DESIGN OF DETENTION BASIN SYSTEM ALONG HIGHWAYS

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
Civil Engineering

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August, 1983
Blacksburg, Virginia

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(ABSTRACT)

A system of detention basins is an effective device for control of storm flood both in terms of quantity and quality. The feasibility of designing detention basins for flood control by use of abandoned spaces near highway interchange and between highway embankments is investigated. Three algorithms are examined for routing inflow hydrographs through interconnected basins under various hydraulic and hydrologic conditions. The programs solve for both the time dependent flow quantities and the extent of pollutant removal in the system for given inflows and pollutant trap efficiencies of the individual basins. The first algorithm is the extended version of the classical single reservoir routing and involves solution of a system of simultaneous nonlinear equations. The other two algorithms employ the so-called linearized or simplified versions of the continuity equation. The algorithms can take care of various possible combinations of inflow, type of connections between basins, and the boundary conditions at the outlet(s). Results from the three algorithms are comparatively analysed and the one which does not require excessively small time step for solution convergence is selected. The Kuo method employing the standard approximation for the mass conservation equations as in classical single reservoir routing is found favorable with respect to the time step required for convergence and hence is selected for application to design examples. Various basin arrangements are included to show the routing results with respect to quantity and quality for different combinations of storm inflows and outlet structure types. Interconnection between basins is found desirable both in terms of quantity and quality control of effluent.

ACKNOWLEDGEMENTS

I express my gratitude and appreciation to my committee chairman, Dr. Chin Y. Kuo for his guidance, constructive criticism and encouragement during the research and preparation of this text. I also express my gratitude to committee members Dr. James M. Wiggert and Dr. G. V. Loganathan for their guidance and encouragement. I would like to express my gratitude also to Dr. J. N. Reddy for his generous assistance and encouragement during the initial stage of research.

I am indebted to the Fulbright Foundation for sponsoring me for the graduate study.

I am thankful to my wife, Sarita for her patience and understanding during the many hours spent in preparing this thesis.

For encouragement, support and guidance throughout my academic career, I express profound gratitude and appreciation to my parents, Niranjan and Krishneshwari Dhaubhadel.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

A = area of cross section

b = width of box culvert

C = pollutant concentration of inflow from catchments

C' = pollutant concentration in the basin

C_s = coefficient of discharge for spillway

$C_{kk'}$ = coefficient in the hydraulic head-discharge relationship, equations (5) and (12)

g = gravitational acceleration

H = stage

H' = stage above invert level

H_s = height of spillway

I = Inflow

K = coefficient of decay

L = length of culvert

L_s = length of spillway

M = mass rate of deposition

N = Manning's coefficient

O, Q = discharge

Q_s = spillway discharge

R = hydraulic radius

S = storage

s = slope

t = time

v = velocity

v_s = settling velocity

Δt = time step

η = trap efficiency

α, β = coefficients in the stage -storage relationship, equation (7)

Subscripts:

i = beginning of time step

j = end of time step

k = basin or boundary designation 1,2,3,4,5 or 6

k' = basin or boundary designation 1,2,3,4,5 or 6

l = subscript i or subscript j

Abbreviations:

MIN = minute

CFS = cubic feet per second

PPM = parts per million

LB/S = pounds per second

FT = feet

CF = cubic feet

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

1.1 General

Although detention storage has long been recognized as an effective means of flood control, the present pace of advancement in detention and retention design can be attributed to the use of computer models to generate catchment hydrographs, pollutant graphs and to route them through detention basins and so on. Availability of high speed computers has made analysis of complex detention systems feasible.

Use of detention basins for storm runoff control has recently attracted much attention in urban storm water management. Their function is to intercept runoff, delay and decrease peak flow and reduce the mean in-stream pollutant concentration. While the control of inflow to the basins reduces the risk of downstream flooding, the reduction in mean pollutant concentration of surface runoff is beneficial to downstream receiving water quality.

Detention facilities are required to control increased runoff due to urban developments. But highway construction usually does not seem to incorporate detention facilities in the design as residential development does. The excessive surface runoff contributed by highway construction because of the increased pavement area can be controlled by incorporating detention facilities within the right of way of highways.

Depending on the topography, a number of sites along highways can be suitably utilized for storm water detention. The spaces near highway interchange and between highway embankments, for example, are good locations where the installation of detention basins is feasible. Interconnections between basins, where possible, can be beneficial for both storm water quantiy and quality control. This is because the interconnecting structures can be designed to control peak stages to some extent, as will be seen later. Storm flow routing, then will involve a system of detention basins.

Mathematical models are derived from the principle of conservation of water mass and pollutant mass to represent their movement, storage and pollutant removal of storm runoff through the basin system. The conservation of mass equation applied to each of the basins in turn will give a system of differential equations to be solved for each case of quantity and quality analysis. Because of the interdependence of the quantities involved within each basin at an instant and their variability with the type of interconnecting structures, it becomes practically impossible to get a closed form solution for the routing problem. Consequently, suitable numerical approximations to the differential equations and algorithms to solve them are needed.

In an attempt to have improvement in the present practices of detention basin design, three algorithms consistent with three different approximations for the continuity equations are studied. In the first algorithm, the differentials are approximated by their differences in a time step and it can be considered as an extension of the simple classical single reservoir routing to the case of multiple basins with a variety of interconnections and boundary conditions. A system of nonlinear simultaneous equations is involved and a standard method like Newton-Raphson procedure is adopted for its numerical solution. With flow volumes obtained as above, mass conservation applied to conservative pollutants passing through each of the basins will give a system of linear equations which are again solved to determine the extent of pollutant removal. The second algorithm uses a less accurate but simplifying approximation as proposed by Malcolm and New (1975). The continuity equations for multi-connected multi-outlet system with possible flow reversals become solvable directly. The third algorithm introduces the modification of the inflow representation as suggested by Shingofen (1982) to the approximation mentioned above. The computation is simplified in the latter two cases but may require use of smaller time steps for acceptable accuracy.

A solution algorithm for analysis and design of multi-basin system for both quantity and quality control of storm runoff is presented. Important factors like interconnecting structures having either pipe flow or open channel flow, time variable tail water conditions, flow reversals in the interconnecting structures, multiple outfalls etc. are considered in the formulation. The algorithm developed can solve routing problems through up to six interconnected basins and should be sufficient to handle most of the systems to be located along highways. With certain modifications it can be used to solve routing problems for both quantity and quality through any number of interconnected basins.

1.2 Literature Review

Stormwater detention basins have historically been applied for quantity control. The general routing equation used in most analyses is based on the principle of mass conservation of water. Flow routing through single reservoirs are found treated in most standard texts (Chow, 1959; Henderson,1966; Wanielista, 1978; Rouse, 1961; Linsley, Kohler and Paulhus, 1975). Techniques on flow routing through interconnected basins have recently appeared in the literature. Kuo (1981) used a control volume approach to individual basins in a system of basins connected in series or in parallel thereby generating a system of functional equations to be solved for the unknown stages at the end of each time step. The method can be readily extended to a system of multi-connected basins. Despite more terms that may be involved in an equation due to multiple connection, the number of unknowns for the system does not exceed the number of basins. In general, the functional relationships are nonlinear in nature owing to the interdependence of the stages during a routing period and the nonlinear stage-storage and stage-discharge relationships.

Malcolm and New (1975) simplified the single reservoir routing equation by assuming that storage change in a time step is caused by inflow and outflow at the beginning of the time step only. It is interesting to note that with this assumption the routing problem is considerably simplified but care should be taken to select sufficiently small time steps for acceptable accuracy. Bradford and Malcolm (1982) employed the above simplification for interconnected twin reservoirs and found that results by the method compared quite favorably with the classical method extended to interconnected reservoirs.

Shingofen (1982) proposed a similar approximation to the continuity equation. Change in storage was assumed to be influenced by the inflows at both the beginning and the end of the time step and by the outflow only at the beginning of the time step. He applied this to flow routing through multi-connected basins. Direct solution of the continuity equation became possible as in the case of approximation adopted by Malcolm and New. In a multi-connected basin system, it is possible to have flow reversals in the interconnecting structures and the simplified methods may require quite small time steps compared to that required with the standard method.

A comparative analysis using the three methods for the case of multi-connected basin system to be sited near highways will be made in the present study.

Detention basins are known to reduce sediment discharge through settling and improve runoff quality by settling of suspended particles of pollutants. Quality control aspects of detention basins have been treated for single basin (Wanielista and Yousef, 1978; Whipple, 1981; Ward, Hann and Barfield, 1977). Medina,Huber and Heany (1981) gave a model for single basin system for pollutant routing. They assumed a first order decay of the pollutants and the continuity equation became directly integrable for the single basin system. The model can be modified for its use to conservative pollutants with consideration of settling instead of decay by introducing trap efficiency instead of coefficient of decay. The method can be extended for application to multiple basin system. For simplicity, only conservative pollutants and complete mixing condition are considered in the present study.

Ferrara (1982) took mass rate of settling of pollutants in a rectangular basin as the product of settling velocity with the surface area and the pollutant concentration in the basin. This approach looks quite simple and the accuracy is questionable. Clearly this assumption will not be appropriate if a particular size of pollutant is to be partly trapped in a basin but the rest of them is to go on for settling in others.

1.3 Study Objective

The objective of the present study is to develop an algorithm which is suitable for quantity and quality analysis of stormwater flow through a multiple basin system. Following the three methods of approximating the continuity equation three different algorithms are formulated. Sensitivity analyses of the methods are carried out for the typical cases of a four basin system along a highway interchange and another two basin system between highway embankments. After selecting a suitable time step for each method,results from these are compared and the one requiring a reasonably small time step for convergence is selected. This is then applied to study a number of possible varieties of situations.

II. DETENTION BASIN SYSTEMS NEAR HIGHWAYS

2.1 Introduction

Depending on the topography a number of sites along the highways can be successfully utilized for storm water detention. One of such sites is at the highway interchange. Usually there are four fairly large spaces enclosed between the interchange ramps which are often unused. These abandoned spaces can be suitable for stormwater detention storage and pollutant removal. Figures 1 is an example of a highway interchange where the spaces may be used as detention basins. As will be discussed in later chapters, interconnection between the basins will in general result in a better overall detention scheme for storm runoff as each basin will take its share of the total storage and the pollutant removal depending on the inflow and the boundary conditions. There exists an unlimited number of possible interconnections and boundary conditions. The selection of a scheme will be guided by its suitability for a particular topography. When the detention capacity of the basin system is not sufficient to control incoming surface runoff, the system may be connected to yet another larger basin nearby.

Another situation where detention storage can be advantageously employed is the space between highway embankments. Figure 2 shows layout of this detention system. Storm runoff from subcatchments are temporarily stored in the basins and released later thereby attenuating the peak flow and delaying its peak time. Like in the case of detention basins at highway interchange, different boundary conditions and input parameters are possible. An emergency spillway is usually provided.

2.2 Example Detention Systems

In the present study the following cases of interconnections and boundary conditions are considered for the design of detention systems at the site of highway interchange and between highway embankments.

Case i : The four basins are connected as shown in figure 3b. Inflows from subcatchments enter into all four basins. The outflow takes place in basin 4 only. Possible reversible flows in the interconnecting structures are accounted for. In addition the following subcases are considered in selecting inputs and formulating the computational algorithm to be discussed later

(a) Inflow hydrographs of subcatchments can be of different frequencies of occurrence and are given.

(b) tailwater conditions are either constant or variable.

(c) Pipe culverts are employed to interconnect the basins and all inlets and outlets are assumed to be submerged.

(d) All interconnection structures are box culverts either flowing full or acting as open channels.

Case ii:The same system as above is considered except that outflow takes place in basin 3 and basin 4 (figure 3a).

Case iii:The four basin system in case ii with inflow entering only at basin 1 is studied (figure 3c).

Case iv:The two basin system between highway embankments is studied as above for various initial and boundary conditions (figure 3f).

III. PRINCIPLES OF HYDROLOGIC ROUTING

3.1 Governing Equation

The law of conservation of mass applied to a basin gives the rate of change of storage as equal to the inflow rate minus the outflow rate. Expressed in differential form.

$$dS/dt = I - O \tag{1}$$

where ,

dS = differential storage

dt = differential time

I = inflow rate

O = outflow rate

The above continuity equation is usually approximated by a difference form given below,

$$(S_j-S_i)/\Delta t=(I_j+I_i)/2-(O_j+O_i)/2 \tag{2}$$

where, subcripts i, j represent the beginning and the end of time interval Δt.

Inflows are known from the inflow hydrographs for the subcatchments and initial conditions of storage and outflow are also known. The equation thus contains two unknowns S_j

and O_j. However the outflow, O_j for a given outlet and boundary conditions is a function of the storage, S_j and thus equation (2) is solvable explicitly.

Depending on the complexity due to interconnection between basins and outflow conditions, different techniques have been devised to solve the continuity equation .

3.2 Classical Single Reservoir Routing

Equation (2) rearranged with knowns on the right hand side gives

$$2S_j/\Delta t+O_j=I_i+I_j+2S_i/\Delta t-O_i \tag{3}$$

Using the stage-storage and stage-discharge curves for the basin, a relationship between O and $2S/\Delta t+O$ is developed for a selected Δt and for a particular outlet condition. Values of O_j for each time step can be found from this relationship since $2S_j/\Delta t+O_j$ can be calculated directly from equation (3).

A schematic representation of the single basin routing is shown in figure 4. This method works well with single basin and constant tailwater depth but is not suitable for multiple interconnected basins with possible flow reversal and outflow controlled by tailwater conditions.

3.3 Routing Through Multiple Basins

This method is referred to as the Kuo method for the purpose of identification in this study. It uses control volume approach to individual basins to obtain functional relationship between stages at the end of a routing step. The routing equation, equation (2) as applied to n number of interconnected basins gives the following system of equations,

basin 1 $(S_{1j}-S_{1i})/\Delta t=(I_{1j}+I_{1i})/2-(O_{1j}+O_{1i})/2$

basin 2 $(S_{2j}-S_{2i})/\Delta t=(I_{2j}+I_{2i})/2-(O_{2j}+O_{2i})/2$

.

.

.

basin k $(S_{kj}-S_{ki})/\Delta t=(I_{kj}+I_{ki})/2-(O_{kj}+O_{ki})/2$

.

.

.

basin n $(S_{nj}-S_{ni})/\Delta t=(I_{nj}+I_{ni})/2-(O_{nj}+O_{ni})/2$

(4)

where,

i,j=beginning and end of time step Δt

I_k =inflow in basin k

O_k =outflow in basin k

S_k =storage in basin k

In these n equations each storage term is related to the stage in the individual basin at the time under consideration by the stage-storage curve.

All terms subscripted i are known from the previous routing step or from the initial condition for the very first step. Inflows from subcatchaments are all known from inflow hydrographs for each basin. The terms O_{kj} indicating discharges from basin k at time j are functions of stages in the basins interconnected with basin k. The stages in the basins interconnected with basin k are in turn functions of stages in the other basins interconnecting them. The outlet conditions are assumed known at all times during the routing period. Hence the unknowns in the n continuity equations are n stages in the basins at the end of a time step Δt. The storages and outflows are nonlinear functions of the stages and hence we have a system of n nonlinear equations to solve for n unknown stages. Because of the nonlinear nature of the equations, initial guesses close to the solution values are important both for efficiency and convergence of solutions.

For orifice flow, the discharge from basin k to basin k' at time l can be written as

$$O_{kk'}=C_{kk'}(H_{kl}-H_{k'l})(|H_{kl}-H_{k'l}|)^{-1/2} \tag{5}$$

where,

$C_{kk'}$= coefficient in the hydraulic head-discharge relationship for outlet kk',

H= stage

k and k'= basin designation 1,2,3,4 etc.

For the case of four basins interconnected with pipe culverts as shown in figure 3a, the flow routing equations are as follows

With basin 1 as a control volume,

$$
\begin{aligned}
(\alpha_1 H_{1_j}^{\beta_1} - \alpha_1 H_{1_i}^{\beta_1})/\Delta t = 0.5(I_{1_j}+I_{1_i}) \\
-0.5C_{12}(H_{1_i}-H_{2_i})(|H_{1_i}-H_{2_i}|)^{-1/2} \\
-0.5C_{12}(H_{1_j}-H_{2_j})(|H_{1_j}-H_{2_j}|)^{-1/2} \\
-0.5C_{13}(H_{1_i}-H_{3_i})(|H_{1_i}-H_{3_i}|)^{-1/2} \\
-0.5C_{13}(H_{1_j}-H_{3_j})(|H_{1_j}-H_{3_j}|)^{-1/2}
\end{aligned}
\tag{6}
$$

where,

α_k and β_k= coefficients in the storage-stage relationship,

$$S_k = \alpha_k H_k^{\beta_k} \tag{7}$$

I_{kl}= inflow into basin k at time l, l=i,j

With basin 2 as a control volume,

$$\begin{aligned}(\alpha_2 H_{2_j}^{\beta_2}-\alpha_2 H_{2_i}^{\beta_2})/\Delta t=0.5(I_{2_j}+I_{2_i})&\\
&-0.5C_{12}(H_{2_i}-H_{1_i})(|H_{2_i}-H_{1_i}|)^{-1/2}\\
&-0.5C_{12}(H_{2_j}-H_{1_j})(|H_{2_j}-H_{1_j}|)^{-1/2}\\
&-0.5C_{24}(H_{2_i}-H_{4_i})(|H_{2_i}-H_{4_i}|)^{-1/2}\\
&-0.5C_{24}(H_{2_j}-H_{4_j})(|H_{2_j}-H_{4_j}|)^{-1/2}\end{aligned} \tag{8}$$

With basin 3 as a control volume,

$$\begin{aligned}(\alpha_3 H_{3_j}^{\beta_3}-\alpha_3 H_{3_i}^{\beta_3})/\Delta t=0.5(I_{3_j}+I_{3_i})&\\
&-0.5C_{13}(H_{3_i}-H_{1_i})(|H_{3_i}-H_{1_i}|)^{-1/2}\\
&-0.5C_{13}(H_{3_j}-H_{1_j})(|H_{3_j}-H_{1_j}|)^{-1/2}\\
&-0.5C_{34}(H_{3_i}-H_{4_i})(|H_{3_i}-H_{4_i}|)^{-1/2}\\
&-0.5C_{34}(H_{3_j}-H_{4_j})(|H_{3_j}-H_{4_j}|)^{-1/2}\\
&-0.5C_{35}(H_{3_i}-H_{5_i})(|H_{3_i}-H_{5_i}|)^{-1/2}\\
&-0.5C_{35}(H_{3_j}-H_{5_j})(|H_{3_j}-H_{5_j}|)^{-1/2}\end{aligned} \tag{9}$$

With basin 4 as a control volume,

$$\begin{aligned}(\alpha_4 H_{4_j}^{\beta_4}-\alpha_4 H_{4_i}^{\beta_4})/\Delta t=0.5(I_{4_j}+I_{4_i})&\\
&-0.5C_{34}(H_{4_i}-H_{3_i})(|H_{4_i}-H_{3_i}|)^{-1/2}\\
&-0.5C_{34}(H_{4_j}-H_{3_j})(|H_{4_j}-H_{3_j}|)^{-1/2}\\
&-0.5C_{24}(H_{4_i}-H_{2_i})(|H_{4_i}-H_{2_i}|)^{-1/2}\\
&-0.5C_{24}(H_{4_j}-H_{2_j})(|H_{4_j}-H_{2_j}|)^{-1/2}\\
&-0.5C_{46}(H_{4_i}-H_{6_i})(|H_{4_i}-H_{6_i}|)^{-1/2}\\
&-0.5C_{46}(H_{4_j}-H_{6_j})(|H_{4_j}-H_{6_j}|)^{-1/2}\\
&-0.5(Q_{sj}+Q_{si})\end{aligned} \tag{10}$$

where,

Q_{sl}= spillway discharge at time l

$$= 0., \text{ if } (H_{4l}-H_s) < 0.$$

$$= C_s L_s (H_{4l}-H_s)^{3/2}, \text{ if} (H_{4l}-H_s) > 0. \qquad (11)$$

C_s= coefficient of discharge for the spillway

H_s= height of the spillway

L_s= perimeter length of the spillway

For open channel flow in a box culvert, delivery curves can be prepared for each canal between two adjacent basins. For a rectangular channel with flat bottom having subcritical flow, the discharge between two basins can be approximated by Manning's equation

$$O_{kk'} = A\ 1.49/N\ R^{2/3}\ s^{1/2}$$

$$= C_{kk'}(H'_{kl}+H'_{k'l})^{5/3}(b+H'_{kl}+H'_{k'l})^{-2/3}$$

$$(H'_{kl}-H'_{k'l})(|H'_{kl}-H'_{k'l}|)^{-1/2} \qquad (12)$$

where,

A= average area of cross section

N= Manning's coefficient

R= hydraulic radius

s= slope of energy line approximated by the hydraulic grade line

H'= stage in a basin above invert level of box culvert

$C_{kk'}$= $1.49b^{5/3}/N\ L^{-1/2}$

b= width of box culvert

L= length of box culvert

Details of the computational method follow. Results from this method, are compared with results from other approximate methods under relevant headings to follow.

3.4 Basin Routing Proposed By Malcolm And New

This method, referred to as the Malcolm and New method, uses a less accurate but simpler approximation for the continuity equation. Increase in storage in a time step is assumed to be caused by inflow and outflow only at the beginning of the time step. For a single basin , the equation of continuity becomes

$$S_j - S_i = (I_i - O_i)\Delta t \tag{13}$$

Since quantities at time i are known, S_j is solved for directly. Stage H_j is next found from the stage-storage relationship and outflow is computed from the stage-discharge curve for given boundary conditions. Bradford and Malcolm (1982) have shown that this method gives quite satisfactory results when the time step is small. For the case of four basins interconnected as shown in figure 3a with pipes, the equations (5)-(8) become

$$\alpha_1 H_{1_j}^{\beta_1} = \alpha_1 H_{1_i}^{\beta_1} + I_{1_i}\Delta t$$
$$-C_{12}\Delta t(H_{1_i} - H_{2_i})(|H_{1_i} - H_{2_i}|)^{-1/2}$$
$$-C_{13}\Delta t(H_{1_i} - H_{3_i})(|H_{1_i} - H_{3_i}|)^{-1/2} \tag{14}$$

$$\alpha_2 H_{2_j}^{\beta_2} = \alpha_2 H_{2_i}^{\beta_2} + I_{2_i}\Delta t$$
$$-C_{12}\Delta t(H_{2_i} - H_{1_i})(|H_{2_i} - H_{1_i}|)^{-1/2}$$
$$-C_{24}\Delta t(H_{2_i} - H_{4_i})(|H_{2_i} - H_{4_i}|)^{-1/2} \tag{15}$$

$$\alpha_3 H_{3_j}^{\beta_3} = \alpha_3 H_{3_i}^{\beta_3} + I_{3_i}\Delta t$$
$$-C_{13}\Delta t(H_{3_i} - H_{1_i})(|H_{3_i} - H_{1_i}|)^{-1/2}$$
$$-C_{34}\Delta t(H_{3_i} - H_{4_i})(|H_{3_i} - H_{4_i}|)^{-1/2}$$
$$-C_{35}\Delta t(H_{3_i} - H_{5_i})(|H_{3_i} - H_{5_i}|)^{-1/2} \tag{16}$$

$$\alpha_4 H_{4_j}^{\beta_4} = \alpha_4 H_{4_i}^{\beta_4} + I_{4_i}\Delta t$$
$$-C_{34}\Delta t(H_{4_i} - H_{3_i})(|H_{4_i} - H_{3_i}|)^{-1/2}$$
$$-C_{24}\Delta t(H_{4_i} - H_{2_i})(|H_{4_i} - H_{2_i}|)^{-1/2}$$
$$-C_{46}\Delta t(H_{4_i} - H_{6_i})(|H_{4_i} - H_{6_i}|)^{-1/2}$$
$$-Q_{si} \tag{17}$$

Stages $H_{1_j}, H_{2_j}, H_{3_j}, H_{4_j}$ are found directly from the equations (10)-(13). Outflows at time j are then found from known stages at time j through stage-discharge relations.

A program has been written to take care of multiple basins with different kinds of interconnections, possible flow reversals and different boundary conditions. Results for the case of four basins in figures 3a, 3b and 3c and for the two basin case in figure 3f are compared with those from the Kuo method and the modified method discussed below.

3.5 Basin Routing Proposed By Shingofen

Shingofen (1982) has suggested a modification in the Malcolm and New method. He proposes to include the inflow at time j in calculating the storage increase or decrease in a time step of routing. Thus the continuity equation for a basin is written as

$$(S_j-S_i)/\Delta t=(I_i+I_j)/2-O_i \tag{18}$$

Storage S_j is obtained directly from the above equation and O_j is found from stage-storage and stage-discharge relations. Here the inflow is represented in the average sense but the outflow at the beginning of a time step only is considered for storage change in the time step. Since an increased inflow will tend to increase the storage and stage, and therefore the outflow, a better representation of inflows only may not necessarily give better accuracy for the quantities to be computed like stage, discharge, etc., as will be seen later. This method is referred as the Shingofen method. The routing equations for the system shown in figure 3a become

$$\begin{aligned}\alpha_1 H_{1_j}^{\beta_2}=\alpha_1 H_{1_i}^{\beta_2}+0.5(I_{1_i}+I_{1_j})\Delta t\\ -C_{12}\Delta t(H_{1_i}-H_{2_i})(|H_{1_i}-H_{2_i}|)^{-1/2}\\ -C_{13}\Delta t(H_{1_i}-H_{3_i})(|H_{1_i}-H_{3_i}|)^{-1/2}\end{aligned} \tag{19}$$

$$\begin{aligned}\alpha_2 H^{\beta_2}=\alpha_2 H^{\beta_2}+0.5(I_{2_i}+I_{2_j})\Delta t\\ -C_{12}\Delta t(H_{2_i}-H_{1_i})(|H_{2_i}-H_{1_i}|)^{-1/2}\\ -C_{24}\Delta t(H_{2_i}-H_{4_i})(|H_{2_i}-H_{4_i}|)^{-1/2}\end{aligned} \tag{20}$$

$$\begin{aligned}\alpha_3 H_{3_j}^{\beta_3}=\alpha_3 H_{3_i}^{\beta_3}+0.5(I_{3_i}+I_{3_j})\Delta t\\ -C_{13}\Delta t(H_{3_i}-H_{1_i})(|H_{3_i}-H_{1_i}|)^{-1/2}\\ -C_{34}\Delta t(H_{3_i}-H_{4_i})(|H_{3_i}-H_{4_i}|)^{-1/2}\\ -C_{35}\Delta t(H_{3_i}-H_{5_i})(|H_{3_i}-H_{5_i}|)^{-1/2}\end{aligned} \tag{21}$$

$$\begin{aligned}\alpha_4 H_{4_j}^{\beta_4}=\alpha_4 H_{4_i}^{\beta_4}+0.5(I_{4_i}+I_{4_j})\Delta t\\ -C_{34}\Delta t(H_{4_i}-H_{3_i})(|H_{4_i}-H_{3_i}|)^{-1/2}\\ -C_{24}\Delta t(H_{4_i}-H_{2_i})(|H_{4_i}-H_{2_i}|)^{-1/2}\\ -C_{46}\Delta t(H_{4_i}-H_{6_i})(|H_{4_i}-H_{6_i}|)^{-1/2}\\ -Q_{si}\end{aligned} \tag{22}$$

Stages $H_{1_j}, H_{2_j}, H_{3_j}$ and H_{4_j} are directly found from these equations. With known stages at time j, outflows at time j are computed from known stage-discharge relationships. A program has been written for this method, the details and the results are discussed in the following chapters.

3.6 Comparison Of Methods

All of the above mentioned methods are based on balancing inflows, outflows and the time rate of storage change. The difference lies in the approximation adopted for incremental storage in a time step. The sketches in figure 5 show the incremental storage approximated by these methods against the actual case. As Δt approaches zero all these methods converge to the true value. For a finite Δt and a multibasin system, the Kuo method employing the nonlinear simultaneous equations will theoretically give better accuracy than the other two methods. For instance, when the inflow and outflow hydrographs are nearly parallel,the Malcolm and New method gives good representation of the incremental storage as does the Kuo method while, for a time step as shown in figure 5, the Kuo method and the Shingofen method are clearly better than Malcolm and New method. Sensitivity analyses for the three methods are carried out and the results are discussed below.

IV. DETENTION BASIN FOR QUALITY MANAGEMENT

4.1 Introduction

Detention facilities may alter the pollutant characteristics and reduce concentration in the storm water by settling process much as they provide storm runoff control by temporary detention and attenuation of flood flows. When the convective forces transporting the pollutants dampen, heavier particles start to fall and are ultimately deposited at the bottom. The result is the overall reduction in effluent pollutant concentration and mass outflow rate from a retention basin. By designing a detention basin with sufficiently long detention time, considerable reduction in effluent pollutant concentration can be achieved. The quality improvement can be significant when the storm water is diverted to pass through a system of detention basins.

4.2 Governing Equation

Assuming complete mixing conditions in the basin the mass balance equation for a pollutant in a detention basin can be written as

$$d(SC')/dt=IC-OC'-KC'S-M \tag{23}$$

where,

S = storage in the basin

C' = concentration of the pollutant in the basin and the effluent

I = inflow

C = influent concentration

O = outflow

K = coefficient of decay

M = time rate of mass deposition

For the sake of simplicity only conservative pollutants are considered in this study. Thus, omitting the decay term, the equation of mass conservation reduces to

$$d(SC')/dt=IC-OC'-M \tag{24}$$

In difference form,

$$\begin{aligned}(S_jC'_j-S_iC'_i)/\Delta t=&(I_i+I_j)C/2\\ &-(O_iC'_i+O_jC'_j)/2\\ &-(M_i+M_j)/2\end{aligned} \tag{25}$$

The inflow and outflow rates and storage volumes are known from the quantity analysis of the basin flows. The quantities at time i are either known from the previous time step or the initial conditions given. Hence C_j and M_j are the two unknowns. The sizes and amounts of the particles deposited depend on their respective settling velocities, influent velocity, basin configuration etc. In general, if a flow through the basin, Q causes an upward water velocity component, v in the basin,the particles with settling velocities greater than v will settle (Poertner, 1974). Hence for a particle to settle the minimum basin area required is Q/v_s where v_s is the settling velocity of the particle. This idealization is however, far from the real flow situation. The settling process may be adversely affected by turbulence present in the flow, temperature differentials between the incoming flow and the water in the basin, density currents etc. There are standard computer codes available for determination of sediment trap efficiency of a basin. For example, 'DEPOSIT' developed at the University of Kentucky (Ward, Haan and Barfield, 1977) can be used to determine the sediment trap efficiency of a detention basin. The 'DEPOSIT' computer code has been extended to study the pollutant trap efficiency at Virginia Tech (Ni, 1983)

4.3 Pollutant Routing Through Multiple Basin System

In the present study, the pollutant trap efficiencies for the individual basins are assumed known. With known trap efficiencies for settleable pollutants and those attached to the settling sediment for each of the basins in a system, the time dependent effluent pollutant concentrations from each basin of the system can be determined from the mass conservation equations applied to the basins in the system.

For the case of four basins interconnected as shown in figure 3a, the pollutant mass conservation equations are

$$\begin{aligned}(S_{1_j}C'_{1_j}-S_{1_i}C'_{1_i})/\Delta t={}&(1-\eta_1)(I_{1_i}C_1+I_{1_j}C_1)/2\\ &-(Q_{12_j}C'_{12_j}+Q_{12_i}C'_{12_i})(1-\eta_{12})/2\\ &-(Q_{13_j}C'_{13_j}+Q_{13_i}C'_{13_i})(1-\eta_{13})/2\end{aligned} \tag{26}$$

$$\begin{aligned}(S_{2_j}C'_{2_j}-S_{2_i}C'_{2_i})/\Delta t={}&(1-\eta_2)(I_{2_i}C_2+I_{2_j}C_2)/2\\ &+(Q_{12_j}C'_{12_j}+Q_{12_i}C'_{12_i})(1-\eta_{12})/2\\ &-(Q_{24_j}C'_{24_j}+Q_{24_i}C'_{24_i})(1-\eta_{24})/2\end{aligned} \tag{27}$$

$$\begin{aligned}(S_{3_j}C'_{3_j}-S_{3_i}C'_{3_i})/\Delta t={}&(1-\eta_3)(I_{3_i}C_3+I_{3_j}C_3)/2\\ &+(Q_{13_j}C'_{13_j}+Q_{13_i}C'_{13_i})(1-\eta_{13})/2\\ &-(Q_{34_j}C'_{34_j}+Q_{34_i}C'_{34_i})(1-\eta_{34})/2\\ &-(Q_{35_j}C'_{3_j}+Q_{35_i}C'_{3_i})(1-\eta_{35})/2\end{aligned} \tag{28}$$

$$
\begin{aligned}
(S_{4_j}C'_{4_j}-S_{4_i}C'_{4_i})/\Delta t = {} & (1-\eta_4)(I_{4_i}C_4+I_{4_j}C_4)/2 \\
& +(Q_{24_j}C'_{23_j}+Q_{24_i}C'_{24_i})(1-\eta_{24})/2 \\
& +(Q_{34_j}C'_{34_j}+Q_{34_i}C'_{34_i})(1-\eta_{34})/2 \\
& -(Q_{46_j}C'_{4_j}+Q_{46_i}C'_{4_i})(1-\eta_{46})/2 \\
& -(Q_{si}C'_{4_i}+Q_{sj}C'_{4_j})/2
\end{aligned}
\tag{29}
$$

where,

subscript, i = beginning of time step

subscript, j = end of time step

subscripts 1,2,3,4 = basin designation

$Q_{kk'}$ = discharge from basin k to basin k'

C'_{kj} = pollutant concentration in k basin at time j

η_k = pollutant trap efficiency of k basin

$C'_{kk'j} = C'_{kj}$ if $Q_{kk'j} \geq 0.$

$= C'_{k'j}$ if $Q_{kk'j} < 0.$

$\eta_{kk'} = \eta_k$ if $Q_{kk'} < 0.$

$= 0.$ if $Q_{kk'} \geq 0.$

Q_{sl} = spillway discharge at time l, $l=i,j$

Flow volumes calculated in quantity analysis are used here with the assumption that the flow volumes are not affected by the volumes of pollutants settled. Complete mixing is assumed and the discharge going out of a basin at an instant is assumed to have the same pollutant concentration as that in the basin. In other words, if there is a flow from one basin to another, the pollutant concentration in the flow is taken as the concentration at the source of this flow. The unknown C_{kj} terms may or may not appear on both sides of the equations depending on whether the discharge is outflow from the basin or inflow to it. The system of simultaneous equations is linear and is solved to find the four unknowns, $C_{kj}(k=1,2,3,4)$ at time j. When the fluctuation of concentration is small, the C_{kj} term appearing on the right hand side can be approximated by the corresponding C_{ki} term. Marching forward to the next time step, pollutant concentrations in each basin for conservative pollutants as functions of time and the resulting systemwide trap efficiency for the routing period is obtained.

