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COMPARISON OF SOME ROUTING TECHNIQUES

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PREFACE

Simplified routing techniques have received much importance in the area of flood routing because of their simplicity in application and lesser data base requirement for their operation in the field.

In the present study five techniques namely Conventional Muskingum Method, Three-Parameter Muskingum type procedure, Muaskingum-Cunge Method, Variable-Parameter Diffusion method and Kalinin-Milyukov method have been considered for comparison in respect of their performance on the data of sub-reach Hathnur to Bhusaval on River Tapti.

This technical report entitled 'Comparison of Some Routing Techniques', is a part of the work programme of 'Flood Studies Division of this Institute. The report has been prepared by Sh. Surendra Kumar, Scientist 'B' under the guidance of Dr. S.M. Seth, Scientist F

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LIST OF SYMBOLS

1. A = Area of cross-section;
2. C_1, C_2, C_3 = Muskingum Coefficients;
3. $\bar{C}$ = Average Speed of the wave;
4. d_1, d_2, d_3 = Three-Parameter Muskingum Coefficients;
5. F_o = Initial variance;
6. F_1 = Model variance;
7. H = Water level;
8. g = Gravitational acceleration;
9. K = Storage coefficient;
10. l = Characteristic length;
11. L = Length of the reach;
12. L_m = Length of the channel (m^{th} sub-reach)
13. n = Roughness coefficient;
14. Pm = Plan area of the inundated flood plain and the channel in the mth sub-reach;
15. Q_j = Discharge at jth time step;
16. Q_{j+1} = Discharge at j+1 th time step;
17. $\bar{Q}_p$ = Average peak discharge;
18. Q = Calculated Outflow;
19. $\bar{Q}$ = Mean of the observed outflow;
20. Q^* = Attenuation of the peak discharge;
21. r = Coefficient for lateral inflow;
22. R = Hydraulic radius;
23. s_o = Bed slope;
    = Water surface slope;
24. S = Storage;
25. s_{fr} = Energy slope;
26. S_m = Bottom slope of the channel (mth sub-reach)
27. Δt = Time interval;
28. T_p = Travel time of the peak,
29. t_p = Time to peak;

30. v_q = Velocity of the lateral inflow in the direction of river flow;

31. W_c = Width of the channel;

32. $\bar{W}$ = Average width of the river;

33. Δx = Length of the sub-reach;

34. w = Speed of the peak;

35. y = Depth of flow;

36. α = Attenuation parameters;

37. ϵ = Weighting factor;

38. η = Efficiency of the model;

39. μ = wave dispersion coefficient;

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ABSTRACT

Simplified routing techniques are still considered to be important tools of flood routing because of their simplicity in application and lesser data required for their solution. In order to judge the performance and capabilities of different techniques, it is necessary to carry out studies with common data base. This study attempts to compare the relative performance of five routing techniques namely Conventional Muskingum method, Three-Parameter Muskingum Method, Muskingum-Cu nge Method, Variable-Parameter Diffusion method and Kalinin-Milyukov method using the flood data of river Tapti between Hathnur and Bhusaval. It is seen that the Three-Parameter Muskingum type procedure is performing best of all. The Conventional Muskigum method and Kalinin-Milyukov-Method rank second and third in performance. The Muskingum-Cunge Method and Variable-Parameter Diffusion method did not perform as good as others. It is suggested to use Three-Parameter Muskingum Method in the field as it has also got the advantage of incorporation of lateral inflow. A sensitivity analysis for all the methods, has also been made to see the effect of the change in parameters on the results. From the analysis, it is seen that the error in inflow is directly reflected in the results hence the inflow data should be collected very accurately. Other parameters, K and ϵ in Conventional Muskingum Method and Three-Parameter Muskingum method, rating curves in Kalinin-Milyukov Method and $\bar{C}$ and α in Variable Parameter Diffusion Method, need to be estimated with proper care and judgement.

1.0 INTRODUCTION

A large number of flood routing methods are known to be successfully applied to various rivers and floods. These methods are classified into two groups, namely hydrological or storage routing and hydraulic routing methods. The hydrological methods are based only on the continuity equation where as the hydraulic method employ both the continuity and momentum equations (i.e. the St. Venant equations).

The storage routing techniques have been widely used, especially in developing countries, for their simplicity. Also, the hydraulic methods involve complicated methods of solution and high requirement of computing facilities. However, if certain simplifications are made to the momentum equation, the hydraulic method will lead to a simpler version than the original one, in which case both the solution and computation are simple and easy. The routing techniques based on a diffusion wave model developed by Hayami (1951), Thomas and Wormleaton (1970), Price (1973), are the best examples for the simplified hydraulic methods. Various method have typical features affecting their performance. In order to judge relative capabilities of a group of methods, it becomes necessary to carry out studies with a common data set of inflow and outflow hydrographs for different river reaches.

This study attempts to compare the relative performance of some of the well known storage routing methods, the Variable Parameter Diffusion Method due to Price (1973), and physically based Kalinin-Milyukov Method to the flood data of river Tapti between Hathnur and Bhusaval. The overall comparison of the methods has been made on the basis of simulation of peak flow, time to peak and the model efficiency. The Conventional Muskingum Method gives the model efficiency in the range from 90.61 to 98.27%. In Three-Parameter Muskingum method the efficiency varies from 91.10% to 98.49%. The Muskingum-Cunge and Variable Parameter Diffusion method for the three events are performing from 91.68%

to 98.39% and from 84.88% to 96.96% respectively and for one event the efficiency is 76.03% and 36.44% respectively. The Kalinin-Milyukov method gives average results, that is, the model efficiency varies from 85.33% to 98.43%. Comparing the methods on the basis, mentioned above, it is seen that the Three Parameter Muskingum method performs better than any other methods and also the method has the ability of incorporation of lateral inflow, therefore, the method has been recommended for use in field. This method is more advantageous to use in the field than the Conventional Muskingum method, with reference to estimation of parameters. The performance of the Kalinin-Milyukov method may improve with the improvement in rating curve. The results by Muskingum-Cunge method and Variable Parameter method may also improve with the improvement in data availablity. A sensitivity analysis for all the methods considered in this study, has also been made to see the effect of change of parameters on the results. It is seen that the error in inflow is directly reflected more or less by the same amount in the results and hence the inflow data should be measured very carefully. The parameter K and ϵ should be estimated with proper care in Conventional Muskingum method and Three-P arameter Muskingum method as these parameters introduce the error significantly. The parameters $\bar{C}$ and α in Muskingum-Cunge and Variable Parameter Diffusion method and rating curves in the Kalinin-Milyukov method should also be estimated carefully.

2.0 REVIEW

Routing can be performed by hydrologic and hydraulic methods, here only simplified methods have been reviewed in brief as follows:

1. Zoch (1934) proposed a single linear reservoir (SLR) model using a series of n-SLRs. He concluded that it can represent only the attenuation of the flood wave.
2. Meyer (1941) proposed a lag and route model which relates the outflow of time (t+z) to storage at time t. The term z represents the response delay time or the time taken for the leading edge of the flood wave to reach the outflow section.
3. Kalinin and Milyukov (1957) proposed a model after their name, which is widely used in USSR and is a physically based n-linear reservoirs model. They computed the length of the reach assuming that there is a single value relationship between the downstream discharge and the stage at the middle of the SLR reach. According to Miller and Cunge (1975), this procedure can be used in practice.
4. Nash (1957) conceptualised the catchment behaviour for a unit impulse input and derived the instantaneous unit hydrograph (IUH) for the catchment.
5. Nash (1959) recognised the problem of formation of negative outflow in the beginning of the solution, and recommended the use of lag and route method especially for steep rising rivers, where this defect is predominant. However, he pointed out that the solution with the negative outflow is mathematically correct.
6. Kulandaiswamy (1966) studied the translatory characteristics of the Muskingum method and pointed out that the Muskingum solution is approximately translatory if the third and higher order derivatives of the inflow is negligible. In his

controversial paper Gill (1979) stresses that the Muskingum solution is purely translatory under the condition laidout by Kulandaiswamy (1966). As a response to this conclusion Singh and Mc-Cann(1980) proved unequivocally that the pure translatory solution is a myth, Strupczewski and Kundzewicz (1980) and Kundzewicz and Strupczewicz (1982) later on showed that the Muskingum solution is approximately translatory when compared with the other value of weighting parameter except 0.5.

7. Harley (1967) and Dooge (1973) suggested the use of n-SLRs in series to partially simulate the translation behaviour of the flood wave in a channel reach.

8. Koussis (1978) developed a variable paarameter Muskingum method based on the diffusion analogy principle, using the same concept as adopted by Cunge (1969), with constant weighting parameter and varying travel time. He found from his experience that weighting parameter is not varying considerably with discharge, but varies with travel time.

