

# **Software (FloodRoute) for computation of the propagation (routing) process of flood wave discharge hydrographs in stretches (reaches, sections) of rivers or canals**

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## **Abstract**

Classically the propagation of flood waves in rivers is mathematically described by the Muskingnum model that analyzes and evaluates flood routing. In this article a new model is introduced for this purpose based on the principles of the hydraulic non-linear reservoir concept. The non-linear reservoir model (FloodRoute) contains two parameters that can be calibrated when over a river reach (section) the inflow and outflow discharges have been measured (observed) over time. With the calibrated parameters predictions can be made for the outflow discharge wave given any inflow wave pattern. Examples of hydraulic wave propagation analysis are given.

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## **1. Introduction**

The classical Muskingnum model describing mathematically the propagation of flood waves in rivers was introduced by MacCarthy (1938, reference 1) and later expanded by Ven Te Chow (1959, reference 2). The principles of the Muskingnum are described in the Appendix.

The flood routing is, in fact, the calculation of the flood hydrograph in the downstream reach (stretch) of the channel.

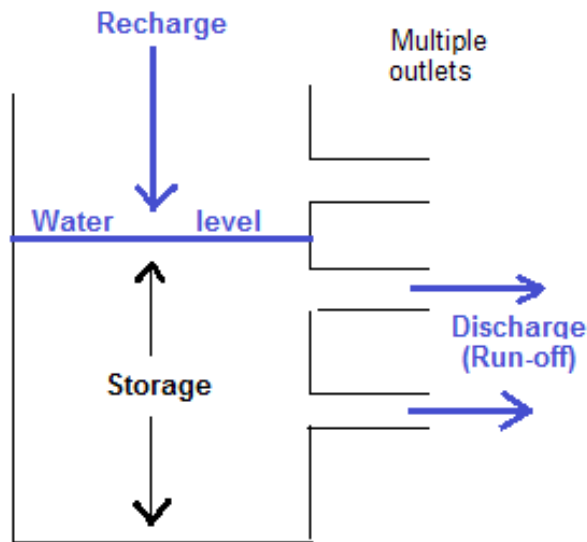
Various hydraulic and hydrological methods are used for flood routing. In other words, the estimation of the flood hydrograph is called ‘flood routing’

The Muskingum flood routing is one of the most important hydrological methods. This model uses continuity equations and relationships between discharge, outflow and flooding values.

In this article it is proposed to introduce another model for the mathematical description of the propagation of flood waves in rivers, based on the principles of a non-linear hydraulic reservoir. For the operation of this model the free FloodRoute software has been designed.

## 2. The hydraulic non-linear reservoir model

In hydrology, the concept of non-linear reservoirs has seldom been applied. Instead of a reservoir with a constant reaction factor, one could employ a non-linear reservoir with a reaction factor that changes linearly with storage (figure 3) instead of being a constant, thus avoiding the difficulty of dealing with a series of reservoirs.



### Non-linear reservoir

As the water level increases  
the discharge increases more  
than proportionally

**Figure 1.** A non-linear reservoir with multiple outlets whereby the discharge increases more than proportionally with the storage.

For the purpose of describing mathematically the propagation of flood waves in rivers. the terms Recharge and Discharge in figure 1 can be replaced by Inflow (R) and Outflow (Q) of the river stretch (reach, section) under consideration respectively.

The outflow Q is a function of the storage S:

$$Q = \alpha * S = (B * Q + C) * S \quad \text{so that} \quad S = Q / (B * Q + C)$$

where the reaction factor or response function  $\alpha$  equals  $B*Q + C$ .

Differentiating S to time T gives  $dS / dT = R - Q = R - \alpha*S$  so that:

$$dS / dT = R - (B*Q + C)*S = R - B*Q*S + C*S$$

Integrating this equation with limits  $Q_1, Q_2, T_1$  and  $T_2$  yields:

$$Q_2 = Q_1 \exp \{ - (B*Q_1 + C)*(T_2 - T_1) \} + R_1 * [ 1 - \exp \{ - (B*Q_1 + C)*(T_2 - T_1) \} ]$$

or :

$$Q_2 = Q_1 \exp \{ - \alpha * (T_2 - T_1) \} + R_1 * [ 1 - \exp \{ - \alpha * (T_2 - T_1) \} ]$$

where:

$T_2 - T_1$  is the time step

$T_1$  is the initial moment of the time step. or the final moment of the previous time step