A subroutine was developed to introduce the pollutant routing through detention basins in the main program. The results of pollutant routing for the systems shown in figures 3a, 3b, 3c and 3f are presented below.

V. COMPUTATIONAL METHODS AND ALGORITHMS

Closed form solution of the simultaneous differential equations of mass conservation involved in flow routing through multibasin system is difficult if not impossible. Hence a numerical method to solve them is desirable. Three algorithms have been considered in accordance with three different approximations employed for mass conservation equations. The first algorithm involves solution of a set of simultaneous nonlinear algebraic equations. These are solved by iterative procedures like Newton's method, secant method etc. Standard text books(Gerald, 1978; Johnson and Riess, 1982) list programs to solve sets of nonlinear equations. Since such programs are also available as IMSL routines in the IBM 370 system, one such subroutine ZSPOW which uses the variation of Newton's method is used in the present case. A subroutine to evaluate the functions derived from the continuity equations and which are to be made zero, is needed. The other two algorithms give direct solutions to the mass conservation equations. However, because of many variables involved in a multibasin system, the use of a computer becomes inevitable. The pollutant mass conservation equations are linearized by using flow volumes computed in the quantity analysis and are solved accordingly. A description of the first algorithm named program DPDMS (Dual Purpose Multiple Detention System) follows.

VI. PROGRAM DUAL PURPOSE MULTIPLE DETENTION SYSTEM (DPMDS)

6.1 Scope and Limitations

The program in its present form can solve flow and pollutant routing through a multi-connected basin system as shown in figure 3d. Any component in the system not required for analysis can be omitted by simply prescribing the discharge coefficient for the unwanted linkage structure as zero and any unwanted input as zero. For example, if a system shown in figure 3e is to be analyzed, the coefficient of discharges for flows between basins 1 and 2 and between basins 1 and 3 can be set equal to zero and so also the inputs to basins 3 and 4. With suitable changes in the program DPMDS can be used for quantity and quality analysis of stormwater flow through any number of detention basins interconnected in any manner. The program handles only conservative pollutants and trap efficiencies of all basins for the pollutant of interest are required as input.

6.2 Program Description

The program DPMDS has three subroutines. The main program reads all input data and computes all inflows and discharges at the beginning of a time step before a call to the IMSL routine ZSPOW is made. ZSPOW uses subroutine FCN to solve a system of nonlinear simultaneous equations with stages at the end of a time step as unknowns. In doing so, it calls a set of subroutines in the system and uses the initial given stages which are input for the very first time step or the guessed values for other time steps and updated subsequently for the following step in the main program. A loop is formed to march in time the computation of unknown stages and updating of initial guesses in calculating the flow quantities.

Subroutine FCN puts the continuity equations in the format of functions to be equated to zero. To account for the possible flow reversals, the continuity equations may involve division by square root of the absolute values of differences in stages. Also a negative outflow at any time requires to be treated as an actual inflow.

Subroutine POLLUT solves the pollutant mass conservation equations. Flow volumes calculated from quantity analysis through the main program are used here with the assumption that flow volumes do not change because of settling of pollutants. For a completely mixed system, the pollutant mass conservation equations then become a linear system of simultaneous equations. An IMSL routine to solve linear system of equations can be used to solve these. However, since the concentration change in a time step is generally small, the pollutant concentration in the flow between any two basins at the end of a time step can be approximated by the pollutant concentration in the basin at the beginning of the time step. Subroutine POLLUT employs this approximation and the system of equations become solvable directly. Also pollutant trap efficiency is applied only to positive inflow to a basin. Negative inflow being actually an outflow for the basin, it does not contribute to pollutant trapping in the basin. Subroutine POLLUT computes concentration and pollutant mass flows as functions of time. It also computes the overall system trap efficiency.

Figure 6 shows a flowchart for the method of computation adopted.

6.3 Input Data

1. Stage-storage relationship: A regression equation of the type storage = $\alpha(\text{stage})^{\beta}$ is assumed. The coefficients α and β for each basin are input as CP and CPP respectively, where P represents the basin designation 1,2,3 or 4.

2. Stages: Initial values of stages for all basins and all boundaries such as tailwater depthsare input as HP1 for basin P, HCX for boundary from basin 3 and HDX for boundary from basin 4. When the tailwater is variable HCX and or HDX are input as functions of time.

3. Inflow hydrographs: Inflow hydrographs to all basins are input as QP's which are functions of time. Here P denotes basin designation. If a basin does not get inflow a value of zero is input for that particular basin.

4. Type of flow in the interconnected structures: NTYPE = 0 and 1 indicate open channel flow and pipe flow respectively. The program as presented can handle pipe flow and open channel flow with a mild slope. If other conditions of linkage and outlets are to be used the program will need some changes to accomodate these.

5. Discharge coefficients: Discharge coefficients for all links and outlets are input as CPQ, where PQ means link between basins P and Q or outlet from basin P to boundary Q. Coefficients specified in the program for discharge are $1.49b/(NL^{1/2})$ for open channel flow with mild slope,

$CA(2g)^{1/2}$ for orifice flow and CL for weir flow. All the symbols used have been described in chapter III. Length and height of the spillway weir in basin 4 are input as LWEIR and HWEIR respectively. The coefficient of discharge for the drop-inlet type spillway is taken as 3.3.

6. Pollutant concentrations: Pollutant concentrations of inflow from subcatchments to all basins are input as CNP

7. Pollutant trap efficiencies: Pollutant trap efficiencies of individual basins for the pollutant of interest are input as TEK, K denoting the basin designation.

8. Number of basins, number of digits of accuracy desired in the computed values and maximum number of iteration to be allowed are specified as N, NSIG and ITMAX respectively.

9. Initial guess values for the stages at the end of the first time step as X(1) for basin 1, X(2) for basin 2 etc. The initial guess values for successive time steps are taken as updated stages for the preceeding step. This should work well with reasonably small time steps. In case of nonconvergence 'terminal error' is indicated and a suitable updating of the guess values should be included.

6.4 Output

A typical output shows all stages, storages, discharges, pollutant concentrations, mass flows as functions of time. Overall system inflows and outflows are also tabulated as functions of time. Peak stage, peak discharge and the peak times including maximum spillway discharge are also tabulated.

VII. RESULTS AND DISCUSSION

Determination of peak stages, peak outflows, pollutant mass flows etc. for storm runoff passing through a detention basin system are important considerations in dual purpose detention basin design. Because of complexities involved in a multibasin system, a fairly simple but accurate method to carry out the routing process is desirable for practical design purposes.

Sensitivity tests on the three algorithms discussed earlier were carried out for storm water quantity and quality routing through three typical multiple basin systems shown as figures 3a, 3c and 3f. Both open channel flow and pipe flow cases were considered for the system in figure 3a and pipe flow was considered for the system in figures 3c and 3f. The results of the sensitivity tests of the Kuo method and the Malcolm and New method are shown in graphical form in figures 7-16. Figures 7, 8, 9, 10 and 11 show the stage in basin 1, the discharge from basin 1 to basin 2, the system outflow, the system mass outflow and the concentration in basin 1 as functions of time as calculated by the Kuo method with various time steps indicated. Figures 12, 13, 14, 15 and 16 are results of sensitivity analysis of the Malcolm and New method in terms of the same time-variable quantities as considered for the Kuo method. Sensitivity analysis of the Shingofen method gave practically the same results as the Malcolm and New method. The results are not included here. The smallest time steps which gave convergence or no appreciable change in the solutions with further decrease were selected for each method. As one would expect, the finally selected time step varies with each method and with each basin system. From figures 7-11 and 12-16, it is evident that a time step of 10 minutes or even 15 minutes yields convergence of solution by the Kuo method applied to the four basin system while a time step of 2.5 minutes is required with the Malcolm and New method applied to the same system. Sensitivity analysis of the Shingofen method also resulted in a time step of 2.5 minutes on convergence. These time steps are selected for comparison of the results. Alternatively a criteria for selection of a time step in terms of percentage change in a computed quantity versus a certain change in the time step could also be used, but this may not be feasible when there is a fluctuation in the computed quantities.

The solution (stage, discharge etc. as functions of time) obtained from the three algorithms with the use of the selected time steps were plotted for comparison and some of these plots are shown in figures 17-21. It is interesting to note that, despite use of different selected time steps, the results from the last two algorithms are different from those from the first algorithm. The differences in peak stage in basin 1 and the maximum discharge from basin 1 to basin 2 by these methods are quite significant. The descrepancies can be attributed to the different approximations involved and to the routing method used for the basin system. In the Kuo method the unknowns are obtained by solving simultaneous equations and any change in a variable in one basin affects all others in the whole system. For every time step all inflows to all basins during the time period are responsible for stage changes during during the period. In the other two methods the continuity equations are solved independently for individual basins and inflows to adjacent basins in a time step do not affect the calculation of quantities in a basin in the same period. Hence it is possible that small differences in each step accumulate to affect the result appreciably. The quantities found by the three methods vary and the amount of discrepancy in a computed quantity will depend on various parameters of the system like inflow rates, type and number of interconnections etc. For a single basin system we would expect the stages as determined by the three algorithms to follow a certain pattern according to the approximations involved. With a multibasin system the interdependence of the variables in the four basins such as discharges and stages is significant. Flow reversals or tendency to adjust water levels simultaneously in the basins may result in patterns unexpected from a single basin system. The computed quantities after the peak time calculated by the Malcolm and New method and the Shingofen method are nearly equal. But stages and outflow quantities with respect to basin 1 calculated by the Kuo method have higher values near the peak than those calculated by the other two methods. After the peak time, the curves diverge with time significantly. This is true also for a two basin system as will be seen later.

Comparison of the three methods for the same four basin system for the case of pipe flow in the interconnecting structures and having inflow hydrograph as input to basin 1 only was also studied.The detailed results are not included in this thesis. It was found that the peak value of stage in basin 1 came out nearly the same for all three methods. On the other hand peak stage for basin 2 as calculated by the

Kuo method was greater than that calculated by the other two methods by about 13 percent. Thus the method of computation employed affected the peak quantities in basin 2 more than those in basin 1 for this particular case.

Some results of quantity and quality routing through the four basin system (figure 3a) with pipe flow by the Kuo method with inflow hydrographs of figure 22 and stage-storage curves of figure 23 are shown in figures 24-28. In actual practice the hydrographs will be the design storm hydrographs of interest for the subcatchments. Time variation of stages, storages and all flow quantities including pollutant mass flows and concentrations were plotted. It can be seen from figures 24-27 that the peaks in the four basins do not occur at the same time. In the present case the peak stage value is lowest in basin 4. If spillway height in basin 4 is to be limited to this peak value, one could fully utilize the additional storage capacity available in the other basins due to higher permissible stages in them, by employing suitable interconnecting structures. This is clearly an advantage of having interconnection between basins.

Inflow hydrographs and stage-storage curves as shown in figures 29 and 30 respectively were used for routing analysis of a four basin system (figure 3a) with open channel flow in the interconnecting structures. The results are shown graphically in figures 31-35.

Table 1 shows the inputs and the results of quantity and quality analyses of stormwater routing through a four basin system as shown in figure 3a. The interconnecting pipes and outlets are assumed to be submerged. A peak flow of 1155 cfs into the system produces a peak outflow of 197 cfs with 83 percent reduction and the peak time is delayed by 90 minutes. It can be seen from the table that peak stage, peak outflow, and peak pollutant mass outflow for the system do not occur at the same time. This is a typical characteristics of a multiple basin system. For example, the maximum stage in the system of 7.34 feet occurs at 150 minutes, while the peak outflow of 197 cfs occurs at 180 minutes. The peak pollutant mass outflow of 2.4 lb per sec occurs at 120 minutes as compared to the peak pollutant mass inflow of 21.7 lb per sec at 80 minutes. Maximum detention storage for the system comes to 4.362 million cubic feet. The overall system pollutant trap efficiency is found to be 68 percent with known trap efficiencies of 0.6, 0.5, 0.4 and 0.3 in the individual basins.

Table 2 gives the input and some important results of quantity and quality analyses for the four basin system as shown in figure 3a with open channel flow in the interconnecting reaches. The importance of the size and nature of the outlet structures and the interconnecting reaches involved in flow routing becomes evident. The sizes chosen for analysis in this case of open channel flow do not give better result as compared to the pipe flow case with respect to system pollutant trap efficiency. The peak values of stage, outflow and pollutant mass outflow in this case are 8.17 ft, 191 cfs and 1.9 lb/s respectively. System pollutant trap efficiency of 64 percent is obtained.

Table 3 shows the comparison of the three methods by their response to flow routing through a four basin system as shown in figure 3a with pipe flow. Peak stages in the four basins obtained by the Malcolm-New and the Shingofen methods are found to be the same. The peak stages obtained by the Kuo method are higher by 2 to 9 percent. System peak flow calculated by the Kuo method is greater than those from the other two methods by about 5 percent. Although stage, discharge etc. at some instant differ by as much as 10 percent, the peak values differ by less than 5 percent. Convergence of the Kuo method was obtained with less than 10 iterations in this case and other cases studied. The other two methods gave converged solutions only for significantly smaller time steps. Execution time for each of the three methods was less than two minutes for all the cases studied.

Results of sensitivity analysis of the Kuo method for the two basin system as shown in figure 3f are presented graphically in figures 36-40. The two basin system is more sensitive to the size of the time step selected as compared to the four basin system. For example, with the same time step the stage-time curves in the two basin case are not as smooth as in the four basin case. Results for the two basins case from the second and the third methods, although not included in this thesis, indicated instability even with a time step of 1.25 minutes. Superiority of the Kuo method was evident from stability considerations. The time dependent quantities calculated by the Malcolm-New and the Shingofen methods behaved erratically with time steps of ten minutes. This may be because slight changes in stages near steady state values causes reversal of flows. The fluctuation once started takes time to dampen. For a time step of 10 minutes with the Malcolm-New and the Shingofen methods the solutions for concentration in basin 1 and the system pollutant mass flows blew up. With a time step of 5 minutes the fluctuations were more than the expected peaks. This kind of situation may sometimes lead to erroneous conclusions.

A time step of 10 minutes for the Kuo method and 1.25 minutes each for the other two methods were selected for the qualitative comparison of the three methods with results shown in figures 41-45. The peaks by the three methods again differ and so do the times of peaks. The Malcolm-New and Shingofen methods again give almost identical results based on the selected time step of 1.25 minutes. The peak stage in basin 1 as found by the Kuo method is greater by about 5 percent compared to the peaks given by the other two methods. Peak flow quantities also differ.

Results of the flow routing simulation through a two basin system of figure 3f with inflow hydrographs given in figure 46 and stage storage curves in figure 47, using the Kuo method are shown in table 4. The peak stage, peak outflow and peak pollutant mass outflow are 15.65 ft, 255 cfs and 2.4 lb/s respectively.System trap efficiency comes to 57 percent.

Table 5 gives the comparison of computed quantities for a four basin system shown in figure 3b with the quantities for a single basin system of equivalent total storage capacity for the same total inflows used. A lower spillway height is required in basin 4 of the four basin system than that in the single basin system to route the same total inflow. The difference in spillway height between the two cases is 0.18 ft for this particular example detention system studied.

VIII. SUMMARY AND CONCLUSIONS

An algorithm which is suitable for quantity and quality analyses of flow routing through multiple detention systems has been devised. Three algorithms each using a different approximation for the mass conservation equation were formulated and their perfomance as applied to four basin and two basin systems with a variety of hydraulic and hydrologic conditions were analyzed before making the final selection.

The Malcolm and New and the Shingofen methods using simplified approximations for the continuity equation were also found to give fair results, usually within 10 percent for the peak values of stages and discharges as compared with the selected Kuo method. But, on occasions they tend to give erratic results especially when fluctuation of these quantities is seen. Based on the findings in this research, the following conclusions can be presented

1. All the three methods give comparable results when convergence of the solution is obtained. The peak stages calculated by the Kuo method are higher and the differences

are within ten percent for all the cases of detention basin systems considered.

2. The algorithm employing the Kuo method is favorable in respect of stability and time step required for solution convergence as compared to the Malcolm and New and the Shingofen methods.

3. The peak stages in the basins do not occur at the same time and they differ from one basin to another. For a design storm of interest in a particular detention system, outlet and interconnecting structures can be designed for optimum use of allowable stage height in each basin.

4. A multiple detention basin system is very effective for control of surface runoff. For an example case of four basin system studied, the peak flow is found to be reduced by 83 percent and the peak time delayed by 90 minutes.

5. In terms of water quality control, the pollutant trap efficiency can be enhanced by allowing interconnection between basins. For individual basin pollutant trap efficiencies ranging from 30 to 60 percent a system pollutant trap efficiency of 68 percent was found for a four basin detention system studied.

The present study has clearly illustrated the methodology in designing a multiple detention basin system with respect to quantity and quality analyses. In order to refine the design method proposed, further research is recommended as follows.

(a). The program in its present form can take care of pipe full flow, open channel flow through box culverts with mild slope and weir flow over spillways. Modification in the program is required for other kinds of flows through the interconnecting structures and outlets.

(b). The program requires pollutant trap efficiency of each individual basin as the input. A computer subprogram to calculate the trap efficiencies from basin and flow data may be desirable. The trap efficiency of a basin need not remain constant for two different flows or for the same flow at different times.

(c). The program can solve flow and pollutant routing through multiple basin system shown in figure 3d and its subsystems. Modification in the program will be required for its use to systems with more basins and more number of interconnections.

(d). In cases where percolation is significant, the effective flow input to the system can be taken as the net inflow hydrograph which is the difference of the inflow hydrograph and the infiltration rate curve.

(e). Non-conservative pollutants can be taken care of in the proposed design method by introducing the coefficient of decay in the quality analysis.

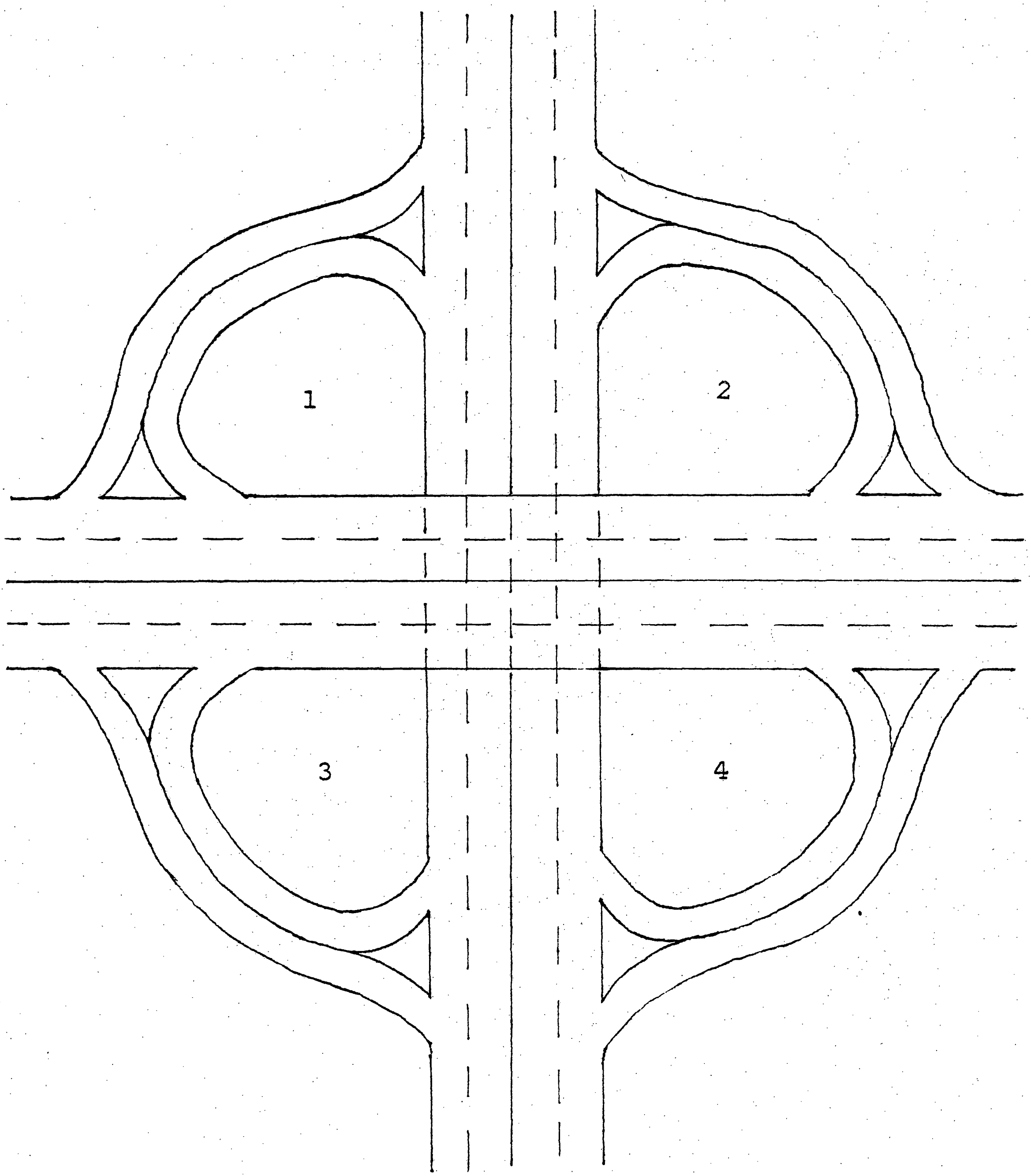


Figure 1. Typical highway interchange with four detention basins.

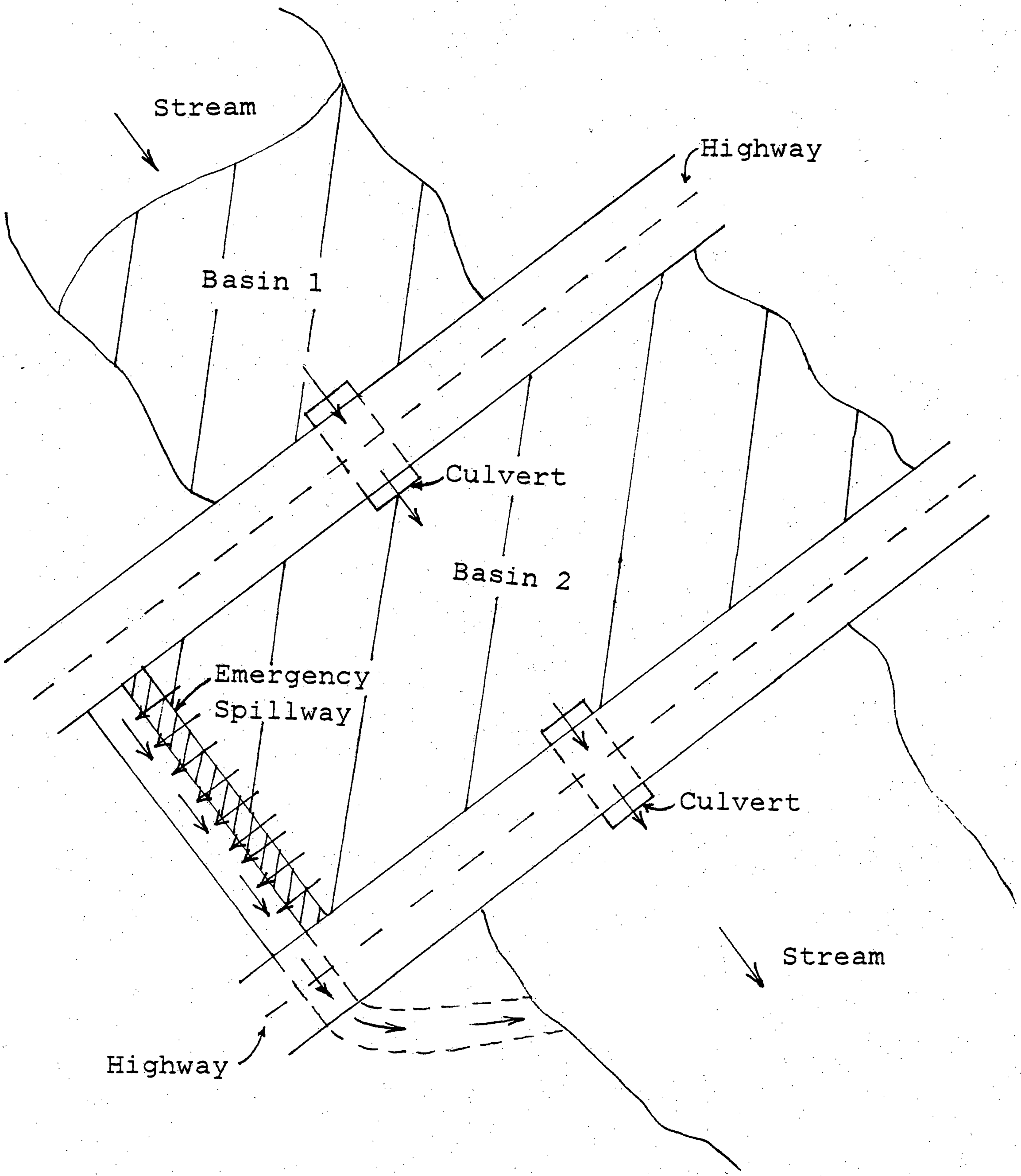


Figure 2. Layout of a two basin detention system between highway embankments.

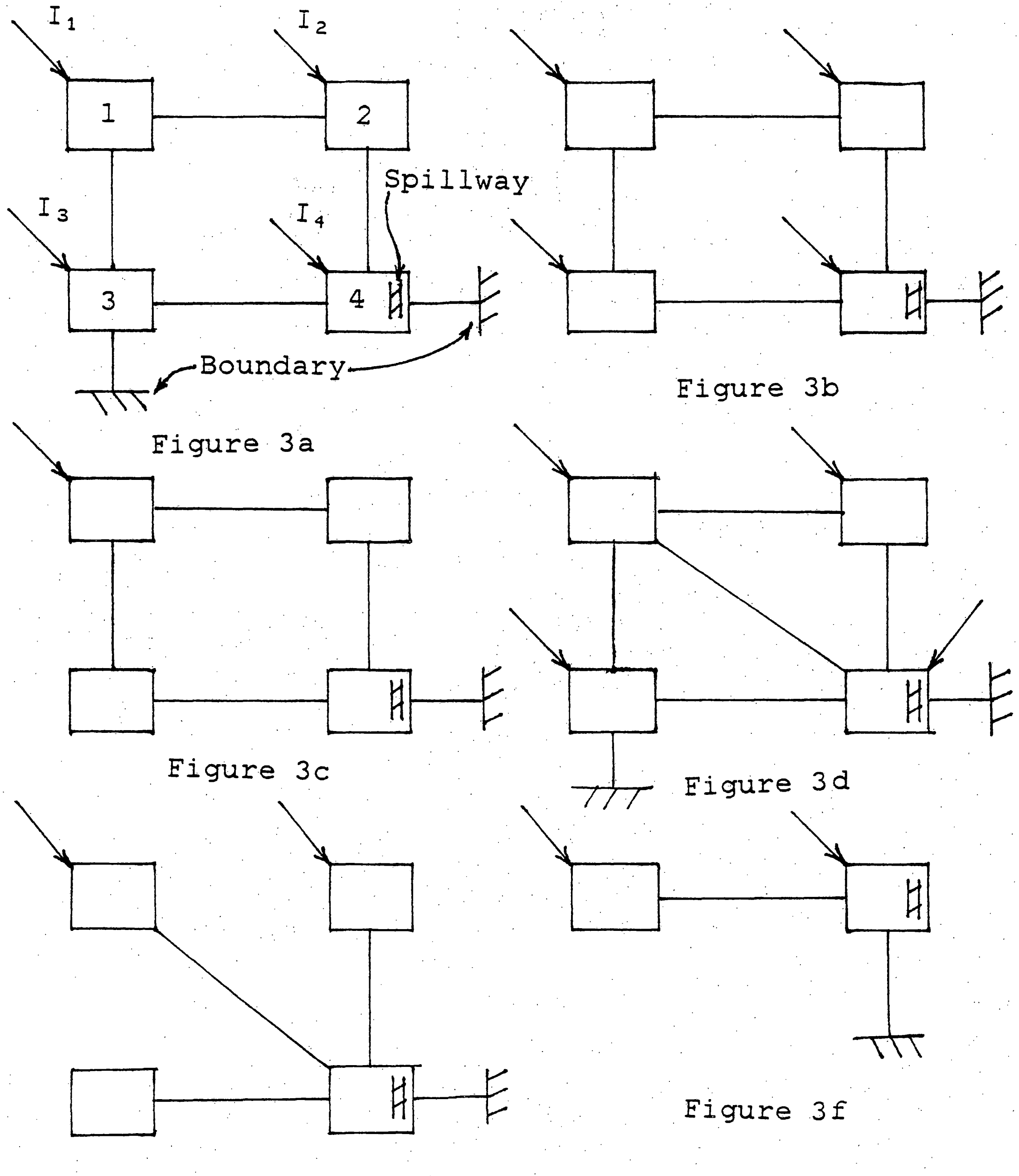


Figure 3a

Figure 3b

Figure 3c

Figure 3d

Figure 3e

Figure 3f

Figure 3. Various cases of multiple detention basin systems.

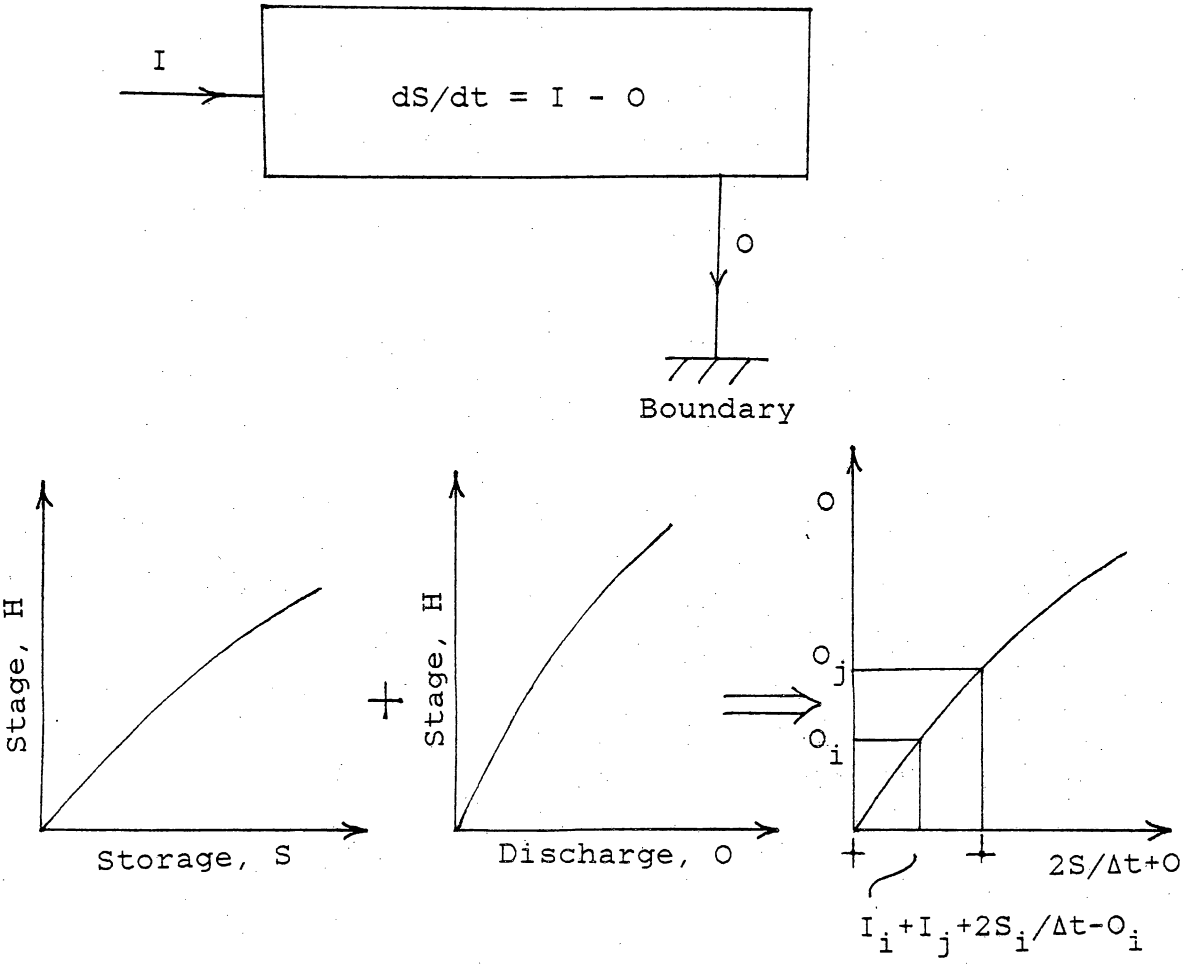
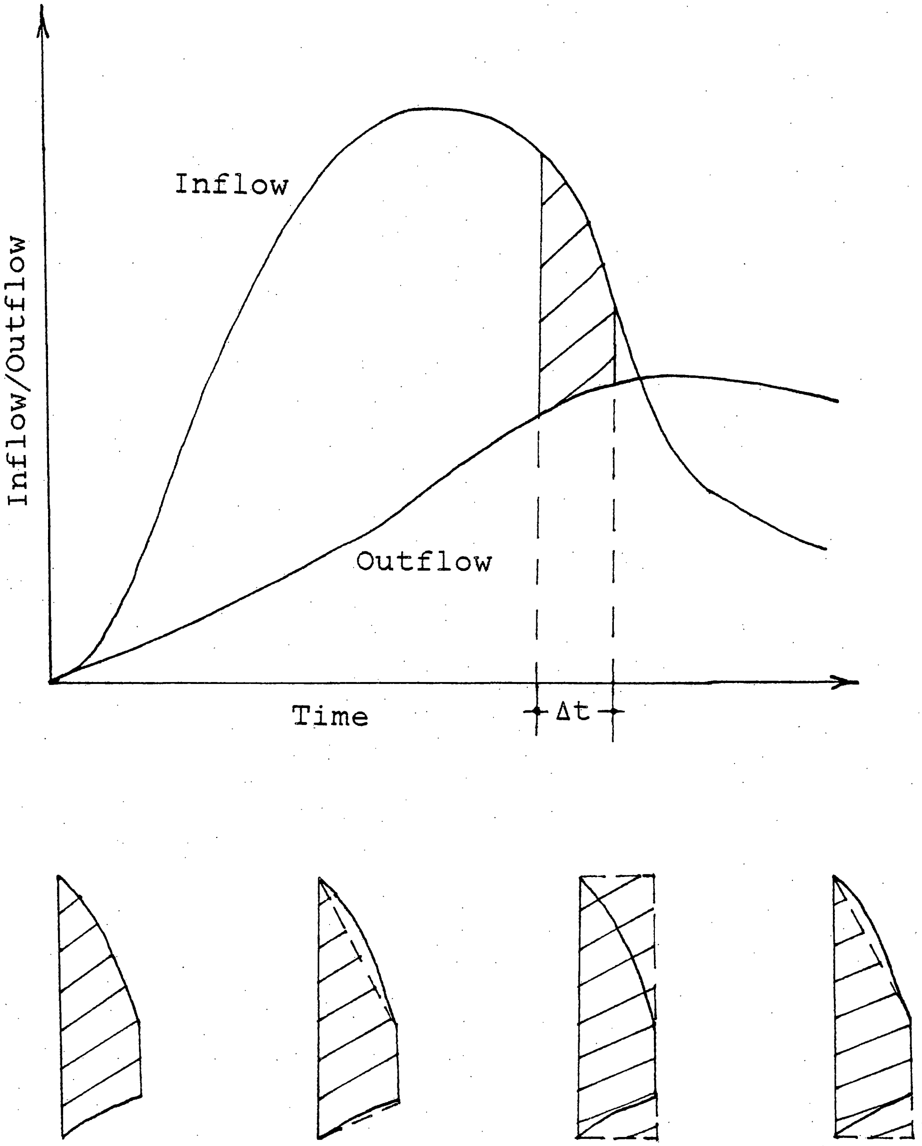


Figure 4. Schematic representation of single basin routing.



