I=1,ITR2)
      READ (5,30) (QDNS(I),I=1,IQDNS)
   30 FORMAT (8F10.5)
      WRITE (6,40)
   40 FORMAT (' ', 21X, 'TIME', 10X, 'DISTANCE', 6X,CALCULATED', 6X,
     1 'PROTOTYPE'/' ', 20X, '(HRS)', 13X, '(M)', 9X, DISCHARGE',
     2 6X, 'DISCHARGE'/)
      RETURN
      END
C   ***************************************************************
      FUNCTION FF(Q, T, DT)
```

```
C   THIS FUNCTION INTERPOLATES USING A CUBIC POLYNOMIAL
    REAL Q(200)
    L = INT(T/DT) + 1
    IF (L .LE. 1) L = 2
    FRI = T / DT - FLOAT(L - 1)
    A = (Q(L + 2) - 3.0*(Q(L + 1) - Q(L)) - Q(L - 1)) / 6.0
    B = (Q(L - 1) - 2.0*Q(L) + Q(L + 1)) * 0.5
    C = (-Q(L+2) + 6.0*Q(L+1) - 3.0*Q(L) - 2.0*Q(L-1)) / 6.0
    D = Q(L)
    FF = ((A*FRI + B)*FRI + C) * FRI + D
    RETURN
    END
```

III-2 VPDM1 PROGRAM

C Q1 - ARRAY FOR THE DISCHARGE ALONG THE REACH AT THE NEW TIME LEVEL.

C Q2 - ARRAY FOR THE DISCHARGE ALONG THE REACH AT THE OLD TIME LEVEL.

C DX - SPACE INCREMENT.

C DXLR - LENGTH OF THE REACH.

C JX - NUMBER OF SPACE GRID POINTS.

C X - ARRAY FOR THE DISTANCES OF THE GRID POINTS ALONG THE CHANNEL.

C DT - TIME INCREMENT.

C LEND - NUMBER OF TIME STEPS.

C T - TIME IN SECONDS.

C TH - TIME IN HOURS.

C KEND - MAXIMUM NUMBER OF ITERATIONS ALLOWED.

C QERROR - MAXIMUM ERROR ALLOWED IN THE NEWTON ITERATION PROCESS.

C EQ - INCREMENT IN THE DISCHARGE BETWEEN SUCCESSIVE VALUES OF THE DATA

C C FOR THE WAVE SPEED AND THE ATTENUATION PARAMETER.

C TITLE - ARRAY WHICH STORES DATA FOR THE HEADING OF THE OUTPUT.

C J1, L1 AND L2 REFERS TO WHEN AND HOW THE RESULTS ARE WRITTEN.

C DTQHYDRO- TIME INTERVAL IN HOURS BETWEEN THE DATA POINTS FOR

C THE INPUT AND OTHER DISCHARGE HYDROGRAPHS.

C QHYDRO - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE HYDROGRAPH

C AT THE UPSTREAM SECTION.

C IQH - NUMBER OF DATA POINTS FOR THE UPSTREAM HYDROGRAPH.

C QTRIB1 - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE HYDROGRAPH

C AT THE FIRST TRIBUTARY.

C ITR1 - NUMBER OF DATA POINTS FOR THE HYDROGRAPH AT THE FIRST TRIBUTARY.

C JT1 - POSITION OF THE INPUT DISCHARGE FROM THE FIRST TRIBUTARY (0 OR 1)

C QTRIB2 - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE HYDROGRAPH

C AT THE SECOND TRIBUTARY.

C ITR2 - NUMBER OF DATA POINTS FOR THE HYDROGRAPH AT THE SECOND TRIBUTARY.

C JT2 - POSITION OF THE INPUT DISCHARGE FROM THE SECOND TRIBUTARY (0 OR JX)

C QINIT - INITIAL DISCHARGE FOR THE FLOW THROUGHOUT THE REACH.

C QINB - BASE VALUE FOR THE LATERAL INFLOW.

C QINA - AMPLITUDE OF THE FUNCTION FOR THE LATERAL INFLOW.

C TQIN - TIME WHEN THE LATERAL INFLOW TAKES ITS MAXIMUM VALUE.

C TSCQIN - TIME SCALE FOR THE LATERAL INFLOW FUNCTION.

C QCF - CUT-OFF DISCHARGE FOR DRAINAGE OFF THE FLOOD PLAIN TO BE INCLUDED.

C INDIC - AN INDICATOR WHICH 0 WHEN THE DISCHARGE AT A SECTION BELOW

C BANK-FULL AND INCREASING, AND 1 WHEN THE DISCHARGE HAS PREVIOUSLY

C EXCEEDED BANK-FULL AND YET IS BELOW BANK-FULL AND DECREASING.

C QDNS - ARRAY WHICH STORES THE DATA FOR THE RECORDED DISCHARGE HYDROGRAPH

C AT THE DOWNSTREAM END OF THE REACH.

C IQDNS - NUMBER OF DATA POINTS FOR THE DOWNSTREAM HYDROGRAPH.

C TDEVN - TIME IN HOURS WHEN THE CALCULATIONS OF THE ERROR PARAMETERS ARE

C BEGUN.

C TOTDIS - AVERAGE RECORDED DISCHARGE AFTER THE TIME TDEVN.

C TOTD - AVERAGE PREDICTED DISCHARGE AFTER THE TIME TDEVN.

C DISDIF - DIFFERENCE BETWEEN THE AVERAGE RECORDED AND PREDICTED DISCHARGES

C AS A PERCENTAGE OF THE RECORDED DISCHARGES.

C DEVN - ULTIMATELY RECORDS THE STANDARD DEVIATION OF THE PREDICTED

```
C     DISCHARGE AS A PERCENTAGE OF THE AVERAGE RECORDED DISCHARGE.
C     ******************************************************* *******
C     THIS PROGRAM SOLVES A GENERALISED CONVECTION-DIFFUSION EQUATION FOR
C     FLOOD ROUTING (VARIABLE PARAMETER DIFFUSION METHOD)
      REAL P1(50),P2(50),B1(50),B2(50),B3(50),R(50), BB(50),RR(50)
      COMMON DX,DT,JX,LEND,DXLR,KEND,TH,J1,L1,L2,QERROR
     1     ,EQ,JT1,JT2,QTRIB1(200),QTRIB2(200), QHYDRO(200),DTQHYD,
     2     QINIT,QINB,QINA,TSCQIN,TQIN,QCF,CCF,ACF,INDIC(50), Q1(50),Q2(50),
     3     AP(100),WSP(100),COEFAP(3,30),COEFWS(3,30),X(50)
     4     ,TDEVN,QDNS(200)
C     FIRST READ IN THE RELEVANT DATA AND PRINT IT OUT FOR EASY REFERENCE
      CALL DATIN
C     DEFINE VARIOUS CONSTANTS USED DURING THE CALCULATIONS
      JXM1=JX-1
      JXM2=JX-2
      DX=DXLR/(JX-1)
      DTX=0.25*DT/DX
      DXSQ=0.5*DT/(DX*DX)
      QJX=QINIT
      QB=QCF
      I=QB/(EQ*3)+1
      CCF=(COEFWS(3,I)*QB+COEFWS(2,I))*QB+COEFWS(1,I)
      ACF=DXSQ*((COEFAP(3,I)*QB+COEFAP(2,I))*QB+COEFAP(1,I))
C     STATEMENTS BEGINING IN COLUMN 13 ARE CONCERNED WITH THE CALCULATION
C     OF THE ERROR PARAMETERS DEVN, TOTDIS AND DISDIF
      TOTDIS=0.0
      DEVN=0.0
      TOTD=0.0
      QP1=QINIT
      QP2=QINIT
      QDNP1=QINIT
      QDNP2=QINIT
      JCOUNT=0
      ICOUNT=0
C     NEXT, GENERATE THE INITIAL VALUES OF Q1, Q2, X AND INDIC.
      DO 2 J=1,JX
      X(J)=DX*(J-1)
      INDIC(J)=0
      Q1(J)=QINIT
      Q2(J)=QINIT
    2 CONTINUE
C     BEGIN THE MAIN TIME LOOP
      T=0.0
      DO 32 L=1,LEND
C     T=T+DT
      TH=T/3600.0
C     EVALUATE THE PROTOTYPE DISCHARGE AT THE DOWNSTREAM BOUNDARY
```