$T_2$  is the final moment of the time step

$Q_2$  is the outflow at  $T_2$

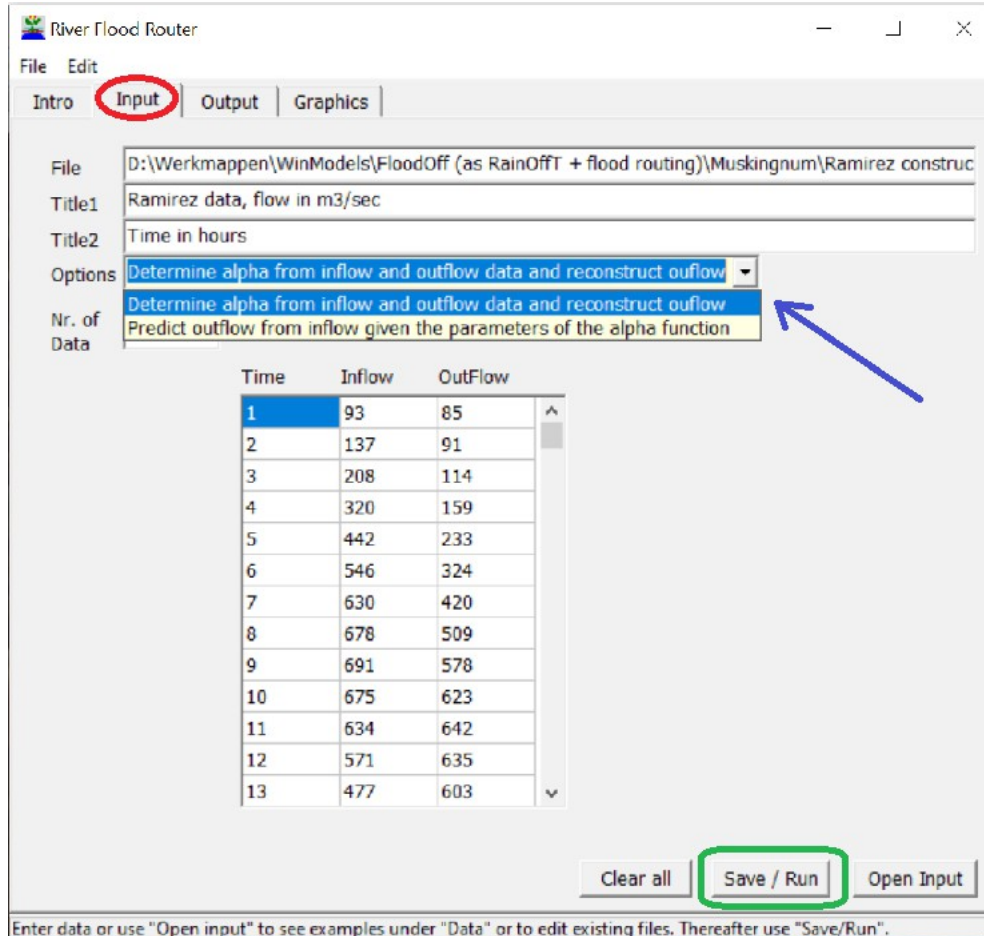
$Q_1$  is the outflow at  $T_1$

$R_1$  is the inflow at  $T_1$

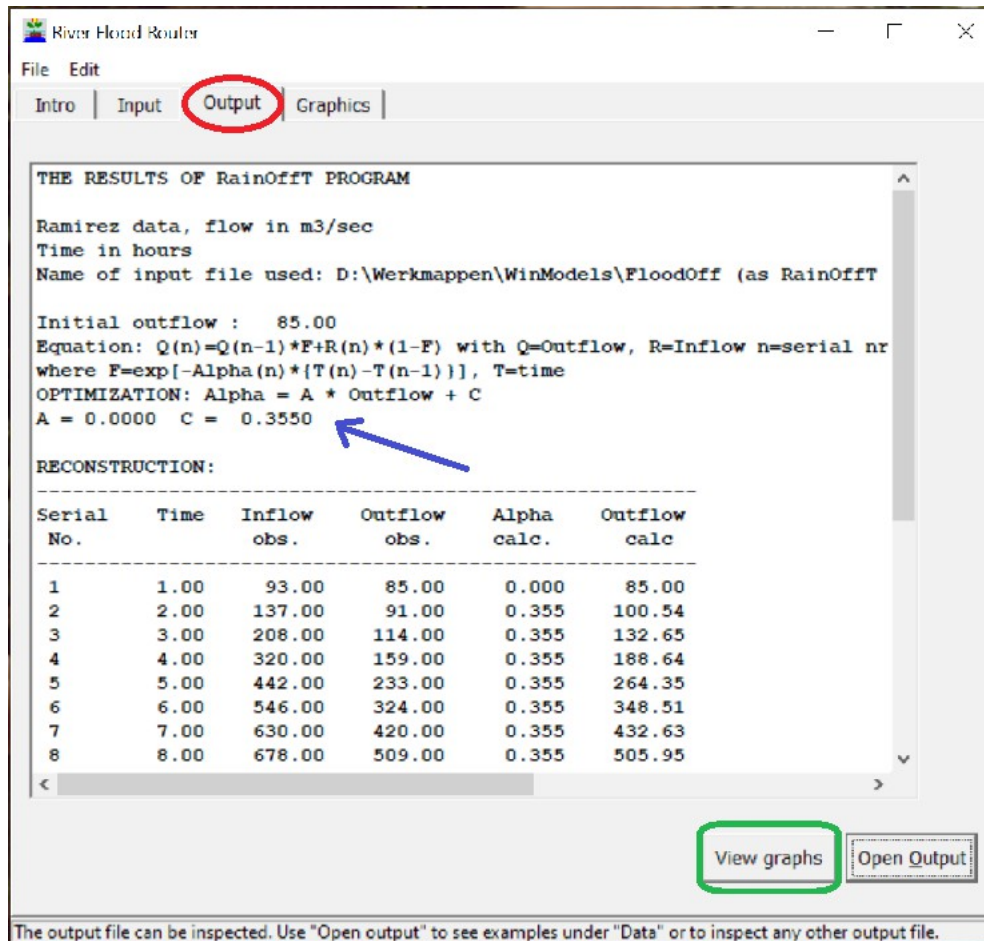
$\alpha$  is the reaction factor or reservoir response function