Actual

Kuo Method

Malcolm & New Method

Shingofen Method

Figure 5. Schematic representation of approximation used in the three methods.

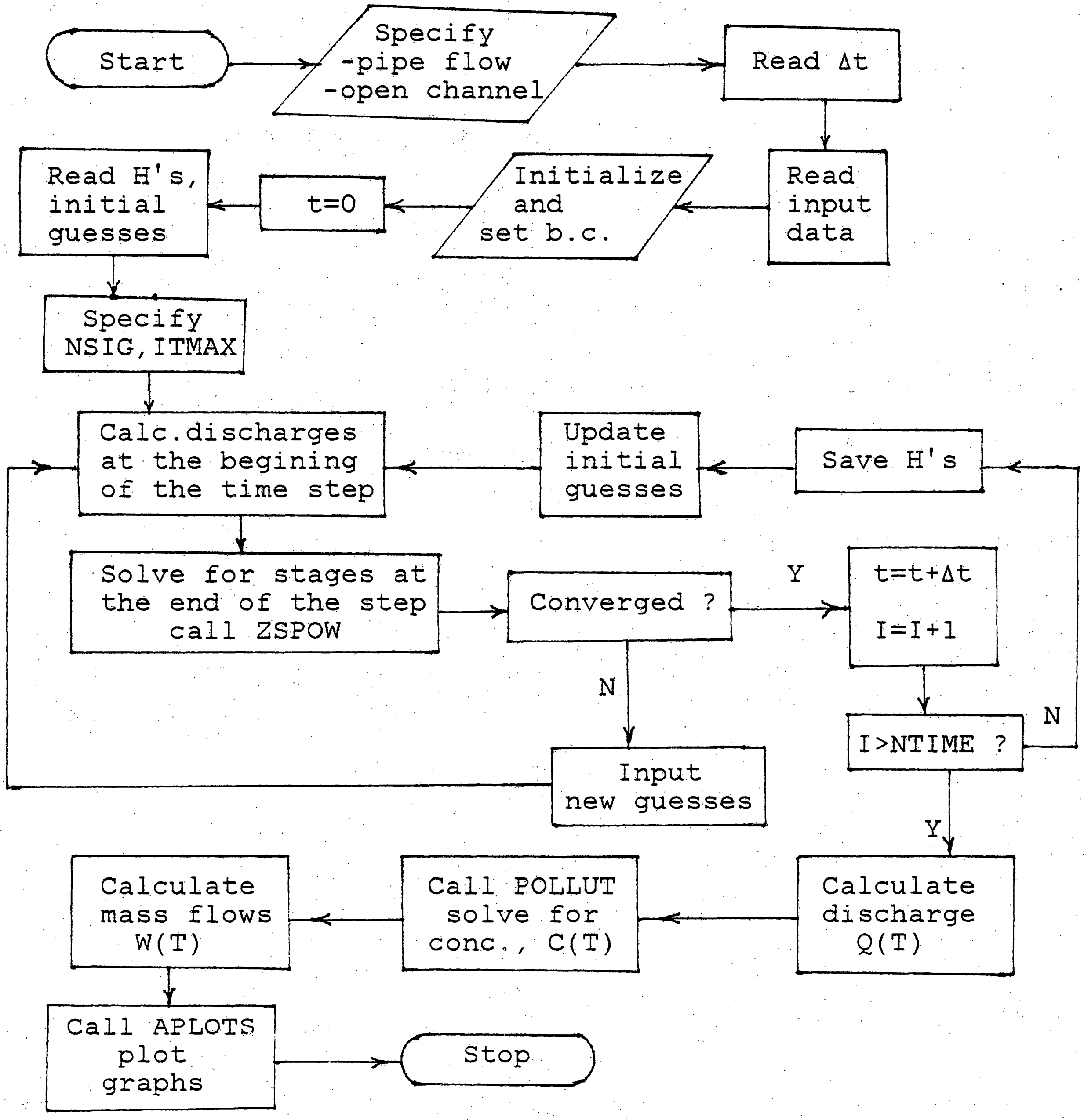


Figure 6. Flowchart of the computer program "Dual Purpose Multiple Detention System (DPMDS)".

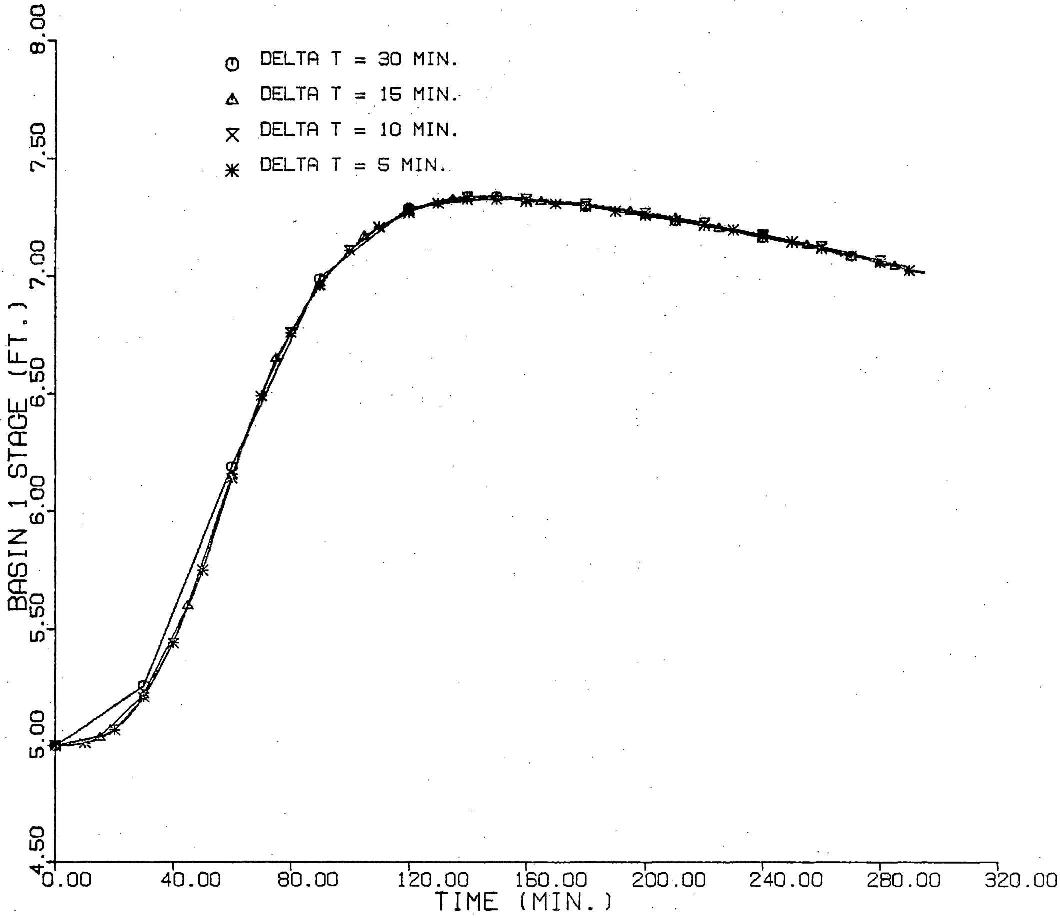


Figure 7. Sensitivity analysis of the Kuo method with respect to stage in basin 1 in figure 3a.

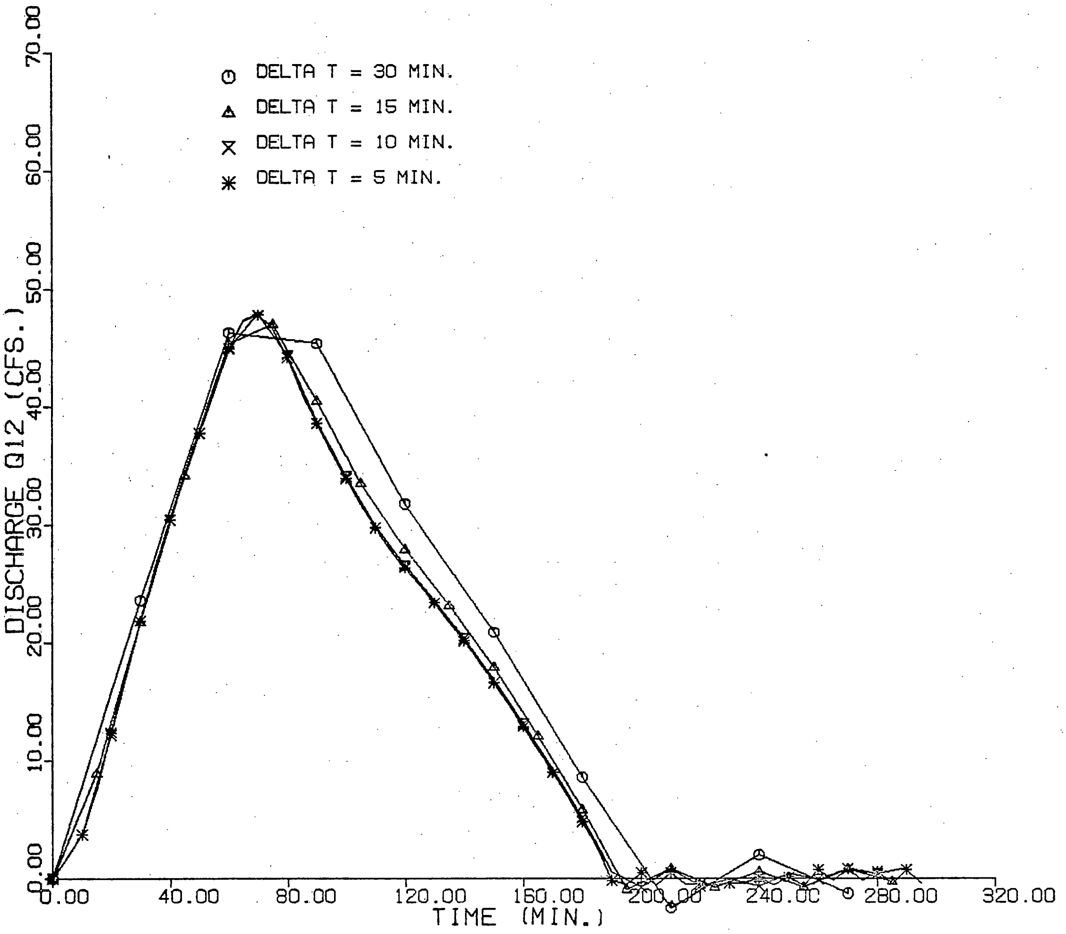


Figure 8. Sensitivity analysis of the Kuo method with respect to discharge from basin 1 to basin 2 in figure 3a.

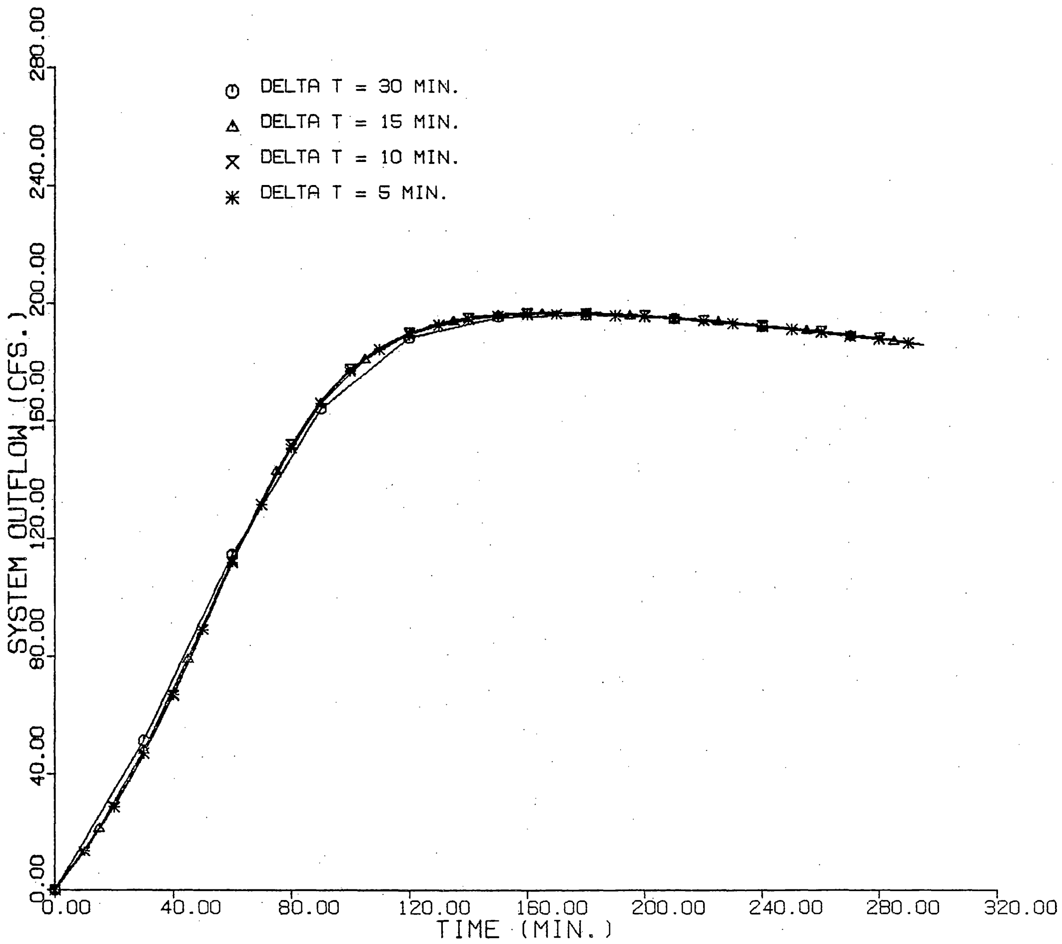


Figure 9. Sensitivity analysis of the Kuo method with respect to system outflow in figure 3a.

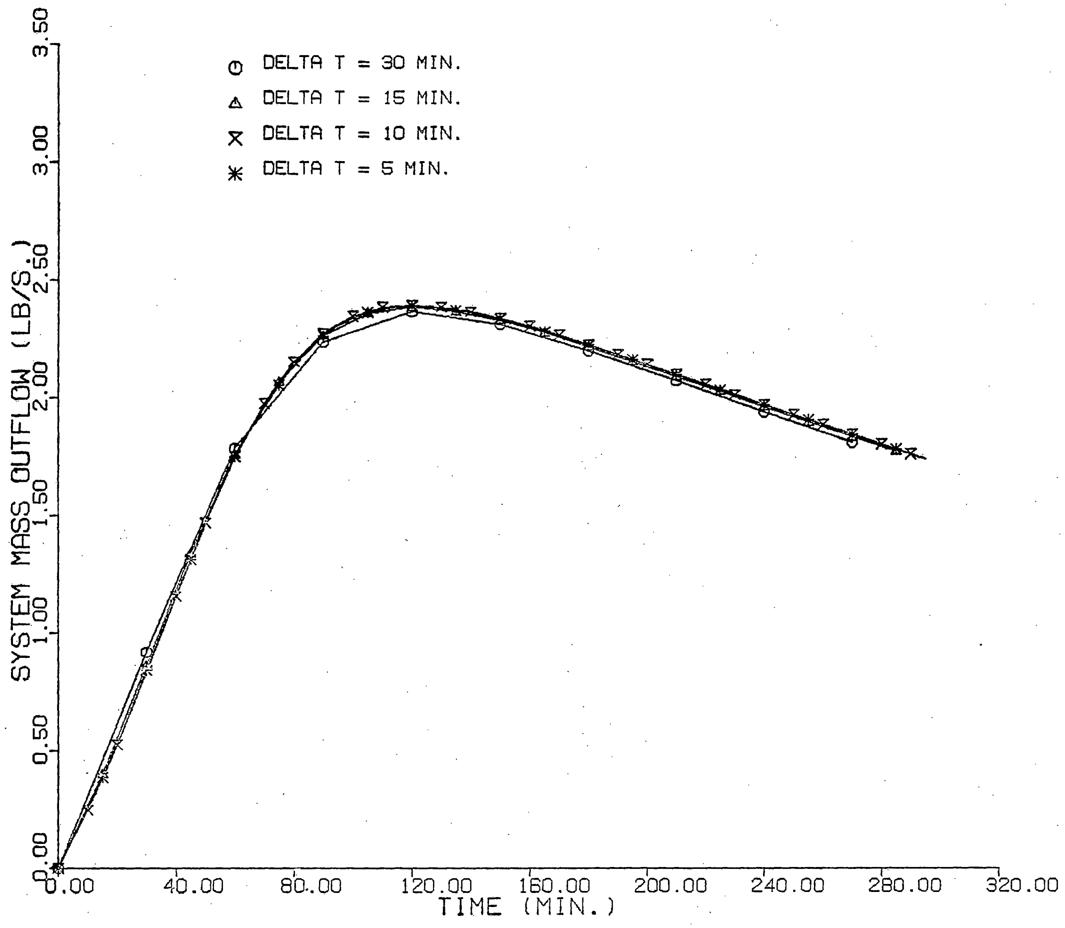


Figure 10. Sensitivity analysis of the Kuo method with respect to system mass outflow in figure 3a.

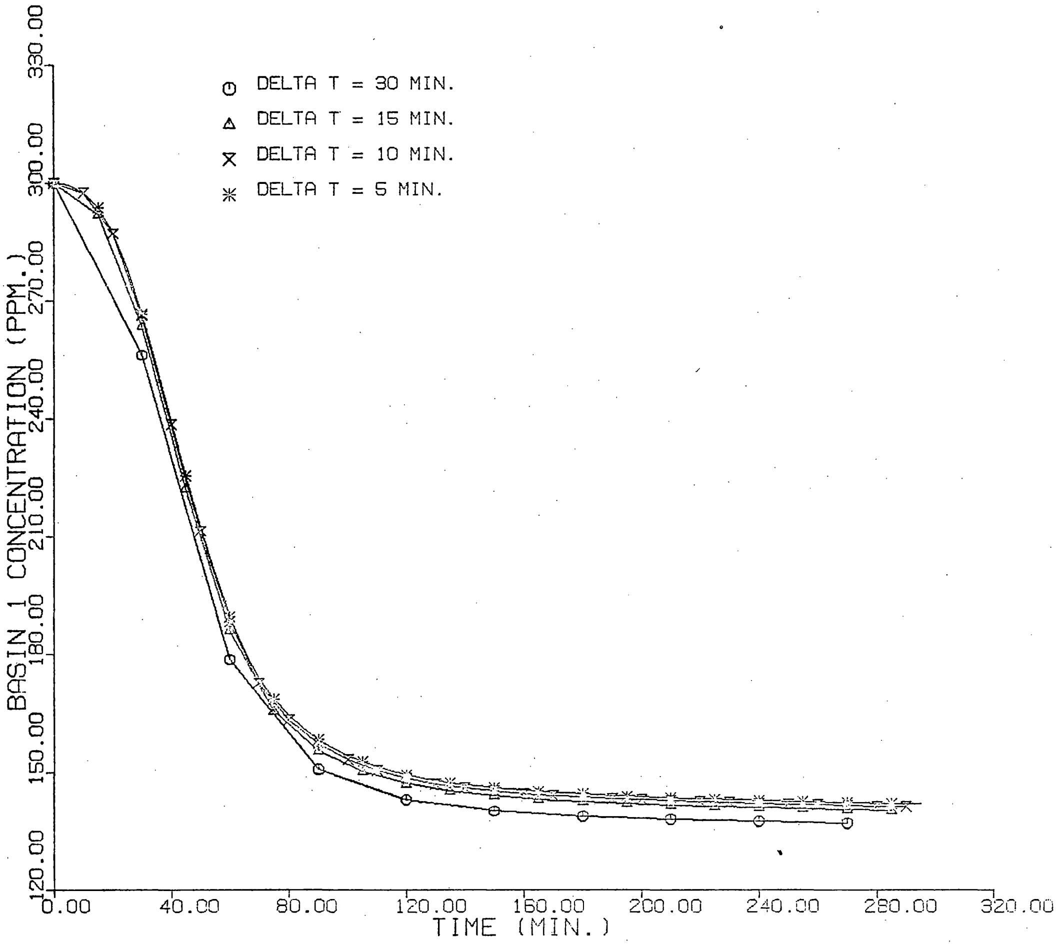


Figure 11. Sensitivity analysis of the Kuo method with respect to concentration in basin 1 in figure 3a.

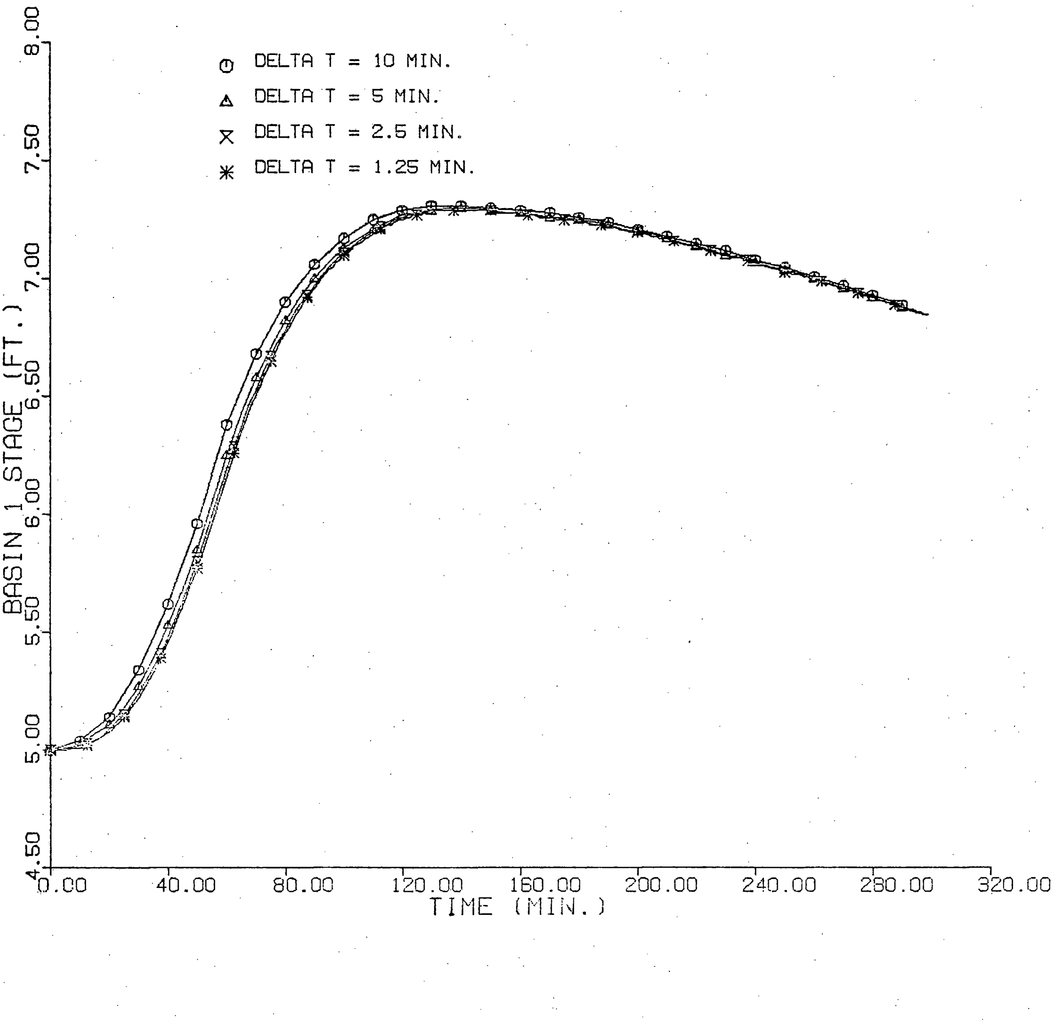


Figure 12. Sensitivity analysis of the Malcolm and New method with respect to stage in basin 1 in figure 3a.

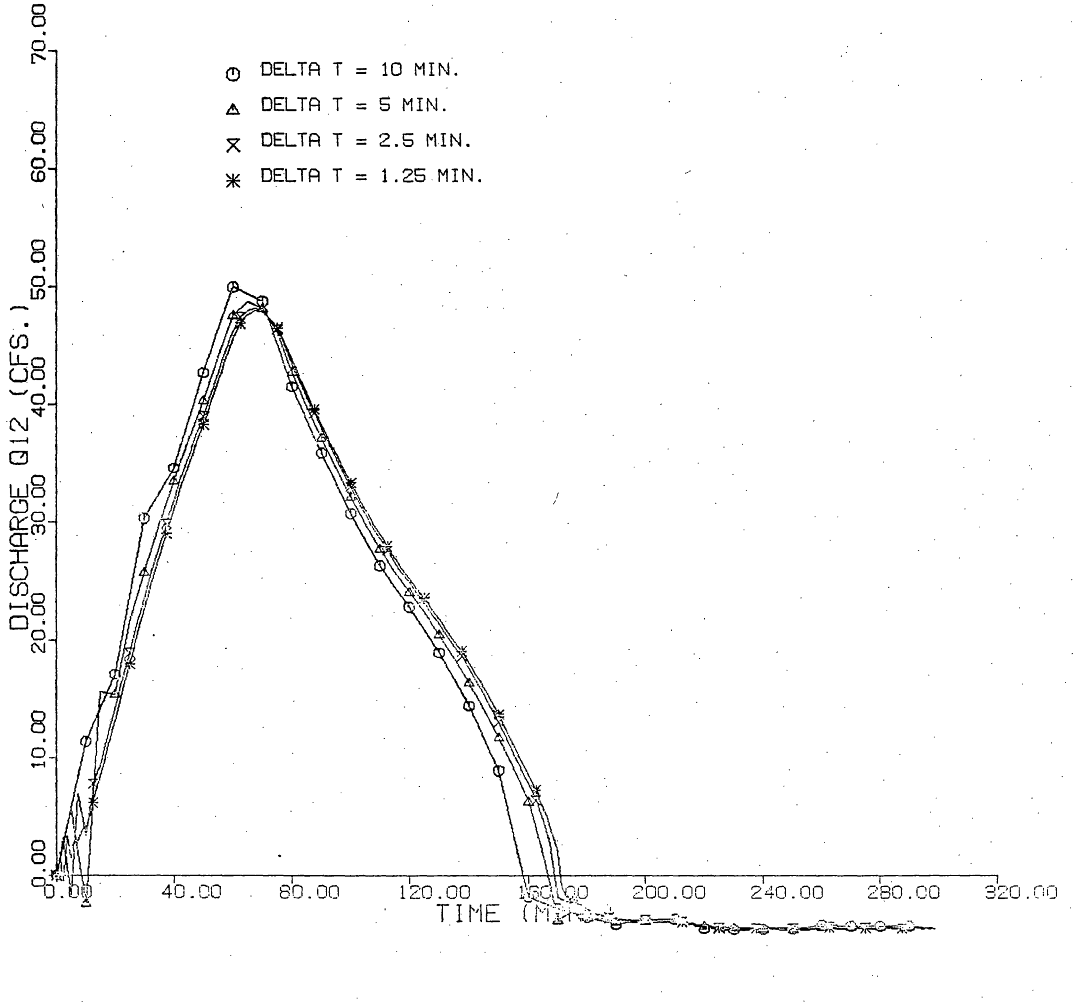


Figure 13. Sensitivity analysis of the Malcolm and New method with respect to discharge from basin 1 to basin 2 in figure 3a.

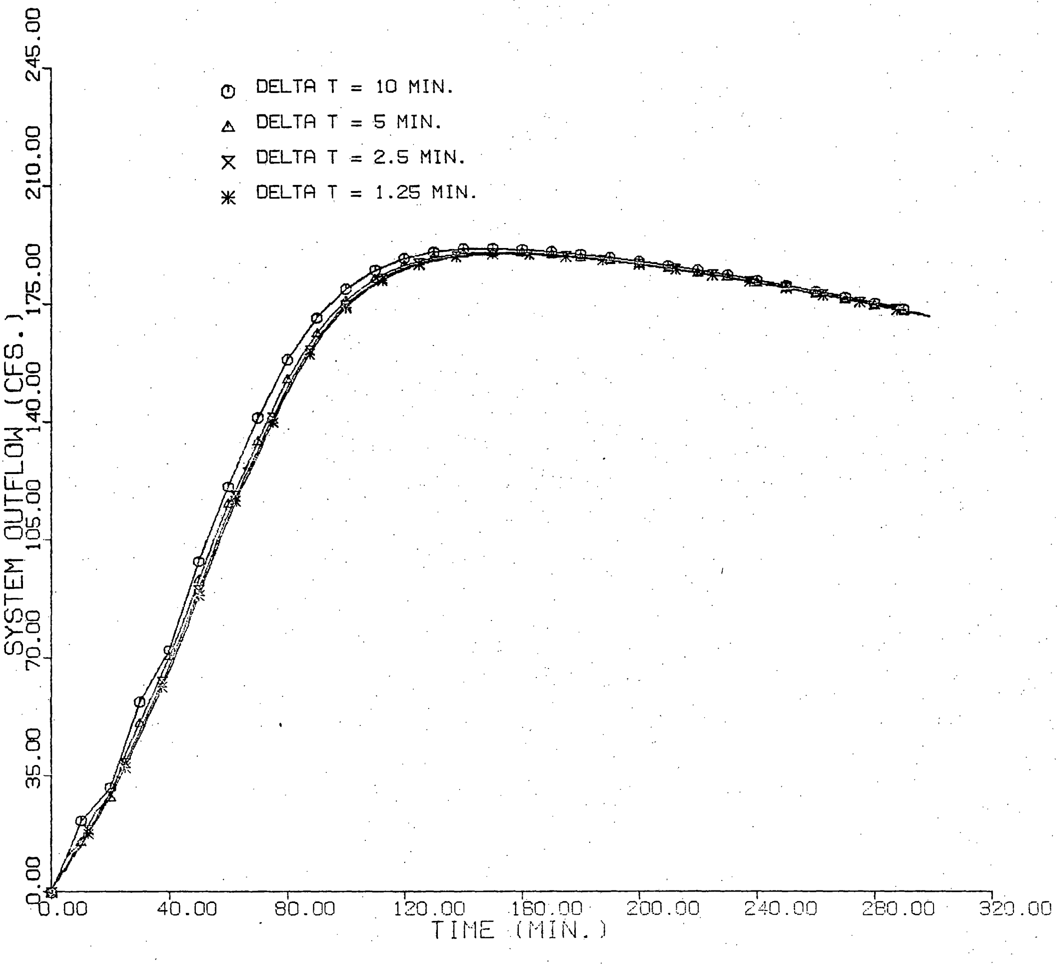


Figure 14. Sensitivity analysis of the Malcolm and New method with respect to system outflow in figure 3a.