```
      QP2=QP1
      QP1=QJX
      QDNP2=QDNP1
      QDN=FF(QDNS,TH,DTQHYD)
      QDNP1=QDN
C     QDN=FF(QDNS,TH,DTQHYD)
C     UPDATE Q1, Q2 AND INDIC
      DO 4 J=1,JX
      QQ=Q2(J)
      IF(Q1(J).GT.QCF) INDIC(J)=1
      Q2(J)=Q1(J)
      Q1(J)=2.0*Q1(J)-QQ
    4 CONTINUE
C     DEFINE THE ARRAYS P1 AND P2 TO STORE FUNCTIONS FOR USE IN LOOP 14
      DO 6 J=2,JXM1
      P1(J)=Q2(J+1)-Q2(J-1)
      P2(J)=Q2(J+1)-2.0*Q2(J)+Q2(J-1)
      IF(P1(J).LE.0) INDIC(J)=0
    6 CONTINUE
C     CALCULATE THE UPSTREAM VALUE FOR Q1. INCLUDE THE DISCHARGE FROM THE
C     TRIBUTARY, IF THERE IS ONE
      QTOT=0.0
      IF(JT1.EQ.1) QTOT=FF(QTRIB1,TH,DTQHYD)
      Q1(1)=FF(QHYDRO,TH,DTQHYD)+QTOT
C     CALCULATE THE NEW VALUE FOR THE DISCHARGE AT THE DOWNSTREAM BOUNDARY
C     IN THE MODEL
      CALL QDOWN
C     NOW FIND THE VALUES FOR THE REST OF THE ARRAY Q1
C     USE THE NEWTON ITERATION PROCESS TO SOLVE THE NON-LINEAR SIMULTANEOUS
C     EQUATIONS
      DO 22 K=1,KEND
      DO 14 J=2,JXM1
      DQP=Q1(J+1)-Q1(J-1)+P1(J)
      QQ=0.5*(Q1(J)+Q2(J))
      IF(INDIC(J).EQ.1) GO TO 10
    8 QB=QQ
      I=QB/(EQ*3)+1
      C=(COEFWS(3,I)*QB+COEFWS(2,I))*QB+COEFWS(1,I)
      DC=2.0*COEFWS(3,I)*QB+COEFWS(2,I)
      ADXSQ=DXSQ*((COEFAP(3,I)*QB+COEFAP(2,I))*QB+COEFAP(1,I))
      DADXSQ=DXSQ*(2.0*COEFAP(3,I)*QB+COEFAP(2,I))
      GO TO 12
   10 IF(Q2(J).GT.QCF) GO TO 8
      C=CCF
      ADXSQ=ACF
      DC=0.0
```