### 3. Operational properties of the FloodRoute model software

The operational properties of the FloodRoute model software (Oosterbaan 2022, reference 3) are illustrated in figures 2 and 3 hereunder.



**Figure 2.** Input menu user interface (red oval). The option selected is: “Determine alpha from inflow and outflow data and reconstruct outflow” (blue arrow). The data have been copied from an Excel spreadsheet and pasted in the table. When the input is completed click “Save / Run” (green square).



**Figure 3.** Output menu user interface (red oval) with calibration results of the parameters *A* and *C* of the response factor *Alpha* (blue arrow) and option to view the graphs (green square).

## 4. Examples of parameter calibration

### 4.1 *The Ramirez data*

Ramirez (reference 4) has given input and output data for a Muskingum model. He obtained the following result.

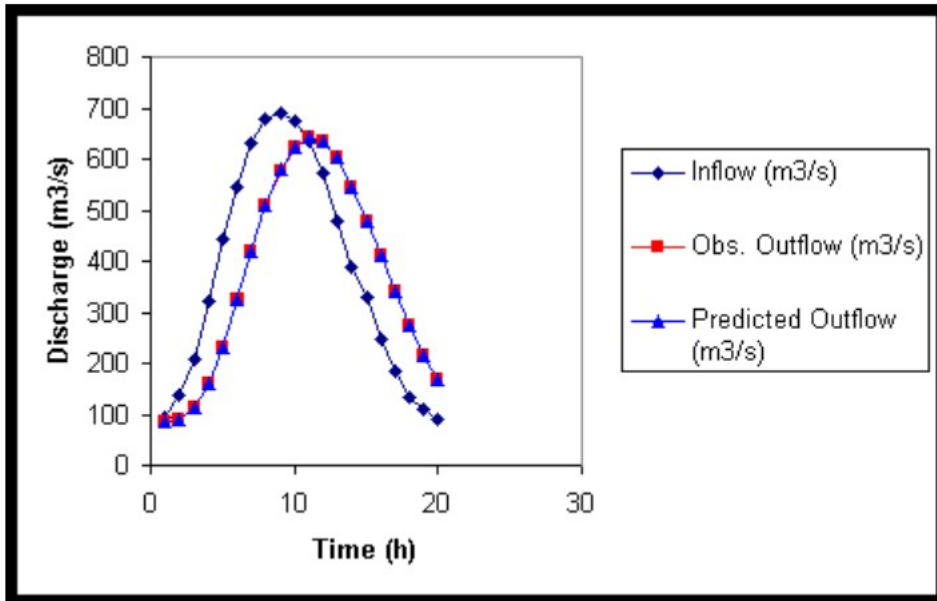
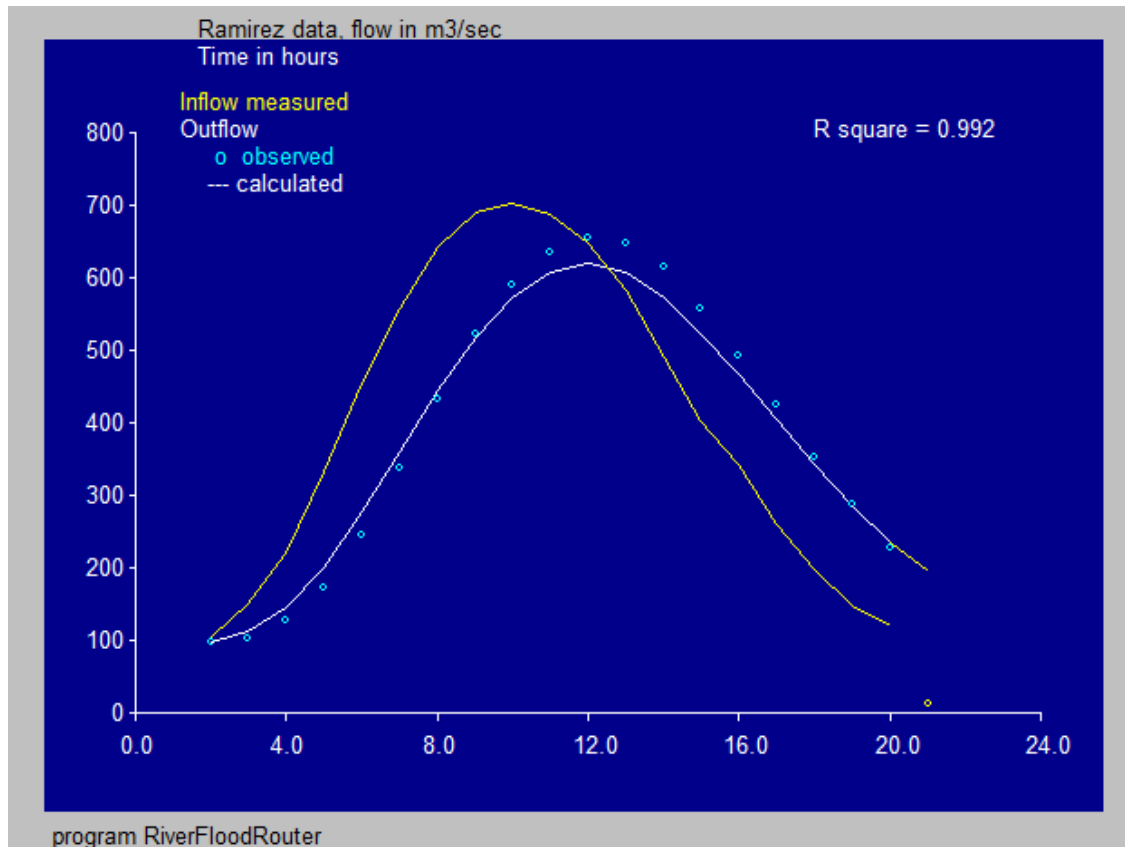