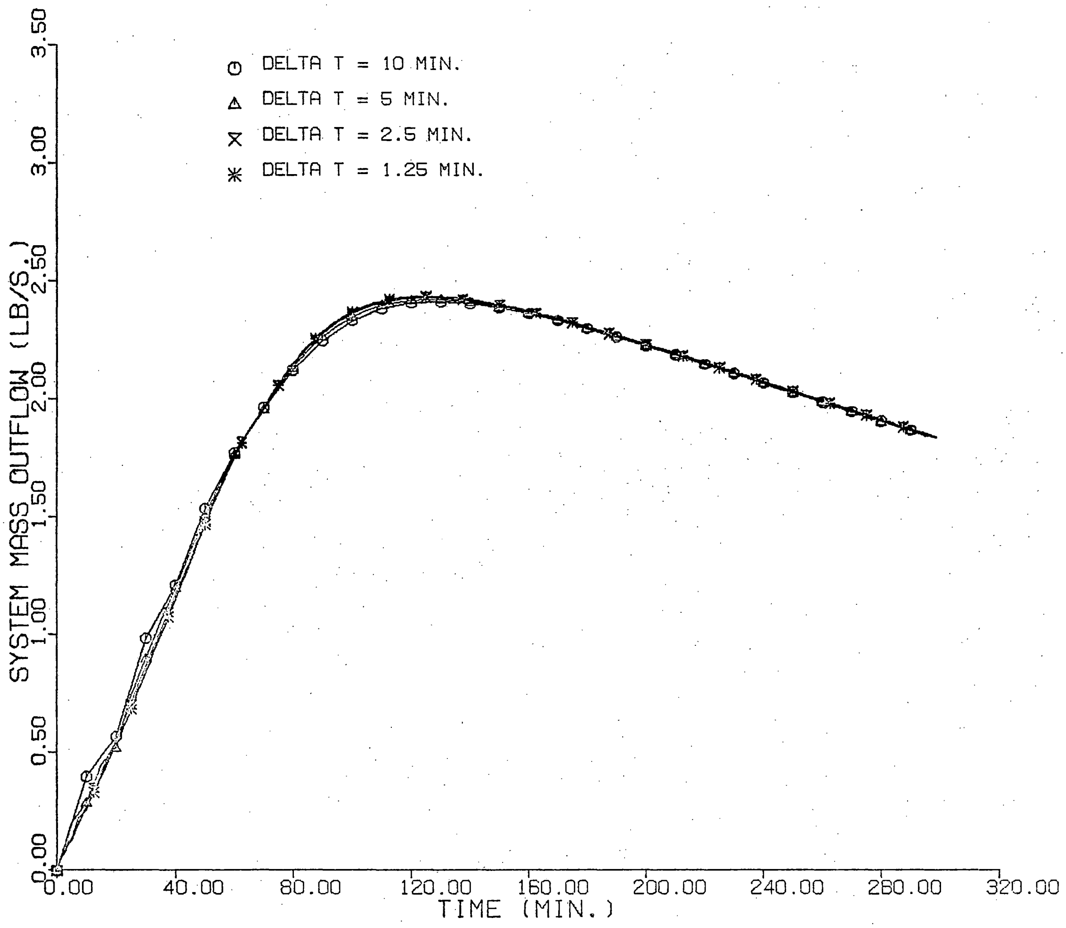


Figure 15. Sensitivity analysis of the Malcolm and New method with respect to system mass outflow in figure 3a.

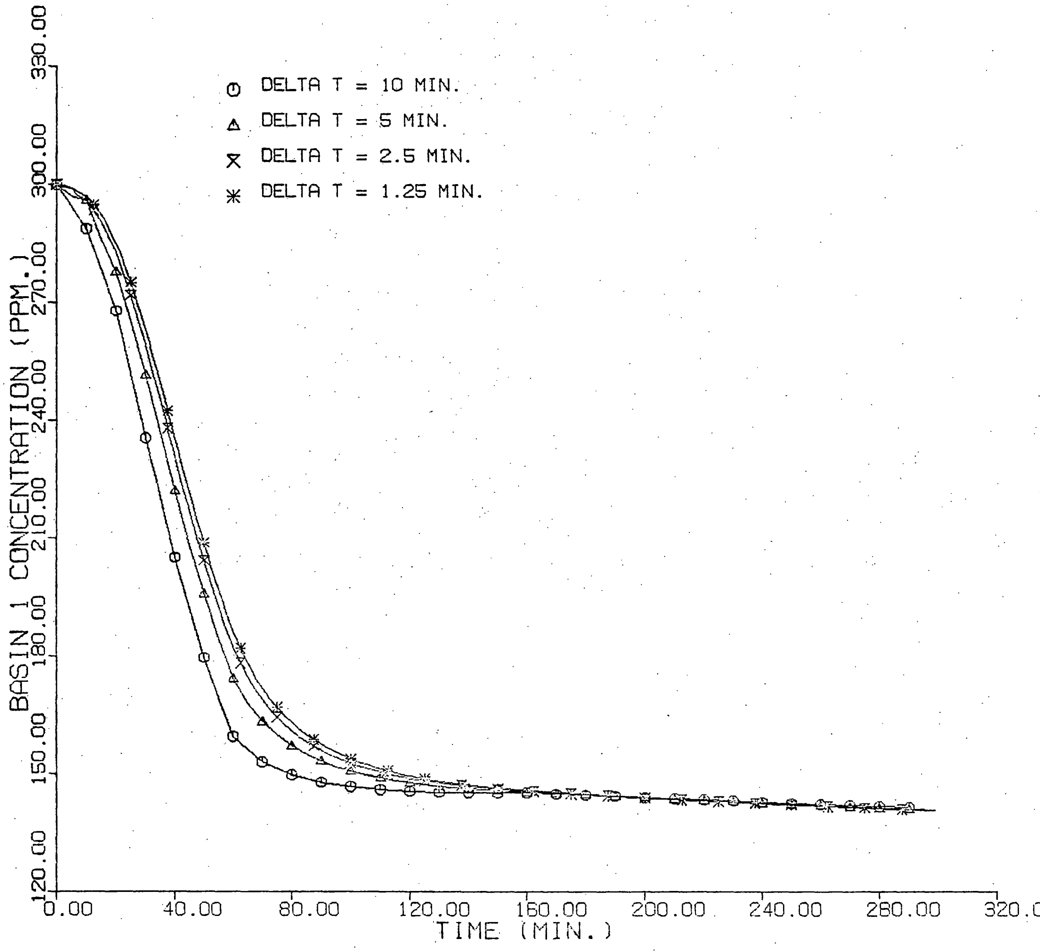


Figure 16. Sensitivity analysis of the Malcolm and New method with respect to concentration in basin 1 in figure 3a.

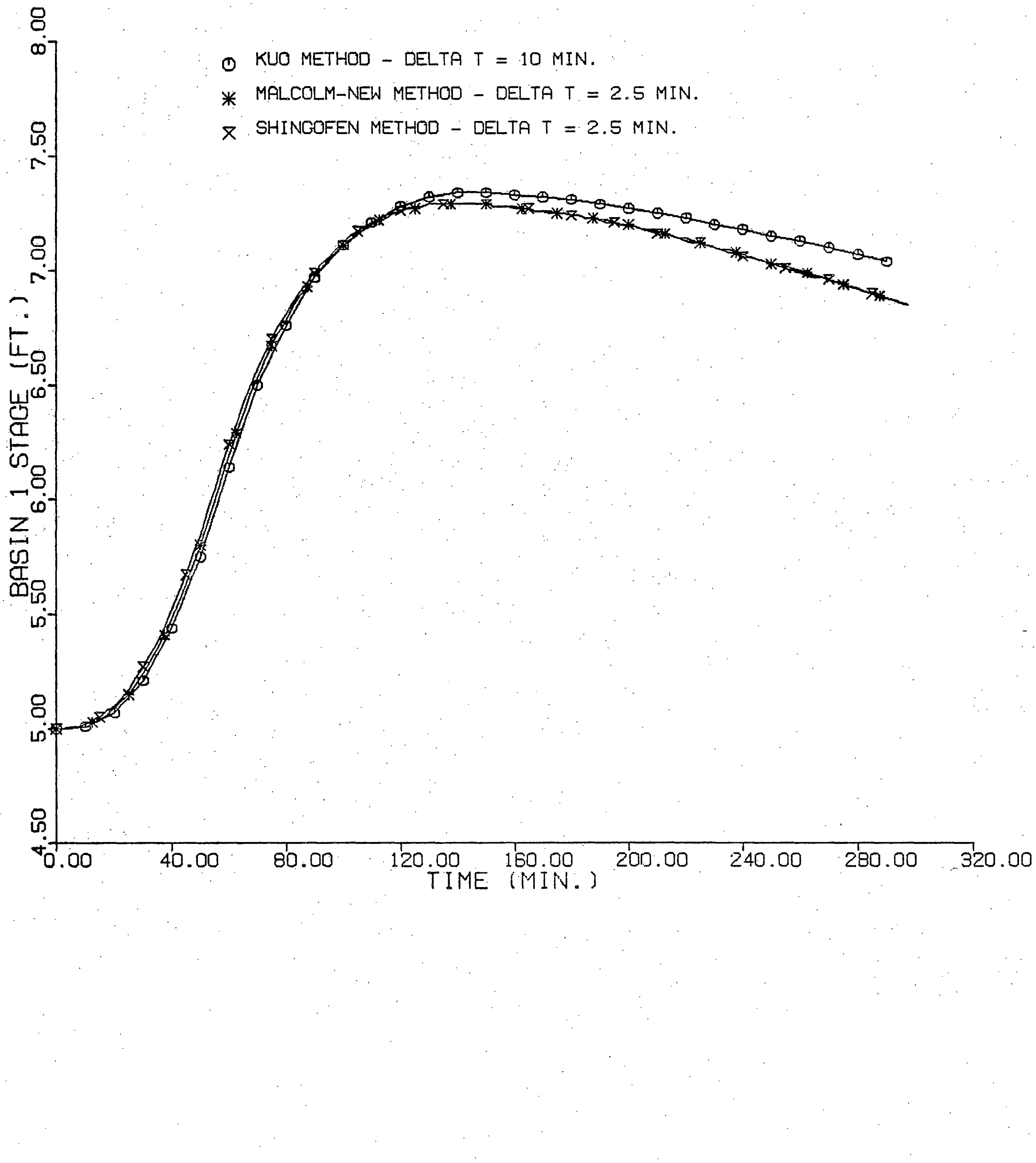


Figure 17. Comparison of the three methods with respect to stage in basin 1 in figure 3a as a function of time.

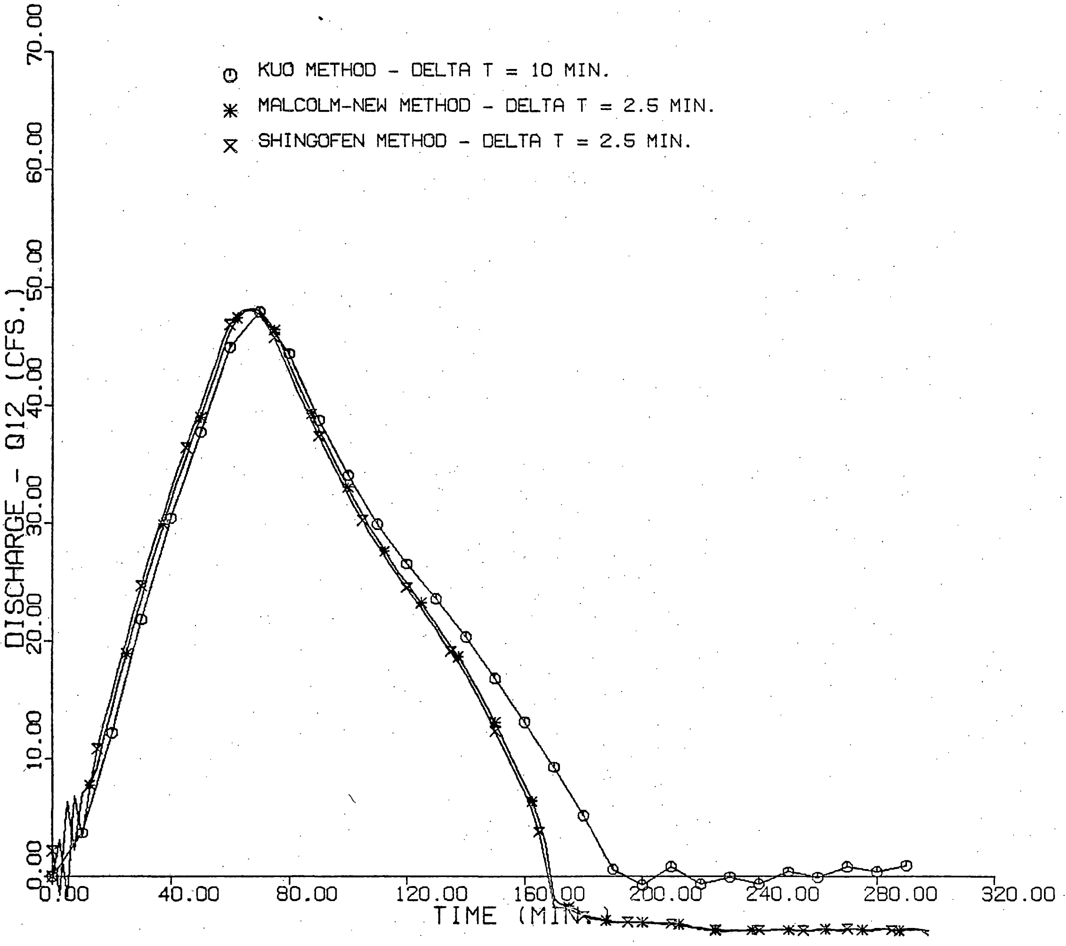


Figure 18. Comparison of the three methods with respect to discharge from basin 1 to basin 2 in figure 3a as a function of time.

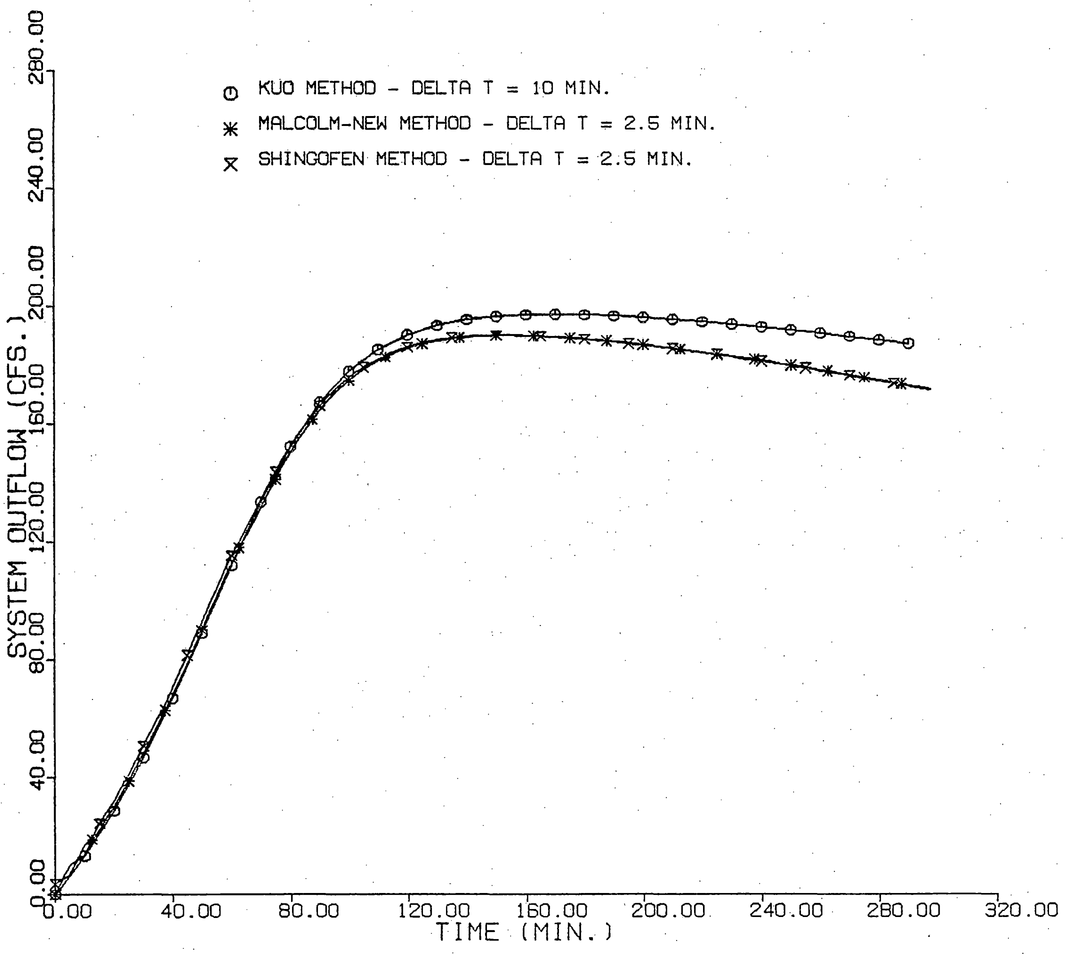


Figure 19. Comparison of the three methods with respect to system outflow in figure 3a as a function of time.

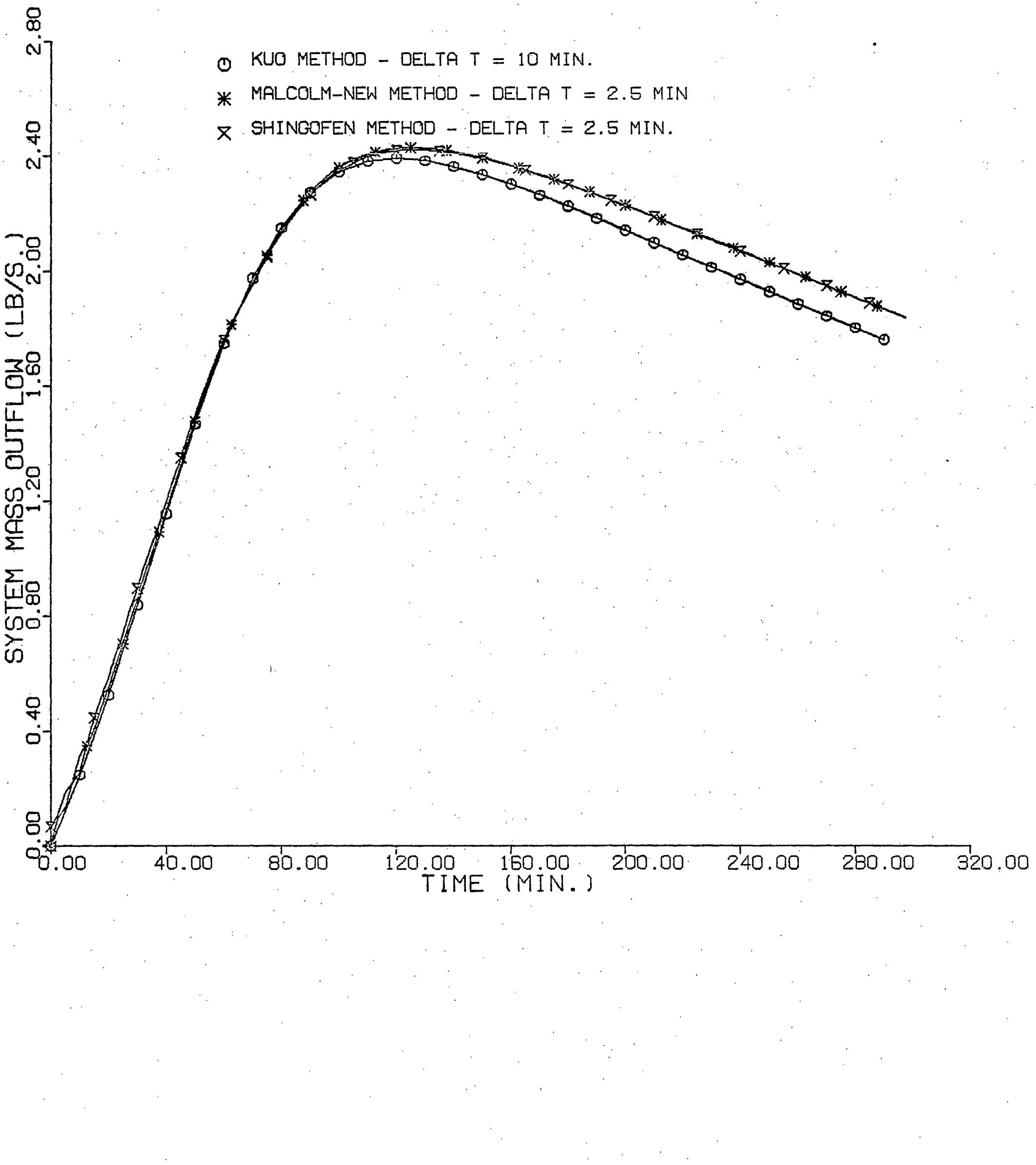


Figure 20. Comparison of the three methods with respect to system mass outflow in figure 3a as a function of time.

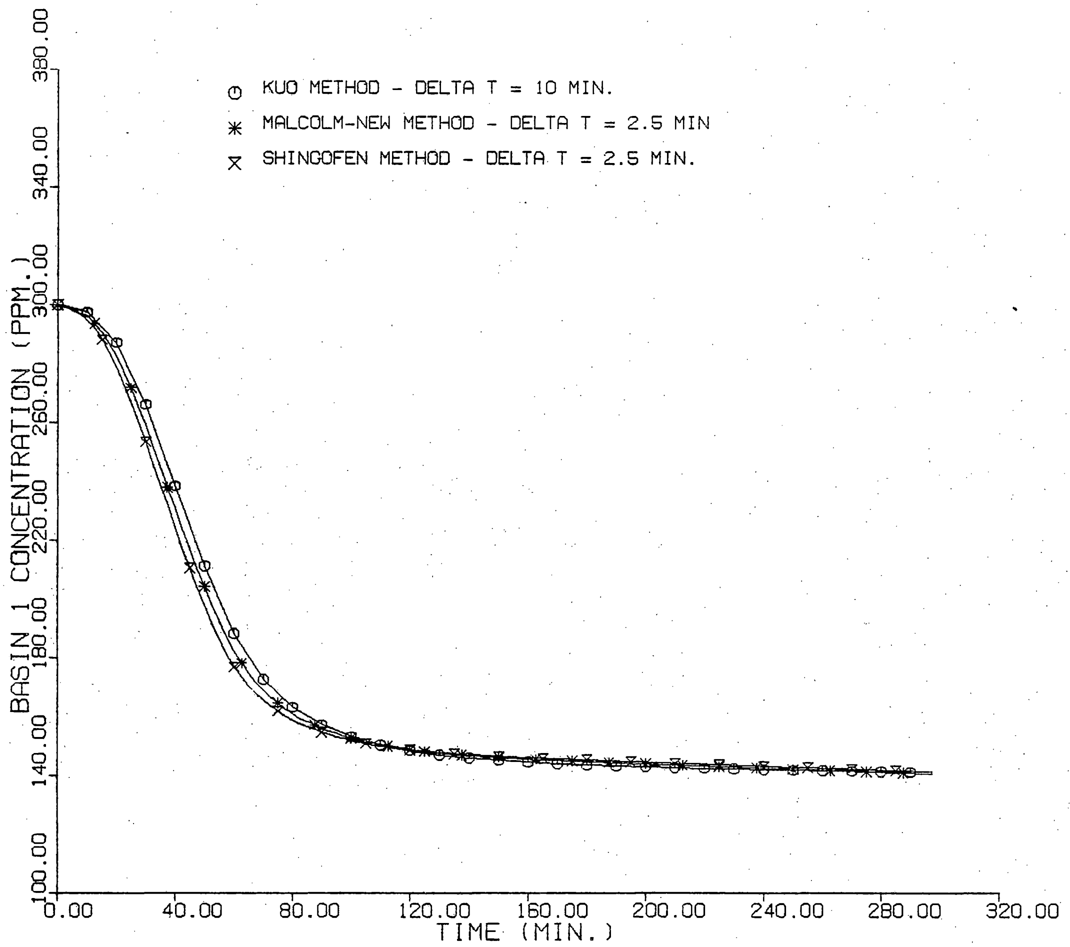


Figure 21. Comparison of the three methods with respect to concentration in basin 1 in figure 3a as a function of time.

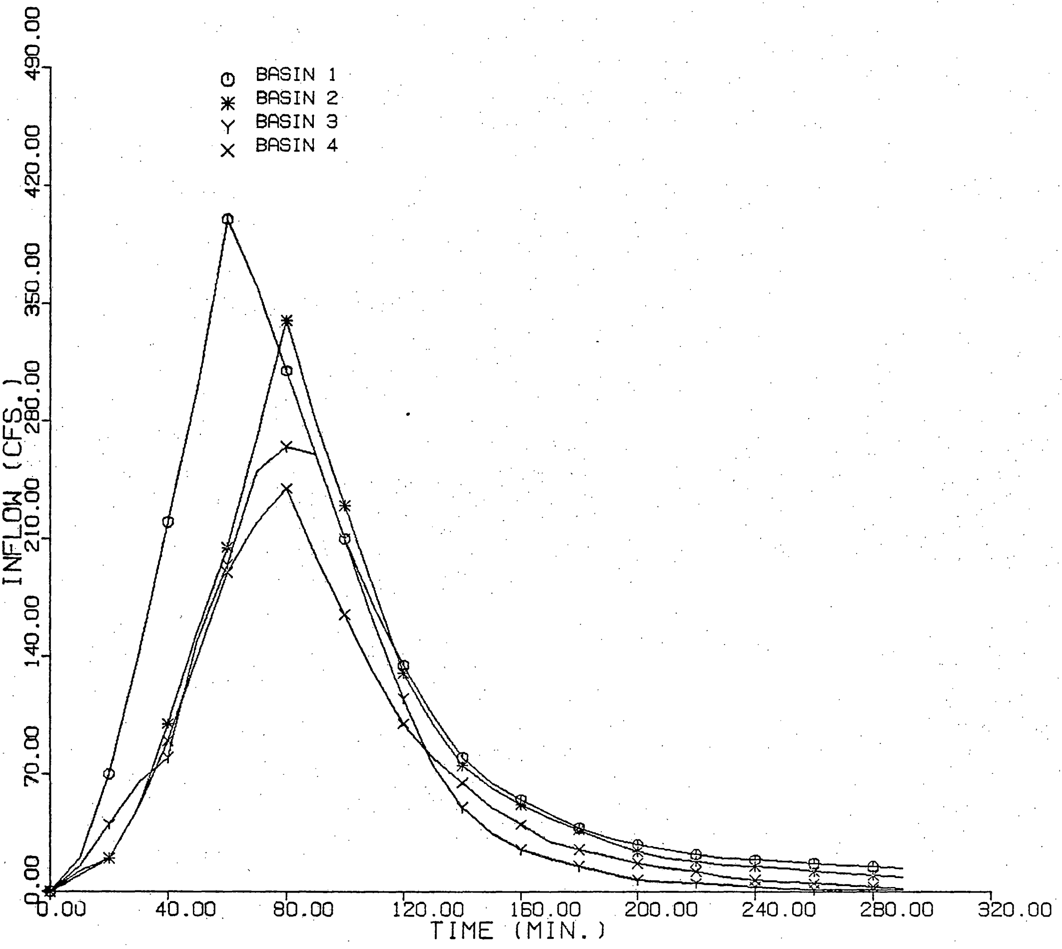


Figure 22. Inflow hydrographs used for a four basin system in figure 3a with pipe flow.

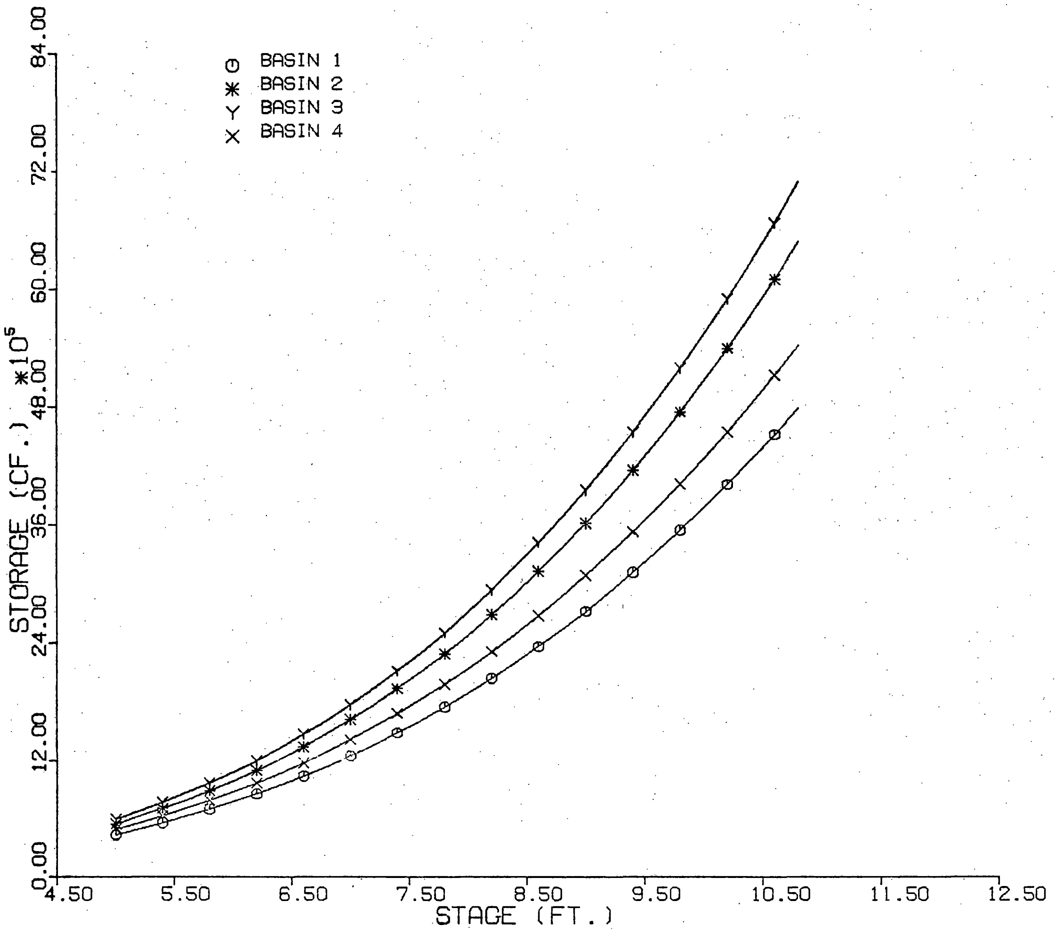


Figure 23. Stage-storage curves used for a four basin system in figure 3a with pipe flow.

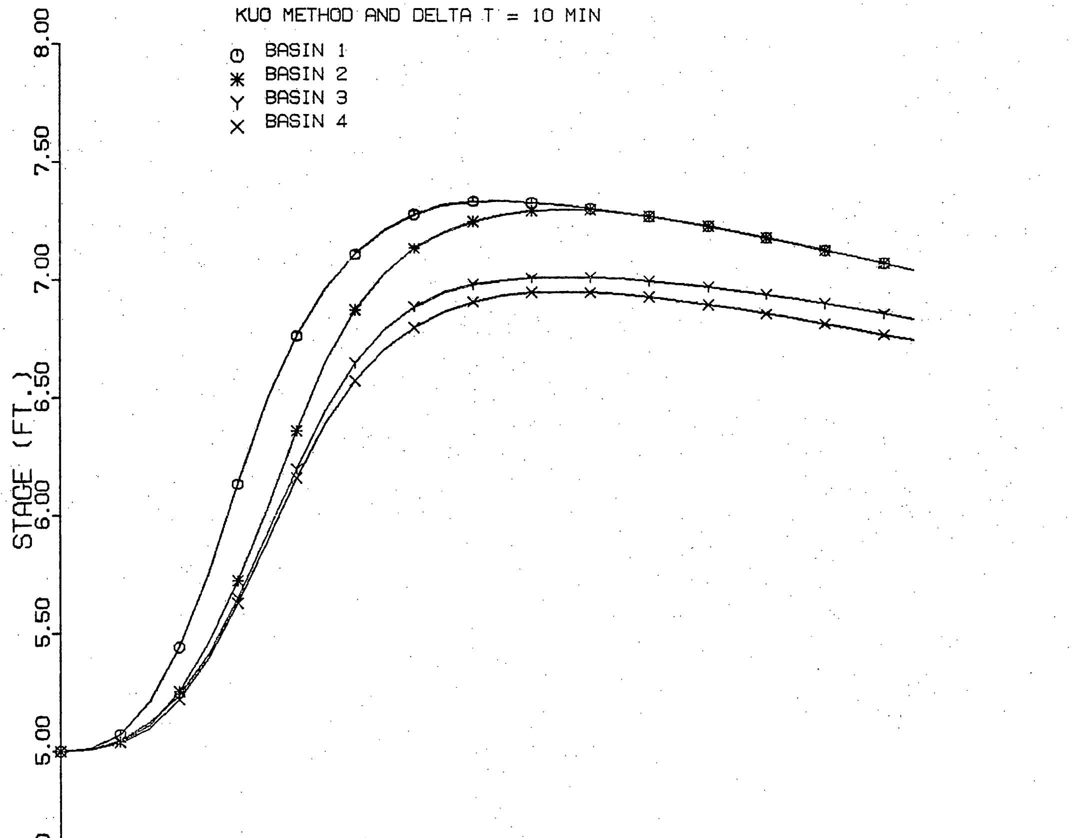


Figure 24. Stages as functions of time for a four basin system in figure 3a with pipe flow.