```
        DADXSQ=0.0
     12 DDQP=Q1(J+1)-2.0*Q1(J)+Q1(J-1)+P2(J)
C    PUT IN AN ARTIFICIAL FUNCTION FOR THE LATERAL INFLOW.
C    IF A SNOW-MELT FLOOD IS BEING SIMULATED IT MAY BE PREFERABLE
C    TO DEFINE QTOT AS SOME CONSTANT TIMES Q1(1)
        TX=(TH-TQIN)/TSCQIN
C        TX=(TH-TQIN)
        QTOT=QINA*EXP(-TX*TX)+QINB
        D1=DQP*DTX-QTOT*DT
        R(J)=Q1(J)-Q2(J)+D1*C-QQ*ADXSQ*DDQP
        B1(J)=-DTX*C-ADXSQ*QQ
        B2(J)=1.0+DC*0.5*D1-DADXSQ*0.5*QQ*DDQP-ADXSQ* (0.5*DDQP-QQ*2.0)
        B3(J)=DTX*C-ADXSQ*QQ
     14 CONTINUE
        B1(2)=0.0
        B3(JXM1)=0.0
C    A GAUSSIAN ELIMINATION PROCEDURE AVOIDS THE USE OF EXCESSIVE STORAGE
C    IN THE COMPUTER
        BB(2)=B2(2)
        RR(2)=R(2)
        DO 16 J=3,JXM1
        BB(J)=B2(J)-B3(J-1)*B1(J)/BB(J-1)
        RR(J)=R(J)-RR(J-1)*B1(J)/BB(J-1)
     16 CONTINUE
        DQ=RR(JXM1)/BB(JXM1)
        Q1(JXM1)=Q1(JXM1)-DQ
        DQM=ABS(DQ)
        JQ=JXM1
        DO 20 JJ=3,JXM1
        J=JX-JJ+1
        DQ=(RR(J)-B3(J)*DQ)/BB(J)
        IF(ABS(DQ).LE.DQM) GO TO 18
        DQM=ABS(DQ)
        JQ=J
     18 Q1(J)=Q1(J)-DQ
     20 CONTINUE
C    CONTINUE THE ITERATION UNLESS THE ACCURACY CONDITION IS SATISFIED,
C    OR THERE HAVE BEEN TOO MANY ITERATIONS
        IF(DQM.LE.QERROR) GO TO 24
     22 CONTINUE
        WRITE(6,300) JQ,DQM
    300 FORMAT(20H TOO MANY ITERATIONS,5X, 13HVALUE OF J = ,I3/
       1    44H MAXIMUM VALUE OF THE DISCHARGE INCREMENT = ,F7.4/)
     24 CONTINUE
C    DEFINE QJX AS THE TOTAL DISCHARGE AT THE DOWNSTREAM BOUNDARY,
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C   INCLUDING A TRIBUTARY IF THERE IS ONE
    QTOT=0.0
    IF(JT2.EQ.JX) QTOT=FF(QTRIB2,TH,DTQHYD)
    QJX=Q1(JX)+QTOT
    PRINT *,QJX
C   CALCULATE VARIOUS ERROR PARAMETERS
    IF(TH.LT.TDEVN) GO TO 26
    DEVN=DEVN+(QJX-QDN)*(QJX-QDN)
    ICOUNT=ICOUNT+1
    JCOUNT=JCOUNT+1
    IF(JCOUNT.NE.2) GO TO 26
    TOTDIS=TOTDIS+2.0*DT*(QDN+QDNP1+QDNP2)/3.0
    TOTD=TOTD+2.0*DT*(QJX+QP1+QP2)/3.0
    JCOUNT=0
C   WRITE OUT THE RESULTS - IF IT IS TIME
 26 IF(L.NE.L1*(L/L1)) GO TO 30
    WRITE(6,301) (TH,X(J),Q1(J),J=1,JX,J1)
301 FORMAT((20X,F6.2,9X,F8.1,8X,E10.3))
 28 WRITE(6,302) TH,X(JX),QJX,QDN                              0
302 FORMAT(20X,F6.2,9X,F8.1,8X,E10.3,8X,E10.3)
    WRITE(6,303)
303 FORMAT(1H ,/)
    T=T+DT
    GO TO 32
 30 IF(L.EQ.L2*(L/L2)) GO TO 28
 32 CONTINUE
    TOTDIS=TOTDIS/((TH-TDEVN)*3600.0)
    TOTD=TOTD/((TH-TDEVN)*3600.0)
    DISDIF=(1.0-TOTD/TOTDIS)*100.0
    DEVN=SQRT(DEVN/FLOAT(ICOUNT))*100.0/TOTDIS
    WRITE(6,304) TOTDIS,DISDIF,DEVN
304 FORMAT(34H AVERAGE RECORDED DISCHARGE = ,F7.2,
   1    9H CUMECS/
   2    56H DIFFERENCE BETWEEN RECORDED AND PREDICTED AVERAGE D,
   3    11HISCHARGE = ,F6.2,1H
   4    26H STANDARD DEVIATION = ,F6.2,1H
    STOP
    END
C   ****************************************************** *************
    SUBROUTINE DATIN
C   THIS SUBROUTINE READS IN THE RELEVANT DATA , WRITES IT OUT FOR EASY
C   REFERENCE, AND CALCULATES THE COEFFICIENTS, COEFAP AND COEFWS,
C   DEFINING THE CURVES FOR THE ATTENUATION PARAMETER, AP, AND THE
C   WAVE SPEED, WSP.
    REAL QX(10),WX(10),APX(10),COEF(5)
    COMMON DX,DT,JX,LEND,DXLR,KEND,TH,J1,L1,L2,QERROR
```

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```
      1   ,EQ,JT1,JT2,QTRIB1(200),QTRIB2(200),QHYDRO(200), DTQHYD,
      2   QINIT,QINB,QINA,TSCQIN,TQIN,QCF,CCF,ACF, INDIC(5),Q1(50),Q2(50),
      3   AP(100),WSP(100),COEFAP(3,30),COEFWS(3,30),X(50)
      4   ,TDEVN,QDNS(200)
C     READ(1,100) (TITLE(I),I=1,60)
C 100 FORMAT(10A8/5A8)
      READ(5,101) JX,LEND,KEND,IWSP,IQH,ITR1,ITR2,JT1,JT2,J1, L1,L2
      1   ,IQDNS
  101 FORMAT(13I3)
      READ(5,102) DXLR,DT,EQ,DTQHYD,QERROR,QINIT,QINB,QINA, TQIN,TSCQIN
      1   ,QCF
      2   ,TDEVN
  102 FORMAT(8E10.2/4E10.2)
C   WRITE OUT THE DATA USED IN RUNNING THE PROGRAM
C     WRITE(3,300) (TITLE(I),I=1,60)
C 300 FORMAT(1H ,(15A8))
      WRITE(6,*) JX,LEND,KEND,IWSP,IQH,ITR1,ITR2,JT1,JT2,J1, L1,L2
      1   ,IQDNS
C   INSERT AN APPROPRIATE FORMAT STATEMENT 301
      WRITE(6,*) DXLR,DT,EQ,DTQHYD,QERROR,QINIT,QINB,QINA,TQIN,
      1   TSCQIN,QCF
      2   ,TDEVN
C   INSERT AN APPROPRIATE FORMAT STATEMENT 302
C   NEXT, EITHER READ IN THE DATA FOR THE WAVE SPEED AND ATTENUATION
C   PARAMETERS TO CALCULATE THE COEFFICIENT FOR THE SMOOTHED
C   QUADRATIC CURVES OR READ IN THE COEFFICIENTS.
      IWSPD3=IWSP/3
C     IF(NPAR.EQ.0) GO TO 10
      READ(5,103) (WSP(I),I=1,IWSP)
  103 FORMAT(8F10.5)
      READ(5,104) (AP(I),I=1,IWSP)
  104 FORMAT(8E10.2)
      WRITE(6,303) EQ,(WSP(I),I=1,IWSP)
  303 FORMAT(1H ,25X,27HDATA FOR THE WAVE SPEED AT ,F4.0,16H CUMEC INTER
      1   VALS/(1H ,10(1PE8.2,3X)))
      WRITE(6,304)
  304 FORMAT(1H ,//)
      WRITE(6,305) EQ,(AP(I),I=1,IWSP)
  305 FORMAT(1H ,20X,38HDATA FOR THE ATTENUATION PARAMETER AT ,F4.0,16H
      1   CUMEC INTERVALS/(1H ,10(1PE8.2,3X)))
C   THE FOLLOWING PROCEDURE SMOOTHS THE DATA FOR THE SPEED AND ATTENUATION
C   PARAMETERS. THIS IS DONE BY FITTING A QUADRATIC CURVE THROUGH 4
C   NEIGHBOURING POINTS.
      DO 8 I=1,IWSPD3
      DO 2 M=1,4
```

```
      I3=3*(I-1)+M

      QX(M)=EQ*(I3-1)

      WX(M)=WSP(I3)

      APX(M)=AP(I3)/DXLR

    2 CONTINUE

      CALL FIT(QX,WX,COEF)

      DO 4 J=1,3

      COEFWS(J,I)=COEF(J)

    4 CONTINUE

      CALL FIT(QX,APX,COEF)

      DO 6 J=1,3

      COEFAP(J,I)=COEF(J)

    6 CONTINUE

    8 CONTINUE
C   WRITE OUT THE COEFFICIENTS TO A CARD FILE OR TO THE LINE PRINTER
C   (CHANGE THE CHANNEL NUMBER IN THE LATER CASE)

      WRITE(6,400) ((COEFWS(J,I),COEFAP(J,I),J=1,3),I=1,IWSPD3)
C       GO TO 12
C  10 PAUSE (RP)
C       READ(5,400) ((COEFWS(J,I),COEFAP(J,I),J=1,3),I=1,IWSPD3)

  400 FORMAT(6E12.6)

      GO TO 12
C   READ IN THE DISCHARG HYDROGRAPHS AT THE UPSTREAM AND DOWNSTREAM ENDS
C   OF THE REACH, TOGETHER WITH THE HYDROGRAPHS FOR THE TWO
C   TRIBUTARIES

   12 READ(5,200) (QHYDRO(I),I=1,IQH)

      IF(ITR1.NE.0) READ(5,200) (QTRIB1(I),I=1,ITR1)

      IF(ITR2.NE.0) READ(5,200) (QTRIB2(I),I=1,ITR2)

      READ(5,200) (QDNS(I),I=1,IQDNS)

  200 FORMAT(8F10.5)
C   WRITE THE HEADINGS FOR THE OUTPUT DATA FROM THE CALCULATIONS

      WRITE(6,306)

  306 FORMAT(1H ,21X,4HTIME,10X,8HDISTANCE,6X, 10HCALCULATED,6X,9HPROTOTY

    1    PE/1H ,20X,5H(HRS),13X,3H(M),9X,9HDISCHARGE,6X, 9HDISCHARGE/)

      RETURN
      END
C **************************************************************************
      SUBROUTINE QDOWN
C   THIS SUBROUTINE CALCULATES THE DISCHARGE AT THE DOWNSTREAM BOUNDARY
C   IN THE MODEL

      DIMENSION XX(10),QX(10),COEFQ(5)

      COMMON DX,DT,JX,LEND,DXLR,KEND,TH,J1,L1,L2,QERROR

    1    ,EQ,JT1,JT2,QTRIB1(200),QTRIB2(200),QHYDRO(200), DTQHYD,

    2    QINIT,QINB,QINA,TSCQIN,TQIN,QCF,CCF,ACF,INDIC(50), Q1(50),Q2(50),

    3    AP(100),WSP(100),COEFAP(3,30),COEFWS(3,30),X(50)

    4    ,TDEVN,QDNS(200)
```

```
C    FIRST FIT A QUADRATIC THROUGH THE LAST FOUR POINTS AT THE OLD TIME
C    LEVEL
     JXM1=JX-1
     JXM2=JX-2
     COEFQ(1)=Q2(JX)
     COEFQ(2)=0.5*(4.0*Q2(JXM1)-Q2(JXM2)-3.0*Q2(JX))
     COEFQ(3)=0.5*(Q2(JXM2)-2.0*Q2(JXM1)+Q2(JX))
C    NOW ITERATE TO FIND THE CORRECT VALUE OF Q2 AT THE FOOT OF THE
C    CHARACTERISTIC. THE WEGSTEIN ITERATION PROCEDURE IS USED HERE
     DELTX=0.0
     QP=Q2(JX)
     QBM2=QP
     QB=QP
     DO 12 K=1,KEND
     DQP=-(COEFQ(2)+2.0*DELTX*COEFQ(3))
     IF(DQP.LT.0.0) INDIC(JX)=0
     IF(INDIC(JX).EQ.1) GO TO 4
   2 QC=QB
     I= QB/(EQ*3)+1
C     PRINT *, EQ
C     PRINT *, QB
     CC=(COEFWS(3,I)*QC+COEFWS(2,I))*QC+COEFWS(1,I)
     GO TO 6
   4 IF(QB.GT.QCF) GO TO 2
     QC=QCF
     CC=CCF
   6 DELTX=CC*DT/DX
     Q=COEFQ(1)+DELTX*(COEFQ(2)+DELTX*COEFQ(3))
     IF(ABS(Q-QP).LE.QERROR) GO TO 14
     IF(K.EQ.1) GO TO 8
     IF(K.LT.KEND) GO TO 10
     WRITE(3,300)
 300 FORMAT(15H ERROR IN QDOWN)
     STOP
   8 QB=Q
     QBM1=Q
     QP=Q
     GO TO 12
  10 QB=Q-(Q-QP)*(Q-QBM1)/(Q-QP-QBM1+QBM2)
     QBM2=QBM1
     QBM1=QB
     QP=Q
  12 CONTINUE
C    FINALLY, CALCULATE THE NEW DOWNSTREAM VALUE FOR Q (Q1)
  14 TX=(TH-TQIN)/TSCQIN
C 14 TX=(TH-TQIN)
```

```fortran
      QQ=QINA*EXP(-TX*TX)+QINB
      PRINT *, QQ
      IF(INDIC(JX)) 3,3,16
    3 ADX=((COEFAP(3,I)*QC+COEFAP(2,I))*QC+ COEFAP(1,I))/(DX*DX)
      GO TO 18
   16 ADX=ACF*2/DT
   18 A=2.0*COEFQ(3)
      Q1(JX)=Q+(CC*QQ+Q*ADX*A)*DT
      PRINT *, Q1(JX)
      RETURN
      END
C ********************************************************* ***************
      FUNCTION FF(Q,T,DT)
C   THIS FUNCTION FITS A CUBIC SPLINE THROUGH THE FOUR DATA POINTS IN THE
C   NEIGHBOURHOOD OF THE POINT AT WHICH THE DEPENDENT VARIABLE IS
C   REQUIRED
      REAL Q(200)
      L=INT(T/DT)+1
      IF(L.LE.1) L=2
      FRI=T/DT-FLOAT(L-1)
      A=(Q(L+2)-3.0*(Q(L+1)-Q(L))-Q(L-1))/6.0
      B=(Q(L-1)-2.0*Q(L)+Q(L+1))*0.5
      C=(-Q(L+2)+6.0*Q(L+1)-3.0*Q(L)-2.0*Q(L-1))/6.0
      D=Q(L)
      FF=((A*FRI+B)*FRI+C)*FRI+D
      RETURN
      END
C ********************************************************* ***************
      SUBROUTINE FIT(X,Y,E)
C   THIS SUBROUTINE FITS A QUADRATIC CURVE THROUGH FOUR POINTS USING THE
C   LEAST SQUARES PROCEDURE.
      DIMENSION X(4),Y(4),E(4)
      DIMENSION A(4),B(4),C(4),D(4)
      C11=(X(2)-X(4))*(X(2)-X(1))
      C21=(X(3)-X(4))*(X(3)-X(1))
      C1=1.
      C2=C11+C21
      C3=1.
      B1=X(4)
      B2=X(2)*C11+X(3)*C21
      B3=X(1)
      A1=X(4)*X(4)
      A2=X(2)*X(2)*C11+X(3)*X(3)*C21
      A3=X(1)*X(1)
      D1=Y(4)
```

```
D2=Y(2)*C11+Y(3)*C21
D3=Y(1)
B2=B2-B1*A2/A1
C2=C2-C1*A2/A1
D2=D2-D1*A2/A1
B3=B3-B1*A3/A1
C3=C3-C1*A3/A1-C2*B3/B2
D3=D3-D1*A3/A1-D2*B3/B2
E(1)=D3/C3
E(2)=(D2-C2*E(1))/B2
E(3)=(D1-B1*E(2)-C1*E(1))/A1
RETURN
END
```