Figure 4. Results of the Muskingum method obtained by Ramirez.

Using these data for calibrations of the parameters B and C of the non-linear reservoir model by means of the FloodRoute software, the following results are encountered.



**Figure 4.** Inflow, measured and simulated outflow using the Ramirez data in the FloodRoute model software program. The parameters of the reaction function (response factor)  $\alpha = (B*Q + C)$  have been calibrated and optimized as  $B = 0.000$  and  $C = 0.355$ .

The fit of the observed outflow data to the calculated (simulated) outflow curve in figure 4 is quite good, but in figure 3 it looks even better. It may be noted that the Ramirez data were created for an educative exercise. A further analysis of the goodness of fit aspects will be given in the next section.

#### 4.2 The Ahwaz data

Hadi Norouzi and Jalal Bazargan (2020, reference 5) have analyzed three flood routing cases. In their study, the recorded data for the Mollasani hydrometric station (station no. 21–308, 48°53' E, 31°35'N) at the upstream part and the Ahwaz hydrometric station (station no. 21–309, 48°40'E, 31°20'N) (Distance 60.5 Km) at the downstream part of the study reach (section) are used, both related to the Karun River in Iran.

The calibration of the parameters of the reaction function (response factor) for the first data series resulted in a calculated (simulated) outflow as demonstrated in figure 5.