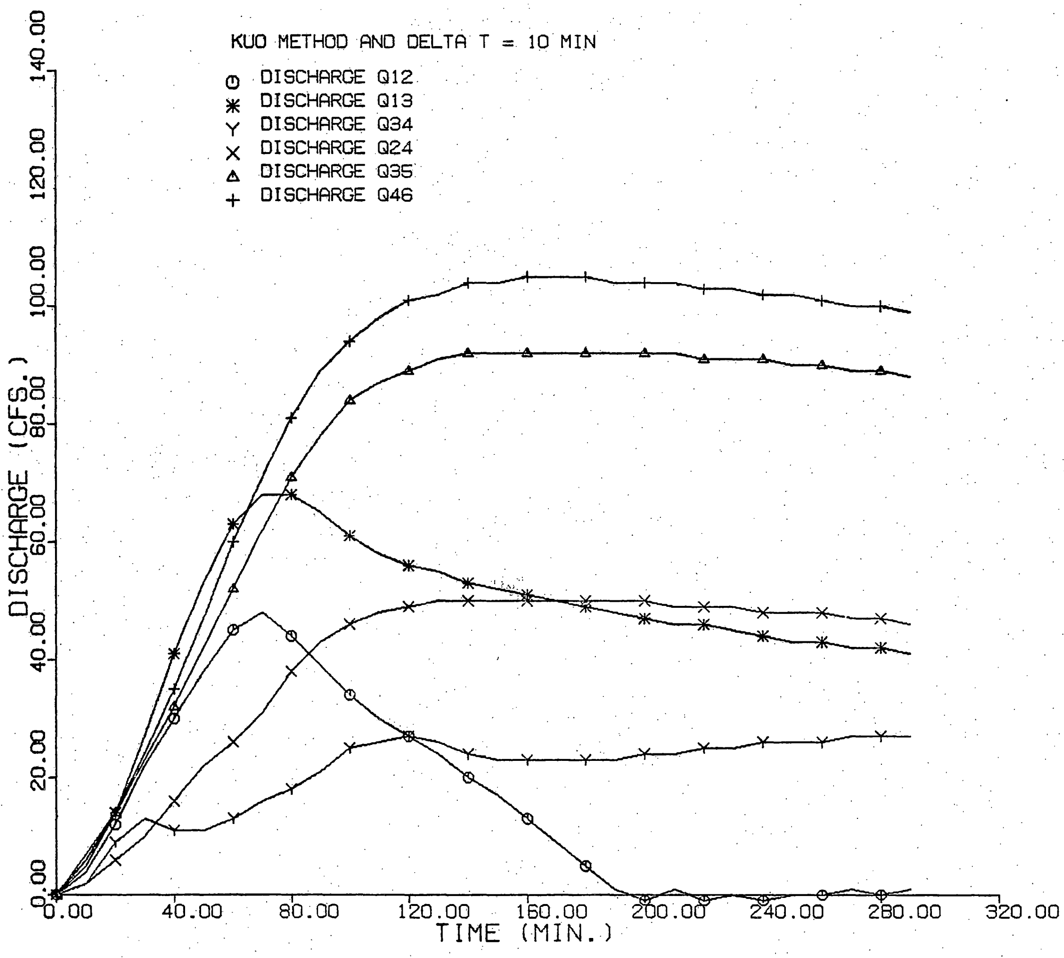


Figure 25. Discharges as functions of time for a four basin system in figure 3a with pipe flow.

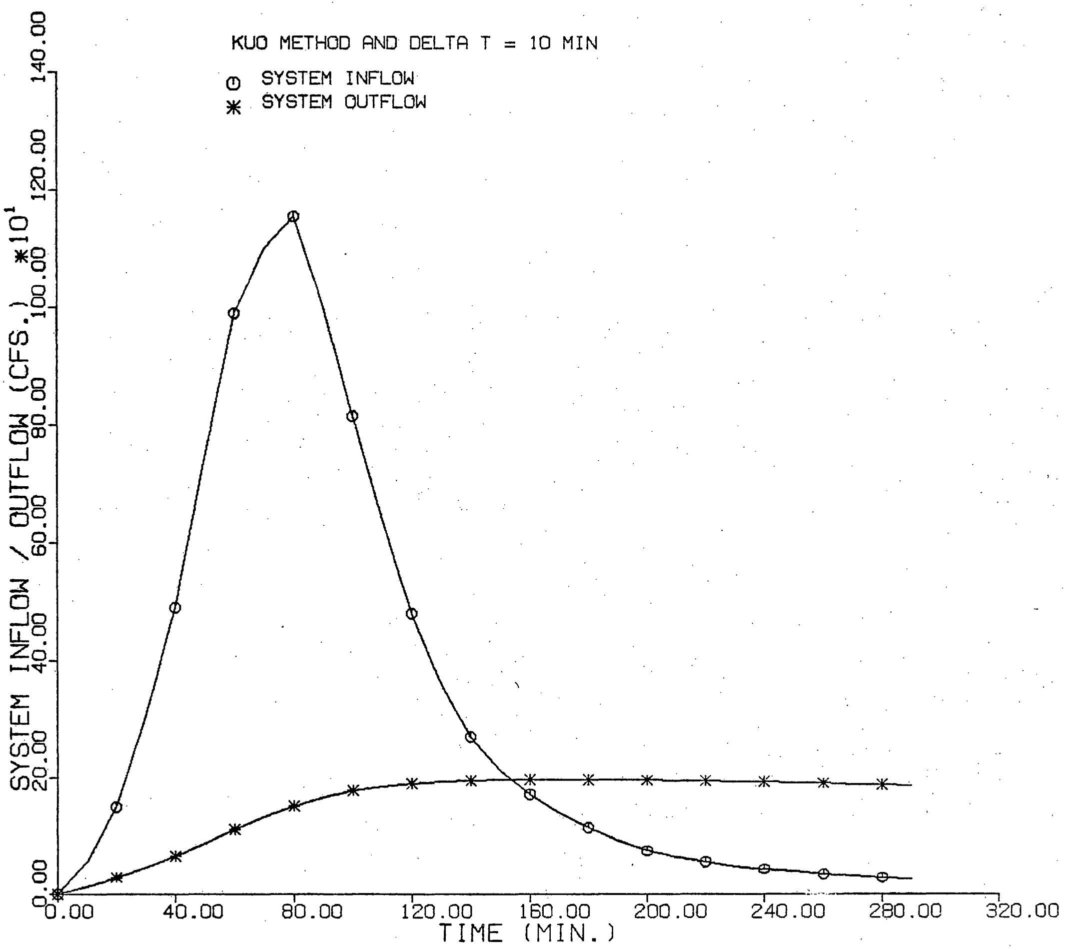


Figure 26. System inflow and system outflow as functions of time for a four basin system in figure 3a with pipe flow.

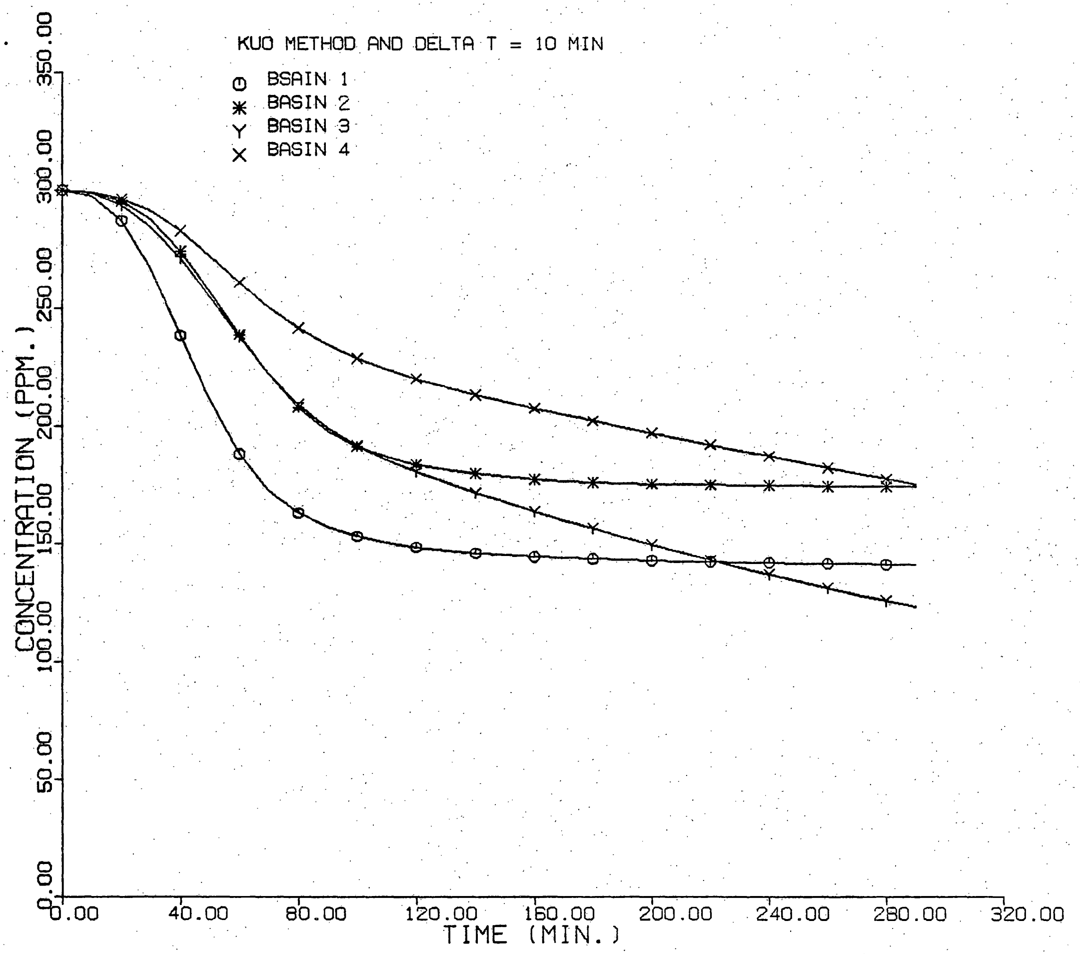


Figure 27. Concentrations as functions of time for a four basin system in figure 3a with pipe flow.

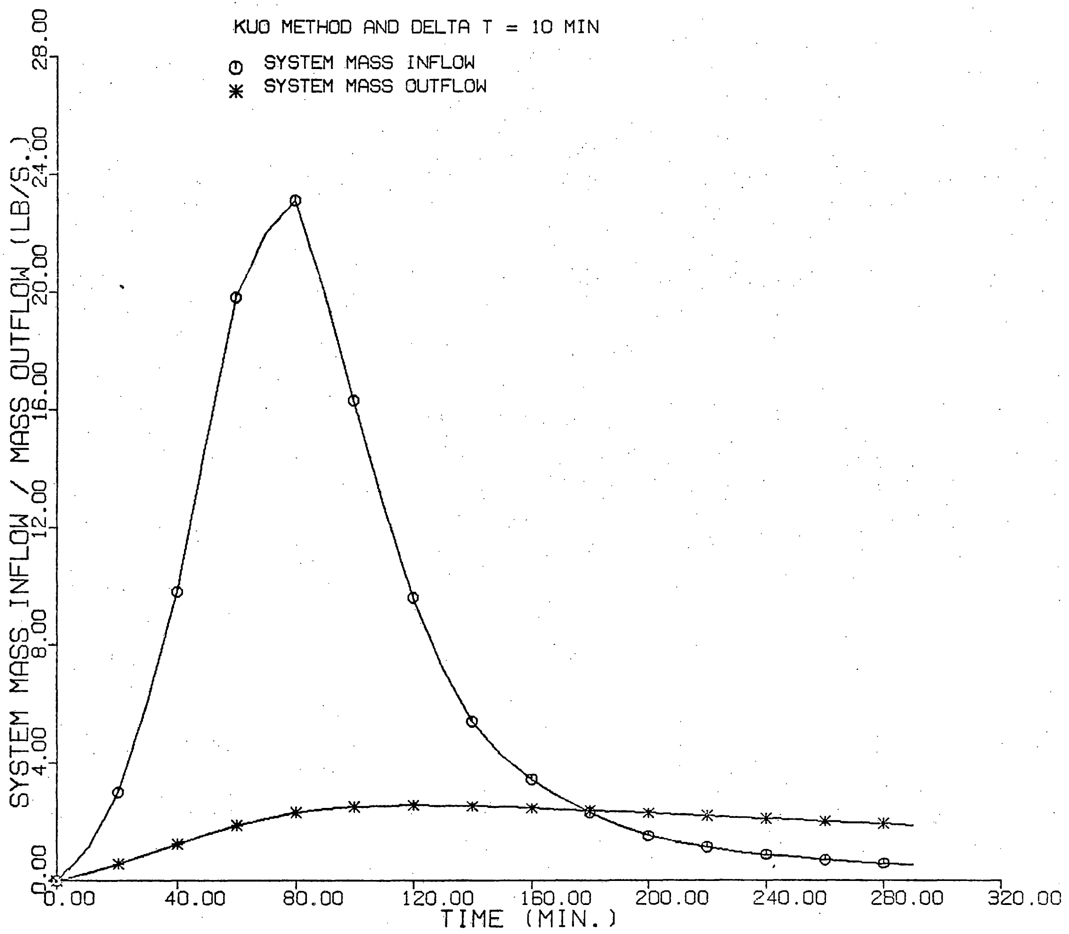


Figure 28. System mass inflow and system mass outflow as functions of time for a four basin system in figure 3a with pipe flow.

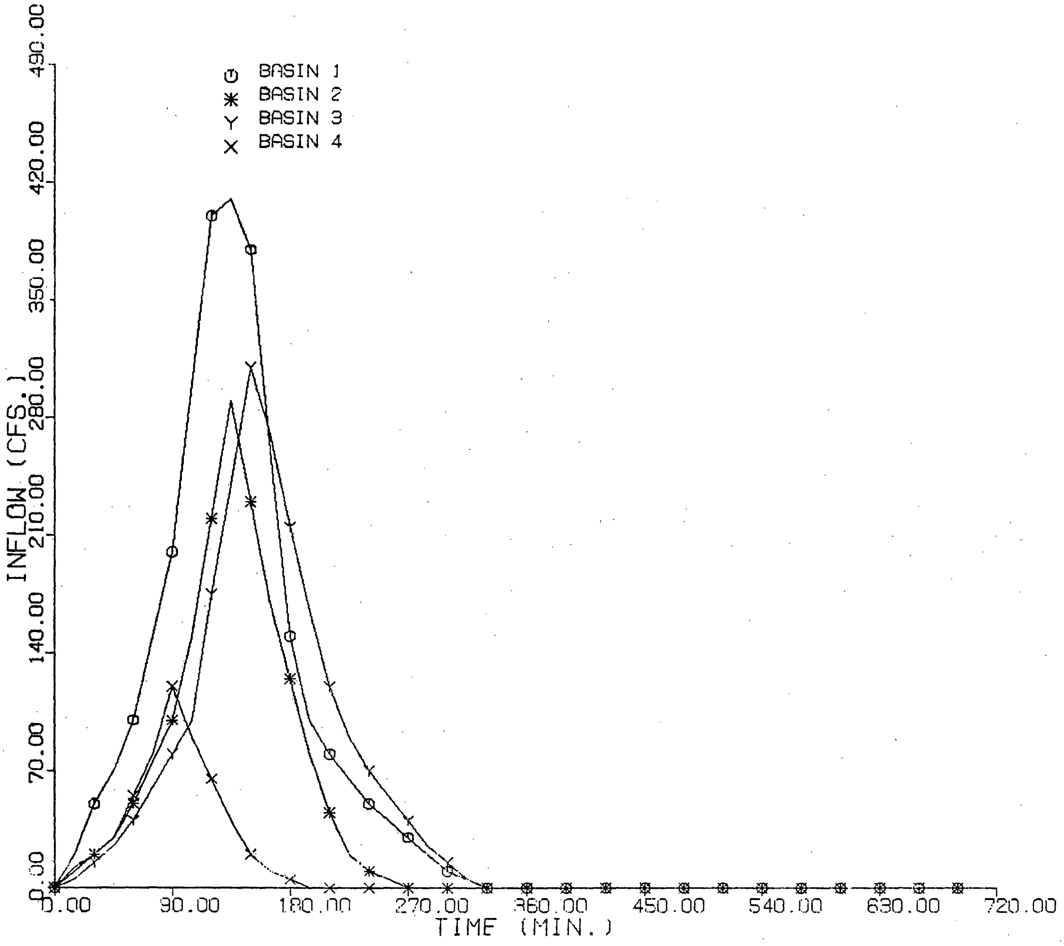


Figure 29. Inflow hydrographs used for a four basin system in figure 3a with open channel flow.

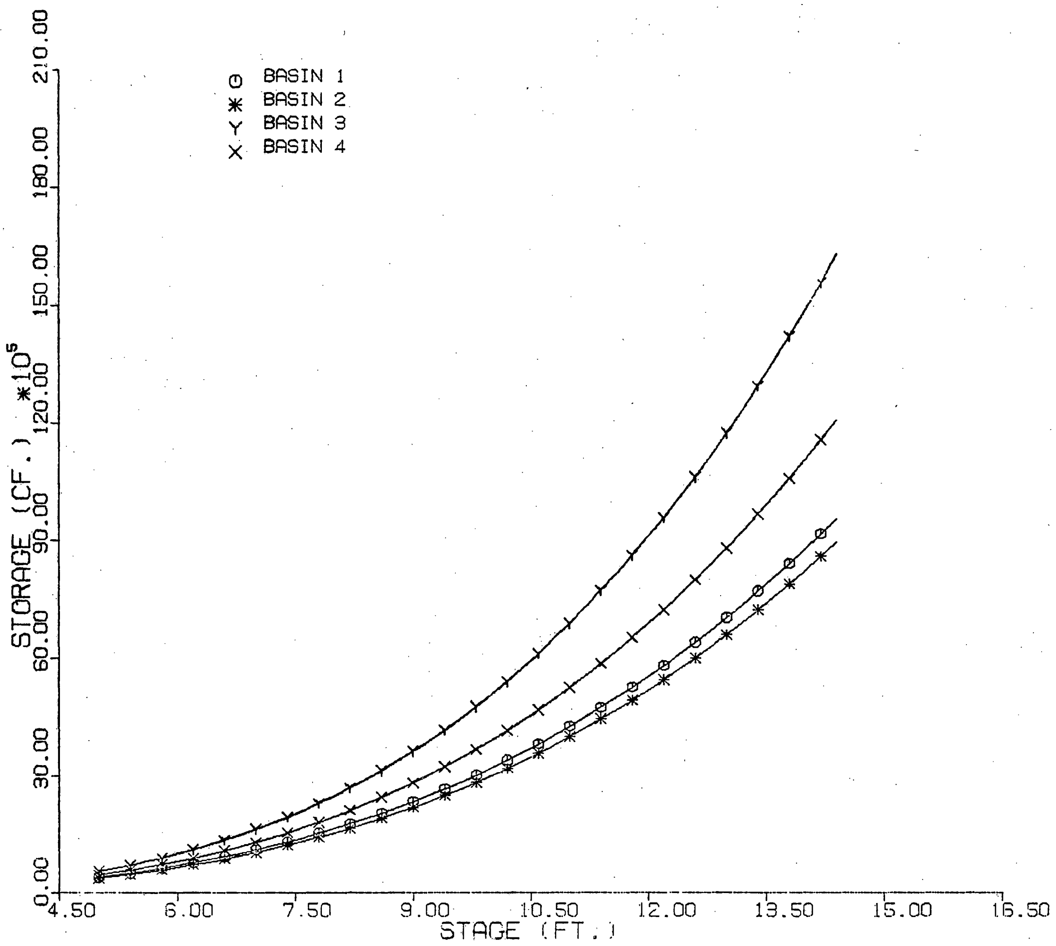


Figure 30. Stage-storage curves used for a four basin system in figure 3a with open channel flow.

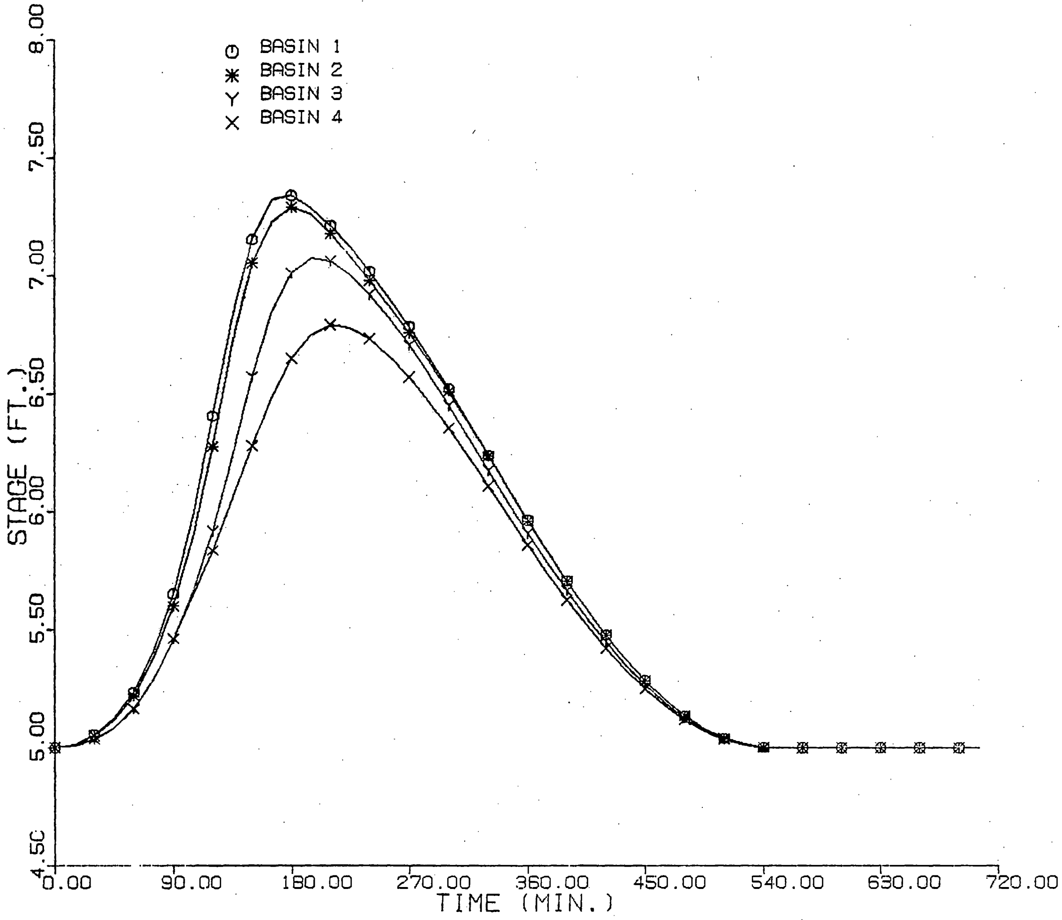


Figure 31. Stages as functions of time for a four basin system in figure 3a with open channel flow.

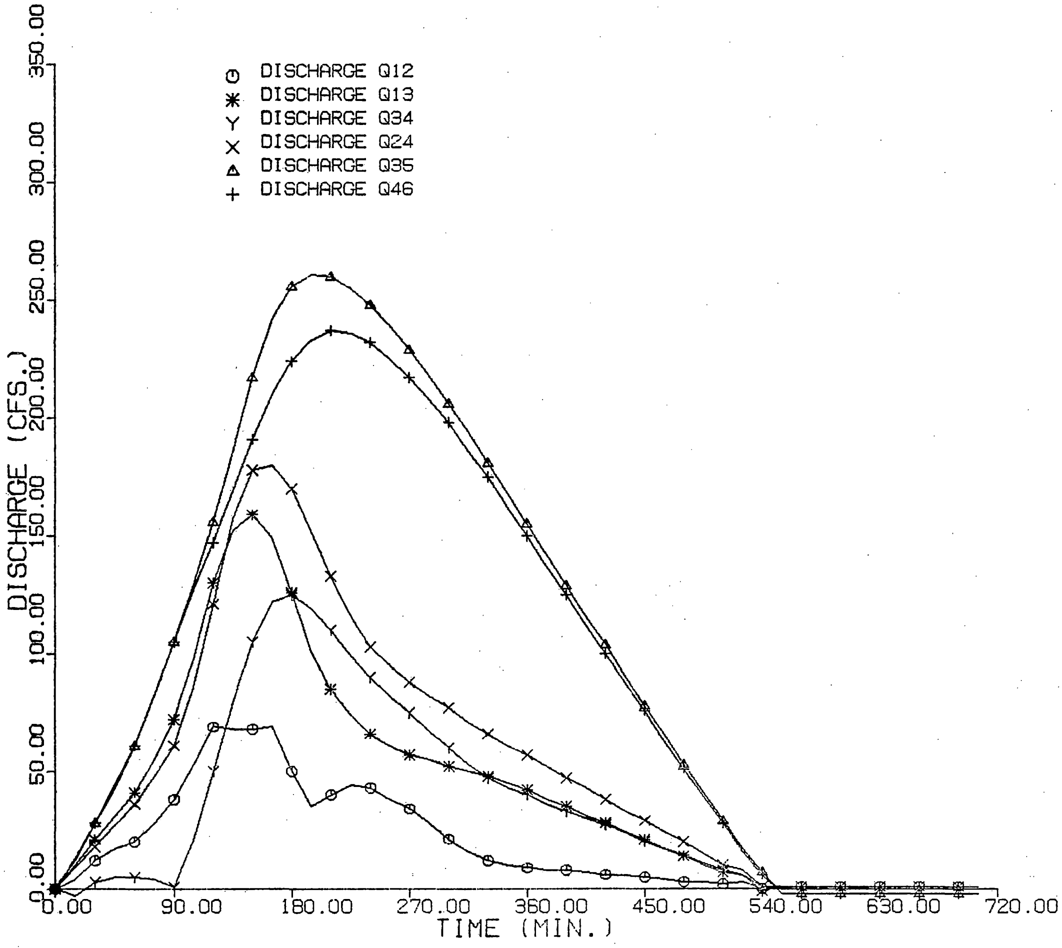


Figure 32. Discharges as functions of time for a four basin system in figure 3a with open channel flow.

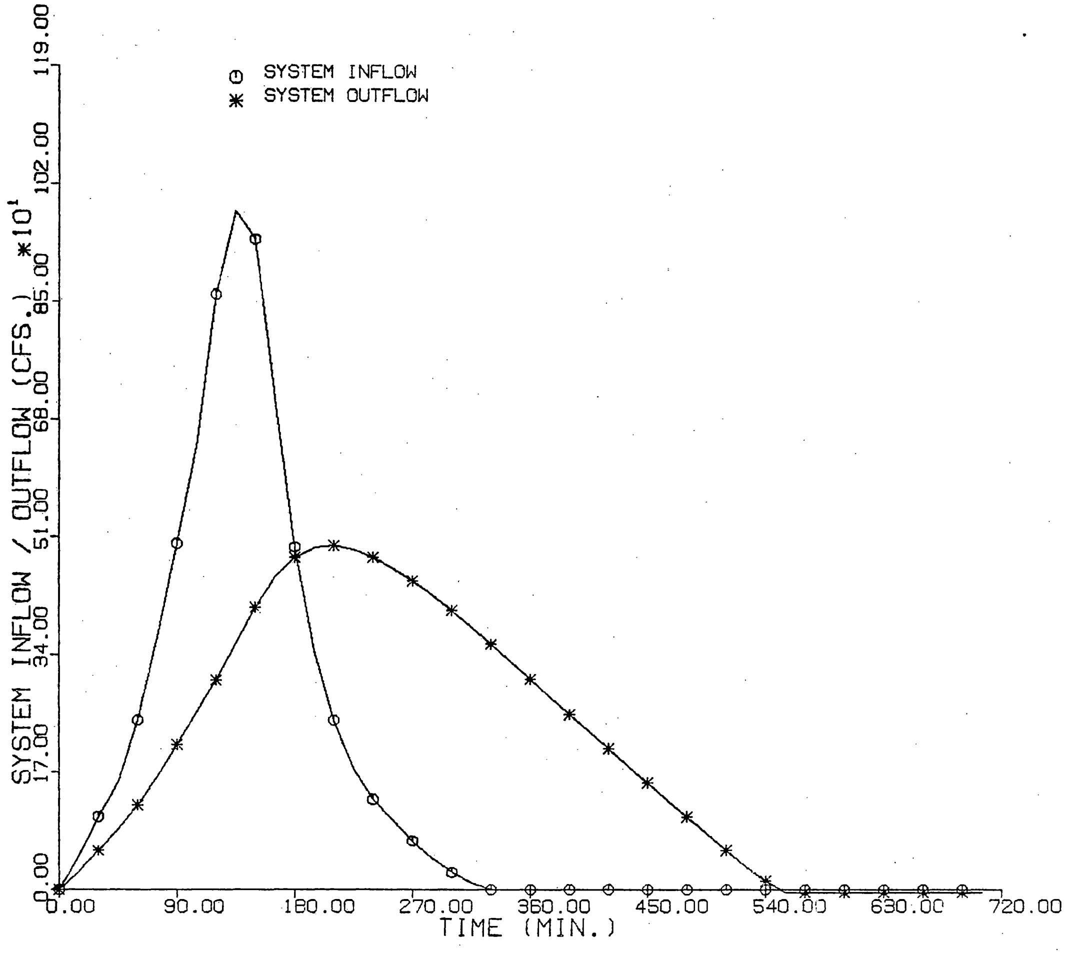


Figure 33. System inflow and system outflow as functions of time for a four basin system in figure 3a with open channel flow.

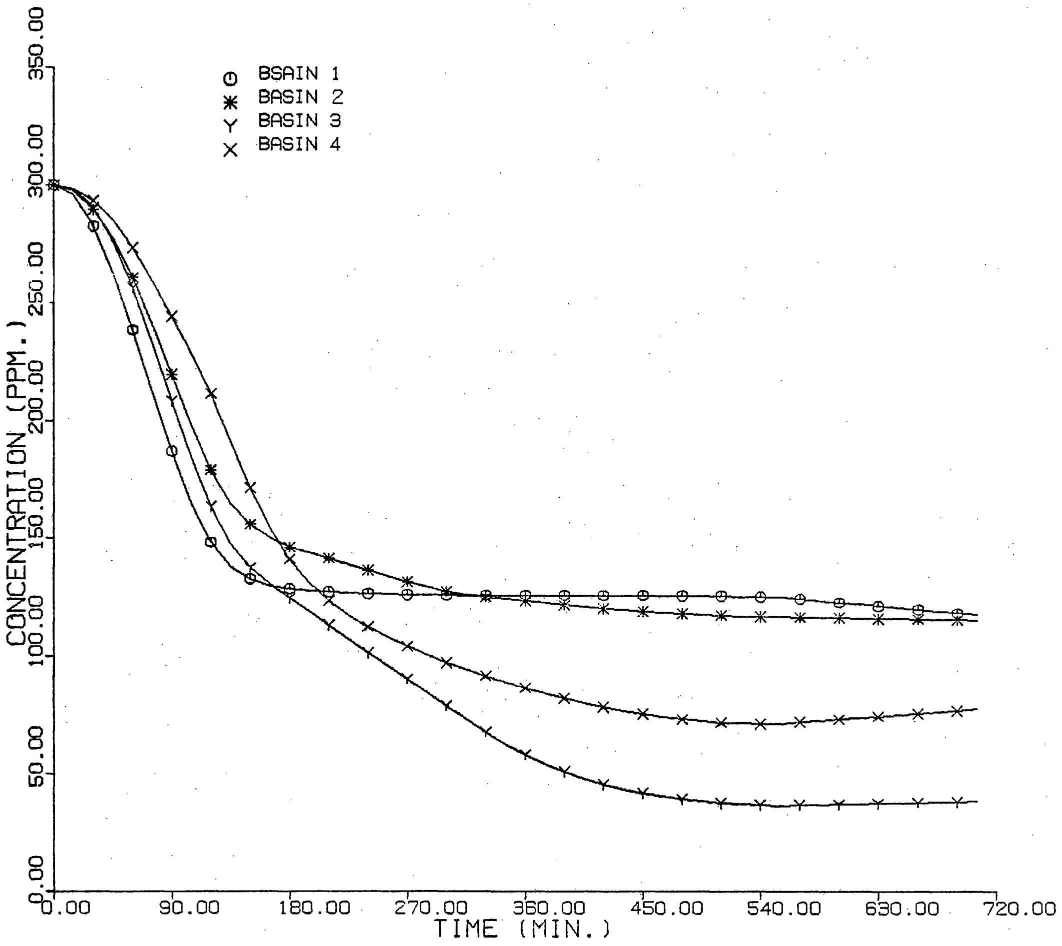


Figure 34. Concentrations as functions of time for a four basin system in figure 3a with open channel flow.

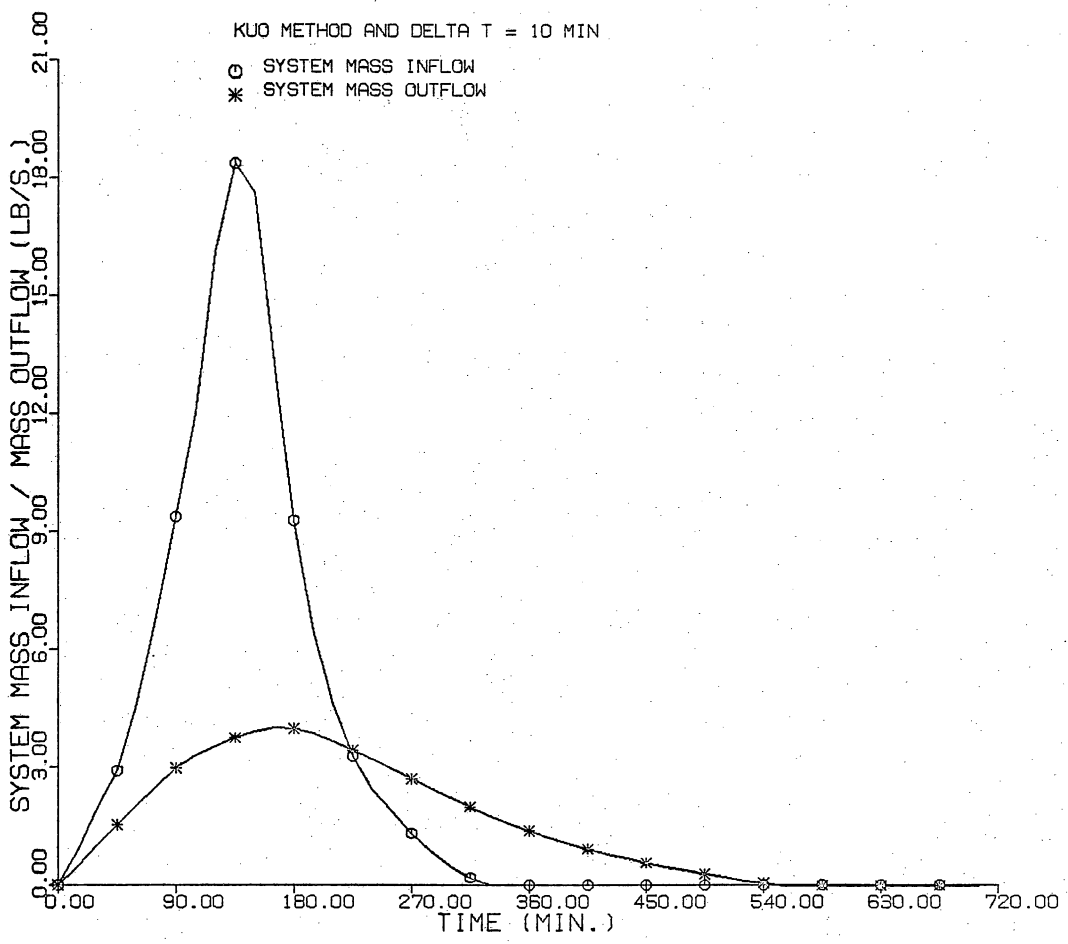


Figure 35. System mass inflow and system mass outflow as functions of time for a four basin system in figure 3a with open channel flow.