9. Ponce and Yevjevich (1978) suggested a simple variable parameter method based on the Muskingum-Cunge Procedure. Usually the routing time interval being fixed, and Δ_x and S_o are specified for each computational cell constituting of Four grid points. Their method involves the determination of flood wave celerity and the unit width discharge for each computational cell.

10. Gill (1979) attempted to solve the puzzle of Muskingum method by modifying the initial conditions required for the solution of Muskingum equations. Instead of considering the initial conditions, at time, o, the inflow is equal to outflow, he considered that the inflow at zero time is equal to the outflow at some time which is more than zero. He argued that the initial conditions given by Kulandaiswamy (1966) and Diskin (1967) assume that the effect of inflow reaches the outlet of the reach under consideration instantaneously which contradicts with the flood movement characteristics in

natural river for which the initial condition given by him is more appropriate.

11. Rangapathi et.al. (1957) have made an attempt to apply the conventional Muskingum method, the constant and variable Parameter Muskingum Cunge methods, the Kulandaiswamy's General Storage Equation method and the Variable Parameter Diffusion method to a reach each in Rivers Narmada and Cauvery. They found that the diffusion methods can also be applaied with improved results but experienced considerable difficulty in calculating the model parameters of all these methods.

12. Bhandari (1988) in his work on flood flow analysis of Tapti River, has used the Muskingum model after correcting the observed outflow for lateral inflow and after routing the lateral inflow is added to get the total outflow.

13. Singh (1988) in his text has mentioned about the ways to incorporate the effect of lateral inflow on routing. According to him, one common practice to account for seepage is to subtract it from the routed outflow hydrograph. Similarly the lateral inflow can be considered by adding the lateral inflow to the outflow hydrograph.

3.0 PROBLEM DEFINITION

In this report five routing techniques namely Conventional Muskingum method, Three-Parameter Muskingum method, Muskingum-Cunge method, Variable Parameter Diffusion method and Kalinin-Milyukov method, have been compared using the flood data of River Tapti between Hathnur and Bhusaval.

4.0 METHODOLOGY

Flood routing can be done by two methods, namely: hydraulic method, and hydrologic method. Hydraulaic methods generally need very large data set for the routing whereas hydrologic methods are very simple in comparison to hydraulic methods and need a limited number of data for the purpose. In this report only hydrologic methods and simplified hydraulic methods are considered for the comparison and are described under different heads as follows:

4.1 Conventional Muskingum Method

The basic Muskingum equations are :

Continuity:

$$Q_j - Q_{j+1} = dS/dt \qquad ...(1)$$

Storage equation:

$$S = K\,(\epsilon\, Q_j + (1-\epsilon)\, Q_{j+1}) \qquad ...(2)$$

when,

K = Storage coefficient,

ϵ = weighting factor

From equations (1) and (2), the following equation can be derived:

$$K \frac{d}{dt} [\epsilon Q_j + (1-\epsilon)\, Q_{j+1}] = Q_j - Q_{j+1} \qquad ...(3)$$

Equation (3) can be rewritten in finite differerce form as below :

$$\frac{K}{\Delta t} [\epsilon Q_j^{n+1} + (1-\epsilon)\, Q_{j+1}^{n+1} - Q_j^n - (1-\epsilon)\, Q_{j+1}^n]$$

$$= \frac{1}{2} [Q_j^{n+1} - Q_{j+1}^{n+1} + Q_j^n - Q_{j+1}^n] \qquad ...(4)$$

This equation can be experessed in a simplified form as below:

$$Q_{j+1}^{n+1} = C_1\, Q_j^n + C_2\, Q_j^{n+1} + C_3\, Q_{j+1}^n \qquad ...(5)$$

where,

$$\left.\begin{aligned} C_1 &= \frac{K\epsilon + 1/2\ \Delta t}{K\ (1+\epsilon) + 1/2\ \Delta t} \\ C_2 &= \frac{1/2\ \Delta t - K\epsilon}{K\ (1-\epsilon) + \frac{1}{2}\ \Delta t} \\ C_3 &= \frac{K\ (1-\epsilon) - 1/2\ \Delta t}{K\ (1-\epsilon) + 1/2\ \Delta t} \end{aligned}\right\} \quad \ldots(6)$$

The sum of C_1, C_2 and C_3 are equal to 1.0. Since Q_j^n, Q_j^{n+1} and Q_{j+1}^n are known for every time increment, routing is accomplished by solving equation (5) recursively.

4.2 Three Parameter Muskingum Method :

The basic Muskingum method represented by equations 1 and 2 earlier, does not take into account the lateral inflow joining the stream or the flow going out from the reach. O'Donnell (1985) extended the basic Muskingum model from two parameter (K and) to three parameter (K,ϵ,r) Muskingum method which takes into account the lateral inflow with the assumption that it is of the shape of inflow. The equations are as follows:

Continuity equation:

$$(1+r)\ Q_j - Q_{j+1} = dS/dt \quad \ldots(7)$$

Storage equation:

$$S = K\ [(1+r)\ Q_j\epsilon + (1-\epsilon)\ Q_{j+1}] \quad \ldots(8)$$

Combining equations (7) and (8) and writing the final euqation in finite difference form, it leads to equation as below:

$$(Q_{j+1}^{n+1}) = d_1\ Q_j^n + d_2\ (Q_j)^{n+1} + d_3\ (Q_{j+1}^n) \quad \ldots(9)$$

where,

$$\left.\begin{aligned} d_1 &= (1+r)\,\frac{K\epsilon + 1/2\,\Delta t}{K(1-\epsilon) + 1/2\,\Delta t} \\ d_2 &= (1+r)\,\frac{1/2\,\Delta t - K\epsilon}{K(1-\epsilon) + 1/2\,\Delta t} \\ d_3 &= \frac{K\,(1-\epsilon) - 1/2\,\Delta t}{K\,(1-\epsilon) + 1/2\,\Delta t} \end{aligned}\right\} \qquad \ldots(10)$$

Equation (9) can be written in matrix form as below :

$$[Q^{n+1}_{j+1}] = [Q^n_j \;\; Q^{n+1}_j \;\; Q^n_{j+1}]\;[d_i] \qquad \ldots(11)$$

$$[p] = [Q]\;[d_i] \qquad \ldots(11a)$$

$$\text{or}\quad [Q]^T\,[P] = [Q]^T\,[Q]\;.\;[d_i] \qquad \ldots(11b)$$

$$\text{or}\quad [d_i] = [R]\;[H]^{-1} \qquad \ldots(12)$$

where,

$$[P] = [Q^{n+1}_{j+1}]\;,\;[Q] = [Q^n_j \;\; Q^{n+1}_j \;\; Q^n_{j+1}],$$

$$[R] = [Q]^T\,[P], \text{ and}$$

$$[H] = [Q]^T\,[Q]$$

If inflow and outflow are known, 'd_i' coefficients can be calculated from equation (12), which will be best also in least square sense. Knowing the values of 'd_i' coefficients, the outflow, assuming the initial value of outflow is equal to the initial values of inflow at the same time, can be reconstructed. The value of 'r' multiplied to inflow will give the amount of lateral inflow present in the reach.

The values of the three parameters can be evaluated from the three equations for 'di'. It gives the direct solution for the three parameters namely K, ϵ and r.

4.3 Muskingum-Cunge Method

In equation (4), if K is defined by:

$$K = \Delta x/\omega \qquad \text{...(12a)}$$

where, x is the length of the reach and ω the speed of the peak, then it can be seen that equation (4) is the finite difference representation of the kinematic wave equation :

$$\frac{\partial Q}{\partial t} + \omega \frac{\partial Q}{\partial x} = 0 \qquad \text{...(13)}$$

Cunge (1969) observed that if the $[Q_j^n]$ is expressed in terms of their Taylor expansions, equation (4) becomes the finite difference representation of the equation.

$$\frac{\partial Q}{\partial t} + \omega \frac{\partial Q}{\partial t} = \frac{\partial^2 Q}{\partial x^2} \qquad \text{...(14)}$$

When $\mu = (1/2 - \epsilon)\ \omega\ \Delta x$ ...(15)

As $\mu = \alpha\ \bar{Q}_p/L$ from equation

$$\frac{\partial Q}{\partial t} + \omega \frac{\partial Q}{\partial x} = \frac{\alpha Q_p}{L} \left(\frac{\partial^2 Q}{\partial x^2}\right) + \omega\ q \qquad \text{...(16)}$$

Therefore,

$$\epsilon = 1/2 - \frac{\alpha\ \bar{Q}_p}{L\ \omega\ \Delta x} \qquad \text{...(17)}$$

where, L is now the length of the whole reach which is divided into a number of subreaches, each of length Δx. Again α is the value of the attenuation parameter corresponding to the particular discharge value. Cunge originally derived equation (7) in terms of the average slope and width of the channel. (α/L) in equation (17) replaces Cunge's factor $(2\ s\ \bar{W})^{-1}$.