III-3 STROUT3 PROGRAM

```
      COMMON /BLK1/ A, B, C, X, Y, W
      COMMON /BLK2/ TP, QP, TPP, QPP
      COMMON /BLK3/ BB, CC, D, F, G, ARF, BET, DEP, DEX, Q
      COMMON /BLK4/ DETT
      COMMON /BLK5/ RRR, BBB
      COMMON /BLK6/ OO, PP
      COMMON /BLK7/ AR
      COMMON /BLK8/ QLATF
      COMMON /BLK9/ SSS, TTT
      COMMON /BLK10/ AB, ELEX, TWX, ELE, TW, AREAA
      COMMON /BLK11/ NE, VOL
      COMMON /BLK12/ DD, P
      COMMON /BLK14/ QPRES, QLAST
      COMMON /BLK15/ RA
      COMMON /BLK17/ QDOT
      DIMENSION A(10,10), B(10,10), C(32,32), X(32), Y(32,1), W(32)
      DIMENSION TP(30), QP(30), TPP(33), QPP(33)
      DIMENSION BB(24,24), CC(24,1), D(24,24), DEP(24), F(24,24),
     1   G(24,1), ARF(24), BET(24), DEX(24), Q(24,1)
      DIMENSION RRR(24), BBB(24)
      DIMENSION OO(24), PP(24)
      DIMENSION DETT(24)
      DIMENSION AR(24)
      DIMENSION AB(30), ELEX(30), TWX(30), ELE(30,10), TW(30,10),
     1   AREAA(30,10)
      DIMENSION NE(30), VOL(30)
      DIMENSION QLATF(24)
      DIMENSION EE(24), FF(24)
      DIMENSION DD(24,24), P(24,24)
      DIMENSION SSS(24), TTT(24)
      DIMENSION YY(32)
      DIMENSION QPRES(24), QLAST(24)
      DIMENSION RA(24,1)
      DIMENSION QDOT(24)
      CALL READD(NS, BASE, MM, NN, TPK, QPK)
      DO 10 IK = 1, NS
      CALL READQA(LL, N, M, L)
      CALL FITT(LL, N, M, L, IK, RRR, BBB)
   10 CONTINUE
      DO 20 IK = 1, NS
      CALL READQA(LL, N, M, L)
      CALL FITT(LL, N, M, L, IK, SSS, TTT)
```

```
 20 CONTINUE
    ACCT = 0
    PRINT 150
    EINF = 96.4
    LT = 1
    DO 30 I = 1, NS
    ARF(I) = RRR(I)
    BET(I) = BBB(I)
 30 CONTINUE
    TK = 24.
    TI = 1.
 40 DO 50 I = 1, NS
    QI = Q(I,1)
    AR(I) = ARF(I) * (QI**BET(I))
    VOL(I) = QI / AR(I)
 50 CONTINUE
    CALL TTPP(NS)
    CALL SORT(N, NS, XMINT)
    DET = XMINT / 3600.
    ACCT = ACCT + DET
    IF (ACCT .GT. BASE) GO TO 140
    DET = DET * 3600.
    CALL STATE(NS, DET, EINF)
    DET = DET / 3600.
    TKI = (TK*TI) - 0.2
    TKK = (TK*TI) + 0.2
    IF (ACCT - TKI) 80, 60, 60
 60 IF (ACCT - TKK) 70, 70, 90
 70 PRINT 160, ACCT, EINF, Q(1,1), Q(2,1), Q(3,1), Q(4,1), Q(5,1)
 80 CONTINUE
    GO TO 100
 90 TI = TI + 1.
100 CONTINUE
    LT = LT + 1
    CALL DISCH(MM, NN, ACCT, TPK, QPK, EINF)
    DO 130 I = 1, NS
    IF (QPRES(I) - QLAST(I)) 110, 120, 120
110 ARF(I) = SSS(I)
    BET(I) = TTT(I)
    GO TO 130
120 ARF(I) = RRR(I)
    BET(I) = BBB(I)
130 CONTINUE
    GO TO 40
140 CONTINUE
150 FORMAT (///, 8X, 'ACCT', 6X, 'EINF', 5X, '2 STATION', 3X,
   1    '3 STATION', 3X, '4 STATION', 2X, '5 STATION', 2X,
```

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```
      2    'DOWN BOUND')
160 FORMAT (/, 4X, F10.2, 6E12.4)
    STOP
    END
    SUBROUTINE READD(NS, BASE, MM, NN, TPK, QPK)
    COMMON /BLK2/ TP, QP, TPP, QPP
    COMMON /BLK3/ BB, CC, D, F, G, ARF, BET, DEP, DEX, Q
    COMMON /BLK8/ QLATF
    COMMON /BLK10/ AB, ELEX, TWX, ELE, TW, AREAA
    COMMON /BLK11/ NE, VOL
    DIMENSION TP(30), QP(30), TPP(33), QPP(33)
    DIMENSION BB(24,24), CC(24,1), D(24,24), DEP(24), F(24,24),
   1   G(24,1), ARF(24), BET(24), DEX(24), Q(24,1)
    DIMENSION QLATF(24)
    DIMENSION AB(30), ELEX(30), TWX(30), ELE(30,10), TW(30,10),
   1   AREAA(30,10)
    DIMENSION NE(30), VOL(30)
    READ (5,20) NS
    READ (5,30) (Q(I,1),DEX(I),I=1,NS)
    READ (5,40) BASE
    READ (5,50) MM, NN
    READ (5,60) (TP(I),QP(I),I=1,MM)
    READ (5,60) (TPP(I),QPP(I),I=1,NN)
    READ (5,70) TPK, QPK
    READ (5,80) (QLATF(I),I=1,NS)
    READ (5,90) (AB(IK),IK=1,NS)
    READ (5,100) (NE(I),I=1,NS)
    DO 10 IK = 1, NS
    NEN = NE(IK)
    DO 10 J = 1, NEN
    READ (5,110) ELE(IK,J), TW(IK,J)
 10 CONTINUE
 20 FORMAT (I2)
 30 FORMAT (8F10.2)
 40 FORMAT (F10.2)
 50 FORMAT (2I3)
 60 FORMAT (8F10.2)
 70 FORMAT (2F10.2)
 80 FORMAT (5F10.2)
 90 FORMAT (5F10.2)
100 FORMAT (5I2)
110 FORMAT (2F10.2)
    RETURN
    END
```

```
      SUBROUTINE READQA(LL, N, M, L)
      COMMON /BLK1/ A, B, C, X, Y, W
      DIMENSION A(10,10), B(10,10), C(32,32), X(32), Y(32,1), W(32)
      READ (5,20) LL
      READ (5,30) N, M, L
      READ (5,40) (X(I),Y(I,1),I=1,N)
      DO 10 I = 1, N
      W(I) = 1.0
   10 CONTINUE
   20 FORMAT (I4)
   30 FORMAT (3I4)
   40 FORMAT (8F10.2)
      RETURN
      END
      SUBROUTINE FITT(LL, N, M, L, IK, EE, FF)
      COMMON /BLK1/ A, B, C, X, Y, W
      COMMON /BLK5/ RRR, BBB
      COMMON /BLK6/ OO, PP
      COMMON /BLK9/ SSS, TTT
      DIMENSION A(10,10), B(10,10), C(32,32), X(32), Y(32,1), W(32)
      DIMENSION RRR(24), BBB(24)
      DIMENSION OO(24), PP(24)
      DIMENSION SSS(24), TTT(24)
      DIMENSION EE(24), FF(24)
      DIMENSION YY(32)
      DIMENSION Y1(5000,10), X1(5000)
      LL = 1
      MM = 0
   10 IF (MM - LL) 20, 160, 160
   20 CONTINUE
      IF (MM) 50, 30, 50
   30 PRINT 130, IK
      DO 40 I = 1, N
      DO 40 J = 1, L
      X(I) = ALOG10(X(I))
      Y(I,1) = ALOG10(Y(I,1))
   40 CONTINUE
   50 DO 60 I = 1, N
      DO 60 J = 1, L
      C(I,J) = 1.0
   60 CONTINUE
      MPI = M + 1
      DO 70 J = 2, MPI
      DO 70 I = 1, N
      C(I,J) = C(I,J - 1) * X(I)
```

```
 70 CONTINUE
    DO 80 I = 1, MPI
    DO 80 J = 1, MPI
    A(I,J) = 0.0
    DO 80 K = 1, N
    A(I,J) = A(I,J) + C(K,I) * C(K,J) * W(K)
 80 CONTINUE
    DO 90 J = 1, L
    DO 90 I = 1, MPI
    B(I,J) = 0.0
    DO 90 K = 1, N
    B(I,J) = B(I,J) + C(K,I) * Y(K,J) * W(K)
 90 CONTINUE
    CALL HUI(A, MPI, B, L, DET)
    DO 110 J = 1, L
    DO 110 I = 1, MPI
    II = I - 1
    IF (II - 0) 110, 100, 110
100 ARF = 10.0 ** B(I,J)
    PRINT 140, ARF
110 CONTINUE
    PRINT 150, B(2,1)
    DO 120 I = 1, N
    DO 120 J = 1, L
    X(I) = 10. ** (X(I))
    Y(I,J) = 10. ** (Y(I,J))
    PB = B(2,1)
    YY(I) = ARF * (X(I)**PB)
120 CONTINUE
    EE(IK) = ARF
    FF(IK) = B(2,1)
    MM = MM + 1
    GO TO 10
130 FORMAT (10X, I2, 5X, 'STATION')
140 FORMAT (25X, 'ARF =', E14.8)
150 FORMAT (25X, 'BET =', E14.8)
160 RETURN
    END
    SUBROUTINE HUI(A, N, B, M, DET)
    DIMENSION A(10,10), B(10,10), IPVOT(30), INDEX(30,2), PIVOT(30)
    EQUIVALENCE (IROW,JROW), (ICOL,JCOL)
    DET = 1.
    DO 10 J = 1, N
 10 IPVOT(J) = 0
    DO 200 I = 1, N
    T = 0.0
```