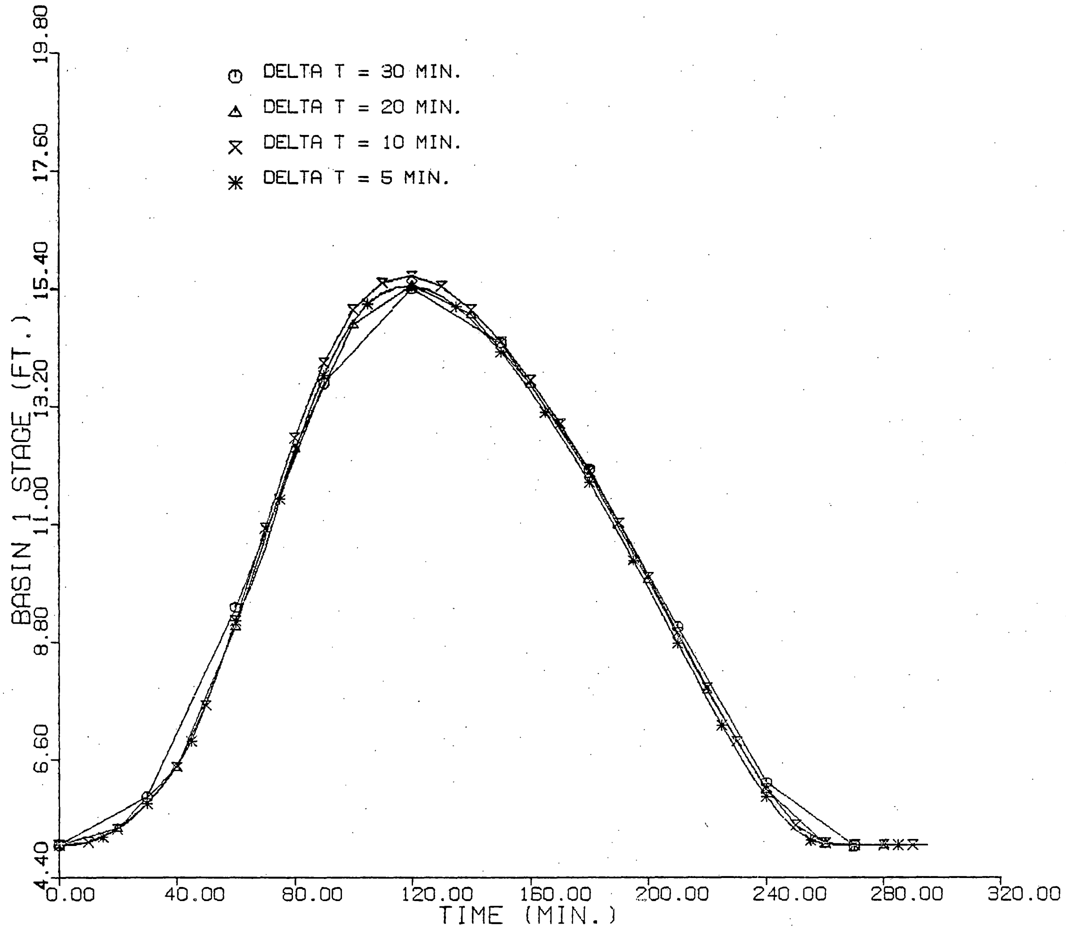


Figure 36. Sensitivity analysis of the Kuo method with respect to stage in basin 1 in figure 3f.

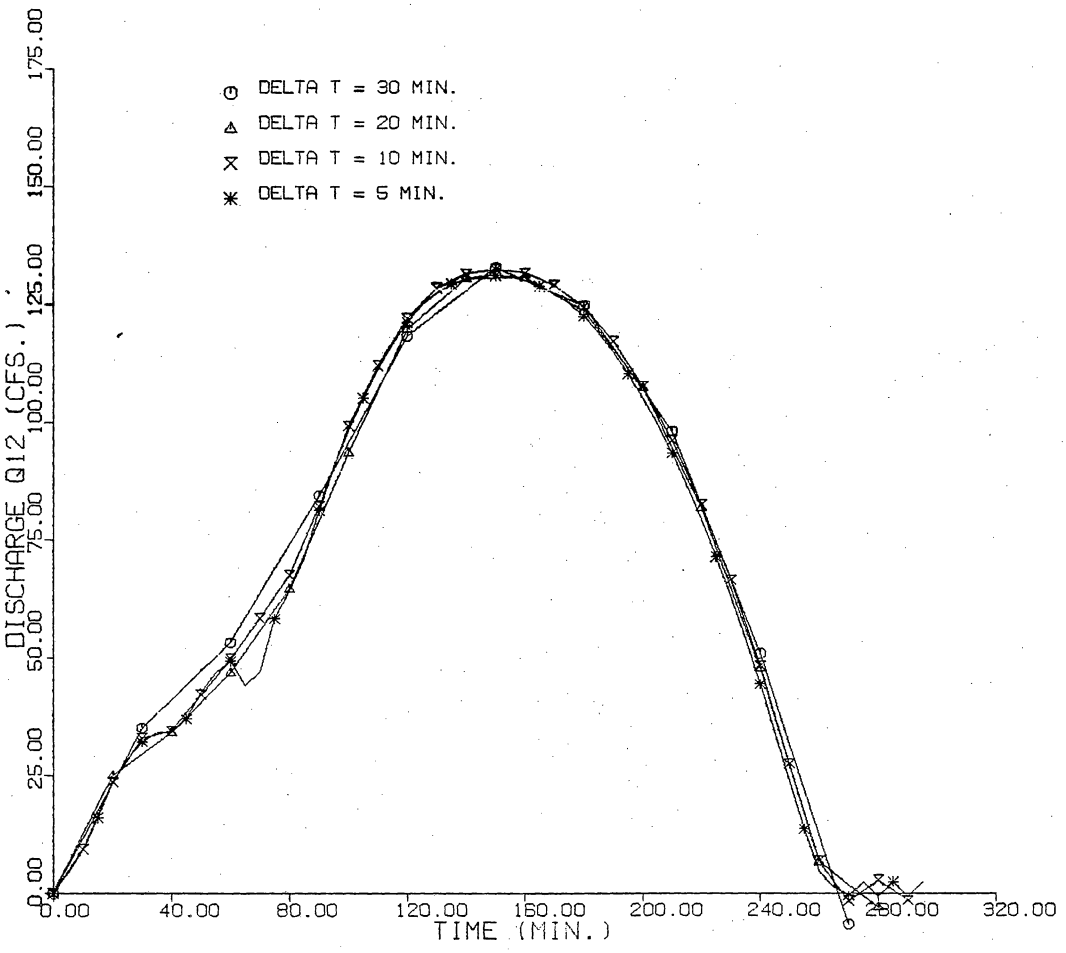


Figure 37. Sensitivity analysis of the Kuo method with respect to discharge from basin 1 to basin 2 in figure 3f.

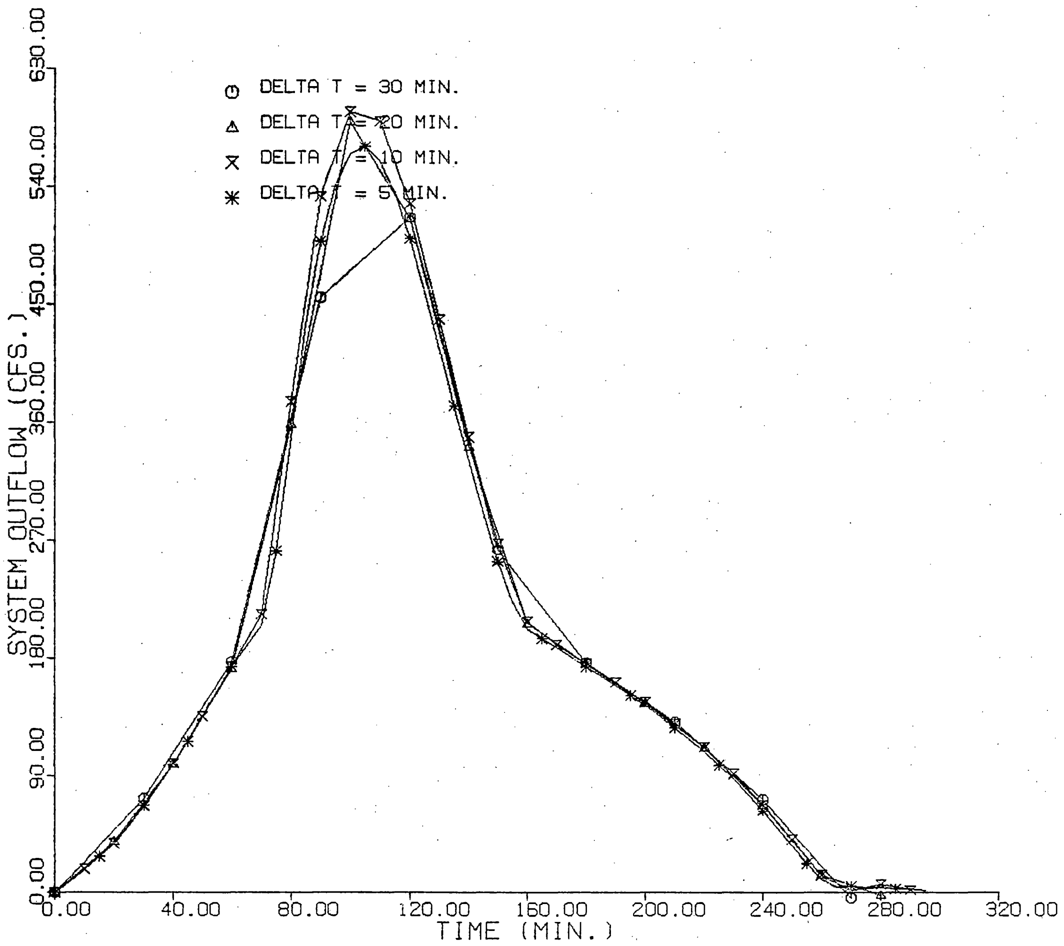


Figure 38. Sensitivity analysis of the Kuo method with respect to system outflow in figure 3f.

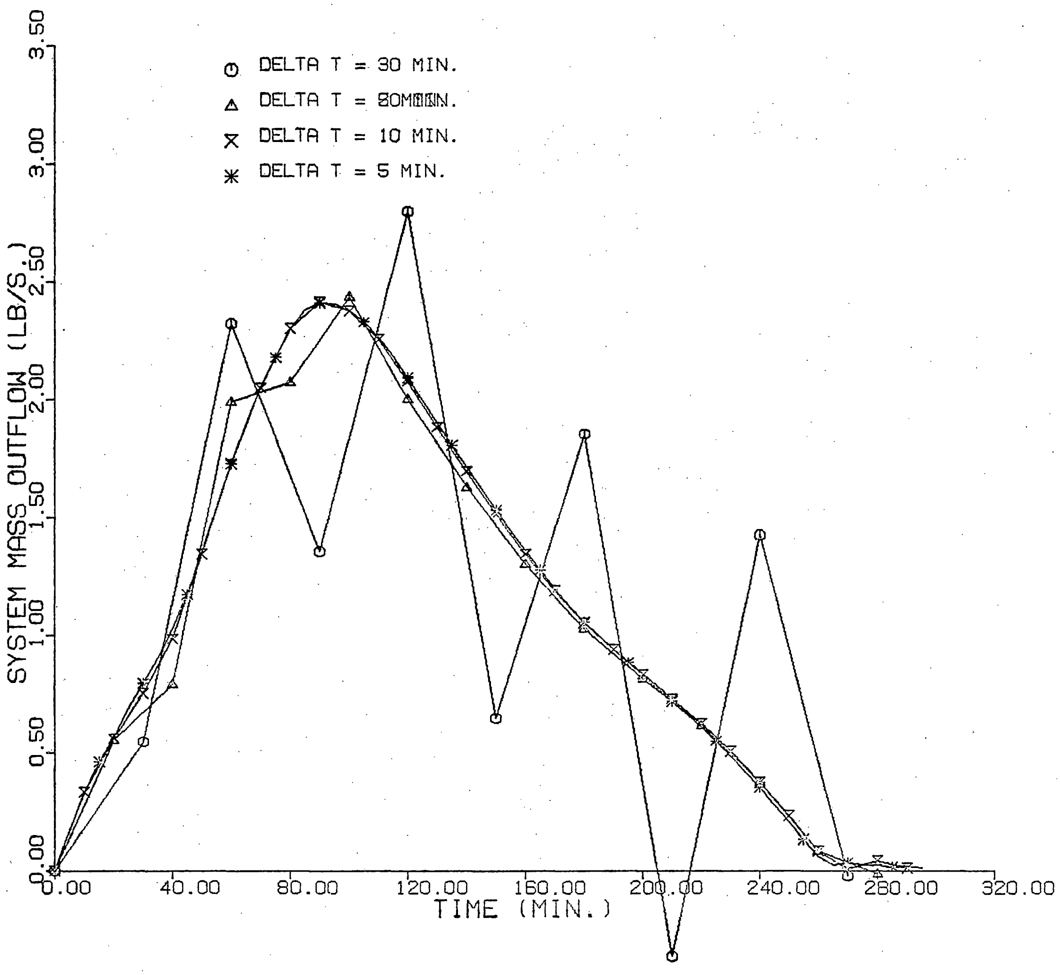


Figure 39. Sensitivity analysis of the Kuo method with respect to system mass outflow in figure 3f.

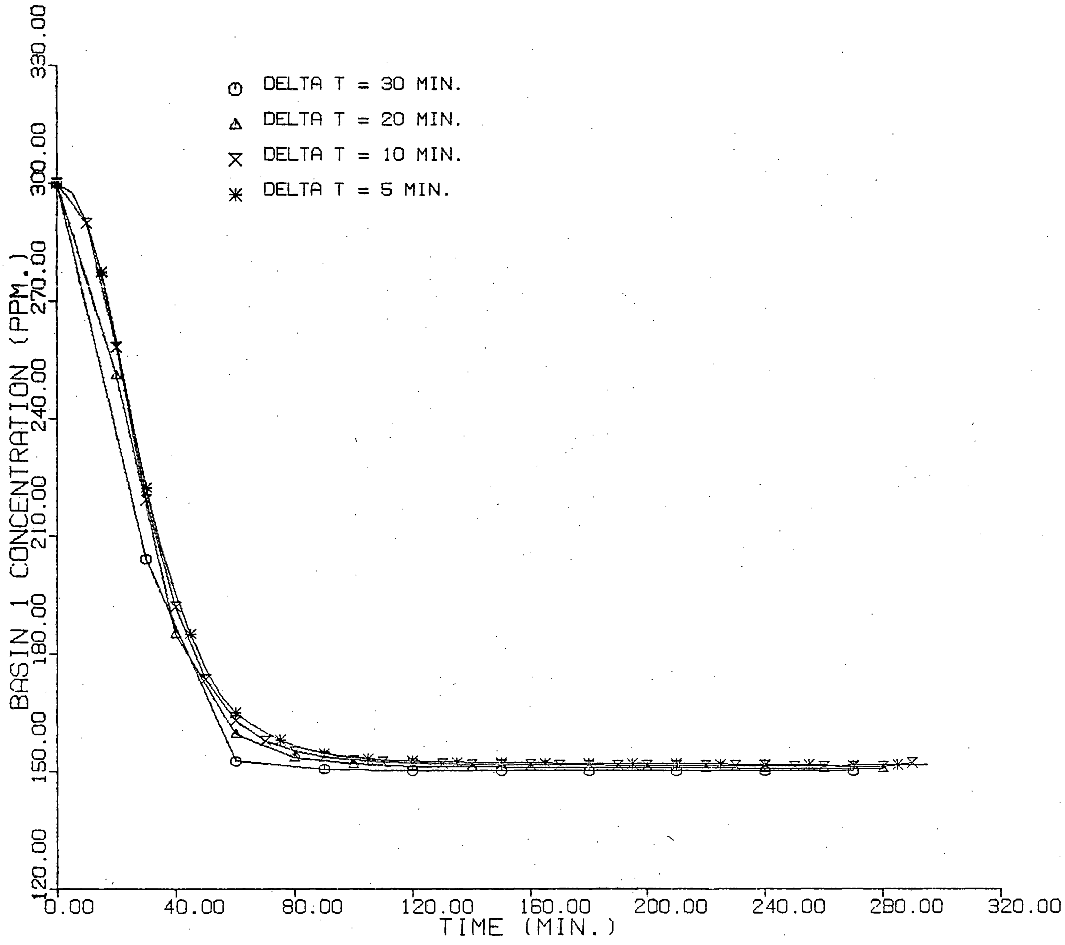


Figure 40. Sensitivity analysis of the Kuo method with respect to concentration in basin 1 in figure 3f.

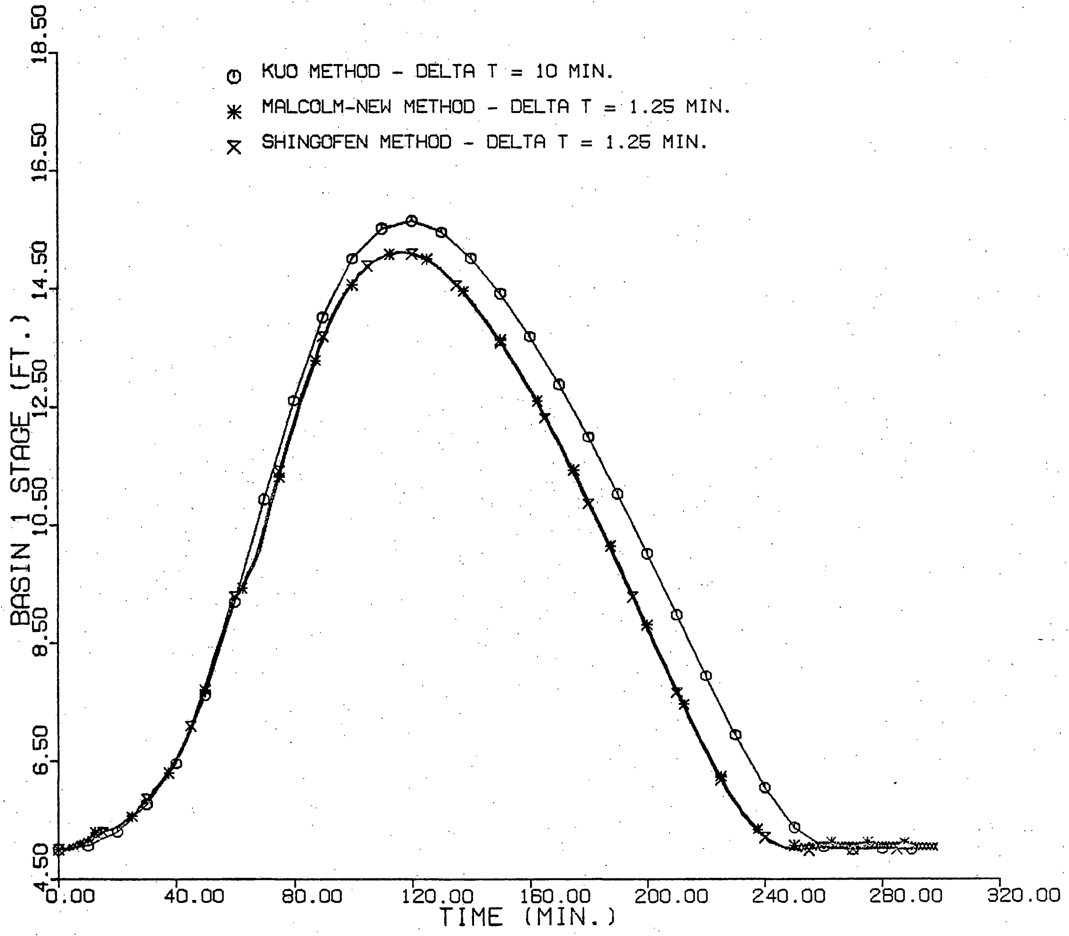


Figure 41. Comparison of the three methods with respect to stage in basin 1 in figure 3f as a function of time.

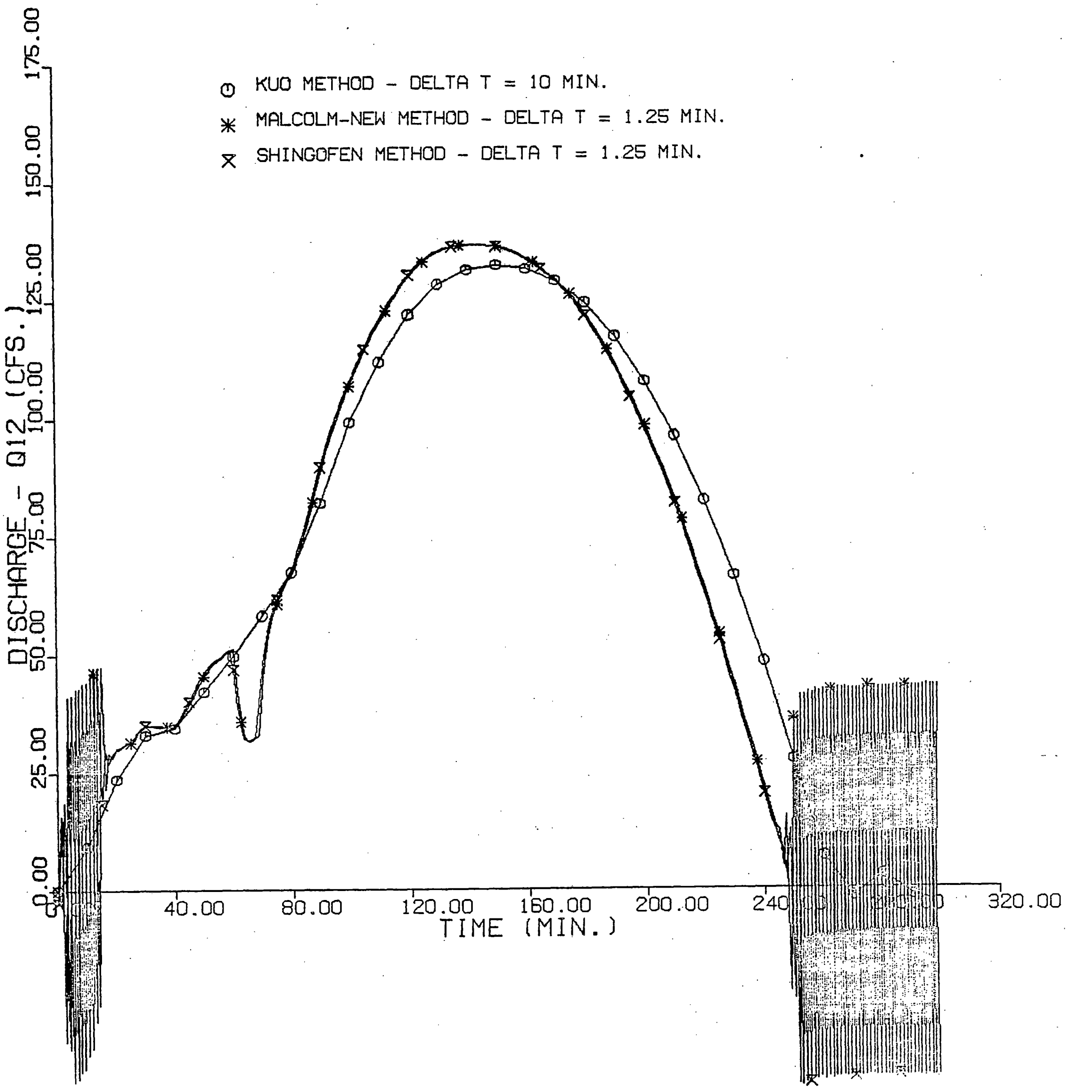


Figure 42. Comparison of the three methods with respect to discharge from basin 1 to basin 2 in figure 3f as a function of time.

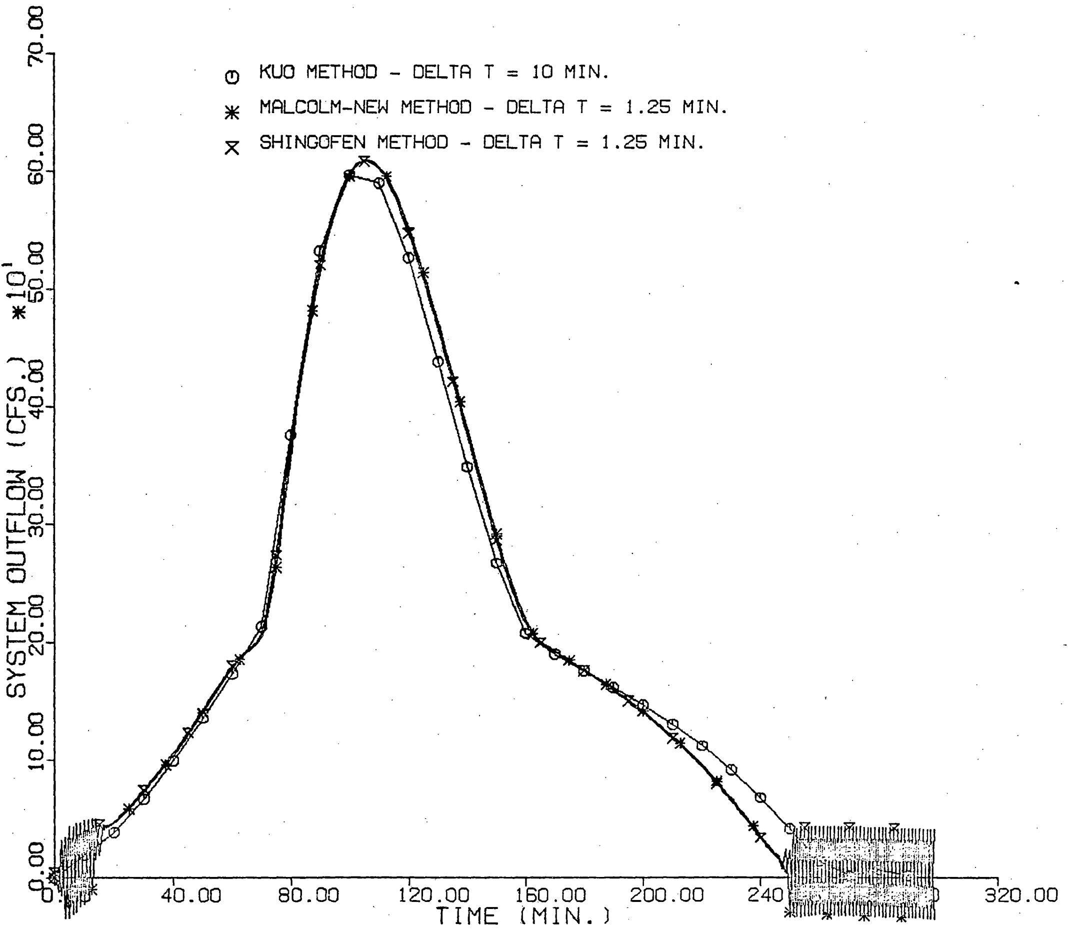


Figure 43. Comparison of the three methods with respect to system outflow in figure 3f as a function of time.

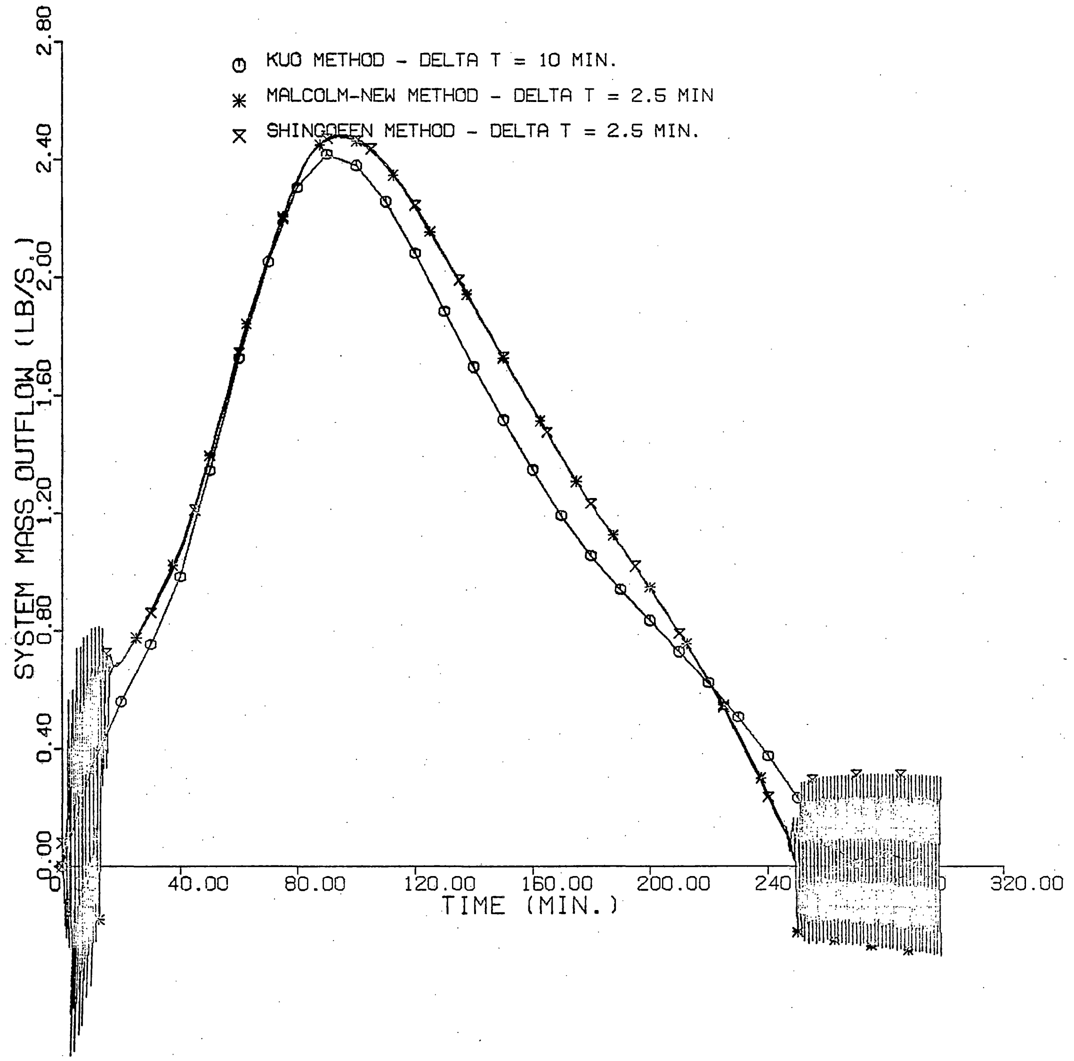


Figure 44. Comparison of the three methods with respect to system mass outflow in figure 3f as a function of time.

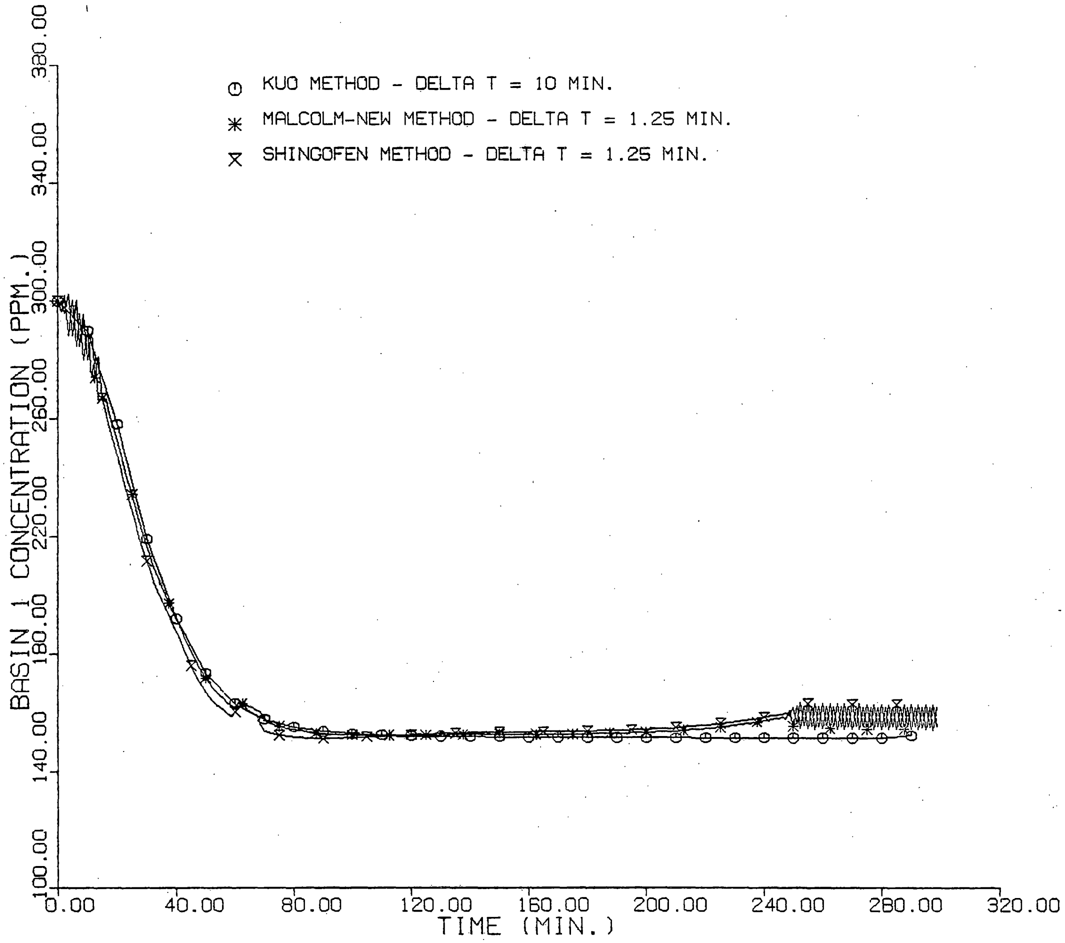


Figure 45. Comparison of the three methods with respect to concentration in basin 1 in figure 3f as a function of time.