Once K and ϵ have been determined, the downstream discharge is calculated from the recurrence relationship given above (equation 5).

The accuracy of the finite difference scheme in equation (4) depends largely on the magnitude of ϵ. For Δt, the curve (Fig. 1) given by Cunge (1969) should be used. For this $\frac{\Delta x}{(\omega \Delta t)}$, for a particular value of ϵ, should be below the curve. This is sufficient to ensure the accuracy of the method

4.3.1 Procedure

A - *Calculate parameters:*

i - Follow the steps suggested for Variable Parameter Diffusion method. in section 4.4.3 (A,B,C and D)*.

ii - Calculate K and ϵ from equation (12 a) and (17).

iii - Read $\frac{L}{\omega \Delta t}$ for this value of ϵ from curve (Fig.1) and calculate Δt.

iv Calculate the three Muskingum parameters from equation (6).

B- *Calculate outflow*:

i - Assume an initial value Q_o^0, for the outflow discharge Q_1^n at the same time and calculate the rest of hydrograph from equation (5).

(Note : The lateral inflow ordinates should be spceified at time interval Δt)

4.4 Variable-Parameter Diffusion Method

The basic equations, St. Venant equations for gradually varying flow in open channels are:

Continuity:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad ...(18)$$

Momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A}\right) = Ag \left(s_o - \frac{\partial y}{\partial x} - s_{f\gamma}\right) + q\, v_q \qquad ...(19)$$

where,

A = Wetted cross-section area;

Q = discharge;

q = lateral inflow/unit length;

g = gravitational acceleration due to gravity;

s = bottom slope of the channel;

y = depth;

s_{fr} = friction slope; and

v_q = velocity component of q along the channel in the d/s direction.

Price (1975) made following conclusions regarding St. Venant equations:

(i) The momentum of the flow in the river is governed primarily by the bottom slopes, and is modified by the water surface slope, $\frac{\partial y}{\partial x}$ which is defined relative to the bottom slope $\frac{\partial y}{\partial x}$ of the channel.

(ii) The acceleration and convection of momentum terms can be ignored,

(iii) The contribution to the momentum in the main channel from tributaries and lateral inflow can be ignored,

(iv) The lateral inflow from small tributaries and direct runoff can be significant under snowmelt conditions, but in general its effect is small, and

(v) The length scale of a flood wave is cosiderably greater than the lengths of most British rivers.

Conclusion (ii) would not of course be true for flow in steep rivers, and the conclusion may also be violated locally for flow through bridges, weirs and other obstractions in the river. However in the latter case it can often be assumed that head loss at such obstructions are included in the appropriate values for the parameters of a particular flood routing method.

His conclusions and recommendations led him to the equation for flow in channel-flood plain systems given below :

$$\frac{\partial Q}{\partial t} + \bar{C}\frac{\partial Q}{\partial x} = Q\frac{\partial}{\partial x}\left(\frac{\alpha}{L}\quad\frac{\partial Q}{\partial x}\right) + \frac{3\alpha}{L}\left(\frac{\partial Q}{\partial x}\right) + \bar{C}_q \quad ...(20)$$

where,

$\bar{C}$ = average speed of the wave, and

α = attenuation parameter.

It can be seen from equation (20) that any solution for the routing of a hydrograph using this equation is liable to be sensitive to the functional form for $\frac{\partial \alpha}{\partial Q}$. In addition, because the curve for $\frac{\partial\alpha}{\partial Q}$ is generally much more difficult to calculate for a particular river than the corresponing curve for $\bar{C}$, Dr. R.K. Price decided to confine attention to the equation given below:

$$\frac{\partial Q}{\partial t} + \bar{C}\frac{\partial Q}{\partial x} = \frac{\alpha}{L} Q \frac{\partial^2 Q}{\partial x^2} + \bar{C} q \qquad \ldots. \qquad (21)$$

The flood routing method based on equation (21) with $\bar{C}$ and α as prescribed functions of Q can be termed as the Variable Parameter Diffusion method.

4.4.1 Attenuation parameter

For evaluation of α, the reach is divided into a number of sub-reaches, so that the geographical width of the prototype flood plain in each sub-reach is approximately uniform. α can be written as :

$$\alpha(Q) = \frac{1}{2}\left[\frac{1}{L_m}\sum_{m=1}^{M}\frac{P_m}{S_m Y_3}\right]^3 \sum_{m=1}^{M}\left(\frac{P_m^2}{L_m S_m^2}\right) \qquad \ldots(22)$$

P_m = plan area of the inundated flood plain and the channel in the mth sub reach;

L_m = length of the channel; and

S_m = bottom slope of the channel.

It has been assumed that the width Wc of the channel is uniform along the reach. α (Q) can readily be found for the largest recorded flood if limits of flooding on the flood plain are known. In addition, α can be calculated for a small inbank flood from following relationship:

$$\alpha = \frac{1}{2W_c}\left[\frac{1}{L_m}\sum_{m=1}^{M}\frac{L_m}{S_m^{1/3}}\right]^{-3}\sum_{m=1}^{M}\left(\frac{L_m}{S_m^2}\right) \qquad \ldots(23)$$

It is very difficult to obtain the intermediate values for α(Q). For this the two extreme points can be joined properly. The shape of the curve will depend upon the flatness of the flood plain.

4.4.2 Convection speed

The convection speed $\bar{C}$ can be calculated from the record of previous floods and by unit hydrograph theory. In the earlier case there should be at least one gauging station with a reasonbly accurate rating curve. The unit hydrograph or similar theory is used when there is no reliable rating curve to obtain the previous discharges of the previous floods to correlate with the observed speeds of those floods, and to generate discharge hydrograph at the upstream section as the input for the flood routing method.

$\bar{C}$ (Q) is properly defined as the average speed along a reach of the flood wave with peak discharge Q under the condition that there is no attenuation. When there is attenuation of the peak discharge the observed speed of the flood peak is a function not only of $\bar{C}$ but also of the shape of the discharge hydrograph. Hayami (1951) derived a relation for the speed.

$$\omega = \frac{L}{T_p} - \frac{2\alpha}{L^2} Q^* \qquad \text{...(24)}$$

Price (1975) suggested for rivers:

$$\bar{C} = \omega + Q^* \frac{d}{dQ} \left(\frac{L}{T_p} \right) \qquad \text{...(25)}$$

4.4.2 Solution Technique

Equation (21) has been solved as below :

The downstream boundary condition for equation (21) are:

Initial condition:

$$Q_j^o = Qinit = \text{constant for } 0 \le j \le J \qquad \text{...(26)}$$

Upstream conditions:

$$Q_o^n = F_1 (n\ t) \text{ for } 0<n \qquad \text{...(27)}$$

Downstream condition:

$$Q_j^{n+1} = Q_j^n, + \left[C_j^{-n}, q_j^n, + \frac{\alpha_j^n}{L} Q_j^n, \left(\frac{\partial^2 Q}{\partial x^2} \right), {}_j^n \right] \Delta t \qquad \text{...(28)}$$

$F_1(t)$ is the recorded discharge hydrograph which is used as the input for the model at the upstream boundary. J'refers to the point at time n Δt on the characteristic curve. (see Fig. 2) through the point [JΔx, (n+1) Δt]. $\Delta x'$ from J' from the downstream boundary is as below :

$$\Delta x' \approx \bar{C}^n_j \, \Delta t \qquad \ldots(29)$$

$Q^n_{j'}$, is then calculated from a quadratic spline through Q^n_j, Q^n_{j-1} and Q^n_{j-2} using $\Delta x'$. But as $\Delta x'$ is itself a function of $\bar{Q}^n_{j'}$, it is necessary to iterate to find an accurate value for $Q_{j'}^n$. Once $Q^n_{j'}$ is known, values for $C^n_{j'}$, $\alpha^n_{j'}$, and $(\partial^2 Q/\partial x^2)^n_{j'}$, can be evaluated and substituted in equation (25) to find Q^{n+1}_j.