```
        DO 60 J = 1, N
        IF (IPVOT(J) - 1) 20, 60, 20
20 DO 50 K = 1, N
        IF (IPVOT(K) - 1) 30, 50, 240    30 IF (ABS(T) - ABS(A(J,K))) 40, 50, 50
40 IROW = J
        ICOL = K
        T = A(J,K)
50 CONTINUE
60 CONTINUE
        IPVOT(ICOL) = IPVOT(ICOL) + 1
        IF (IROW - ICOL) 70, 110, 70
70 DET = -DET
        DO 80 L = 1, N
        T = A(IROW,L)
        A(IROW,L) = A(ICOL,L)
80 A(ICOL,L) = T
        IF (M) 110, 110, 90
90 DO 100 L = 1, N
        T = B(IROW,L)
        B(IROW,L) = B(ICOL,L)
100 B(ICOL,L) = T
110 INDEX(I,1) = IROW
        INDEX(I,2) = ICOL
        PIVOT(I) = A(ICOL,ICOL)
        DET = DET * PIVOT(I)
        A(ICOL,ICOL) = 1.
        DO 120 L = 1, N
120 A(ICOL,L) = A(ICOL,L) / PIVOT(I)
        IF (M) 150, 150, 130
130 DO 140 L = 1, M
140 B(ICOL,L) = B(ICOL,L) / PIVOT(I)
150 DO 200 LI = 1, N
        IF (LI - ICOL) 160, 200, 160
160 T = A(LI,ICOL)
        A(LI,ICOL) = 0.
        DO 170 L = 1, N
170 A(LI,L) = A(LI,L) - A(ICOL,L) * T
        IF (M) 200, 200, 180
180 DO 190 L = 1, M
190 B(LI,L) = B(LI,L) - B(ICOL,L) * T
200 CONTINUE
        DO 230 I = 1, N
        L = N - I + 1
        IF (INDEX(L,1) - INDEX(L,2)) 210, 230, 210
210 JROW = INDEX(L,1)
```

```
      JCOL = INDEX(L,2)
      DO 220 K = 1, N
      T = A(K,JROW)
      A(K,JROW) = A(K,JCOL)
      A(K,JCOL) = T
220 CONTINUE
230 CONTINUE
240 RETURN
      END
      SUBROUTINE TTPP(NS)
      COMMON /BLK3/ BB, CC, D, F, G, ARF, BET, DEP, DEX, Q
      COMMON /BLK4/ DETT
      COMMON /BLK7/ AR
      COMMON /BLK10/ AB, ELEX, TWX, ELE, TW, AREAA
      COMMON /BLK11/ NE, VOL
      DIMENSION BB(24,24), CC(24,1), D(24,24), DEP(24), F(24,24),
     1   G(24,1), ARF(24), BET(24), DEX(24), Q(24,1)
      DIMENSION DETT(24)
      DIMENSION AR(24)
      DIMENSION AB(30), ELEX(30), TWX(30), ELE(30,10), TW(30,10),
     1   AREAA(30,10)
      DIMENSION NE(30), VOL(30)
      DO 10 IK = 1, NS
      NEN = NE(IK)
      AREAA(IK,1) = AB(IK)
      DO 10 J = 2, NEN
      JJ = J - 1
      ELEDIF = ELE(IK,J) - ELE(IK,JJ)
      AREAA(IK,J) = AREAA(IK,JJ) + ((TW(IK,J) - TW(IK,JJ)) /2.0) *
     1   ELEDIF + TW(IK,JJ) * ELEDIF
10 CONTINUE
      DO 90 IK = 1, NS
      NEN = NE(IK)
      MM = NEN
      SAR = AR(IK)
      SARE = AREAA(IK,MM)
      IF (SAR - SARE) 30, 20, 20
20 ELEX(IK) = ELE(IK,MM)
      TWX(IK) = TW(IK,MM)
      GO TO 80
30 MI = MM - 1
      IF (AR(IK) - AREAA(IK,MI)) 60, 40, 50
40 ELEX(IK) = ELE(IK,MI)
      TWX(IK) = TW(IK,MI)
      GO TO 80
```

400

```fortran
50 AR1 = AREAA(IK,MI)
   EL1 = ELE(IK,MI)
   TW1 = TW(IK,MI)
   RATI = (AR(IK) - AR1) / (AREAA(IK,MM) - AR1)
   ELEX(IK) = EL1 - (ELE(IK,MM) - EL1) * RATI
   TWX(IK) = TW1 + (TW(IK,MM) - TW1) * RATI
   GO TO 80
60 MM = MM - 1
   IF (MM .EQ. 1) GO TO 70
   GO TO 30
70 TWX(IK) = TW(IK,1)
   ELEX(IK) = ELE(IK,1)
80 DEP(IK) = AR(IK) / TWX(IK)
   DETT(IK) = DEX(IK) / (VOL(IK) + SQRT(32.2*DEP(IK)))
90 CONTINUE
   RETURN
   END
   SUBROUTINE SORT(N, NS, XMINT)
   COMMON /BLK4/ DETT
   DIMENSION DETT(24)
   DO 20 I = 1, NS
   AMIN = DETT(I)
   LOCMIN = I
   DO 10 J = 1, NS
   IF (DETT(J) .GT. AMIN) GO TO 10
   AMIN = DETT(J)
   LOCMIN = J
10 CONTINUE
   DETT(LOCMIN) = DETT(I)
   DETT(I) = AMIN
   XMINT = DETT(I)
20 CONTINUE
   RETURN
   END
   SUBROUTINE STATE(N, DET, EINF)
   COMMON /BLK3/ BB, CC, D, F, G, ARF, BET, DEP, DEX, Q
   COMMON /BLK5/ RRR, BBB
   COMMON /BLK6/ OO, PP
   COMMON /BLK7/ AR
   COMMON /BLK8/ QLATF
   COMMON /BLK9/ SSS, TTT
   COMMON /BLK12/ DD, P
   COMMON /BLK14/ QPRES, QLAST
   COMMON /BLK15/ RA
   COMMON /BLK17/ QDOT
```

401

```
      DIMENSION BB(24,24), CC(24,1), D(24,24), DEP(24), F(24,24),
     1   G(24,1), ARF(24), BET(24), DEX(24), Q(24,1)
      DIMENSION RRR(24), BBB(24)
      DIMENSION OO(24), PP(24)
      DIMENSION AR(24)
      DIMENSION QLATF(24)
      DIMENSION DD(24,24), P(24,24)
      DIMENSION SSS(24), TTT(24)
      DIMENSION QPRES(24), QLAST(24)
      DIMENSION RA(24,1)
      DIMENSION QDOT(24)
      DO 70 I = 1, N
      QPW = 1. - BET(I)
      TOP = Q(I,1) ** QPW
      IF (I - 1) 20, 20, 10
   10 IF (I - N) 30, 40, 40
   20 II = I + 1
      DX = DEX(I) + DEX(II)
      BOT = ARF(I) * BET(I) * DX
      QT = EINF - Q(II,1)
      GO TO 50
   30 LI = I - 1
      II = I + 1
      DX = DEX(I) + DEX(II)
      BOT = ARF(I) * BET(I) * DX
      QT = Q(LI,1) - Q(II,1)
      GO TO 50
   40 LI = I - 1
      QT = Q(LI,1) - Q(I,1)
      BNT = ((ARF(I)*BET(I))*DEX(I))
      QDOT(I) = (TOP*QT) / BNT
      GO TO 60
   50 QDOT(I) = (TOP*QT) / BOT
   60 CONTINUE
      QLAST(I) = Q(I,1)
      Q(I,1) = Q(I,1) + (QDOT(I)*DET)
      QPRES(I) = Q(I,1)
   70 CONTINUE
      RETURN
      END
      SUBROUTINE DISCH(MM, NN, ACCT, TPK, QPK, EINF)
      COMMON /BLK2/ TP, QP, TPP, QPP
      DIMENSION TP(30), QP(30), TPP(33), QPP(33)
      IF (ACCT .GE. TPP(1)) GO TO 10
      IF (ACCT .LE. TP(MM)) GO TO 20
```

```
      IF (ACCT - TPK) 40, 30, 110
10  E = QPP(1)
      GO TO 110
20  E = QP(1)
      GO TO 180
30  E = QPK
      GO TO 180
40  IF (ACCT - TP(MM)) 70, 50, 60
50  E = QP(MM)
      GO TO 180
60  E = (((ACCT - TP(MM))*(QPK - QP(MM)))/(TPK - TP(MM))) + QP(MM)
      GO TO 180
70  MI = MM - 1
      IF (ACCT - TP(MI)) 100, 80, 90
80  E = QP(MI)
      GO TO 180
90  E = (((ACCT - TP(MI))*(QP(MM) - QP(MI))) /(TP(MM) - TP(MI))) +
    1   QP(MI)
      GO TO 180
100 MM = MM - 1
      GO TO 70
110 IF (ACCT - TPP(NN)) 130, 120, 140
120 E = QPP(NN)
      GO TO 180
130 E = ((QPK - QPP(NN))*((TPP(NN) - ACCT) /(TPP(NN) - TPK))) + QPP(NN)
      GO TO 180
140 NI = NN - 1
      IF (ACCT - TPP(NI)) 160, 150, 170
150 E = QPP(NI)
      GO TO 180
160 E = ((QPP(NN) - QPP(NI))*((TPP(NI) - ACCT) /(TPP(NI) - TPP(NN)))) +
    1   QPP(NI)
      GO TO 180
170 NN = NN - 1
      GO TO 140
180 CONTINUE
      EINF = E
      RETURN
      END
```

III-4 SVNLMM PROGRAM