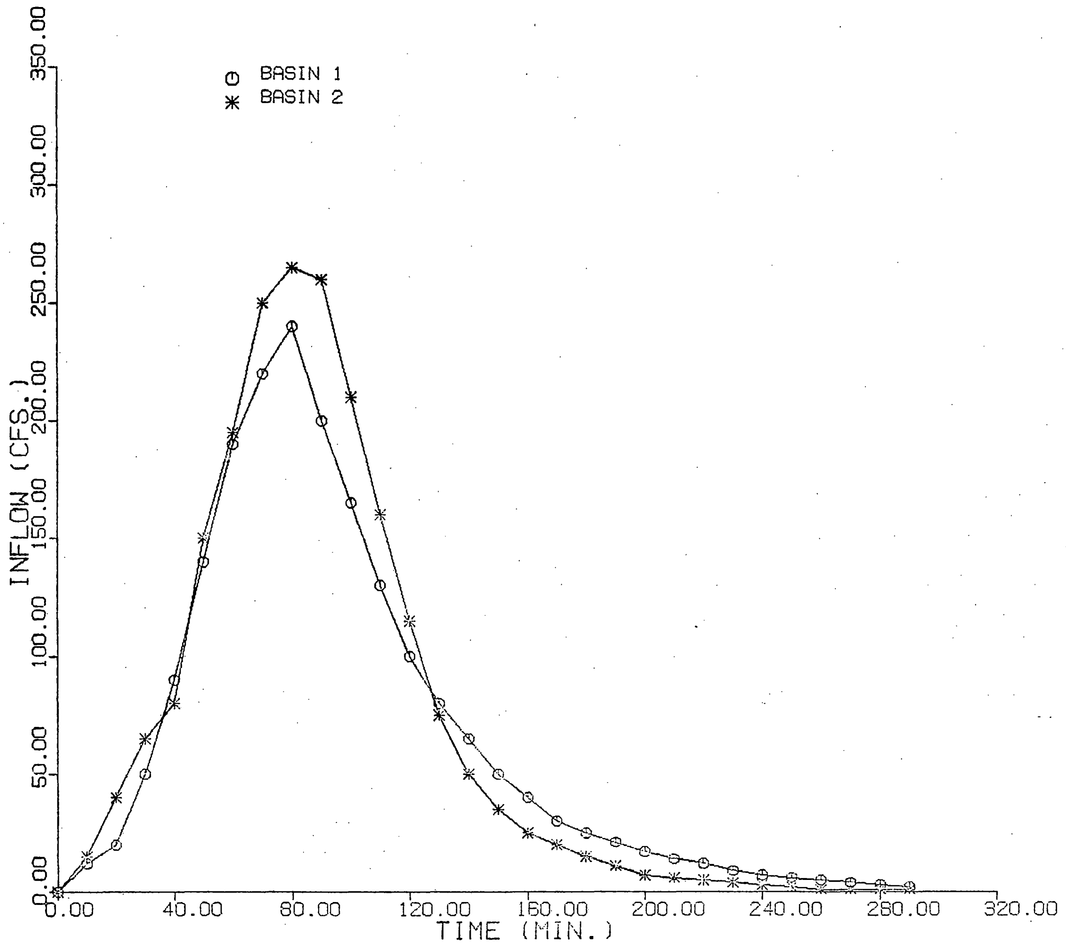


Figure 46. Inflow hydrographs used for a two basin system in figure 3f.

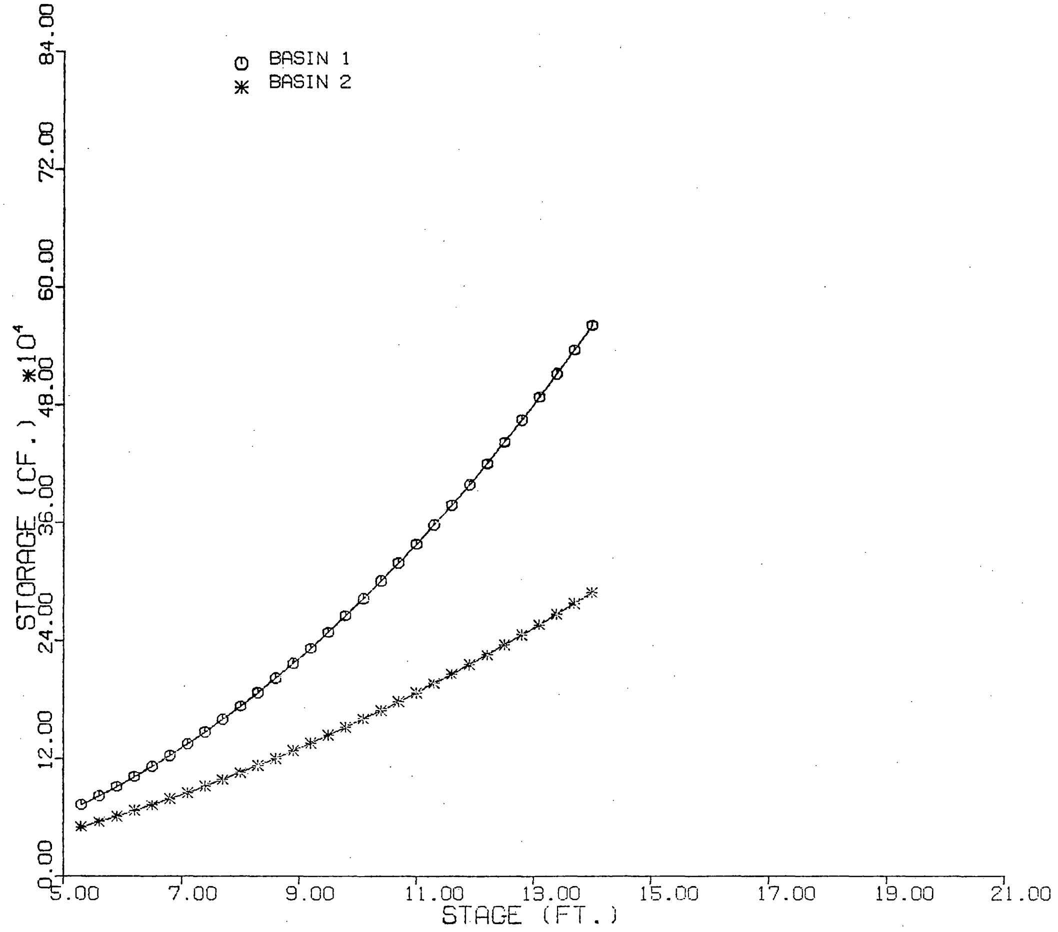


Figure 47. Stage-storage curves used for a two basin system in figure 3f.

TABLE 1. INPUT DATA AND IMPORTANT RESULTS FOR A FOUR BASIN SYSTEM WITH PIPE FLOW

INPUT:

INFLOW HYDROGRAPHS : FIGURE 22
PEAK INFLOW = 1155 CFS, TIME TO PEAK = 90 MIN

STAGE-STORAGE CURVES : FIGURE 23

DISCHARGE COEFF. FOR OUTLETS

CIJ= COEFF.FOR OUTLET STRUCTURE CONNECTING I AND J BASINS
J= 5,6 - NATURAL DRAIN BOUNDARIES

C12	C13	C34	C14	C35	C46
70.00	90.00	90.00	85.00	75.00	65.00

INFLOW POLLUTANT CONCENTRATIONS, PPM

BASIN 1	BASIN 2	BASIN 3	BASIN 4
300	300	300	300

TRAP EFFICIENCIES

0.60	0.50	0.40	0.30

PEAK POLLUTANT MASS INFLOW = 21.7 LB/S
TIME TO PEAK = 80 MIN

RESULTS:

SYSTEM PEAK STAGE = 7.34 FT
TIME AT PEAK = 150 MIN
PEAK OUTFLOW = 197 CFS, TIME TO PEAK = 180 MIN

PEAK POLLUTANT MASS OUTFLOW = 2.4 LB/S
TIME TO PEAK = 120 MIN

OVERALL SYSTEM TRAP EFFICIENCY = 0.68

TABLE 2. INPUT DATA AND IMPORTANT RESULTS FOR A FOUR BASIN SYSTEM WITH OPEN CHANNEL FLOW

INPUT:

INFLOW HYDROGRAPHS : FIGURE 29
PEAK INFLOW = 980 CFS, TIME TO PEAK = 150 MIN

STAGE-STORAGE CURVES : FIGURE 30

DISCHARGE COEFF. FOR OUTLETS

CIJ= COEFF.FOR OUTLET STRUCTURE CONNECTING I AND J BASINS
J= 5,6 - NATURAL DRAIN BOUNDARIES

C12	C13	C34	C14	C35	C46
52.90	52.90	52.90	52.90	52.90	52.90

INFLOW POLLUTANT CONCENTRATIONS, PPM

BASIN 1	BASIN 2	BASIN 3	BASIN 4
300	300	300	300

TRAP EFFICIENCIES

0.60	0.50	0.40	0.30

PEAK POLLUTANT MASS INFLOW = 18.4 LB/S
TIME TO PEAK = 80 MIN

RESULTS:

SYSTEM PEAK STAGE = 8.17 FT
TIME AT PEAK = 180 MIN
PEAK OUTFLOW = 191 CFS, TIME TO PEAK = 285 MIN

PEAK POLLUTANT MASS OUTFLOW = 1.9 LB/S
TIME TO PEAK = 160 MIN

OVERALL SYSTEM TRAP EFFICIENCY = 0.64

TABLE 3. COMPARISON BETWEEN THE THREE METHODS AS APPLIED TO A FOUR BASIN SYSTEM

NOTE :

THE UNITS FOR THE QUANTITIES IN THIS TABLE ARE AS FOLLOWS

TIME	MIN
FLOW QUANTITY	CFS
CONCENTRATION	PPM
MASS FLOW	LB/S
STAGE	FT
STORAGE	MILLION CF

INPUT PARAMETERS ARE THE SAME AS IN TABLE 1.

TERMINOLOGY: P1=BASIN 1
Q12=DISCHARGE FROM BASIN 1 TO BASIN 2
M=MASS FLOW RATE

ITEM	KUO METHOD	MALCOLM-NEW METHOD	SHINGOFEN METHOD
TIME STEP	10.0	2.5	2.5
MAX.INFLOW P1	400.0	400.0	400.0
MAX.INFLOW P2	340.0	340.0	340.0
MAX.INFLOW P3	265.0	265.0	265.0
MAX.INFLOW P4	240.0	240.0	240.0
SYS.PEAK INFLOW	1155.0	1155.0	1155.0
TIME TO PEAK	90.0	90.0	90.0
INFLUENT CONC. FOR ALL INFLOWS	300.0	300.0	300.0
MAX.MASSFLOW P1	7.50	7.50	7.50
MAX.MASS FLOW P2	6.38	6.38	6.38
MAX.MASS FLOW P3	4.97	4.97	4.97
MAX.MASS FLOW P4	4.50	4.50	4.50
SYS.MAX.M.FLOW	21.66	21.66	21.66
TIME AT MAX.	90.0	90.0	90.0
MAX.STAGE P1	7.34	7.29	7.29
MAX.STAGE P2	7.30	7.26	7.26
MAX.STAGE P3	7.01	6.84	6.84
MAX.STAGE P4	6.95	6.84	6.84
SYS.MAX.STAGE	7.34	7.29	7.29

(TABLE 3 CONTINUED)

MAX.DET.STOR.P1	0.995	0.979	0.979
MAX.DET.STOR.P2	1.300	1.270	1.270
MAX.DET.STOR.P3	1.180	1.041	1.041
MAX.DET.STOR.P4	0.887	0.819	0.819
SYS.MAX.D.STOR	4.362	4.109	4.109
ABS.MAX.Q12	48.0	48.0	48.0
ABS.MAX.Q13	68.0	72.0	73.0
ABS.MAX.Q24	27.0	15.0	15.0
ABS.MAX.Q34	50.0	56.0	56.0
ABS.MAX.Q35	92.0	86.0	88.0
ABS.MAX.Q46	105.0	102.0	102.0
SYS.PEAK OUTFLOW	197.0	188.0	190.0
TIME TO PEAK	180.0	177.5	177.5
ABS.MAX.M12	0.53	0.53	0.52
ABS.MAX.M13	0.74	0.78	0.77
ABS.MAX.M24	0.31	0.78	0.77
ABS.MAX.M34	0.57	0.62	0.62
ABS.MAX.M35	1.01	1.06	1.06
ABS.MAX.M46	1.39	1.37	1.37
SYS.PEAK MASS OUTFLOW	2.39	2.43	2.43
TIME TO PEAK	120.0	122.5	122.5
CONC.P1 AT PEAK MASS OUTFLOW	148.0	149.0	149.0
CONC.P2 AT PEAK	184.0	182.0	182.0
CONC.P3 AT PEAK	181.0	195.0	195.0
CONC.P4 AT PEAK	220.0	220.0	220.0
SYSTEM POLLUTANT TRAP EFFICIENCY	0.68	0.68	0.68

TABLE 4. INPUT DATA AND IMPORTANT RESULTS FOR
FOR A TWO BASIN SYSTEM

INPUT:

INFLOW HYDROGRAPHS : FIGURE 46
PEAK INFLOW = 505 CFS, TIME TO PEAK = 90 MIN

STAGE-STORAGE CURVES : FIGURE 47

DISCHARGE COEFF. FOR OUTLETS

CIJ= COEFF.FOR OUTLET STRUCTURE
CONNECTING I AND J BASINS
J= 3 - NATURAL DRAIN BOUNDARIES

C12	C23
70.00	90.00

INFLOW POLLUTANT CONCENTRATIONS, PPM

BASIN 1	BASIN 2
300	300

TRAP EFFICIENCIES

0.40	0.50

PEAK POLLUTANT MASS INFLOW = 9.5 LB/S
TIME TO PEAK = 80 MIN

RESULTS:

SYSTEM PEAK STAGE = 15.65 FT
TIME AT PEAK = 120 MIN
PEAK OUTFLOW = 255 CFS, TIME TO PEAK = 100 MIN

PEAK POLLUTANT MASS OUTFLOW = 2.4 LB/S
TIME TO PEAK = 100 MIN

OVERALL SYSTEM TRAP EFFICIENCY = 0.57

TABLE 5. COMPARISON OF A FOUR BASIN SYSTEM WITH AN EQUIVALENT SINGLE BASIN SYSTEM

	FOUR BASIN SYSTEM	'EQUIVALENT' SINGLE BASIN SYSTEM
COEFFICIENTS IN THE STAGE-STORAGE RELATIONSHIP		
BASIN 1	3000./3.1	13040./3.16
BASIN 2	3200./3.2	""
BASIN 3	3500./3.2	""
BASIN 4	3400./3.1	""
PEAK STAGE P1(FT)	7.40	7.23
PEAK STAGE P2(FT)	7.35	"
PEAK STAGE P3(FT)	7.24	"
PEAK STAGE P4(FT)	7.05	"
PEAK INFLOW(CFS)	1155.	1155.
TIME TO PEAK(MIN)	90.0	90.0
PEAK OUTFLOW(CFS)	107.	112.
TIME TO PEAK(MIN)	200.0	190.0
PEAK POLLUTANT MASS OUTFLOW(LB/S)	1.41	1.63
OVERALL SYSTEM TRAP EFFICIENCY	0.81	0.78