Given the values for Q^{n+1}_o, Q^{n+1}_j and the $[Q^n_j]$ it remains to solve the set of non-linear simulatenous equations in the $[Q_j^{n+1})$. These equations are solved by Newton iteration procedure (Amein and Fang, 1970). This procedure involves the evaluation of the finite-difference expression for estimated values of the $[Q^{n+1}_j]$. The finite difference expression for equation (21) is :

$$\Omega_j \equiv Q^{n+1}_j - Q^n_j + \frac{\Delta t}{4\Delta x} \bar{C}\ (Q_a)\ [Q^{n+1}_{j+1} - Q^{n+1}_{j-1} + Q^n_{j+1} - Q^n_{j-1}]$$

$$- \bar{C}\ (Qa)\ q^{n+1}_j$$

$$- \frac{\Delta t}{2L_{\Delta x}{}^2}\ \alpha\ (Qa)\ Qa\ [Q^{n+1}_{j+1} - 2\ Q^{n+1}_j + Q^{n+1}_{j+1}$$

$$+ Q^n_{j+1} - 2\ Q^n_j + Q^n_{j-1}] = 0 \qquad \ldots(30)$$

for all $1 \leq j \leq j-1$, where

$$Q = \frac{1}{2}\ [Q^{n+1}_j + Q^n_j] \qquad \ldots(31)$$

The (Q^{n+1}_j) are then replaced by a set $[Q^{n+1}_j + dQ^{n+1}_j]$, where the $[dQ^{n+1}_j]$ are the solution of the simultaneous linear equations:

$$a_{j,j-1}\ dQ^{n+1}_{j+1} + a_{j,j}\ dQ^{n+1}_j + a_{j,j+1}\ dQ^{n+1}_{j+1} = \Omega_j \qquad \ldots(32)$$

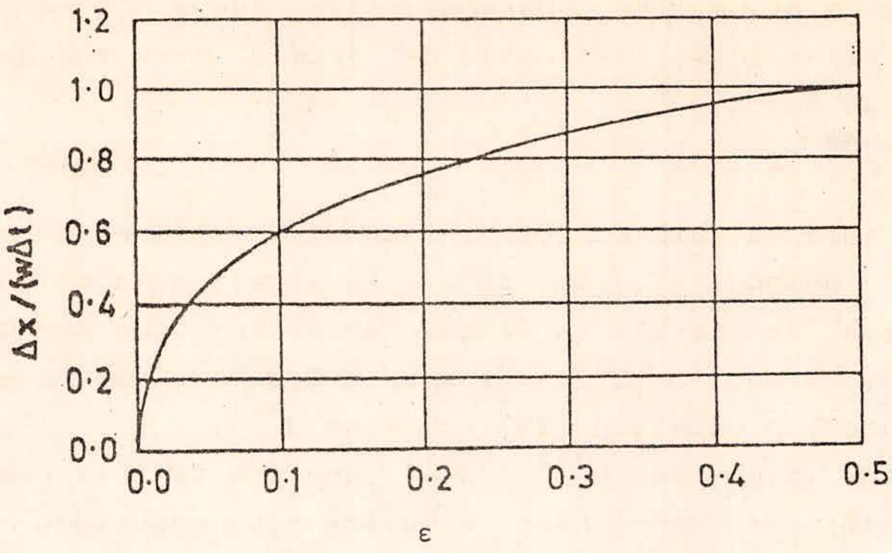


Fig. 1 : Curve for $\Delta x/(w\Delta t)$ Vs. ε

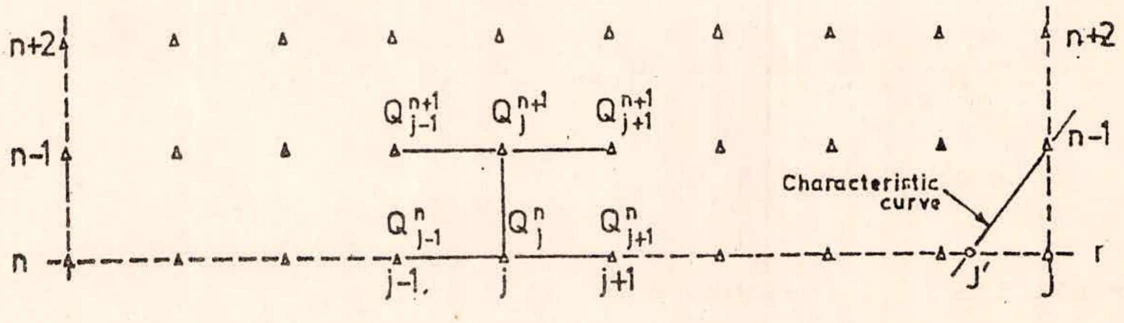


Fig. 2 : Finite Difference Net

Because of the banded nature of the matrix $[a_{j,k}]$ it has been solved by Gaussian elimination procedure. Then trial and error procedure is adopted to calculate the new values of $[Q_j^{n+1}]$.

For maximum accuracy of the implicit finite difference scheme, Δx and Δt should be chosen so that :

$$\frac{\Delta x}{\Delta t} \geq \bar{C}ave \qquad \ldots(33)$$

where, $\bar{C}ave$ is an average value for $\bar{C}$ defined over the anticipated range of values for Q. There are two constraints to be satisfied for Δt, one is :

$$\Delta t < 2\left(\frac{1}{Q}\frac{d^2Q}{dt^2}\right)^{-1/2} \qquad \ldots(34)$$

where the right hand side of this inequality is evaluated at the peak of the upstream hydrograph. The second is :

$$\Delta t < \frac{\bar{C}\ min}{\left|\frac{dQ}{dt}\right| max \left|\frac{dc}{dQ}\right| max} \qquad \ldots(35)$$

where $\left|\frac{dQ}{dt}\right|$ max is the maximum gradient of the upstream hydrograph $\bar{C}$ min and $\left|\frac{dC}{dQ}\right|$ max are the min. and max. values of $\bar{C}$ and $\left|\frac{dC}{dQ}\right|$ in the range of discharge anticipated at the downstream boundary. In practice Δt should be determined first from equations (33) and (35) and Δx should be calculated from equation (33). Finally, Δx is adjusted so that $\frac{L}{\Delta x}$ is an integer.

4.4.3 Procedure

A - *Attenuation parameter:*

(1) Define the flood plain as the known area inundated by the largest recorded flood, or as estimated from a survey map.

(2) Divide the reach into a number of subreaches of uniform width.

(3) For each subreach measure the length, Lm of the channel the average slope s_m, of the channel, the plan area, Pm, of the flood plain (including the plan area of the channel)

(4) For the whole reach calculate the length L of the channel, and an average width, $\bar{W}c$ of the channel.

(5) Calculate the attenuation parameter from equation (22) and (23) and join their points by a curve.

B - *Convection speed:*

(i) Extract the times of travel Tp of the peak of the largest recorded flood and the inbank flood from records. Define the speed by L/Tp.

C - *Curvature of U/S hydrograph:*

(i) Find time to peak, tp. Mark the two points on the hydrograph at a time interval Δt (nearest hour)-

$$\Delta t = tp/5 \qquad \ldots(36)$$

Δt not greater than 3 hrs

(ii) Calculate the curvature at peak from

$$\frac{\partial^2 Q_p}{\partial t^2} = \frac{Q_1 + Q_{-1} - 2\,Q_p}{(\Delta t)^2} \qquad \ldots(37)$$

Q_1 and Q_{-1} are the discharges either side of the peak Q_p

D - *Attenuation of peak discharge :*

(i)

$$Q^* = \frac{\alpha_p}{(L/T_p)^3}\, Q_p \left|\frac{d^2 Q_p}{dt^2}\right| \qquad \ldots(38)$$

(ii) If $Q^*/Q_p > 0.1$, read e fine Q^* by

$$Q^*_{new} = Q_p\,[1-\exp\,(-\frac{Q^*}{\bar{Q}_p})] \qquad \ldots(39)$$

and define w_p by:

$$\omega_p = \frac{L}{T_p} - \frac{2\alpha_p}{L^2}\, Q^*_{new} \qquad \ldots(40)$$

(iii) Define the avearage peak discharge, $\bar{Q}_p$ for each flood by

$$\bar{Q}_p = Q_p - \frac{1}{2}\, Q^*_{new} \qquad \ldots(41)$$

(iv) Plot the values of α_p and w_p with the values of $\bar{Q}_p$. Plot the points on a graph.

(v) Calculate the downstream hydrograph using the procedure.