```
      DIMENSION O(200),XI(200),STT(200)
      REAL TT
      READ(5,*)N,ALPHA,X,XM
      DO 7 I=1,N
      READ(5,*)XI(I)
    7 CONTINUE
      WRITE(6,*)'TIME INFLOW STORAGE OUTFLOW'
      STT=1.20
      TT=0.0
      DI=12.
      DT=2.0
      DO 8 J=1,N
      Y=1./XM
      DST=-(1/(1-X))*((STT(J)/ALPHA)**Y)+((1/(1-X))*XI(J))
      DST=DST/DI
      STT(J+1)=STT(J)+DST*DT
      O(J)= (1/(1-X))*((STT(J)/ALPHA)**Y)-((X/(1-X))*XI(J))
      WRITE(6,22) TT,XI(J),STT(J),O(J)
      TT=TT+DT
   22 FORMAT(4F10.3)
    8 CONTINUE
      STOP
      END
```

III-5 H-J PROGRAM

```
C
      C   MAIN LINE PROGRAM FOR SUBROUTINE HOOKE.
C
      COMMON/ONE/ RK(3),EPS(3),Q(3),QQ(3),W(3),NSTAGE,MAXK,
     1    NKAT,EPSY,ALPHA,BETA,QD,IPRINT,NI,NO
      COMMON/TWO/ AD(21),C(21),D(21)
C
      NI = 7
      NO = 6
C
      DO 10 I = 1,21
      READ(5,*) AD(I), C(I), D(I)
   10 CONTINUE
      READ (NI,001) NSTAGE, IPRINT, MAXK, NKAT
  001 FORMAT (8I10)
      READ (NI,002) (RK(II), II=1,NSTAGE)
  002 FORMAT (8E10.4)
      READ (NI,002) (EPS(JJ), JJ=1,NSTAGE)
      READ (NI,003) ALPHA, BETA, EPSY
  003 FORMAT (8E10.4)
      QD = 0.0
      WRITE(6,*) RK(1), RK(2),RK(3)
C
      CALL HOOKE
      STOP
      END
C
C
      SUBROUTINE HOOKE
C
      COMMON/ONE/ RK(3),EPS(3),Q(3),QQ(3),W(3),NSTAGE,MAXK,
     1    NKAT,EPSY,ALPHA,BETA,QD,IPRINT,NI,NO
      COMMON/TWO/ AD(21),C(21),D(21)
C
C
      WRITE (NO,001)
  001 FORMAT (1H1,10X,37HHOOKE AND JEEVES OPTIMIZATION ROUTINE)
      WRITE (NO,002) ALPHA, BETA, MAXK, NKAT
  002 FORMAT (//,2X,10HPARAMETERS,/,2X,8HALPHA = ,F5.2,4x,
     1    7HBETA = ,F5.2,4X,8HITMAX = ,I4,4X,7HNKAT = ,I3)
      WRITE (NO,003) NSTAGE
  003 FORMAT (/,2X,22HNUMBER OF VARIABLES = ,I3)
      WRITE (NO,004)
  004 FORMAT (/,2X,18HINITIAL STEP SIZES)
      DO 6 I=1,NSTAGE
```

```
      WRITE (NO,005) I, EPS(I)
005  FORMAT (/,2X,4HEPS(,I2,4H) = ,E16.8)
   6 CONTINUE
      WRITE (NO,007) EPSY
007  FORMAT (/,2X,43HERROR IN FUNCTION VALUES FOR CONVERGENCE = ,E16.8)
      KFLAG = 0
      DO 601 I=1,NSTAGE
      Q(I) =RK(I)
      W(I) = 0.0
601  CONTINUE
      KAT =0.0
      KK1 =0
  70 KCOUNT =0
      WBEST = W(NSTAGE)
      CALL OBJECT (SUM,RK)
      KK1= KK1+ 1
      BO =SUM
      IF (KK1.EQ. 1) QD = SUM
      IF (KK1.EQ. 1) GO TO 201
      IF(BO.GT.QD) KFLAG = 1
      IF (BO.LT.QD) QD = BO
C
   C  ESTABLISHING THE SEARCH PATTERN
C
201  DO 55 I = 1,NSTAGE
      QQ(I)=RK(I)
      TSRK = RK(I)
      RK(I) = RK(I) + EPS(I)
      CALL OBJECT (SUM,RK)
      KK1= KK1 + 1
      W(I) = SUM
      IF (W(I).LT.QD) GO TO 58
      RK(I) = RK(I) - 2.0*EPS(I)
      CALL OBJECT (SUM,RK)
      KK1 = KK1 + 1
      W(I) = SUM
      IF (W(I) .LT.QD) GO TO 58
      RK(I) = TSRK
      IF (I.EQ. 1) GO TO 513
      W(I) =W(I-1)
      GO TO 613
513  W(I) =BO
613  CONTINUE
      KCOUNT =1+ KCOUNT
      GO TO 55
  58 QD= W(I)
```

406

```
      QQ(I) =RK(I)
   55 CONTINUE
      IF (IPRINT) 60, 65, 60
   60 WRITE (NO,100) KK1
C
      C   RECORD RESPONSES AND LOCATION
C
      WRITE(NO,102)
      WRITE(NO,207) (RK(I), I=1,NSTAGE), QD
C
      C   TEST TO DETERMINE TERMINATION OF PROGRAM
C
   65 IF (KK1.GT.MAXK) GO TO 94
      IF (KAT .GE. NKAT) GO TO 94
      IF (ABS(W(NSTAGE)-WBEST).LE.EPSY) GO TO 94
C
      C   IF ALL AXES FAIL REDUCE STEP SIZE
C
      IF (KCOUNT .GE. NSTAGE ) GO TO 28
      DO 26 I= 1,NSTAGE
      RK(I) =RK(I) + ALPHA*(RK(I) - Q(I))
   26 CONTINUE
      DO 25 I = 1,NSTAGE
      Q(I) =QQ(I)
   25 CONTINUE
      GO TO 70
C
      C   REDUCE STEP SIZE
C
   28 KAT = KAT + 1
      IF (KFLAG .EQ. 1) GO TO 202
      GO TO 204
  202 KFLAG = 0
      DO 203 I=1,NSTAGE
      RK(I) = Q(I)
  203 CONTINUE
  204 DO 80 I=1,NSTAGE
      EPS(I) =EPS(I) *BETA
   80 CONTINUE
      IF (IPRINT) 85, 70, 85
   85 WRITE (NO,101) KAT
      GO TO 70
   94 WRITE (NO,460) (EPS(I), I=1,NSTAGE)
      WRITE (NO,461) (RK(I), I=1,NSTAGE)
      WRITE (NO,462) QD
      DO 104 I=1,NSTAGE
  104 WRITE (NO,103) I, RK(I)
```

407