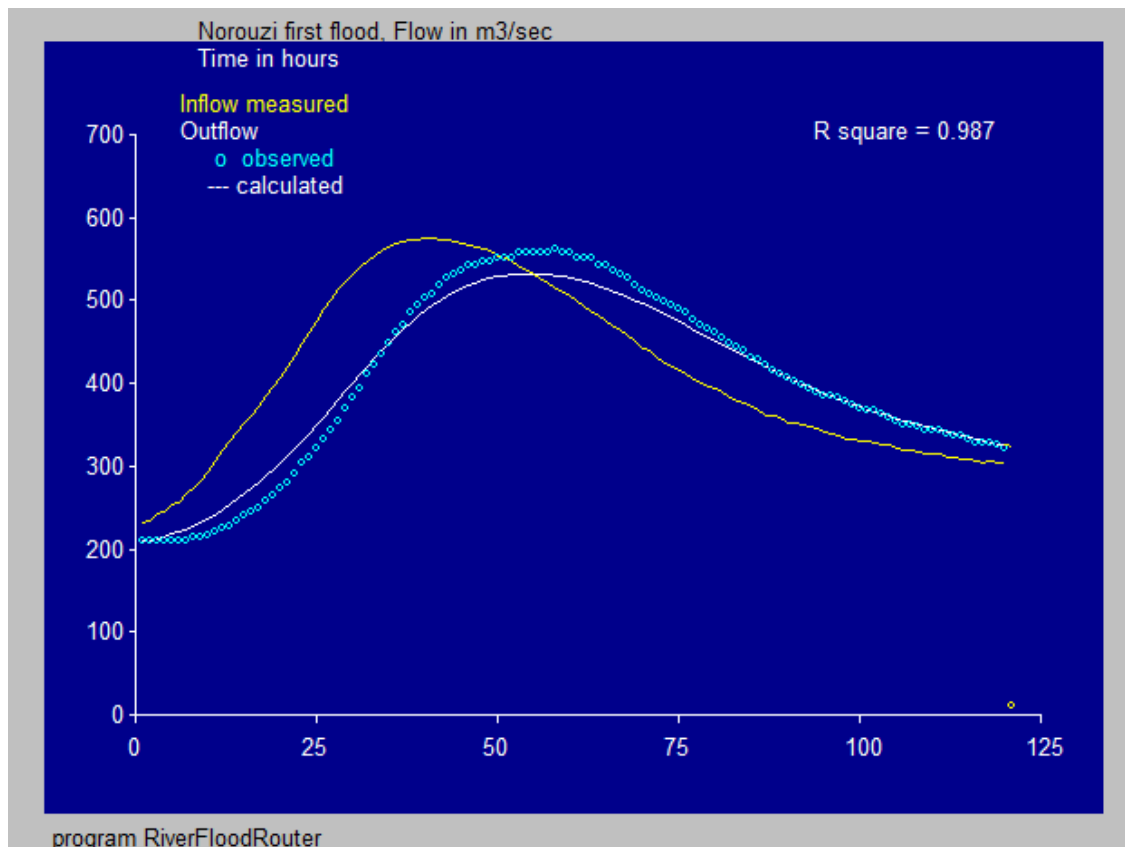


Figure 5. Output graphs of the calibration phase for the first data series (first food). The parameters of the response function Alpha are  $A = 0.0000$  and  $C = 0.0750$ . The observed (blue dots) and calculated (simulated) outflow graphs coincide nicely with a high R-square value (0,987) close to its maximum value 1.

The calibration of the parameters of the reaction function (response factor) for the second data series resulted in a calculated (simulated, white curve) outflow as demonstrated in figure 6.