4.5 Kalinin-Milyukov Method:

A method which has a quite different approach but more logical was presented by two Russian Scientists Kalinin and Milyukov (1957) and hence the method is named after them. This is physically based n-linear reservoirs model. It is physically based because the length of the reach which can be modelled by a single linear reservoir (SLR) is given in terms of the channel and flow characteristics of the reach. They computed the length of the reach assuming that there is a single value relationship between the downstream discharge and the stage (Fig.3) at the middle of the SLR reach. The discharge Q can be expressed as a function of stage at the middle of the reach as follows:

$$Q = f\ (Hm) \qquad \ldots(42)$$

$$Q = f\ (H,\ s) \qquad \ldots(43)$$

Where,

s = the water surface slope,

H_m = Water level at M,

H = Water level at B

The total derivative of Q is given as

$$dQ = \frac{\partial Q}{\partial H}\,dH + \frac{\partial Q}{\partial s}\,ds \qquad \ldots(44)$$

$$= 0 \qquad \ldots(45)$$

where,

$dH = -l\ ds$

The negative sign means that H is reducing in the downstream direction. The 'l' is as marked in the figure 4. Substituting the equation (45) in (44):

$$-\frac{\partial Q}{\partial H}\,.l\ ds + \frac{\partial Q}{\partial s}\,ds = 0 \qquad \ldots(46)$$

$$\text{or } l = (\partial Q/\partial s)/(\partial Q/\partial H) \qquad \ldots(47)$$

If the Manning's equation is assumed to be applicable to the flow:

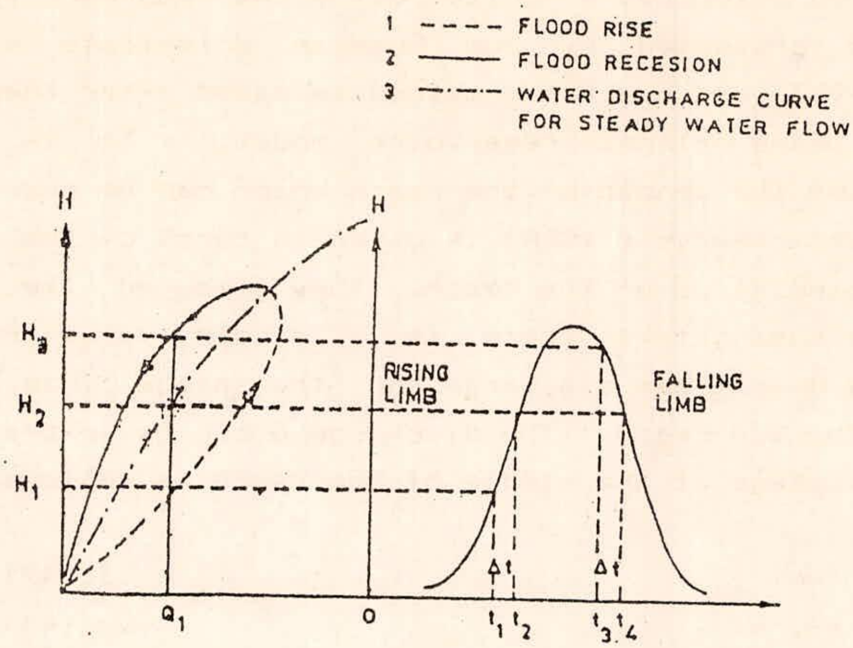


Fig. 3 : Idealized Loop Rating Curve

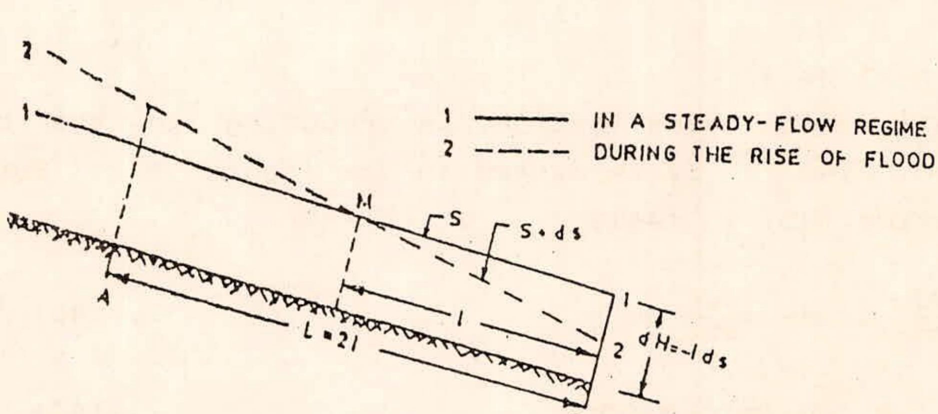


Fig. 4 : Schematic Diagram of Water Surface in a Reach

$$Q = \frac{1}{n} AR^{2/3} s^{1/2} \qquad \ldots(48)$$

$$\frac{\partial Q}{\partial s} = \frac{1}{n} AR^{2/3} \frac{1}{2s}$$

$$= \frac{Q}{2s} \qquad \ldots(49)$$

Substituting this in equation (47):

$$l = \frac{Q}{2\, s\, (\frac{\partial Q}{\partial H})} \qquad \ldots(50)$$

The equation (50) can be arrived at even with other uniform flow equations like Chezy's, etc. The length 'l' is known as characteristic length. The length '2l' acts as a linear reservoir.

4.5.1 Routing parameters:

Assuming that the water surface in a reach where routing is to be done, is a straight line as shown in Figure 4 the following can be deducted:

Storage in a reach S = f (Stage at a section).

Since stage and discharge (not necessarily of the same section) are related single valuedly, storage can be expressed as:

$$S = f\ (\text{Weighted discharge, } Q_m)$$
$$= f\ (\epsilon Q_j + (-\ \epsilon)\ Q_{j+1}) \qquad \ldots(51)$$

where,

ϵ, Q_j, Q_{j+1} are all same as described earlier.

If this weighted discharge is occuring at a distance 'l' from the middle of the reach considered, Q_m can be interpolated as:

$$Q_m = Q_{j+1} + \frac{Q_{j+1} - Q_j}{L} \left(\frac{L}{2} - l \right) \qquad \ldots(52)$$

where 'L' is the length of reach.

Now,

$$S = f\ (Q_m)$$
$$= f \left(\left(\frac{1}{2} - \frac{l}{L} \right) Q_j + \left(\frac{1}{2} + \frac{l}{L} \right) Q_{j+1} \right) \qquad \ldots(53)$$

The equation (53) can be written in the form of Muskingum equation as below :

$$S = K \left[\left(\frac{1}{2} - \frac{}{L}\right) Q_j + \left(\frac{1}{2} + \frac{}{L}\right) Q_{j+1} \right] \qquad ...(54)$$

where,

$$\epsilon = \frac{1}{2} - \frac{1}{L}$$

If the reach length is 21 then $\epsilon = 0$ when 'L' is very large, ϵ tends to be 0.5.

The Parameter 'K' can be calculated as:

$$K = \frac{L}{C} \qquad ...(55)$$

where,

$$C = \frac{dQ}{dA} = \frac{dQ}{W\ dH} \qquad ...(56)$$

W = width of the river

'C' can be obtained from the rating curve and the width of the river at the downstream section.

Now, the equation (54) with the continuity equation as explained in the section 4.1, the routing can be done.

4.5.2 Procedure

The following steps are used to route the flood by Kalinin-Milyukov method :

(i) Find the value of 'K' form equation (55) with the help of the cross-sectional data and routing curve at downstream section.

(ii) Find the value of 'l' from equation (50) with the help of the rating curve and the flow characteristics of the flood.(iii) Find the value of x.

(iv) Route the flood using regression equation explained in section 4.1.

4.6 Model Efficiency

The efficiency of the model in simulating the outflow is calculated as below:

$$\eta = (1 - \frac{F_1}{F_o}) \times 100$$

and $F_1 = \sum_{i=1}^{n} (Qi - \hat{Q}i)^2$, and

$$F_o = \sum^{n} (Qi - \bar{Q}i)^2$$

where,

η = efficiency of the model (percent)

F_1 = model variance

Fo = initial variance

Qi = observed outflow

$\bar{Q}_i$ = mean of the observed outflow

$\hat{Q}_1$ = Calculated outflow

5.0 DATA REQUIREMENT

The type of data required for the routing of a flood through a reach, depends upon the particular model used. The data requirement for all the methods described in this report, namely Conventional Muskingum method, Three-Parameter Muskingum type procedure, Muskingum-Cunge method, Variable Parameter Diffusion method and Kalinin Milyukov method, is given seperately for each method as follows:

5.1 Conventional Muskingum Method:

(i) upstream hydrograph

(ii) value of K and ϵ

(iii) initial value of d/s hydrgrograph (at time = 0)

5.2 Three-Parameter Muskingum type procedure:

(i) inflow hydrograph

(ii) outflow hydrograph

5.3 Muskingum-Cunge Method:

(i) survey map of the area concerned

(ii) average width, length and slope of the river reach

(iii) upstream hydrographs, and time of travel (T_p) of the

5.4 Variable-Parameter Diffusion Method:

(i) same as for Muskingum-Cunge method.