```
      WRITE (NO,100)
  100 FORMAT (//,2X,33HNUMBER OF FUNCTION EVALUATIONS = ,I8)
  101 FORMAT (/,2X,18HSTEP SIZE REDUCED ,I2 ,6H TIMES)
  102 FORMAT (1X,26HEND OF EACH PATTERN SEARCH/)
  103 FORMAT (//,2X,8HFINAL X(,I2,4H) = ,1PE16.8)
  207 FORMAT(1X,18HVARIABLES AND SUMN,3X,9E12.4//)
  465 FORMAT (10X,3HSUM,3X,E14.5)
  460 FORMAT (1X, 18H THE FINAL EPS ARE, 4F20.8/)
  461 FORMAT (1X, 18H THE FINAL RK ARE , 5F20.8/)
  462 FORMAT (1X, 24H THE MINIMUM RESPONSE IS, F20.8/)
      RETURN
      END
      SUBROUTINE OBJECT (SUMN,AKE)
C
      COMMON/ONE/ RK(3),EPS(3),Q(3),QQ(3),W(3),NSTAGE,MAXK,
     1    NKAT,EPSY,ALPHA,BETA,QD,IPRINT,NI,NO
      COMMON/TWO/ AD(21),C(21),D(21)
      DIMENSION AKE(3)
C
      X1 =AKE(1)
      X2 =AKE(2)
      X3 =AKE(3)
C
      B = 0.0
      DO 100 I=1,21
      DO 11 M=1,21
      B1 = (AD(I)- X1*(X2*C(I)+ (1 - X2)*D(I))**X3)**2
      B = B1 + B
   11 CONTINUE
  100 CONTINUE
      SUMN = B
      WRITE(6,*) AKE(1),AKE(2),AKE(3), SUMN
      RETURN
      END
```

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Station Tunstall
Period of Record 1/1982   Station number 022164

Rainfall in MMX10 — PTR CHECK

Day																									Total	Total	Diff	Day
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2	0	0	0	0	0	0	48	2	0	2	8	4	0	0	0	2	4	6	10	2	0	2	0	0		90	83	2
3	2	0	2	0	0	0	8	0	6	20	26	36	28	4	0	20	12	10	4	2	6	2	2	0	190	194	-4	3
4	0	0	0	0	2	2	2	8	8	4	20	6	4	2	4	10	12	8	8	4	4	6	6	8	128	137	-9	4
5	6	4	0	4	0	0	2	0	2	0	0	2	2	2	2	4	2	4	2	2	2	2	2	0	46	105	-59	5
6	2	2	0	2	2	2	2	0	2	2	0	0	2	2	0	0	2	2	0	0	2	0	2	0	28	33	-5	6
7	0	0	2	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	8	41	-33	7
8	0	4	0	2	0	2	4	0	2	2	2	2	2	2	0	2	2	2	2	2	2	0	2	2	40	98	-58	8
9	2	2	0	2	2	0	2	2	0	2	2	0	2	0	2	2	2	0	2	2	0	2	2	0	32	23	9	9
10	0	4	0	0	2	2	0	2	2	0	0	2	0	2	0	2	2	0	2	0	0	2	0	0	24	0	24	10
11	0	2	2	0	0	0	2	0	2	0	0	0	2	0	2	0	0	2	2	0	0	0	2	2	20	2	18	11
12	0	2	2	0	0	0	4	0	0	2	0	0	2	2	0	0	2	2	0	0	0	2	0	0	20	0	20	12
13	2	2	0	0	0	2	0	2	0	0	2	0	2	0	0	2	2	0	2	0	2	2	0	0	22	0	22	13
14	2	0	2	2	0	0	2	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	12	0	12	14
15	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	6	0	6	15
16	0	0	0	0	2	2	0	2	0	2	2	2	0	6	4	4	0	2	4	2	0	2	2	4	42	0	42	16
17	2	2	4	4	6	6	2	4	6	2	2	2	4	0	4	2	2	4	4	2	2	4	4	2	76	2	74	17
18	2	4	2	4	2	2	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	20	10	10	18
19	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	6	2	0	0	0	0	0	0	0	10	15	-5	19
20	0	0	0	0	0	0	0	0	0	0	6	2	0	0	0	0	0	0	0	2	2	2	0	0	14	20	-6	20
21	0	0	0	0	0	0	0	0	6	0	0	2	2	4	10	6	0	2	0	0	0	0	0	0	32	32	0	21
22	0	0	2	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	6	4	2	22
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23
24	0	0	0	0	0	0	0	0	0	2	0	0	0	2	2	2	0	0	0	0	0	0	0	0	8	6	2	24
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	2	0	0	0	0	0	0	0	0	10	9	1	25
26	0	0	0	0	0	0	0	6	2	0	2	20	2	0	0	0	2	0	0	0	0	0	0	0	34	35	-1	26
27	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	12	10	27
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	8	9	-1	30
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	31

Monthly Totals   948   870

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Station Tunstall
Period of Record 2/1984 Station number 022164

Rainfall in MMX10 — PTR CHECK

Day																									Total	Total	Diff	Day
1	2	4	0	2	0	2	10	14	6	4	6	2	2	2	2	2	2	0	2	2	2	0	2	2	72	73	-1	1
2	2	2	2	2	2	2	4	6	4	4	4	4	2	2	0	2	2	2	2	8	6	8	2	4	78	10	68	2
3	4	6	10	12	16	12	10	10	8	8	6	4	6	4	6	4	2	0	2	2	0	4	2	6	144	16	128	3
4	6	6	6	10	20	14	14	26	24	30	26	30	10	4	2	2	0	2	0	2	0	0	2	0	236	31	205	4
5	2	0	2	0	4	6	6	6	2	2	2	42	0	4	6	12	18	22	10	6	4	2	4	16	178	63	115	5
6	20	20	14	12	8	6	12	4	4	2	2	2	2	0	2	0	2	0	0	2	0	0	0	2	116	42	74	6
7	0	0	2	0	2	0	0	2	2	0	0	2	0	0	0	2	54	2	0	4	4	0	0	0	76	111	-35	7
8	2	0	0	2	2	2	0	2	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	14	0	14	8
9	0	0	0	0	2	0	2	2	0	0	0	0	4	0	4	8	14	14	10	6	4	2	2	0	74	0	74	9
10	2	8	14	14	12	12	12	8	12	10	12	8	4	16	4	4	14	12	16	26	4	2	10	14	250	1	249	10
11	24	12	12	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	1	51	11
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	18
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38	-38	20
21	8	26	26	6	0	0	0	2	0	2	0	0	0	0	0	0	2	0	0	2	18	4	0	0	96	56	40	21
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	2	2	0	0	2	0	0	0	14	16	-2	22
23	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	1	39	23
24	0	0	0	0	0	0	0	2	4	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	10	10	0	24
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25
26	0	10	2	0	0	0	0	0	2	2	4	4	2	6	2	0	0	0	2	0	0	0	0	0	36	35	1	26
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27
28	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	28
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	12	16	-4	29

Monthly Totals 1500 520

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Appendix (IV) Monthly Rainfall of Allenheads Station.

Station Allenheads
Period of Record 3/1986

Northumbrian Water Authority
Station number 015339

Rainfall in MMX10

Day																									Total	Total	Diff	Day
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	2	0	0	6	0	0	1
2	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	2
3	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	2	0	6	0	0	3
4	2	4	4	0	0	4	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	4
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	4	2	0	0	12	0	0	5
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	2	0	0	0	2	10	0	0	8
9	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	9
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
12	0	0	0	0	0	0	0	0	0	0	0	0	0·	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
16	0	2	2	2	2	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	16
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
18	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	6	0	0	18
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	22	22	8	2	64	0	0	19
20	2	0	0	0	0	0	2	12	2	0	0	0	0	0	0	2	8	8	10	6	8	6	6	2	74	0	0	20
21	2	0	0	0	0	0	0	0	0	0	0	0	0	2	8	2	0	0	0	0	0	0	2	4	20	0	0	21
22	2	0	0	0	2	2	32	20	12	16	38	26	42	28	32	40	2	0	0	0	0	0	0	4	298	0	0	22
23	14	0	2	4	4	4	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	23
24	0	0	4	4	10	8	0	2	6	2	2	0	0	0	0	0	0	0	0	0	0	0	0	4	42	0	0	24
25	0	6	14	16	2	2	0	4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0	25
26	0	0	0	0	0	0	0	0	0	0	2	8	2	0	2	0	10	16	16	12	14	2	6	4	94	0	0	26
27	4	2	0	8	4	0	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0	0	0	24	0	0	27
28	0	0	8	0	0	0	4	0	0	0	4	4	4	6	8	0	0	0	6	8	0	0	0	0	52	0	0	28
29	0	0	0	0	0	0	0	0	4	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	29
30	4	8	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	8	24	0	0	30
31	8	16	2	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	31

Monthly Totals   898

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Appendix V

Appendix V-1 Symbols Definition of M-C2 Program

Q1- Array for the discharge along the reach at the new time level.

Q2- Array for the discharge along the reach at the old time level.

DX- Space increment.

DXLR-Length of the reach.

JX - Number of space grid points.

X - Array for the distance of the grid points along the channel.

DT - Time increment.

T - Time in seconds.

TH - Time in hours.

LEND - Number of time steps.

TITLE - Array which stores data for the heading of the output.

J1, L1, and L2 refers to when and how the results are written.

WSP - Wave speed.

AP - Attenuation parameter.

QCON - Discharge constant.

C1, C2, C3, and C4 are parameters in the Muskingum Method.

DTQHYDRO - Time interval in hours between the data points for the input and other discharge hydrographs.

QHYDRO - Array which stores the data for the recorder discharge hydrograph

at the upstream section.

IQH - Number of data points for the upstream hydrograph.

QTRIB1- Array which stores the data for the recorded discharge hydrograph at the first tributary.

ITR1 - Number of data points for the hydrograph at the first tributary.

JT1 - Position of the input discharge from the first tributary.

QTRIB2 - Array which stores the data for the recorded discharge hydrograph at the second tributary.

ITR2 - Number of data points for the hydrograph at the second tributary.

JT2 - Position of the input discharge from the second tributary.

QINIT - Initial discharge for the flow throughout the reach.

QINB - Base value for the lateral flow.

QINA - Amplitude of the function for the lateral flow.

TQIN - Time when the lateral flow takes its maximum value.

TSCQIN - Time scale for the lateral flow function.

QDNS - Array which stores the data for the recorded discharge hydrograph at the downstream end of the reach.

IQDNS - Number of data points for the downstream hydrograph.

TDEVN - Time in hours when the calculations of the error parameters are begun.

TOTDIS - Average recorded discharge after the time TDEVN.

TOTD - Average predicted discharge after the time TDEVN.

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DISDIF - Difference between the average recorded and predicted discharges as a percentage of the recorded discharges.

DEVN - Ultimately records the standard deviation of the predicted discharge as a percentage of the average recorded discharge.

Q1- Array for the discharge along the reach at the new time level.

Q2- Array for the discharge along the reach at the old time level.

DX- Space increment.

DXLR-Length of the reach.

JX - Number of space grid points.

X - Array for the distance of the grid points along the channel.

DT - Time increment.

T - Time in seconds.

TH - Time in hours.

KEND - Maximum number of iteration allowed.

QERROR - Maximum error allowed in the Newton iteration process.

FQ - Increment in the discharge between successive values of the data for the wave speed and the attenuation parameter.

TITLE - Array which stores data for the heading of the output.

J1, L1, and L2 refers to when and how the results are written.

WSP - Wave speed.

AP - Attenuation parameter.

QCON - Discharge constant.

C1, C2, C3, and C4 are parameters in the Muskingum Method.

DTQHYDRO - Time interval in hours between the data points for the input

and other discharge hydrographs.

QHYDRO - Array which storesthe data for the recorder discharge hydrograph at the upstream section.

IQH - Number of data points for the upstream hydrograph.

QTRIB1- Array which stores the data for the recorded discharge hydrograph at the first tributary.

ITR1 - Number of data points for the hydrograph at the first tributary.

JT1 - Position of the input discharge from the first tributary.

QTRIB2 - Array which stores the data for the recorded discharge hydrograph at the second tributary.

ITR2 - Number of data points for the hydrograph at the second tributary.

JT2 - Position of the input discharge from the second tributary.

QINIT - Initial discharge for the flow throughout the reach.

QINB - Base value for the lateral flow.

QINA - Amplitude of the function for the lateral flow.

TQIN - Time when the lateral flow takes its maximum value.

TSCQIN - Time scale for the lateral flow function.

QCF - Cut-off Discharge for drainage off the flood plain to be included.

INDIC - An indication which is 0 when the discharge at a section is below bank-full and increasing, and 1 when the discharge has previously exceeded bank-full and yet is below bank-full and decreasing.

QDNS - Array which stores the data for the recorded discharge hydrograph at the downstream end of the reach.

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IQDNS - Number of data points for the downstream hydrograph.

TDEVN - Time in hours when the calculations of the error parameters are begun.

TOTDIS - Average recorded discharge after the time TDEVN.

TOTD - Average predicted discharge after the time TDEVN.

DISDIF - Difference between the average recorded and predicted discharges as a percentage of the recorded discharges.

DEVN - Ultimately records the standard deviation of the predicted discharge as a percentage of the average recorded discharge.

Appendix V-3 Symbols Diffenition of SVNLMM Program

N - Number of points.

ALPHA - Nonlinear Muskingum Equation Parameter.

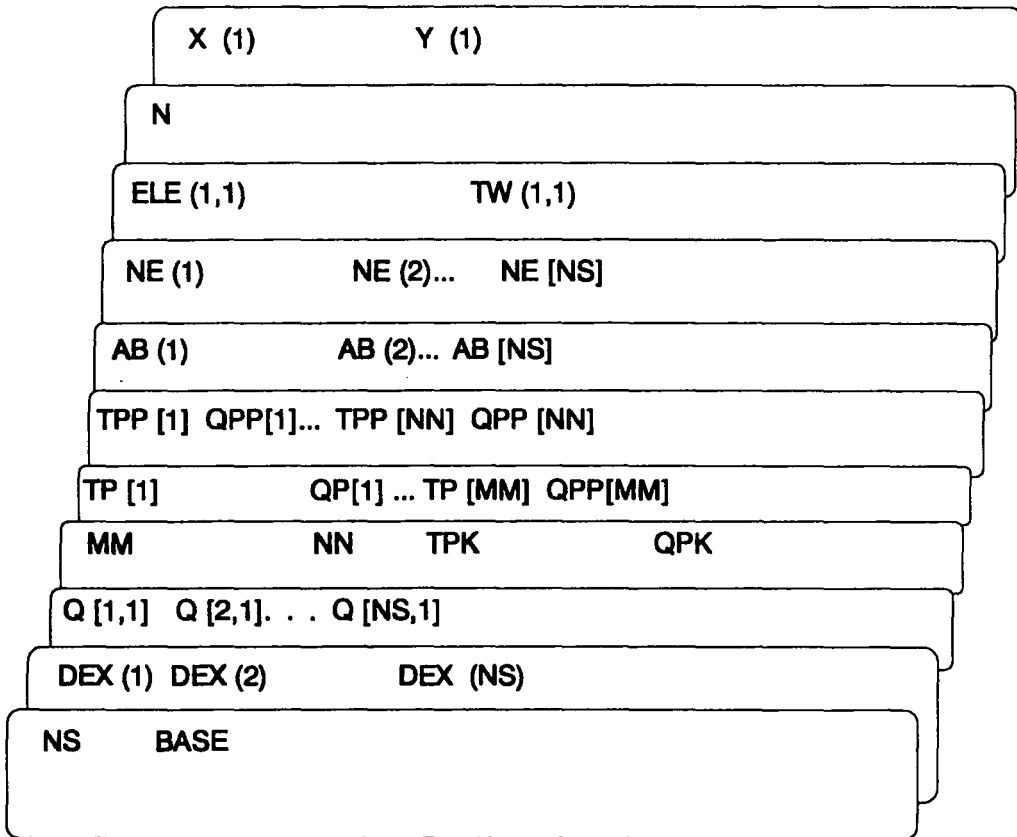X - Nonlinear Muskingum Equation Parameter.

XM - Nomlinear Muskingum Equation Parameter.

STT - Initial Storage.

DT - Time Interval.

Appendix V-3

Arrangement of Input Data for Program "STROUT 33".