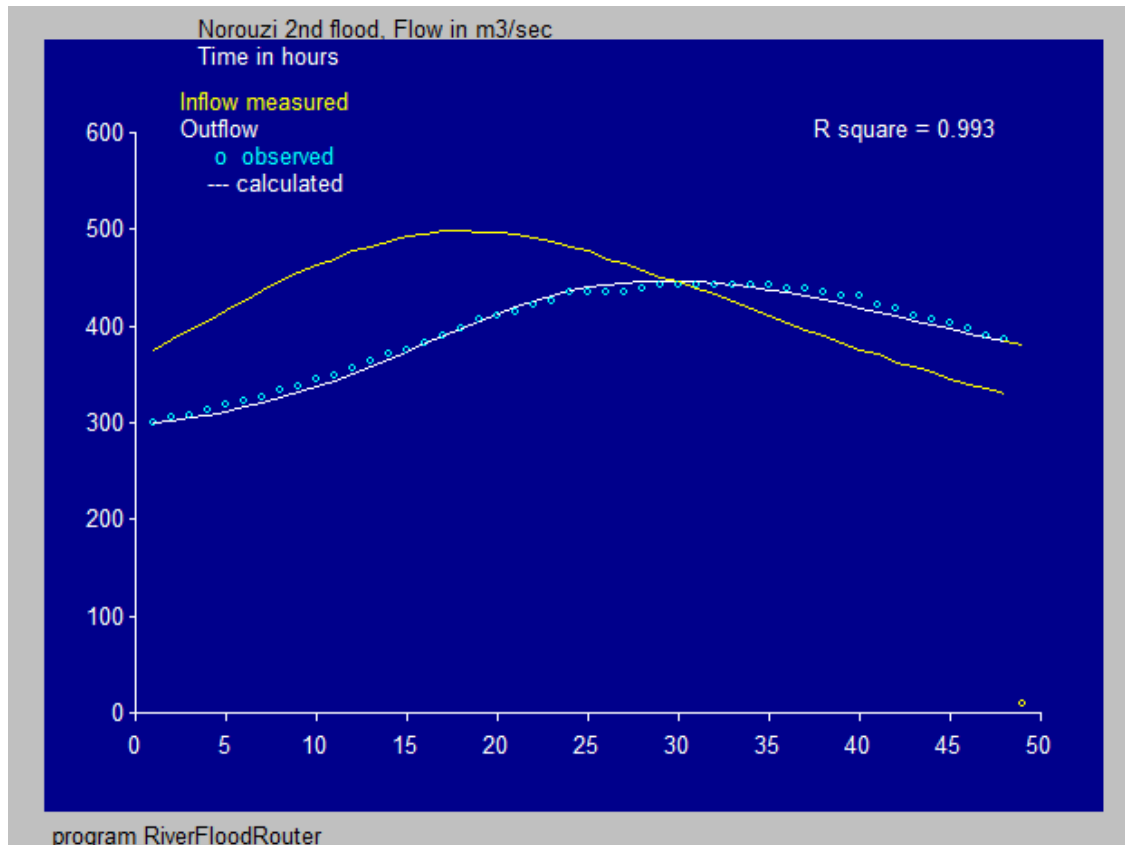
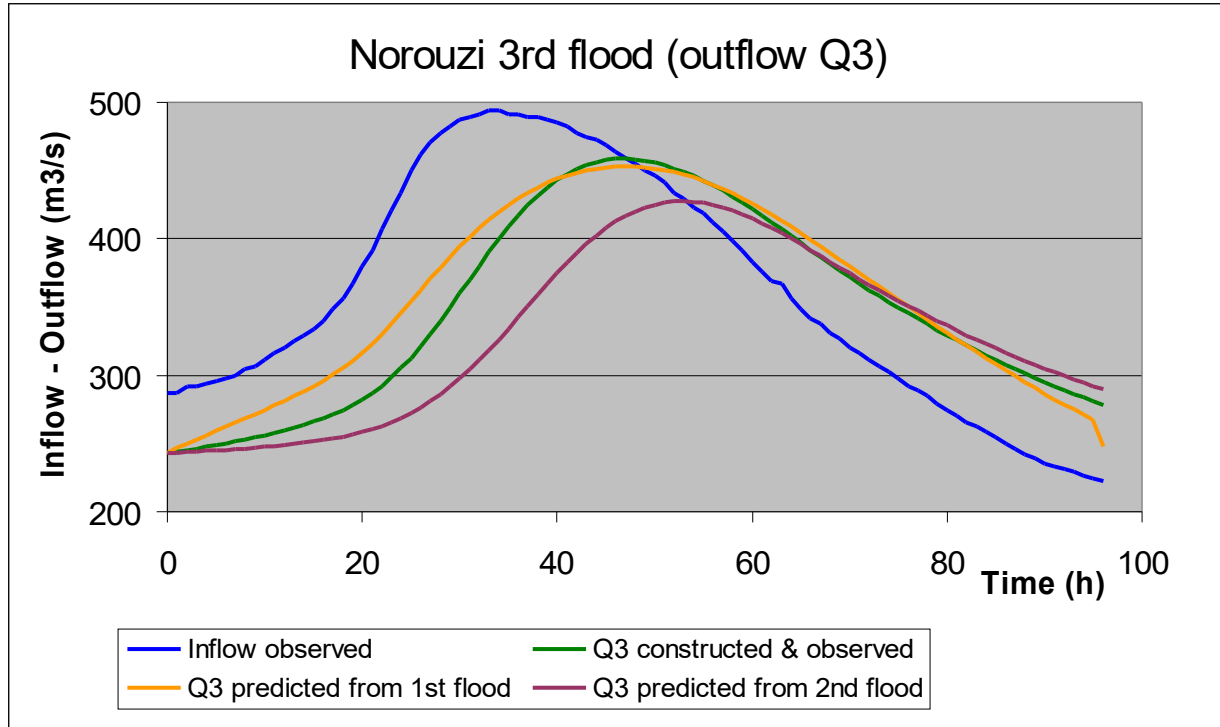


Figure 6. Output graphs of the calibration phase for the second data series (second flood). The parameters of the response function Alpha are  $A = 0.0005$  and  $C = -0.114$ . The observed (blue dots) and calculated (simulated, white curve) outflow graphs coincide nicely with a high R-square value (0,993) close to its maximum value 1.

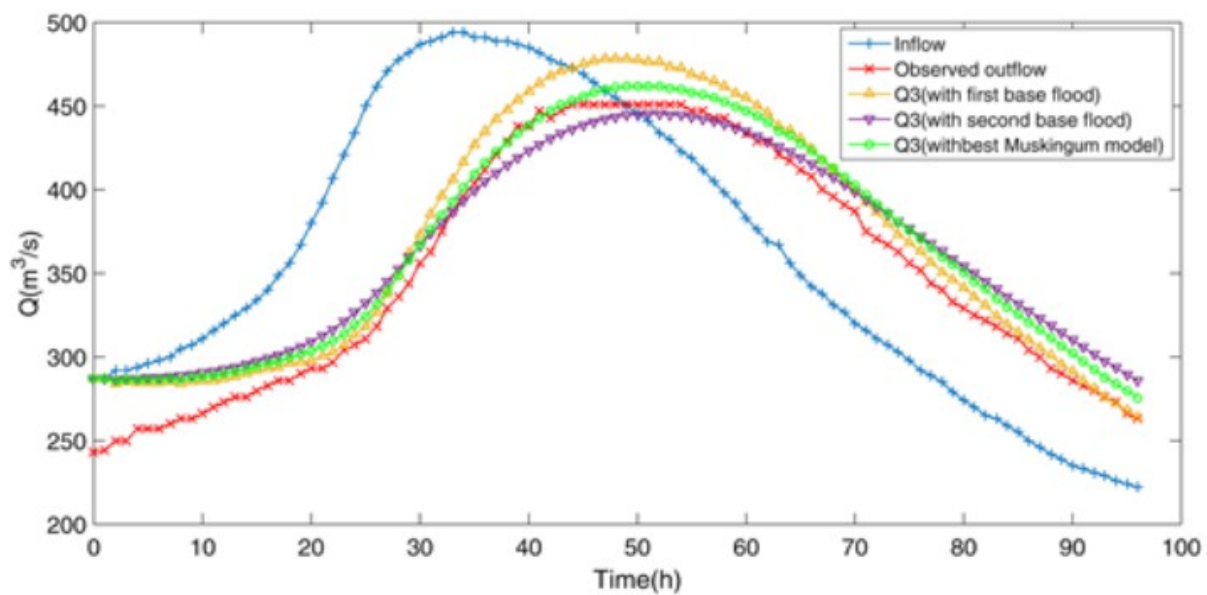
## 5. Example of flood wave prediction in Ahwaz