5.5 Kalinin Milyukov Method:

(i) cross-sections of the river at both ends of the river reach, length of the reach and its slope.

(ii) stage-discharge relationship (rating curve at either or both ends of the river reach).

6.0 APPLICATION

River System and Basin Characteristics:

Tapti is second largest river of Central India which flows westward and discharges into Gulf of Cambay (Arabian Sea). Tapti takes its origin in Multai hills in the Gavilgadh hill ranges of Satpura mountain in Madhya Pradesh.

The Tapti basin extends over an area of 65145 sq.km. and lies between east longitude of 72^{O} 38' to 78^{O} 17' and north latitude 20^{O} 5' to 22^{O} 3' situated in Deccan Plateau. The river is 724 km. long rises at an elevation of 752 m above M.S.L. and runs generally due west, joining the Arabian Sea Approximately 15 km. West of the city of Surat. A basin map of Tapti river is given at figure 5.

Physiography:

The Basin has alongated shape with maximum length of 587 km. from east to West and maximum width of 201 Km. from North to South. This basin has two well defined physical regions viz. hilly regions and plains. It can be divided into four sections as given in Table 1.

Tributaries:

The Tapti receives several tributaries, generally from left Bank, The details of important tributaries with their catchment area, length and meeting point with Tapti are given in Table 2. The line diagram of Tapti river is given in Fig. 6.

Monsoon and Rainfall:

The average annual rainfall of the catchment is 78.8 cm. More than 90 percent of rainfall occurs during South-West monsoon from mid of June to mid of October. and about 50 percent of rainfall is received in the month of July and August.

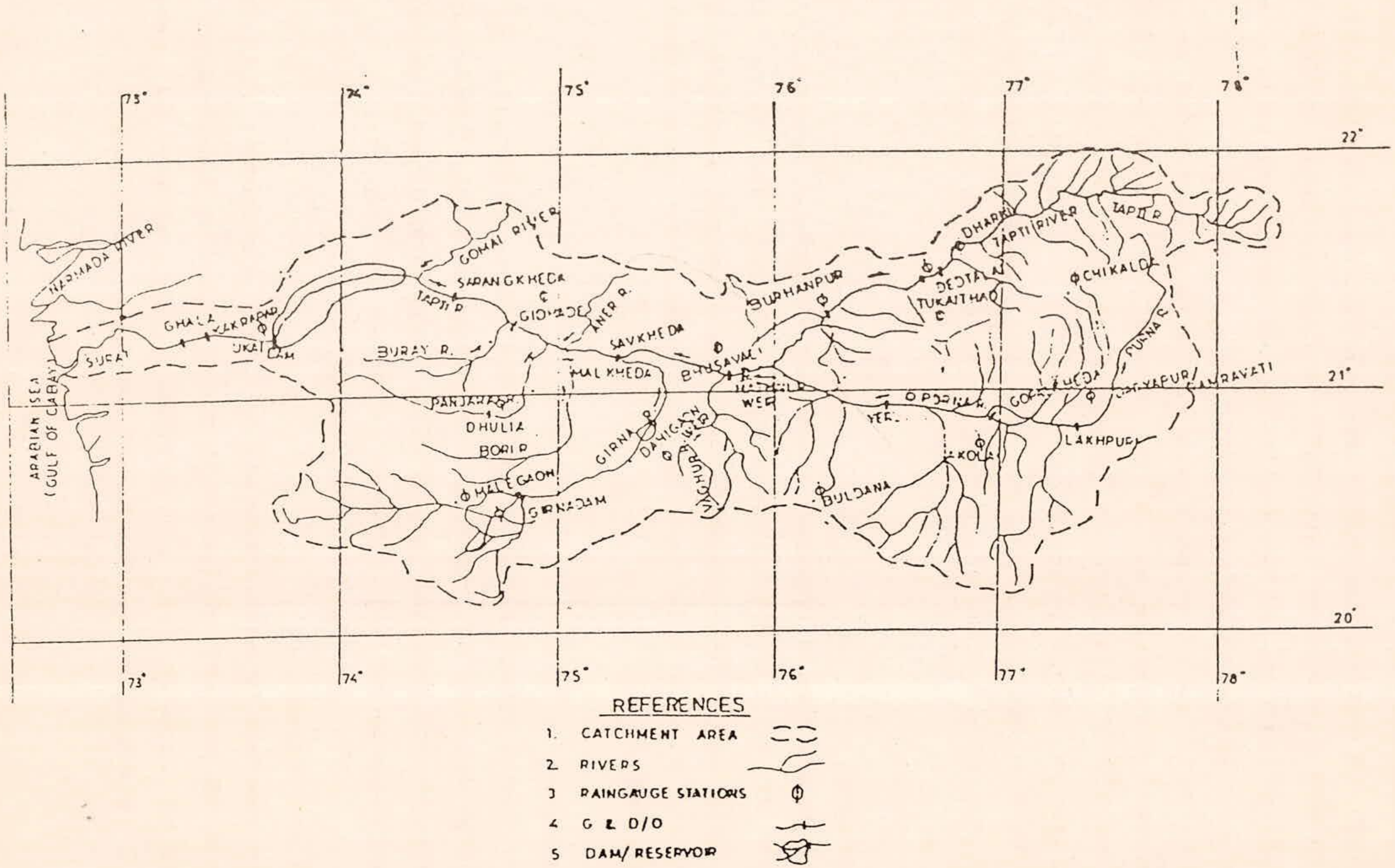


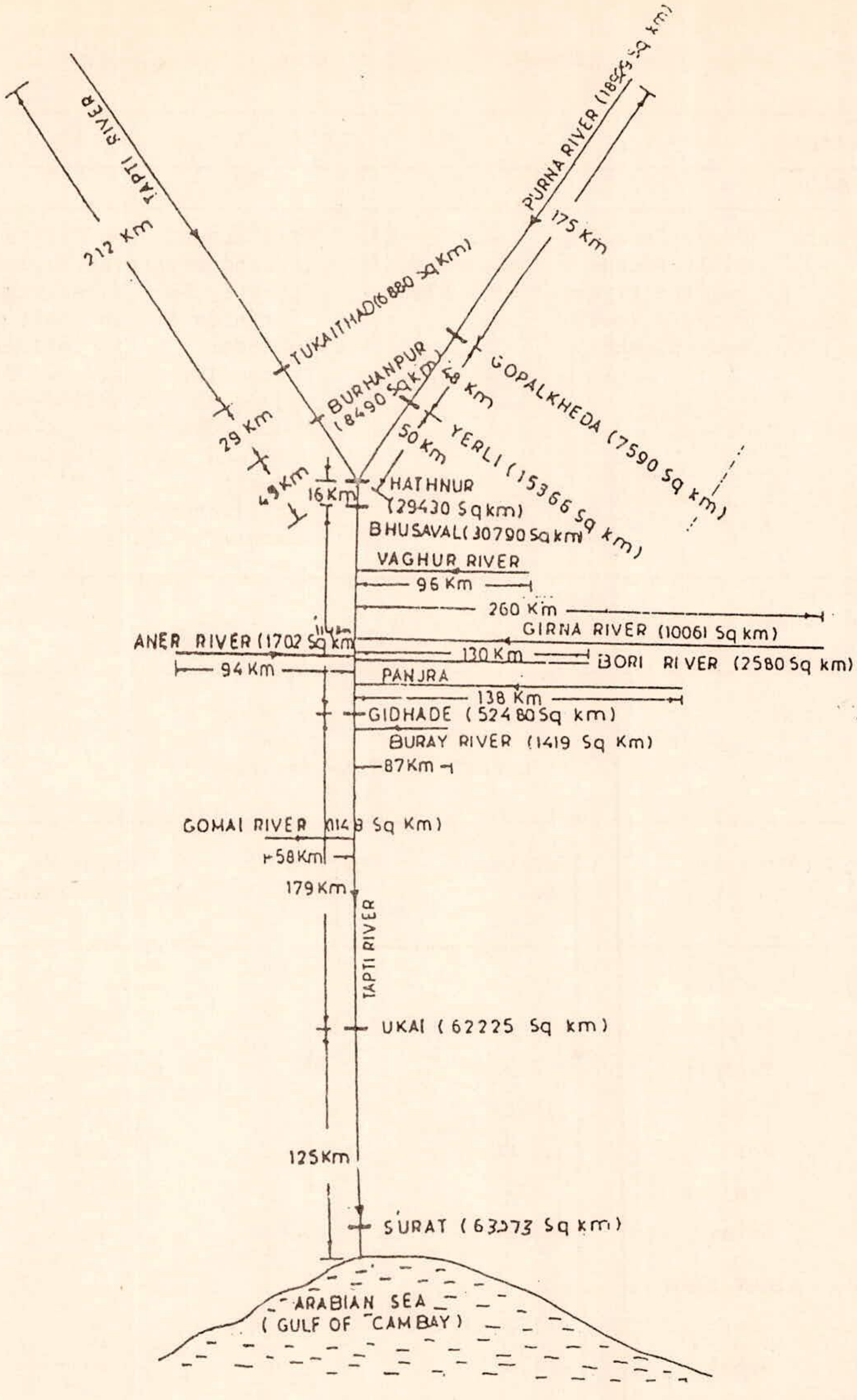
Fig. 5 : Index Map of Tapti Basin

Table 1 : Catchment Characteristics of Tapti Basin

Section	I	II	III	IV
Length	241	290	80	113
Terrain	Dense forests, hilly ranges hug the river banks. Rocky bed and steep	Rich fertile plains generally black soil	Hill tract, covered with forests, No. of rapids & in lower reach river widens to about 900m. Wild and almost unhabitated reach	Low flat alluvial plains of Gujarat River meanders and last 48 km. is influenced by tides. Black soil combined with coastal alluvium clays
Average bed slope m/km.	2.16	0.52	0.56	0.35