DIFFERENCE IN SPILLWAY HEIGHT IN BASIN 4 FOR THE TWO CASES = 0.18 FT

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APPENDIX A

COMPUTER PROGRAM DPMDS LISTING

```
      IMPLICIT REAL*4(A-H,O-Z)
      INTEGER NSIG,N,ITMAX,IER,NTIME
      REAL*4 FNORM,F(4),X(4),PAR(4),WK(54)
      COMMON/BLK1/CA,CB,CC,CD,CB4,CB5,CA4,CA5,CC4,CC5,CC6,
     *CD4,CD5,CD6
      COMMON/BLK2/CAA,CBB,CCC,CDD,HEX,HCEX,COEFF,LWEIR,HWEIR
     *,BAB,BBC,BDA,BCD,BEX,BCEX,ABL,BCL,CDL,DAL,EXL,CEXL,XN
      COMMON/BLK3/QA(30),QB(30),QC(30),QD(30),T(30),QSPILL(30)
     *,QBA(30),QBC(30),QCD(30),QAD(30),QDEX(30),QCEX(30)
     *,SB2(30),SA2(30),SC2(30),SD2(30),QIMX,QOMX,QSPLX
      COMMON/BLK4/CBI,CAI,CCI,CDI,TEB,TEA,TEC,TED
      COMMON/BLK5/NTIME,DELTT,NTYPE
      EXTERNAL FCN
      DIMENSION Z(30),V1(30),V2(30),V3(30),V4(30),HX(48,4)
     *,HB2(30),HA2(30),HC2(30),HD2(30),QINT(30),QEXT(30)
C   INPUT:
C   N=NO. OF UNKNOWN STAGES
C   NSIG=NO. OF SIGNIFICANT DIGITS OF ACCURACY DESIRED
C   ITMAX=MAX. NO. OF ITERATIONS TO BE ALLOWED
C   NTIME=TOTAL NO. OF ROUTING STEPS
C   NTYPE=0 ----PIPE FLOW
C   NTYPE=1 ----OPEN CHANNEL FLOW
      N=4
      NSIG=4
      ITMAX=20
      READ(5,135)NTYPE,NTIME
  135 FORMAT(2I5)
C INITIAL GUESSES X(I)
      READ(5,1)X(1),X(2),X(3),X(4)
    1 FORMAT(4F10.5)
C READ INFLOW CONCENTRATIONS
      READ(5,131)CBI,CAI,CCI,CDI
  131 FORMAT(4F10.5)
C READ TRAP EFFICIENCIES FOR THE BASINS
      READ(5,132)TEB,TEA,TEC,TED
  132 FORMAT(4F10.5)
C   READ COEFFICIENTS OF STAGE-STORAGE RELATIONS
      READ(5,2)CB,CA,CC,CD
```

```
    2  FORMAT(4F10.5)
       READ(5,7)CBB,CAA,CCC,CDD
    7  FORMAT(4F10.5)
       IF(NTYPE.EQ.0) GO TO 136
C READWIDTH OF CHANNELS
       READ(5,233)BAB,BBC,BCD,BDA,BEX,BCEX
  233  FORMAT(6F10.5)
C READ LENTHS OF CHANNELS
       READ(5,1114)ABL,BCL,CDL,DAL,EXL,CEXL,XN
 1114  FORMAT(7F10.5)
       CAB=1.49*BAB**1.667/(XN*SQRT(ABL))
       CBC=1.49*BBC**1.667/(XN*SQRT(BCL))
       CAD=1.49*BDA**1.667/(XN*SQRT(DAL))
       CCD=1.49*BCD**1.667/(XN*SQRT(CDL))
       CEX=1.49*BEX**1.667/(XN*SQRT(EXL))
       CCEX=1.49*BCEX**1.667/(XN*SQRT(CEXL))
       GO TO 137
   136 CONTINUE
       READ(5,3)CAB,CBC,CCD,CDA,CEX,CCEX
    3  FORMAT(6F10.5)
C   READ DEPTHS AT START TO BE UPDATED FOR NEXT STEP
   137 READ(5,4)HA1,HB1,HC1,HD1,HEX,HCEX
    4  FORMAT(6F10.5)
       WRITE(6,700)
   700 FORMAT(//15X,'ROUTING RESULTS FOR ILLUSTRATIVE
      *CASE  '/15X,39('*')//)
       WRITE(6,701)
   701 FORMAT(/10X,'BASIN NO.',T25,'1',T35,'2',
      *T45,'3',T55,'4'/10X,45('-')//)
       WRITE(6,702)
   702 FORMAT(/15X,'STAGE-STORAGE RELATION
      *V=A*Y**B'/15X,32('-')/)
       WRITE(6,703) CB,CA,CC,CD
   703 FORMAT(7X,'COEFF. A=',T20,4F10.0)
       WRITE(6,704) CBB,CAA,CCC,CDD
   704 FORMAT(7X,'COEFF.B=',T20,4F10.3)
       WRITE(6,781)
   781 FORMAT(/16X,'Y',T25,'V1',T35,'V2',T45,'V3',
      *T55,'V4'/10X,42('-')/)
       Z(1)=5.
       DO 114 I=1,NTIME
       IF(I.EQ.1) GO TO 113
       Z(I)=Z(I-1)+0.2
   113 V1(I)=CB*Z(I)**CBB
       V2(I)=CA*Z(I)**CAA
       V3(I)=CC*Z(I)**CCC
       V4(I)=CD*Z(I)**CDD
       WRITE(6,115)Z(I),V1(I),V2(I),V3(I),V4(I)
   114 CONTINUE
   115 FORMAT(/9X,F10.2,4F10.0)
```

```
      WRITE(6,705)
  705 FORMAT(//15X,'INFLOW HYDROGRAPHS'/15X,18('-')/)
      WRITE(6,706)
  706 FORMAT(/8X,'TIME,T',T20,'Q1(T)',T30,'Q2(T)',
     *T40,'Q3(T)',T50,'Q4(T)/T12,6('-'),T20,5('-')
     *,T30,5('-'),T40,5('-'),T50,5('-')/)
C READ  INFLOW  HYDROGRAPHS  AT  INTERVALS  OF  C  TIME  STEP  IN
MINUTES
      DO 104 I=1,NTIME
      READ(5,105)QB(I),QA(I),QC(I),QD(I),T(I)
  104 CONTINUE
      WRITE(6,707)(T(I),QB(I),QA(I),QC(I),QD(I),I=1,30)
  707 FORMAT(3X,F10.2,4F10.0)
  105 FORMAT(5F10.5)
      WRITE(6,740)
  740 FORMAT(//15X,'DISCHARGE COEFF. FOR
     *OUTLETS'/15X,28('-')/)
      WRITE(6,1111)
 1111 FORMAT(/15X,'CIJ= COEFF.FOR OUTLET STRUCTURE
     *CONNECTING I AND J BASINS')
      WRITE(6,720)
  720 FORMAT(15X,'J=5,6 - NATURAL DRAIN BOUNDARIES')
      WRITE(6,1112)
 1112 FORMAT(T15,'C12',T25,'C13',T35,'C34',T45,'C14',
     *T55,'C35',T65,'C46'/T15,3('-'),T25,3('-')
     *,T35,3('-'),T45,3('-'),T55,3('-'),T65,3('-')/)
      HX(1,1)=HB1
      HX(1,2)=HA1
      HX(1,3)=HC1
      HX(1,4)=HD1
      K=1
    6 DELTT=(T(K+1)-T(K))*60.
      CB1=CB*HB1**CBB+(QB(K+1)+QB(K))/2.*DELTT
      CB4=CAB*DELTT/2.
      CB5=CBC*DELTT/2.
      IF(NTYPE.EQ.0) GO TO 138
      IF(HB1.EQ.HA1) GO TO 51
C  INVERT LEVEL OF OUTLETS TAKEN AT 5 FT
      IF(HB1+HA1.LE.10.) GO TO 51
      CB2=CB4*((HB1+HA1-10.)/2.)**1.667*(HB1-HA1)
     */(SQRT(ABS(HB1-HA1)))/
     *(BAB+HB1+HA1-10.)**.667
      GO TO 52
   51 CB2=0.
   52 IF(HB1.EQ.HC1) GO TO 53
      IF(HB1+HC1.LE.10.) GO TO 53
      CB3=CB5*((HB1+HC1-10.)/2.)**1.667*(HB1-HC1)
     */(SQRT(ABS(HB1-HC1)))/
     *(BBC+HB1+HC1-10.)**.667
      GO TO 54
```

```
53 CB3=0.
54 CA1=CA*HA1**CAA+(QA(K+1)+QA(K))/2.*DELTT
   CA4=CAB*DELTT/2.
   CA5=CAD*DELTT/2.
   IF(HA1.EQ.HB1) GO TO 55
   IF(HA1+HB1.LE.10.) GO TO 55
   CA2=CA4*((HA1+HB1-10.)/2.)**1.667*(HA1-HB1)
  */(SQRT(ABS(HA1-HB1)))/
  *(BAB+HA1+HB1-10.)**.667
   GO TO 56
55 CA2=0.
56 IF(HA1.EQ.HD1) GO TO 57
   IF(HA1+HD1.LE.10.) GO TO 57
   CA3=CA5*((HA1+HD1-10.)/2.)**1.667*(HA1-HD1)
  */(SQRT(ABS(HA1-HD1)))/
  *(BDA+HA1+HD1-10.)**.667
   GO TO 58
57 CA3=0.
58 CC1=CC*HC1**CCC+(QC(K+1)+QC(K))/2.*DELTT
   CC4=CBC*DELTT/2.
   CC5=CCD*DELTT/2.
   IF(HC1.EQ.HB1) GO TO 59
   IF(HC1+HB1.LE.10.) GO TO 59
   CC2=CC4*((HC1+HB1-10.)/2.)**1.667*(HC1-HB1)
  */(SQRT(ABS(HC1-HB1)))/
  *(BBC+HC1+HB1-10.)**.667
   GO TO 60
59 CC2=0.
60 IF(HC1.EQ.HD1) GO TO 61
   IF(HC1+HD1.LE.10.) GO TO 61
   CC3=CC5*((HC1+HD1-10.)/2.)**1.667*(HC1-HD1)
  */(SQRT(ABS(HC1-HD1)))/
  *(BCD+HC1+HD1-10.)**.667
   GO TO 62
61 CC3=0.
76 CC6=CCEX*DELTT/2.
   IF(HC1.EQ.HCEX) GO TO 77
   IF(HC1+HCEX.LE.10.) GO TO 77
   CC7=CC6*((HC1+HCEX-10.)/2.)**1.667*(HC1-HCEX)
  */(SQRT(ABS(HC1-HCEX))
  *)/(BCEX+HC1+HCEX-10.)**.667
   GO TO 62
77 CC7=0.
62 CD1=CD*HD1**CDD+(QD(K+1)+QD(K))/2.*DELTT
   CD4=CCD*DELTT/2.
   CD5=CAD*DELTT/2.
   IF(HD1.EQ.HC1) GO TO 63
   IF(HC1+HC1.LE.10.) GO TO 63
   CD2=CD4*((HD1+HC1-10.)/2.)**1.667*(HD1-HC1)
  */(SQRT(ABS(HD1-HC1)))/
```

```
    *(BCD+HD1+HC1-10.)**.667
     GO TO 64
 63  CD2=0.
 64  IF(HD1.EQ.HA1) GO TO 65
     IF(HD1+HA1.LE.10.) GO TO 65
     CD3=CD5*((HD1+HA1-10.)/2.)**1.667*(HD1-HA1)
    */(SQRT(ABS(HD1-HA1)))/
    *(BDA+HD1+HA1-10.)**.667
     GO TO 66
 65  CD3=0.
 66  CD6=CEX*DELTT/2.
     IF(HD1.EQ.HEX) GO TO 67
     IF(HD1+HEX.LE.10.) GO TO 67
     CD7=CD6*((HD1+HEX-10.)/2.)**1.667*(HD1-HEX)
    */(SQRT(ABS(HD1-HEX)))/
    *(BEX+HC1+HCEX-10.)**.667
     GO TO 139
 67  CD7=0.
     GO TO 139
138  CONTINUE
     IF(HB1.EQ.HA1) GO TO 151
     CB2=CB4*(HB1-HA1)/(SQRT(ABS(HB1-HA1)))
     GO TO 152
151  CB2=0.
152  IF(HB1.EQ.HC1) GO TO 153
     CB3=CB5*(HB1-HC1)/(SQRT(ABS(HB1-HC1)))
     GO TO 154
153  CB3=0.
154  CA1=CA*HA1**CAA+(QA(K+1)+QA(K))/2.*DELTT
     CA4=CAB*DELTT/2.
     CA5=CDA*DELTT/2.
     IF(HA1.EQ.HB1) GO TO 155
     CA2=CA4*(HA1-HB1)/(SQRT(ABS(HA1-HB1)))
     GO TO 156
155  CA2=0.
156  IF(HA1.EQ.HD1) GO TO 157
     CA3=CA5*(HA1-HD1)/(SQRT(ABS(HA1-HD1)))
     GO TO 158
157  CA3=0.
158  CC1=CC*HC1**CCC+(QC(K+1)+QC(K))/2.*DELTT
     CC4=CBC*DELTT/2.
     CC5=CCD*DELTT/2.
     IF(HC1.EQ.HB1) GO TO 159
     CC2=CC4*(HC1-HB1)/(SQRT(ABS(HC1-HB1)))
     GO TO 160
159  CC2=0.
160  IF(HC1.EQ.HD1) GO TO 161
     CC3=CC5*(HC1-HD1)/(SQRT(ABS(HC1-HD1)))
     GO TO 162
161  CC3=0.
```

```
  176 CC6=CCEX*DELTT/2.
      IF(HC1.EQ.HCEX) GO TO 177
      CC7=CC6*(HC1-HCEX)/(SQRT(ABS(HC1-HCEX)))
      GO TO 162
  177 CC7=0.
  162 CD1=CD*HD1**CDD+(QD(K+1)+QD(K))/2.*DELTT
      CD4=CCD*DELTT/2.
      CD5=CDA*DELTT/2.
      IF(HD1.EQ.HC1) GO TO 163
      CD2=CD4*(HD1-HC1)/(SQRT(ABS(HD1-HC1)))
      GO TO 164
  163 CD2=0.
  164 IF(HD1.EQ.HA1) GO TO 165
      CD3=CD5*(HD1-HA1)/(SQRT(ABS(HD1-HA1)))
      GO TO 166
  165 CD3=0.
  166 CD6=CEX*DELTT/2.
      IF(HD1.EQ.HEX) GO TO 167
      CD7=CD6*(HD1-HEX)/(SQRT(ABS(HD1-HEX)))
      GO TO 139
  167 CD7=0.
  139 CONTINUE
C DROP-INLET TYPE SPILLWAY
C INPUT WEIR LENGTH AND CREST HEIGHT
      HWEIR=10.0
      LWEIR=20.0
      COEFF=3.3
      IF(HD1.GT.HWEIR) CD7=CD7+COEFF*LWEIR
     **(HD1-HWEIR)**1.5
      PAR(1)=-CB1+CB2+CB3
      PAR(2)=-CA1+CA2+CA3
      PAR(3)=-CC1+CC2+CC3+CC7
      PAR(4)=-CD1+CD2+CD3+CD7
  122 CONTINUE
      CALL ZSPOW(FCN,NSIG,N,ITMAX,PAR,X,FNORM,WK,IER)
      DO 100 I=1,4
      HX(K+1,I)=X(I)
  100 CONTINUE
      K=K+1
      IF(K.GE.NTIME) GO TO 900
      HB1=X(1)
      HA1=X(2)
      HC1=X(3)
      HD1=X(4)
      GO TO 6
  900 CONTINUE
      L=0
      M=0
      DO 991 I=1,NTIME
      QSPILL(I)=0.0
```

```
991 CONTINUE
    QSPLX=0.0
    QIMX=0.0
    QOMX=0.0
    DO 901 K=1,NTIME
    HB2(K)=HX(K,1)
    HA2(K)=HX(K,2)
    HC2(K)=HX(K,3)
    HD2(K)=HX(K,4)
    SB2(K)=CB*HB2(K)**CBB
    SA2(K)=CA*HA2(K)**CAA
    SC2(K)=CC*HC2(K)**CCC
    SD2(K)=CD*HD2(K)**CDD
    IF(NTYPE.EQ.0) GO TO 140
    IF(HB2(K).EQ.HA2(K)) GO TO 902
    QBA(K)=CAB*((HB2(K)+HA2(K)-10.)/2.)**1.667
   **(HB2(K)-HA2(K))/(SQRT(ABS(HB2(K)-HA2(K))))
   */(BAB+HB2(K)+HA2(K)-10.)**.667
    GO TO 913
902 QBA(K)=0.0
913 IF(HB2(K).EQ.HC2(K)) GO TO 903
    QBC(K)=CBC*((HB2(K)+HC2(K)-10.)/2.)**1.667
   **(HB2(K)-HC2(K))/(SQRT(ABS(HB2(K)-HC2(K))))
   */(BBC+HB2(K)+HC2(K)-10.)**.667
    GO TO 908
903 QBC(K)=0.0
908 IF(HC2(K).EQ.HD2(K)) GO TO 904
    QCD(K)=CCD*((HC2(K)+HD2(K)-10.)/2.)**1.667
   **(HC2(K)-HD2(K))/(SQRT(ABS(HC2(K)-HD2(K))))
   */(BCD+HC2(K)+HD2(K)-10.)**.667
    GO TO 909
904 QCD(K)=0.0
909 IF(HA2(K).EQ.HD2(K)) GO TO 905
    QAD(K)=CAD*((HA2(K)+HD2(K)-10.)/2.)**1.667
   **(HA2(K)-HD2(K))/(SQRT(ABS(HA2(K)-HD2(K))))
   */(BDA+HA2(K)+HD2(K)-10.)**.667
    GO TO 910
905 QAD(K)=0.0
910 IF(HD2(K).EQ.HEX) GO TO 906
    QDEX(K)=CEX*((HD2(K)+HEX-10.)/2.)**1.667
   **(HD2(K)-HEX)/(SQRT(ABS(HD2(K)-HEX)))
   */(BEX+HD2(K)+HEX-10.)**.667
    GO TO 911
906 QDEX(K)=0.0
911 IF(HC2(K).EQ.HCEX) GO TO 807
    QCEX(K)=CCEX*((HC2(K)+HCEX-10.)/2.)**1.667
   **(HC2(K)-HCEX)/(SQRT(ABS(HC2(K)-HCEX)))
   */(BCEX+HC2(K)+HCEX-10.)**.667
    GO TO 941
140 CONTINUE
```

```
      IF(HB2(K).EQ.HA2(K)) GO TO 802
      QBA(K)=CAB*(HB2(K)-HA2(K))/SQRT(ABS(HB2(K)-HA2(K)))
      GO TO 813
  802 QBA(K)=0.0
  813 IF(HB2(K).EQ.HC2(K)) GO TO 803
      QBC(K)=CBC*(HB2(K)-HC2(K))/SQRT(ABS(HB2(K)-HC2(K)))
      GO TO 808
  803 QBC(K)=0.0
  808 IF(HC2(K).EQ.HD2(K)) GO TO 804
      QCD(K)=CCD*(HC2(K)-HD2(K))/SQRT(ABS(HC2(K)-HD2(K)))
      GO TO 809
  804 QCD(K)=0.0
  809 IF(HA2(K).EQ.HD2(K)) GO TO 805
      QAD(K)=CDA*(HA2(K)-HD2(K))/SQRT(ABS(HA2(K)-HD2(K)))
      GO TO 810
  805 QAD(K)=0.0
  810 IF(HD2(K).EQ.HEX) GO TO 806
      QDEX(K)=CEX*(HD2(K)-HEX)/SQRT(ABS(HD2(K)-HEX))
      GO TO 811
  806 QDEX(K)=0.0
  811 CONTINUE
  868 IF(HD2(K).GT.HWEIR) QSPILL(K)=COEFF*LWEIR
     **(HD2(K)-HWEIR)**1.5
      IF(HC2(K).EQ.HCEX) GO TO 807
      QCEX(K)=CCEX*(HC2(K)-HCEX)/SQRT(ABS(HC2(K)-HCEX))
      GO TO 941
  807 QCEX(K)=0.0
  941 QINT(K)=QA(K)+QB(K)+QC(K)+QD(K)
      QEXT(K)=QDEX(K)+QCEX(K)+QSPILL(K)
      IF(QSPLX.GE.QSPILL(K)) GO TO 765
      QSPLX=QSPILL(K)
      HSPILL=HD2(K)
      GO TO 766
  765 CONTINUE
      IF(K.EQ.1) GO TO 764
  766 IF(QIMX.GE.QINT(K)) GO TO 761
      QIMX=QINT(K)
      L=K
      GO TO 762
  761 QIMX=QIMX
      L=L
  762 IF(QOMX.GE.QEXT(K)) GO TO 763
      QOMX=QEXT(K)
      M=K
      GO TO 764
  763 QOMX=QOMX
      M=M
  764 CONTINUE
      TIPK=L*DELTT/60.
      TOPK=M*DELTT/60.
```

```
901 CONTINUE
    WRITE(6,733)
733 FORMAT(/15X,'STAGE AS A FUNCTION OF TIME'/
   *15X,27('-')/)
    WRITE(6,713)
713 FORMAT(/9X,'TIME,T',T20,'H1(T)',
   *T30,'H2(T)',T40,'H3(T)',T50,'H4(T
   *)'/T10,6('-'),T20,5('-'),T30,
   *5('-'),T40,5('-'),T50,5('-')/)
    WRITE(6,714)(T(I),HB2(I),HA2(I),HC2(I),
   *HD2(I),I=1,30)
714 FORMAT(5X,5F10.3)
    WRITE(6,715)
715 FORMAT(/15X,'STORAGE AS A FUNCTION OF TIME'
   */15X,29('-')/)
    WRITE(6,716)
716 FORMAT(/10X,'TIME,T',T20,'S1(T)',
   *T30,'S2(T)',T40,'S3(T)',T50,'S4(T
   *)'/T10,6('-'),T20,5('-'),T30,5('-'),
   *T40,5('-'),T50,5('-')/)
    WRITE(6,717)(T(I),SB2(I),SA2(I),SC2(I),
   *SD2(I),I=1,30)
717 FORMAT(5X,5F10.0)
    WRITE(6,718)
718 FORMAT(/15X,'DISCHARGE THROUGH OUTLET
   *STRUCTURES'/15X,35('-')/)
    WRITE(6,719)
719 FORMAT(/15X,'QIJ(T)=DISCHARGE FROM I-BASIN
   *TO J-BASIN AT TIME,T')
    WRITE(6,730)
730 FORMAT(15X,'J=5,6 - NATURAL DRAIN BOUNDARIES')
    WRITE(6,721)
721 FORMAT(15X,'QINT(T)=TOTAL INPUT TO THE SYSTEM')
    WRITE(6,722)
722 FORMAT(15X,'QEXT(T)=TOTAL OUTPUT FROM THE SYSTEM')
    WRITE(6,723)
723 FORMAT(/T6,'Q12(T)',T15,'Q13(T)',T24,'Q34(T)',
   *T33,'Q14(T)',T42,'Q35(T)',T51,'Q45(T)',
   *T60,'QINT(T)',T69,'QEXT(T)'
   */T6,6('-'),T15,6('-'),T24,6('-'),T33,6('-'),
   *T42,6('-'),T51,6('-')
   *,T60,7('-'),T69,7('-')/)
    WRITE(6,24)(QBA(I),QBC(I),QCD(I),QAD(I),QCEX(I),
   *QDEX(I),QINT(I),QEXT(I),I=1,30)
24  FORMAT(8F9.0)
    WRITE(6,724)QIMX,TIPK
724 FORMAT(15X,'PEAK INFLOW=',F6.0,10X,'TIME
   *TO PEAK=',F6.2)
    WRITE(6,725)QOMX,TOPK
725 FORMAT(15X,'PEAK OUTFLOW=',F6.0,10X,'TIME
```

```
     *TO PEAK=',F6.2)
      WRITE(6,726)QSPLX,HSPILL
  726 FORMAT(/5X,'MAX.SPILLWAY DISCHARGE=',F6.0,
     *5X,'STAGE AT MAX.SPILL=',F5.0/)
      CALL POLLUT
C     CALL APLOT
      RETURN
      END
C
      SUBROUTINE FCN(X,F,N,PAR)
      IMPLICIT REAL*4(A-H,O-Z)
      INTEGER NSIG,N,ITMAX,IER
      REAL*4 FNORM,F(4),X(4),PAR(4),WK(54)
      COMMON/BLK1/CA,CB,CC,CD,CB4,CB5,CA4,CA5,CC4,
     *CC5,CC6,CD4,CD5,CD6
      COMMON/BLK2/CAA,CBB,CCC,CDD,HEX,HCEX,COEFF,LWEIR,
     *HWEIR,BAB,BBC,BDA,BCD,BEX,BCEX,ABL,BCL,CDL,DAL,
     *EXL,CEXL,XN
      COMMON/BLK5/NTIME,DELTT,NTYPE
      IF(NTYPE.EQ.0) GO TO 141
      IF(X(1)+X(2).LE.10.) X(1)=X(2)
      IF(X(1)+X(3).LE.10.) X(1)=X(3)
      IF(X(1)+X(4).LE.10.) X(1)=X(4)
      IF(X(2)+X(3).LE.10.) X(2)=X(3)
      IF(X(2)+X(4).LE.10.) X(2)=X(4)
      IF(X(3)+X(4).LE.10.) X(3)=X(4)
      IF(X(3)+HCEX.LE.10.) X(3)=HCEX
      IF(X(3)+HEX.LE.10.) X(3)=HEX
      IF(X(1).EQ.X(2).AND.X(1).EQ.X(3)) GO TO 11
      IF(X(1).EQ.X(2).AND.X(1).NE.X(3)) GO TO 12
      IF(X(1).NE.X(2).AND.X(1).EQ.X(3)) GO TO 13
      F(1)=CB*X(1)**CBB+PAR(1)
     *+CB4*((X(1)+X(2)-10.)/2.)**1.667*(X(1)-X(2))
     */SQRT(ABS(X(1)-X(2)))
     */(BAB+X(1)+X(2)-10.)**.667
     *+CB5*((X(1)+X(3)-10.)/2.)**1.667*(X(1)-X(3))
     */SQRT(ABS(X(1)-X(3)))
     */(BAB+X(1)+X(3)-10.)**.667
      GO TO 14
   11 F(1)=CB*X(1)**CBB+PAR(1)
      GO TO 14
   12 F(1)=CB*X(1)**CBB+PAR(1)
     *+CB5*((X(1)+X(3)-10.)/2.)**1.667*(X(1)-X(3))
     */SQRT(ABS(X(1)-X(3)))
     */(BBC+X(1)+X(3)-10.)**.667
      GO TO 14
   13 F(1)=CB*X(1)**CBB+PAR(1)
     *+CB4*((X(1)+X(2)-10.)/2.)**1.667*(X(1)-X(2))
     */SQRT(ABS(X(1)-X(2)))
     */(BAB+X(1)+X(2)-10.)**.667
```

```
14 CONTINUE
    IF(X(2).EQ.X(1).AND.X(2).EQ.X(4)) GO TO 15
    IF(X(2).EQ.X(1).AND.X(2).NE.X(4)) GO TO 16
    IF(X(2).NE.X(1).AND.X(2).EQ.X(4)) GO TO 17
    F(2)=CA*X(2)**CAA+PAR(2)
   *+CA4*((X(2)+X(1)-10.)/2.)**1.667*(X(2)-X(1))
   */SQRT(ABS(X(2)-X(1)))
   */(BAB+X(2)+X(1)-10.)**.667
   *+CA5*((X(2)+X(4)-10.)/2.)**1.667*(X(2)-X(4))
   */SQRT(ABS(X(2)-X(4)))
   */(BDA+X(2)+X(4)-10.)**.667
    GO TO 18
15  F(2)=CA*X(2)**CAA+PAR(2)
    GO TO 18
16  F(2)=CA*X(2)**CAA+PAR(2)
   *+CA5*((X(2)+X(4)-10.)/2.)**1.667*(X(2)-X(4))
   */SQRT(ABS(X(2)-X(4)))
   */(BDA+X(2)+X(4)-10.)**.667
    GO TO 18
17  F(2)=CA*X(2)**CAA+PAR(2)
   *+CA4*((X(2)+X(1)-10.)/2.)**1.667*(X(2)-X(1))
   */SQRT(ABS(X(2)-X(1)))
   */(BAB+X(2)+X(1)-10.)**.667
18 CONTINUE
    IF(X(3).EQ.X(1).AND.X(3).EQ.X(4).AND.X(3).EQ.HCEX)
   *GO TO 33
    IF(X(3).EQ.X(1).AND.X(3).NE.X(4).AND.X(3).EQ.HCEX)
   *GO TO 34
    IF(X(3).NE.X(1).AND.X(3).EQ.X(4).AND.X(3).EQ.HCEX)
   *GO TO 35
    IF(X(3).EQ.X(1).AND.X(3).EQ.X(4).AND.X(3).NE.HCEX)
   *GO TO 36
    IF(X(3).EQ.X(1).AND.X(3).NE.X(4).AND.X(3).NE.HCEX)
   *GO TO 37
    IF(X(3).NE.X(1).AND.X(3).EQ.X(4).AND.X(3).NE.HCEX)
   *GO TO 38
    F(3)=CC*X(3)**CCC+PAR(3)
   *+CC4*((X(3)+X(1)-10.)/2.)**1.667*(X(3)-X(1))
   */SQRT(ABS(X(3)-X(1)))
   */(BBC+X(3)+X(1)-10.)**.667
   *+CC5*((X(3)+X(4)-10.)/2.)**1.667*(X(3)-X(4))
   */SQRT(ABS(X(3)-X(4)))
   */(BCD+X(3)+X(4)-10.)**.667
   *+CC6*((X(3)+HCEX-10.)/2.)**1.667*(X(3)-HCEX)
   */SQRT(ABS(X(3)-HCEX))
   */(BCEX+X(3)+HCEX-10.)**.667
    GO TO 39
33  F(3)=CC*X(3)**CCC+PAR(3)
    GO TO 39
34  F(3)=CC*X(3)**CCC+PAR(3)
```

```
  *+CC5*((X(3)+X(4)-10.)/2.)**1.667*(X(3)-X(4))
  */SQRT(ABS(X(3)-X(4)))
  */(BCD+X(3)+X(4)-10.)**.667
   GO TO 39
35 F(3)=CC*X(3)**CCC+PAR(3)
  *+CC4*((X(3)+X(1)-10.)/2.)**1.667*(X(3)-X(1))
  */SQRT(ABS(X(3)-X(1)))
  */(BBC+X(3)+X(1)-10.)**.667
   GO TO 39
36 F(3)=CC*X(3)**CCC+PAR(3)
  *+CC6*((X(3)+HCEX-10.)/2.)**1.667*(X(3)-HCEX)
  */SQRT(ABS(X(3)-HCEX))
  */(BCEX+X(3)+HCEX-10.)**.667
   GO TO 39
37 F(3)=CC*X(3)**CCC+PAR(3)
  *+CC5*((X(3)+X(4)-10.)/2.)**1.667*(X(3)-X(4))
  */SQRT(ABS(X(3)-X(4)))
  */(BCD+X(3)+X(4)-10.)**.667
  *+CC6*((X(3)+HCEX-10.)/2.)**1.667*(X(3)-HCEX)
  */SQRT(ABS(X(3)-HCEX))
  */(BCEX+X(3)+HCEX-10.)**.667
   GO TO 39
38 F(3)=CC*X(3)**CCC+PAR(3)
  *+CC4*((X(3)+X(1)-10.)/2.)**1.667*(X(3)-X(1))
  */SQRT(ABS(X(3)-X(1)))
  */(BBC+X(3)+X(1)-10.)**.667
  *+CC6*((X(3)+HCEX-10.)/2.)**1.667*(X(3)-HCEX)
  */SQRT(ABS(X(3)-HCEX))
  */(BCEX+X(3)+HCEX-10.)**.667
39 CONTINUE
   IF(X(4).EQ.X(3).AND.X(4).EQ.X(2).AND.X(4).EQ.HEX)
  *GO TO 23
   IF(X(4).EQ.X(3).AND.X(4).NE.X(2).AND.X(4).EQ.HEX)
  *GO TO 24
   IF(X(4).NE.X(3).AND.X(4).EQ.X(2).AND.X(4).EQ.HEX)
  *GO TO 25
   IF(X(4).EQ.X(3).AND.X(4).EQ.X(2).AND.X(4).NE.HEX)
  *GO TO 26
   IF(X(4).EQ.X(3).AND.X(4).NE.X(2).AND.X(4).NE.HEX)
  *GO TO 27
   IF(X(4).NE.X(3).AND.X(4).EQ.X(2).AND.X(4).NE.HEX)
  *GO TO 28
   F(4)=CD*X(4)**CDD+PAR(4)
  *+CD4*((X(4)+X(3)-10.)/2.)**1.667*(X(4)-X(3))
  */SQRT(ABS(X(4)-X(3)))
  */(BCD+X(4)+X(3)-10.)**.667
  *+CD5*((X(4)+X(2)-10.)/2.)**1.667*(X(4)-X(2))
  */SQRT(ABS(X(4)-X(2)))
  */(BDA+X(4)+X(2)-10.)**.667
  *+CD6*((X(4)+HEX-10.)/2.)**1.667*(X(4)-HEX)
```

```
     */SQRT(ABS(X(4)-HEX))
     */(BEX+X(4)+HEX-10.)**.667
      GO TO 29
  23  F(4)=CD*X(4)**CDD+PAR(4)
      GO TO 29
  24  F(4)=CD*X(4)**CDD+PAR(4)
     *+CD5*((X(4)+X(2)-10.)/2.)**1.667*(X(4)-X(2))
     */SQRT(ABS(X(4)-X(2)))
     */(BDA+X(4)+X(2)-10.)**.667
      GO TO 29
  25  F(4)=CD*X(4)**CDD+PAR(4)
     *+CD4*((X(4)+X(3)-10.)/2.)**1.667*(X(4)-X(3))
     */SQRT(ABS(X(4)-X(3)))
     */(BCD+X(4)+X(3)-10.)**.667
      GO TO 29
  26  F(4)=CD*X(4)**CDD+PAR(4)
     *+CD6*((X(4)+HEX-10.)/2.)**1.667*(X(4)-HEX)
     */SQRT(ABS(X(4)-HEX))
     */(BEX+X(4)+HEX-10.)**.667
      GO TO 29
  27  F(4)=CD*X(4)**CDD+PAR(4)
     *+CD5*((X(4)+X(2)-10.)/2.)**1.667*(X(4)-X(2))
     */SQRT(ABS(X(4)-X(2)))
     */(BDA+X(4)+X(2)-10.)**.667
     *+CD6*((X(4)+HEX-10.)/2.)**1.667*(X(4)-HEX)
     */SQRT(ABS(X(4)-HEX))
     */(BEX+X(4)+HEX-10.)**.667
      GO TO 29
  28  F(4)=CD*X(4)**CDD+PAR(4)
     *+CD4*((X(4)+X(3)-10.)/2.)**1.667*(X(4)-X(3))
     */SQRT(ABS(X(4)-X(3)))
     */(BCD+X(4)+X(3)-10.)**.667
     *+CD6*((X(4)+HEX-10.)/2.)**1.667*(X(4)-HEX)
     */SQRT(ABS(X(4)-HEX))
     */(BEX+X(4)+HEX-10.)**.667
  29  CONTINUE
      GO TO 142
 141  CONTINUE
      IF(X(1).EQ.X(2).AND.X(1).EQ.X(3)) GO TO 111
      IF(X(1).EQ.X(2).AND.X(1).NE.X(3)) GO TO 112
      IF(X(1).NE.X(2).AND.X(1).EQ.X(3)) GO TO 113
      F(1)=CB*X(1)**CBB+PAR(1)+CB4*(X(1)-X(2))
     */(SQRT(ABS(X(1)-X(2))))
     *+CB5*(X(1)-X(3))/(SQRT(ABS(X(1)-X(3))))
      GO TO 114
 111  F(1)=CB*X(1)**CBB+PAR(1)
      GO TO 114
 112  F(1)=CB*X(1)**CBB+PAR(1)+CB5*(X(1)-X(3))
     */(SQRT(ABS(X(1)-X(3))))
      GO TO 114
```

```
113 F(1)=CB*X(1)**CBB+PAR(1)+CB4*(X(1)-X(2))
   */(SQRT(ABS(X(1)-X(2))))
114 CONTINUE
    IF(X(2).EQ.X(1).AND.X(2).EQ.X(4)) GO TO 115
    IF(X(2).EQ.X(1).AND.X(2).NE.X(4)) GO TO 116
    IF(X(2).NE.X(1).AND.X(2).EQ.X(4)) GO TO 117
    F(2)=CA*X(2)**CAA+PAR(2)+CA4*(X(2)-X(1))
   */(SQRT(ABS(X(2)-X(1))))
   *+CA5*(X(2)-X(4))/(SQRT(ABS(X(2)-X(4))))
    GO TO 118
115 F(2)=CA*X(2)**CAA+PAR(2)
    GO TO 118
116 F(2)=CA*X(2)**CAA+PAR(2)+CA5*(X(2)-X(4))
   */(SQRT(ABS(X(2)-X(4))))
    GO TO 118
117 F(2)=CA*X(2)**CAA+PAR(2)+CA4*(X(2)-X(1))
   */(SQRT(ABS(X(2)-X(1))))
118 CONTINUE
    IF(X(3).EQ.X(1).AND.X(3).EQ.X(4).AND.X(3).EQ.
   *HCEX) GO TO 133
    IF(X(3).EQ.X(1).AND.X(3).NE.X(4).AND.X(3).EQ.
   *HCEX) GO TO 134
    IF(X(3).NE.X(1).AND.X(3).EQ.X(4).AND.X(3).EQ.
   *HCEX) GO TO 135
    IF(X(3).EQ.X(1).AND.X(3).EQ.X(4).AND.X(3).NE.
   *HCEX) GO TO 136
    IF(X(3).EQ.X(1).AND.X(3).NE.X(4).AND.X(3).NE.
   *HCEX) GO TO 137
    IF(X(3).NE.X(1).AND.X(3).EQ.X(4).AND.X(3).NE.
   *HCEX) GO TO 138
    F(3)=CC*X(3)**CCC+PAR(3)+CC4*(X(3)-X(1))/(SQRT
  *(ABS(X(3)-X(1))))
   *+CC5*(X(3)-X(4))/(SQRT(ABS(X(3)-X(4))))
   *+CC6*(X(3)-HCEX)/(SQRT(ABS(X(3)-HCEX)))
    GO TO 139
133 F(3)=CC*X(3)**CCC+PAR(3)
    GO TO 139
134 F(3)=CC*X(3)**CCC+PAR(3)+CC5*(X(3)-X(4))/(SQRT
   *(ABS(X(3)-X(4))))
    GO TO 139
135 F(3)=CC*X(3)**CCC+PAR(3)+CC4*(X(3)-X(1))/
   *(SQRT(ABS(X(3)-X(1))))
    GO TO 139
136 F(3)=CC*X(3)**CCC+PAR(3)+CC6*(X(3)-HCEX)/
   *(SQRT(ABS(X(3)-HCEX)))
    GO TO 139
137 F(3)=CC*X(3)**CCC+PAR(3)+CC5*(X(3)-X(4))/
   *(SQRT(ABS(X(3)-X(4))))
   *+CC6*(X(3)-HCEX)/(SQRT(ABS(X(3)-HCEX)))
    GO TO 139
```

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138 F(3)=CC*X(3)**CCC+PAR(3)+CC4*(X(3)-X(1))/
   *(SQRT(ABS(X(3)-X(1))))
   *+CC6*(X(3)-HCEX)/(SQRT(ABS(X(3)-HCEX)))
139 CONTINUE
    IF(X(4).EQ.X(3).AND.X(4).EQ.X(2).AND.X(4).
   *EQ.HEX) GO TO 123
    IF(X(4).EQ.X(3).AND.X(4).NE.X(2).AND.X(4).
   *EQ.HEX) GO TO 130
    IF(X(4).NE.X(3).AND.X(4).EQ.X(2).AND.X(4).
   *EQ.HEX) GO TO 125
    IF(X(4).EQ.X(3).AND.X(4).EQ.X(2).AND.X(4).
   *NE.HEX) GO TO 126
    IF(X(4).EQ.X(3).AND.X(4).NE.X(2).AND.X(4).
   *NE.HEX) GO TO 127
    IF(X(4).NE.X(3).AND.X(4).EQ.X(2).AND.X(4).
   *NE.HEX) GO TO 128
    F(4)=CD*X(4)**CDD+PAR(4)+CD4*(X(4)-X(3))/(
   *SQRT(ABS(X(4)-X(3))))
   *+CD5*(X(4)-X(2))/(SQRT(ABS(X(4)-X(2))))
   *+CD6*(X(4)-HEX)/(SQRT(ABS(X(4)-HEX)))
    GO TO 129
123 F(4)=CD*X(4)**CDD+PAR(4)
    GO TO 129
130 F(4)=CD*X(4)**CDD+PAR(4)+CD5*(X(4)-X(2))/(
   *SQRT(ABS(X(4)-X(2))))
    GO TO 129
125 F(4)=CD*X(4)**CDD+PAR(4)+CD4*(X(4)-X(3))/(
   *SQRT(ABS(X(4)-X(3))))
    GO TO 129
126 F(4)=CD*X(4)**CDD+PAR(4)+CD6*(X(4)-HEX)/(
   *SQRT(ABS(X(4)-HEX)))
    GO TO 129
127 F(4)=CD*X(4)**CDD+PAR(4)+CD5*(X(4)-X(2))/(
   *SQRT(ABS(X(4)-X(2))))
   *+CD6*(X(4)-HEX)/(SQRT(ABS(X(4)-HEX)))
    GO TO 129
128 F(4)=CD*X(4)**CDD+PAR(4)+CD4*(X(4)-X(3))/(
   *SQRT(ABS(X(4)-X(3))))
   *+CD6*(X(4)-HEX)/(SQRT(ABS(X(4)-HEX)))
129 IF(X(4).GT.HWEIR) F(4)=F(4)+COEFF*LWEIR*(X(4)
   *-HWEIR)**1.5
131 CONTINUE
142 CONTINUE
    RETURN
    END
    SUBROUTINE POLLUT
    IMPLICIT REAL*4(A-H,O-Z)
    INTEGER NSIG,N,ITMAX,IER,NTIME
    COMMON/BLK3/QA(30),QB(30),QC(30),QD(30),T(30),
   *QSPILL(30),QBA(30),QBC(30),QCD(30),QAD(30)
```

```
     *,QDEX(30),QCEX(30),SB2(30),SA2(30),SC2(30),
     *SD2(30),QIMX,QOMX,QSPLX
      COMMON/BLK4/CBI,CAI,CCI,CDI,TEB,TEA,TEC,TED
      COMMON/BLK5/NTIME,DELTT,NTYPE
      DIMENSION CNB(30),CNA(30),CNC(30),CND(30)
     *,CNBA(30),CNBC(30),CNAD(30),CNCD(30)
      DIMENSION WINB(30),WINA(30),WINC(30),WIND(30)
     *,WBA(30),WBC(30),WCD(30),WAD(30),WCX(30),WDX(30)
     *,WOUB(30),WOUA(30),WOUC(30),WOUD(30),WINT(30)
     *,WEXT(30)
C READ INPUT CONCENTRATION,INITIAL CONC IN THE BASINS
      DO 130 I=1,30
      CNB(1)=CBI
      CNA(1)=CAI
      CNC(1)=CCI
      CND(1)=CDI
      IF(I.EQ.1) GO TO 130
      IF((QBA(I-1)+QBA(I))/2.GT.0.) GO TO 10
      CNBA(I)=CNA(I-1)
      TEBBA=TEB
      TEABA=0.
      GO TO 20
   10 CNBA(I)=CNB(I-1)
      TEBBA=0.
      TEABA=TEA
   20 CONTINUE
      IF((QBC(I-1)+QBC(I))/2.GT.0.) GO TO 30
      CNBC(I)=CNC(I-1)
      TEBBC=TEB
      TECBC=0.
      GO TO 40
   30 CNBC(I)=CNB(I-1)
      TEBBC=0.
      TECBC=TEC
   40 CONTINUE
      IF((QAD(I-1)+QAD(I))/2.GT.0.) GO TO 50
      CNAD(I)=CND(I-1)
      TEAAD=TEA
      TEDAD=0.
      GO TO 60
   50 CNAD(I)=CNA(I-1)
      TEAAD=0.
      TEDAD=TED
   60 CONTINUE
      IF((QCD(I-1)+QCD(I))/2.GT.0.) GO TO 70
      CNCD(I)=CND(I-1)
      TECCD=TEC
      TEDCD=0.
      GO TO 80
  70  CNCD(I)=CNC(I-1)
```

```
      TECCD=0.
      TEDCD=TED
   80 CONTINUE
C AVERAGE CONCENTRATION FOR OUTFLOW APPROXIMATED AS
C THE VALUE AT THE BEGINING OF THE TIME STEP
      CNB(I)=(((1-TEB)*(QB(I-1)+QB(I))/2.*CBI
     *-(1-TEBBA)*(QBA(I-1)+QBA(I))/2.*CNBA(I)
     *-(1-TEBBC)*(QBC(I-1)+QBC(I))/2.*CNBC(I))*DELTT
     *+SB2(I-1)*CNB(I-1))/SB2(I)
      CNA(I)=(((1-TEA)*(QA(I-1)+QA(I))/2.*CAI
     *+(1-TEABA)*(QBA(I-1)+QBA(I))/2.*CNBA(I)
     *-(1-TEAAD)*(QAD(I-1)+QAD(I))/2.*CNAD(I))*DELTT
     *+SA2(I-1)*CNA(I-1))/SA2(I)
      CNC(I)=(((1-TEC)*(QC(I-1)+QC(I))/2.*CCI
     *+(1-TECBC)*(QBC(I-1)+QBC(I))/2.*CNBC(I)
     *-(1-TECCD)*(QCD(I-1)+QCD(I))/2.*CNCD(I))*DELTT
     *+SC2(I-1)*CNC(I-1)
     *-(QCEX(I-1)+QCEX(I))/2.*CNC(I-1)*DELTT)/SC2(I)
      CND(I)=(((1-TED)*(QD(I-1)+QD(I))/2.*CDI
     *+(1-TEDAD)*(QAD(I-1)+QAD(I))/2.*CNAD(I)
     *+(1-TEDCD)*(QCD(I-1)+QCD(I))/2.*CNCD(I))*DELTT
     *+SD2(I-1)*CND(I-1)
     *-(QDEX(I-1)+QDEX(I))*CND(I-1)/2.*DELTT
     *-(QSPILL(I-1)+QSPILL(I))*CND(I-1)/2.*DELTT)/SD2(I)
  148 CONTINUE
  130 CONTINUE
      WIN=0.
      WOUT=0.
      DO 149 I=1,30
      WINB(I)=QB(I)*CBI
      WINA(I)=QA(I)*CAI
      WINC(I)=QC(I)*CCI
      WIND(I)=QD(I)*CDI
      WINT(I)=WINB(I)+WINA(I)+WINC(I)+WIND(I)
      IF(QBA(I)-0.) 161,162,163
  161 WBA(I)=QBA(I)*CNC(I)
  162 WBA(I)=QBA(I)*CNB(I)
  163 WBA(I)=QBA(I)*CNB(I)
      IF(QBC(I)-0.) 164,165,166
  164 WBC(I)=QBC(I)*CNC(I)
  165 WBC(I)=QBC(I)*CNB(I)
  166 WBC(I)=QBC(I)*CNB(I)
      IF(QCD(I)-0.) 167,168,169
  167 WCD(I)=QCD(I)*CND(I)
  168 WCD(I)=QCD(I)*CNC(I)
  169 WCD(I)=QCD(I)*CNC(I)
      IF(QAD(I)-0.) 170,171,172
  170 WAD(I)=QAD(I)*CND(I)
  171 WAD(I)=QAD(I)*CNA(I)
  172 WAD(I)=QAD(I)*CNA(I)
```

```
      WCX(I)=QCEX(I)*CNC(I)
      WDX(I)=QDEX(I)*CND(I)
      WOUB(I)=WBA(I)+WBC(I)
      WOUA(I)=-WBA(I)+WAD(I)
      WOUC(I)=-WBC(I)+WCD(I)+WCX(I)
      WOUD(I)=-WCD(I)-WAD(I)+WDX(I)
      WEXT(I)=WCX(I)+WDX(I)
      WIN=WIN+WINT(I)*DELTT
      WOUT=WOUT+WEXT(I)*DELTT
  149 CONTINUE
      DO 785 I=1,30
      CNB(I)=CNB(I)*1000.
      CNA(I)=CNA(I)*1000.
      CNC(I)=CNC(I)*1000.
      CND(I)=CND(I)*1000.
  785 CONTINUE
      SYSTRP=(WIN-WOUT)/WIN
      WRITE(6,708)
  708 FORMAT(/15X,'INFLOW POLLUTANT CONCENTRATIONS'
     */15X,31('-')/)
      WRITE(6,775)
  775 FORMAT(/T25,'BASIN1',T35,'BASIN2',T45,'BASIN3'
     *,T55,'BASIN4'/)
      WRITE(6,709) CBI,CAI,CCI,CDI
  709 FORMAT(9X,'FOR T=0-TN',T20,4F10.3)
      WRITE(6,710)
  710 FORMAT(//15X,'MASS INFLOW RATES'/15X,19('-')/)
      WRITE(6,711)
  711 FORMAT(/10X,'TIME,T',T20,'M1(T)',T30,'M2(T)',
     *T40,'M3(T)',T50,'M4(T)'/T10,6('-'),T20
     *,5('-'),T30,5('-'),T40,5('-'),T50,5('-')/)
      WRITE(6,712)(T(I),WINB(I),WINA(I),WINC(I),WIND(I)
     *,I=1,30)
  712 FORMAT(4X,5F9.2)
      WRITE(6,776)
  776 FORMAT(//15X,'TRAP EFFICIENCIES'/15X,17('-')/)
      WRITE(6,778) TEB,TEA,TEC,TED
  778 FORMAT(8X,'FOR T=0-TN',T20,4F10.3)
      WRITE(6,793)
  793 FORMAT(//15X,'POLLUTANT CONCENTRATIONS IN BASINS'
     */15X,29('-')/)
      WRITE(6,794)
  794 FORMAT(/T20,'C1(T)',T30,'C2(T)',T40,'C3(T)',T50,'
     *C4(T)'/T20,5('-'),T30,5('-'),T40,5('-'),T50,5('-')/)
      WRITE(6,795)(CNB(I),CNA(I),CNC(I),CND(I),I=1,30)
  795 FORMAT(15X,4F10.3)
      WRITE(6,726)
  726 FORMAT(//15X,'POLLUTANT MASS FLOWS'/15X,21('-')/)
      WRITE(6,787)
  787 FORMAT(/T5,'M12(T)',T14,'M13(T)',T23,'M34(T)',T32,
```

```
     *'M24(T)',T41,'M35(T)',T50,'M46(T)'
     */T5,6('-'),T14,6('-'),T23,6('-'),T32,6('-'),
     *T41,6('-'),T50,6('-')/)
      WRITE(6,789)(WBA(I),WBC(I),WCD(I),WAD(I),WCX(I)
     *,WDX(I),I=1,30)
  789 FORMAT(6F9.2)
      WRITE(6,727)
  727 FORMAT(/T5,'M1(T)',T14,'M2(T)',T23,'M3(T)',T32,
     *'M4(T)',T41,'MINT(T)',T50,'MEXT(T)'
     */T5,6('-'),T14,6('-'),T23,6('-'),T32,6('-'),T41
     *,6('-'),T50,6('-')/)
      WRITE(6,779)(WOUB(I),WOUA(I),WOUC(I),WOUD(I),WINT(I)
     *,WEXT(I),I=1,30)
  779 FORMAT(6F9.2)
      WRITE(6,729)SYSTRP
  729 FORMAT(//15X,'OVERALL SYSTEM TRAP EFFICIENCY=',F7.3)
C PLOTS PPL:SENSITIVITY, PRR:ALL PLOTS, OPRR1:OPEN CHANNELS
C PCM1:COMPARISION, PEL:SENS 2BASIN, PEMB:ALL 2B, PCEM:COMP
C     CALL PPL
C     CALL PRR
C     CALL OPRR1
C     CALL PCM1
C     CALL PEL
C     CALL PEMB
C     CALL PCEM
      RETURN
      END
```