```
┌──────────────────────────────────────────────────────────┐
│    X (1)              Y (1)                               │
│ ┌──────────────────────────────────────────────────────┐ │
│ │  N                                                    │ │
│ │ ┌──────────────────────────────────────────────────┐ │ │
│ │ │ ELE (1,1)                TW (1,1)                 │ │ │
│ │ │ ┌──────────────────────────────────────────────┐ │ │ │
│ │ │ │ NE (1)           NE (2)...    NE [NS]         │ │ │ │
│ │ │ │ ┌──────────────────────────────────────────┐ │ │ │ │
│ │ │ │ │ AB (1)           AB (2)... AB [NS]        │ │ │ │ │
│ │ │ │ │ ┌──────────────────────────────────────┐ │ │ │ │ │
│ │ │ │ │ │ TPP [1] QPP[1]... TPP [NN]  QPP [NN]  │ │ │ │ │ │
│ │ │ │ │ │ ┌──────────────────────────────────┐ │ │ │ │ │ │
│ │ │ │ │ │ │ TP [1]        QP[1] ... TP [MM]  QPP[MM] │ │ │ │ │
│ │ │ │ │ │ │ ┌──────────────────────────────┐ │ │ │ │ │ │
│ │ │ │ │ │ │ │ MM         NN    TPK      QPK │ │ │ │ │ │
│ │ │ │ │ │ │ │ Q [1,1]  Q [2,1]. . . Q [NS,1] │ │ │ │ │
│ │ │ │ │ │ │ │ DEX (1) DEX (2)      DEX (NS) │ │ │ │ │
│ │ │ │ │ │ │ │ NS    BASE                    │ │ │ │ │
└──────────────────────────────────────────────────────────┘
```

NS   -   Number of reaches along the river.

BASE   - The simulation time for the simulated hydrograph.

DEX (1)   - Distance for subreach 1.

DEX (2)   - Distance for subreach 2.

DEX (NS)- Distance for the NS-th subreach.

Q (1,1)   - Initial base flow at subreach 1.

Q (2,1)   - Initial base flow at subreach 2.

Q (NS,1)   - Initial base flow at the NS-th subreach.

MM   - The number of ordinates of the rising limb of the upstream boundary
         inflow hydrograph.

NN   - The number of the ordinates of the recession limb of the upstream
         boundary inflow hydrograph.

TPK   - The time at the peak of the upstream boundary inflow hydrograph.

QPK   - The peak discharge of the upstream boundary inflow hydrograph.

TP(1)   - The time at the 1st ordinate of the rising limb of the inflow
    hydrograph.

QP(1)   - The discharge rate at the 1st ordinate of the rising limb of the
inflow
         hydrograph.

TP(2)   - The time at the 2nd ordinate of the rising limb of the inflow
         hydrograph.

QP(2)   - The discharge rate at the 2nd ordinate of the rising limb of
         the inflow hydrograph.

TP(MM)   - The time at the MM-th ordinate of the rising limb of the
         inflow hydrograph.

QP(MM)   - The discharge rate at the MM-th ordinate of the rising limb
         of the inflow hydrograph.

TPP(1)   - The time at the 1st ordinate of the recession limb of the inflow
         hydrograph.

QPP(1)   - The discharge rate at the 1st ordinate of the recession limb
         of the inflow hydrograph.

TPP(2)   - The time at the 2nd ordinate of the recession limb of the
         inflow hydrograph.

QPP(2)   - The discharge rate at the 2nd ordinate of the recession limb
         of the inflow hydrograph.

TPP(NN)   - The time at the NN-th ordinate of the recession limb of the inflow
         hydrograph.

QPP(NN)   - The discharge rate at the NN-th ordinate of the recession limb
         of the inflow hydrograph.

AB(1)   - The cross-sectional area of the first subreach at steady state
         condition.

AB(2)   - The cross-sectional area of the 2nd subreach at steady state
         condition.

AB(NS)   - The cross-sectional area of the NS-th subreach at the steady
         state condition.

NE(1)   - The number of elevations will given for computing the

cross-sectional area at the 1st subreach.

NE(2)   - The number of elevations will given for computing the cross-sectional area at the 2nd subreach.

NE(NS)   - The number of elevations will given for computing the cross-sectional area at the NS-th subreach.

ELE(1,1)   - The 1st level of the water surface elevation for the 1st river subreach.

TW(1,1)   - The top width correspondance to the first level elevation for the 1st subreach.

ELE(1,2)   - The 2nd level of the water surface elevation for the 1st river reach.

TW(1,2)   - The top width correspondance to the 2nd level elevation for 1st subreach.

ELE(1,NE(1)) - The NE(1)-th level of the water surface elevation for the 1st river subreach.

TW(1,NE(1)) - The top width correspondance to the NE(1)-th level elevation for the 1st subreach.

Each river subreach should have the same sets of datas for the following 2nd subreach to NS-th subreach.

N   - The number of the paired datas of discharge and cross-sectional area for a certain subreach.

X(1)   - The discharge rate.

Y(1)   - The cross-sectional area.

Discharge rate and cross-sectional area are in the increasing form.

Each river subreach should have the same sets of datas for the following 2nd to the NS-th subreach.