Table 2 : Details of Tributaries

Sl. No.	Tributary	Catchment Area sq.km.	Length of run km.	River Km. at confluence
(A).	LEFT BANK			
1.	Purna	18929	334	282
2.	Vaghur	2592	96	340
3.	Girna	10061	260	372
4.	Bori	2580	130	386
5.	Panjhra	3257	138	400
6.	Buray	1419	87	424
(B).	RIGHT BANK			
7.	Aner	1702	94	362
8.	Gomai	1148	58	481



REMARKS: FIG. GIVEN IN BRACKET IS C.A. UP TO THAT SITE/RIVER
(TOTAL C.A. OF BASIN = 65145 Sq Km)

Fig. 6 : Line Diagram of the Tapti Basin

The upper area is rainfall prone and about 75 percent o flood volume is received from this area. At a time daily rainfall of about 30 cm has been recorded at a raingauge station.

Temperature:

The mean minimum temperature varies from 11.1° C to 14.4°C but the temperature below freezing point has also been recorded. The mean maximum temperature ranges from 38°C to 48°C. and dust storms are common in the western area. The mean temperature in the basin varies from 25°C to 30°C.

Evaporation:

Sufficient data on evaporation is not available, however the evaporation losses assumed from Ukai Project is 138 mm/year and for Upper Tapti Basin is 244 mm/year.

Water Resources Structures:

There are no. of small, medium and major projects in the basin, almost 80-90 percent of water potential is utilised. The major irrigation projects already completed are (i) Ukai Dam (on Tapti) (ii) Girna Dam (on Trib. Girna) (iii) Hathnur Weir (on Tapti) (iv) Dahigaon Weir (on Trib. Girna).

The Ukai Dam is a multipurpose dam and lies at tail end of the river. After construction of this dam the flood problem of the Surat City and tail reach has been solved, but an efficient inflow forecast is required for regulation of flow from this dam.The location of all these projects are shown in figure 5.

Storm Movement:

Tapti Catchment is often hit by storm caused by depressions originating both from Arabian Sea and Bay of Bengal which causes heavy rains resulting in High floods. Although the Tapti catchment is not being directly affected by storm track, but as it falls in South-Western sector of storms, it gets well distributed rainfall over its entire catchment except its extreme western end, where a steep isophyetal gradient exists due to influence of western ghats. Many times the depression moves along the river courses synchronising with the movement of flood. This phenomena causes devastating floods. In addition to this, many times high tides with tidal wave synchronises with floods resulting in devastation.

Availability of data:

The runoff data in compiled form were available in the M.E. Thesis by Bhandari (1988) and these have directly been taken from that thesis. The reach selected in from Hathnur to Bhusaval, 16 km. in length. The plan area has been calculated from the topo-sheets available at NIH in the scale of 1:50,000.

7.0 RESULTS AND DISCUSSION

Five simplified routing techniques namely Conventional Muskingum Method (CM), Three-Parameter Muskingum Method (TPM), Muskingum-Cunge method (MC), Variable Parameter Diffusion Method (VPD) and Kalinin-Milyukov method (KM) have been compared. The data of River Tapti between Hathnur and Bhusaval have been used for the analysis. Four events have been used for the purpose. The details of the four events are given in Table 3, in which Δt is the time interval between the ordinates of the flood data. It can be seen from Table 3 that as the peak of the flow is increasing, the lateral inflow contribution towards the reach is deceasing and in one case when the peak is highest of all the four events the negative lateral inflow occurs. This may be due to the contribution of groundwater (base flow). When the flow in the river is less, groundwater flows towards the river from the aquifer and when there is high flow in the river recharging of the aquifer occurs resulting in the loss of water in the river. This lateral inflow has been taken into account assuming that, it joins or diverts from the river at the upstream end of the reach.

7.1 Comparison of the techniques:

A comparative statement of all routing techniques is given in Table 4 in which CM stands for Convention Muskingum Method, TPM for Three-Parameter Muskingum method, MC for Muskingum-Cunge Method, VPD for Variable Parameter Diffusion Method and KM for Kalinin-Milyukov method. The results by each method are described as below:

In CM method, the parameters K and ϵ have been calculated by the method of moments, least-squares method and the graphical method and the combination which gives the maximum efficiency, is adopted for the calculation of outflow hydrograph. From the Table 4 it is seen that the error in peak is in the range of -5.10% to +6.39% and the model efficiency is in the range of 90.61% to

Table 3 : Details of the Events

Event No.	Flood Year	Δt (hrs)	Peak (cumec)	Inflow t_p (hr)	Vol. (MCM)	Peak (cumec)	Outflow t_p (hr)	Vol. (MCM)	Lateral Inflow (% of inflow)
1	Aug. 83 (11-18)	5.0	7036	40	1582.31	6410	45	1521.23	(-) 2.63
2	Aug. 85 (02-06)	4.0	1924	20	303.44	2300	24	393.84	(+) 29.79
3	July 86 (16-18)	2.0	2180	14	146.34	2550	16	163.87	(+) 11.98
4	Aug. 88 (22-27)	8.0	4577	30	977.82	4654	30	1035.14	(+) 5.86

Table 4 : Results of Routing Techniques

Event No.	Routing techniques	Obs. peak (cumec)	Outflow t_p (hr)	Cal. peak (cumec)	Outflow t_p (hr)	Error in peak (%)	Model var./ Initial var.	Model eff. (%)
1.	CM	6410	45	6654	40	(+) 3.81	0.022	97.84
	TPM			6530	40	(+) 1.87	0.017	98.32
	MO			6654	45	(+) 3.81	0.039	96.08
	VPD			6671	45	(+) 4.07	0.060	94.05
	KM			6736	45	(+) 5.08	0.030	97.01
2.	CM	2300	24	2447	24	(+) 6.39	0.039	96.08
	TPM			2304	24	(+) 0.17	0.020	97.99
	MO			2419	24	(+) 5.17	0.083	91.68
	VPD			2384	24	(+) 3.65	0.151	84.88
	KM			2517	24	(+) 9.43	0.057	94.25
3.	CM	2550	16	2420	16	(-) 5.10	0.094	90.61
	TPM			2405	16	(-) 5.69	0.089	91.10
	MO			2158	18	(-)15.37	0.240	76.03
	VPD			2024	20	(-)20.63	0.663	36.44
	KM			2306	20	(-) 9.57	0.147	85.33
4.	CM	4654	30	4812	36	(+) 3.39	0.017	98.27
	TPM			4628	36	(-) 0.56	0.015	98.49
	MO			4760	36	(+) 2.27	0.016	98.39
	VPD			4757	36	(+) 2.21	0.030	96.96
	KM			4685	36	(+) 0.67	0.016	98.43

98.27%. In two cases the time to opeak is exactly matching and in the remaining cases the time to peak is differing by one time step.

In TPM, the three 'di' coefficients are determined by matrix inversion procedure and then the three parameters are calculated using the relation available between the three parameters and the 'di coefficients. The parameters so calculated are also best in the least square sense. From Table-4 it is seen that the error in peak is in the range of -5.69% to +1.87% and the model efficiency is in between 91.10% to 98.49%. The performance of this method regarding simulation of time to peak is similar to that for CM method.