In figure 7 the parameters of reservoir function as determined from the first and second data series (the 1st and 2nd flood) have been used to predict the outflow wave for the third data series (the 3rd flood or Q3).



**Figure 7.** Predicted outflow wave for the third data series (the 3rd flood or Q3) using the parameters of reservoir function as determined from the first data series (the 1st flood, orange curve) and the second data series (the 2nd flood, purple curve) .

Figure 8 presents similar results as reported by Hadi Norouzi and Jalal Bazargan (2020, reference 5) using the Muskingum method. The curves for the predicted outflow waves based on the findings of the first and second data series have the same color as in figure 7: orange and purple respectively. There is a considerable agreement between the predicted curves for each case.



**Figure 8.** Results reported by Hadi Norouzi and Jalal Bazargan (2020, reference 5)

In figure 8 there is a small difference between the red curve (observed outflow) and the green curve (the outflow simulated with the Muskingum model), while in figure 7 this difference is hidden. Therefore, the next figure (figure 9) is included to clarify the minor difference between the observed outflow (white curve) and outflow simulated with the FloodRoute model (blue dots).

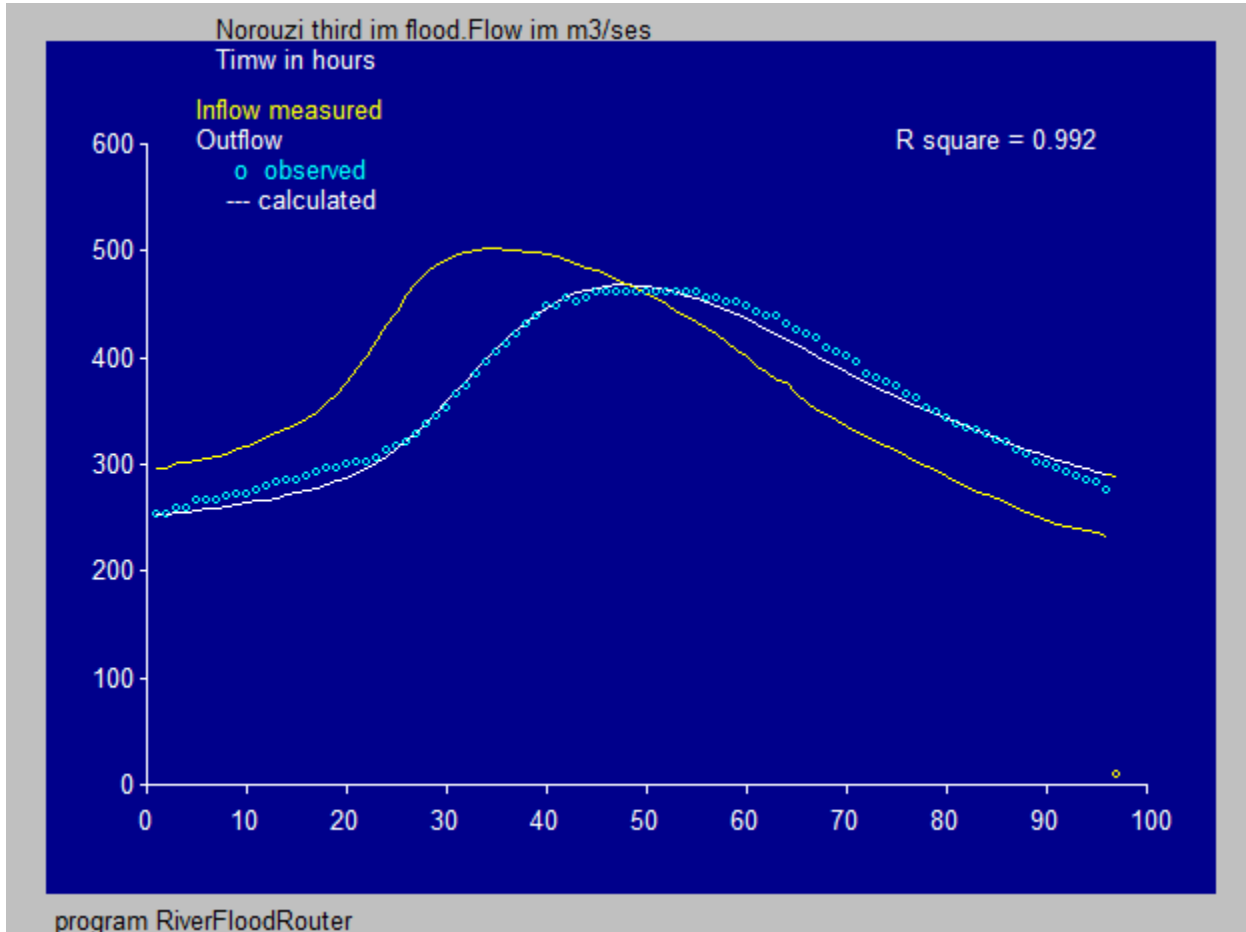


Figure 9. There is minor difference between the observed outflow (white curve) and outflow simulated with the FloodRoute model (blue dots), but the goodness of fit defined by the R-square value (0.992) is very high and almost perfect (when R-square equals 1).

## 6. Summary and conclusion

It has been shown that the FloodRoute model can produce a simulated outflow wave that closely resembles the observed wave. Further, the calibrated (optimized) parameters of the response function belonging to the non-linear reservoir model employed are able to take part in a prediction of outflow waves for which no observed outflow waves are available that is as correct as the Muskingum model used by Hadi Norouzi and Jalal Bazargan (2020, reference 5).