The calculation of C and α and C (Q) and α (Q) for MC and VPD respectively has been done on the basis of limited no. of data availabale for the purpose. Even after this handicapa the attempt has been made to apply these methods in the field. In three cases, the peak flow has been simulated by these methods within the error of 3.81% to 5.17% and 2.2% to 4.07% respectively Only in one case (event no. 3) the variation is 15.37% in the cases of MC and 20.63% in the case of VPD. This might be because of the unreliable values of $\bar{C}$ and α for this peak flow. In the case of MC the model efficiency is ranging from 91.68% to 98.39% in three cases and for one event (event no. 3) the efficiency is 76.03%, that is the model is not performing satisfactorily for this event. The same is case with VPD. In the three cases the model efficiency is in between 84.88% to 96.96% and for the event no. 3, the efficiency is 36.44%. For this event the model is performing poorly.

The Kalinin-Milyukov method is simulating the peaks of the four events within the range of 0.67% to 9.57% and the performance of the model is, within efficiency of 85.33% to 98.43%. The case of average results by KM method might be because of the error involved in the establishment of rating curve and in the measurement of the physical data of the river.

As discussed earlier, it is evident that the TPM is performing best among all methods in simulating the outflow hydrograph. The CM method is also simulating the outflow satisfactorily and in ranking performance wise, it stands second. In the case of CM, the parameters have been calculated, as discussed earlier, by three methods and that combination of the parameters which gives the best results is adopted for simulation. In this case the estismatison of the parameters is a tedious job while in the case of TPM it is very easy to estimate the parameters.

Kalinin-Milyukov method, an established method of flood routing using the physical characteristics of the river, gives average results while it is applied on Tapti data (Table -4). It should be applied to the river reach for which a reasonably accurate rating curve, cross-section and longitudinal section of the river are available. The results may improve with the improvement in the data availability.

Muskingum-Cunge and Variable-Parameter Diffusion method, though better than the Conventional Muskingum method (NERC, 1975) don't perform as the other methods do. This might be due to the lack of information availabale for the establishment of C(Q) and α(Q) curves. More information about the physical properties of the river is required.

7.2 Sensitivity Study

To study the effect of error in different routing parameters used in the methods of flood routing and errors in inflow, sensitivity analysis has been made. For this purpose, considering the inflow and parameters/varaibles as known, the outflow was computed. This computed outflow was assumed as given outflow (Q_{sc}) for sensitivity study. The inflow was then increased by 10% and keeping the parameters same for the concerned method, the outflow was computed and compared with Q_{peak}, time to peak and efficiency to indicate the effect of error in inflow.

On similar lines, the inflow was then decreased by 10% and outflow compared with Q_{sc}. Similarly, the parameters of the concerned method are one at a time were changed by + 10% or 10% and outflow was computed for the given inflow and compared with Q_{sc}

The results of sensitivity analysis are given in Table.5. It is evident from the Table that the error in the inflow is directly reflected in the results in all the routing techniques by the same amsount except in KM method in which it is slightly less. Therefore, the inflow data should be collected with proper care and judgement. More care should be given in the estimation of 'K' in TPM and KM than the care given in CM method as the error in the peak discharges in TPM and KM is double of that in CM with the same amount of change in value of 'K'. The change in ϵ in both the cases (CM and TPM) does not affect much. The parameters $\bar{C}$ and α in the MC and VPD should be selected carefully but somewhat more carefully in VPD.

The change in rating curve (U/S or D/S) in Kalinin Milyukov Method also affects the results more than change in any other variable, except the change in inflow, hence the establishment of rating curve also needs special attention.

Table 5 : Results of the Sensitivity Analysis

Run No.	Variable changed to	Outflow (obs.)		Cal. Outflow		Error in peak (%)	Mod. Var./ Ini. var.	Model eff. (%)
		Peak (cumec)	t_p (hrs)	Peak (cumec)	t_p (hrs)			
A.	Conventional Muskingum Method							
1.	1.10*INFLOW	6654	30	7319	40	9.99	0.042	95.83
2.	0.90*INFLOW			5989	40	-9.99	0.042	95.83
3.	1.10* K			6643	40	-0.17	0.00005	99.995
4.	0.90* K			6664	40	0.15	0.00006	99.994
5.	1.10* ϵ			6654	40	0.00	0.00003	99.997
6.	0.90* ϵ			6654	40	0.00	0.00002	99.998
B.	Three Parameter Muskingum Method							
7.	1.10*INFLOW	6530	40	7182	40	9.98	0.043	95.66
8.	0.90*INFLOW			5877	40	-10.00	0.043	95.66
9.	1.10* K			6508	40	- 0.34	0.0001	99.993
10.	0.90* K			6551	40	0.32	0.0001	99.993
11.	1.10* ϵ			6528	40	- 0.03	0.0000	99.999
12.	0.90* ϵ			6530	40	0.00	0.0000	99.998
13.	1.10* r			6500	40	- 0.46	0.0001	99.991
14.	0.90* r			6560	30	0.46	0.0001	99.991
C.	Muskingum-Cunge Method							
15.	1.10*INFLOW	6654	45	7344	45	10.37	0.045	95.46
16.	0.90*INFLOW			5964	45	-10.37	0.045	95.46
17.	1.10* C			6659	45	0.08	0.0003	99.97
18.	0.90* C			6643	45	-0.17	0.0001	99.99
19.	1.10*ALPHA			6648	45	-0.09	0.00001	99.999
20.	0.90*ALPHA			6660	45	0.09	0.00002	99.998

contd.....

Table 5 (contd.)

Run No.	Variable changed to	Outflow (obs.) Peak (cumec)	Outflow (obs.) t_p (hrs)	Cal. Outflow Peak (cumec)	Cal. Outflow t_p (hrs)	Error in peak (%)	Mod. var./ Ini. var.	Model eff. (%)
D.	Variable Parameter Diffusion Method							
21.	1.10* INFLOW	6671	45	7366	45	10.42	0.053	94.72
22.	0.90* INFLOW			5962	45	-10.63	0.053	94.72
23.	1.10* C			6671	45	0.00	0.010	99.02
24.	0.90* C			6664	45	-0.10	0.010	99.00
25.	1.10* ALPHA			6667	45	-0.06	0.009	99.06
26.	0.90* ALPHA			6673	45	0.03	0.009	99.06
E.	Kalinin-Milyukov Method							
27.	1.10* INFLOW	6736	45	7317	45	8.63	0.011	98.87
28.	0.90* INFLOW			6154	45	-8.64	0.101	89.93
29.	1.10* K			6714	45	-0.33	0.018	98.20
30.	0.90* K			6755	45	0.28	0.018	98.22
31.	1.10* S_o			6707	45	-0.43	0.019	98.12
32.	0.90* S_o			6670	45	0.98	0.019	98.12
33.	1.10* RAT (U/S)			6618	45	-1.75	0.019	98.10
34.	0.90* RAT (U/S)			6618	45	1.75	0.019	98.10
35.	1.10* RAT (D/S)			6602	45	-1.99	0.019	98.06
36.	0.90* RAT (D/S)			6637	45	1.47	0.019	98.14

8.0 CONCLUSION

Hydraulic methods need a large amount of data and computation facility, because of this, simplified hydraulic/hydrologic methods are preferred over them. In this report five routing techniques namely Conventional Muskingum Method, Three-parameter Muskingum type procedure, Muskingum-Cunge Method, Variable Parameter Diffusion Method and Kalinin-Milyukov method of flood routing have been considered for comparison using data for subreach of river Tapti. A sensitivity analysis has also been made to see the effect of different input variables on the results.

From this analysis, it can be concluded that Three-Parameter Muskingum type procedure is performing best of all the methods considered in the report. This method has got the advantage that it takes lateral inflow into account and hence has got good applicability in the field.

In the case of Conventional Muskingum method, the parameters K and ϵ should be known accurately. The presence of lateral inflow is to be considered carefully before applying the method. In this report, the parameters have been calculated by three methods, which is somewhat tedious job. Hence, Three-parameter Muskingum Method is preferable for field application.

The Muskingum-Cunge and Variable Parameter methods, are not performing as well as the other methods. The improvement in the data base may improve the results.

The Kalinin-Milyukov method, a tested method, gives somewhat average performance in this study. The results may improve with the improvement in the establishment of rating curve.

From the sensitivity analysis, it is seen that the inflow should be measured accurately because the error in the inflow data is directly reflected in the results. Other input variables like K and ϵ in CM and TPM, rating curves in KM, and $\bar{C}$ and α in VPD, also need to be estimated with proper care and judgement.

The above conclusions are however, based on limited data for one river reach. In order to draw general conclusions on relative merits/demerits of flood routing methods. it would be necessary to carryout more studies on similar lines using data sets for a number of reaches and rivers covering a wide range of discharges (inflows, lateral flows etc). This report provides useful reference material for such studies.

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