The FloodRoute software program is unique in the sense that it provides a simple input menu for the data (figure 2) and the all the calculations are done automatically, while the mathematical results are clearly revealed (figure 3) and the corresponding graphics are easily made available.

## 7. References

### Reference 1.

McCarthy, G.T. 1938. The unit hydrograph and flood routing, Conference of North Atlantic Division, US Army Corps of Engineers, New London, CT. US Engineering.

### Reference 2.

Chow V. T. 1959. Open Channel Hydraulics. McGraw-Hill Book Company, New York, NY

### Reference 3.

Oosterbaan, R.J. 2022. Free FloodRoute software. Download from:

<https://www.waterlog.info/floodrout.htm>

### Reference 4.

Jorge A. Ramirez. CE322 Basic Hydrology, Muskingum Routing – Example.

[https://www.engr.colostate.edu/~ramirez/ce\\_old/classes/cive322-](https://www.engr.colostate.edu/~ramirez/ce_old/classes/cive322-Ramirez/CE322_Web/Example_MuskingumRouting.htm)

[Ramirez/CE322\\_Web/Example\\_MuskingumRouting.htm](https://www.engr.colostate.edu/~ramirez/ce_old/classes/cive322-Ramirez/CE322_Web/Example_MuskingumRouting.htm)

### Reference 5.

Hadi Norouzi and Jalal Bazargan. 2020. Flood routing by linear Muskingum method using two basic floods data using particle swarm optimization (PSO) algorithm. Water Supply Volume 20, Issue 5.

<https://iwaponline.com/ws/article/20/5/1897/74285/Flood-routing-by-linear-Muskingum-method-using-two>

## 8. Appendix (Principles of the Muskingum model)

Figure A schematically shows the reaches (stretches) of a river and various water storage situations that are of importance for the analysis of the mathematics for the routing of flood waves.

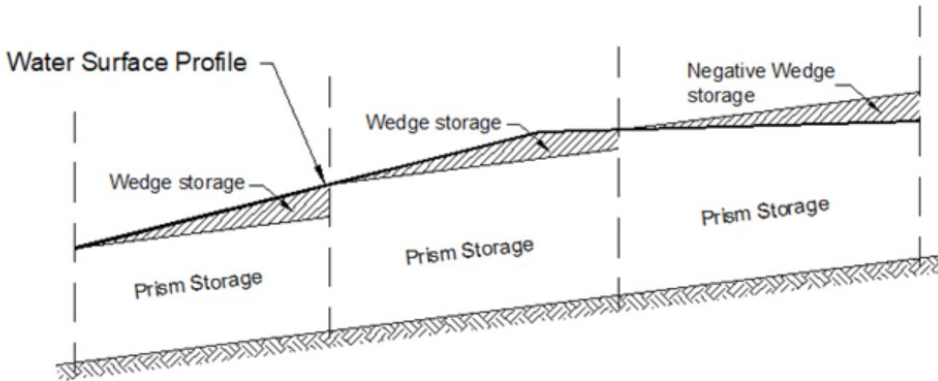


Figure A. Muskingum representation of channel storage reproduced by Linsley, Kohler and Paulus, 1982, Hydrology for Engineers (McGraw-Hill Series in Water Resources and Environmental Engineering).

Figure B presents an inflow and an outflow discharge wave in and out from a river section over time

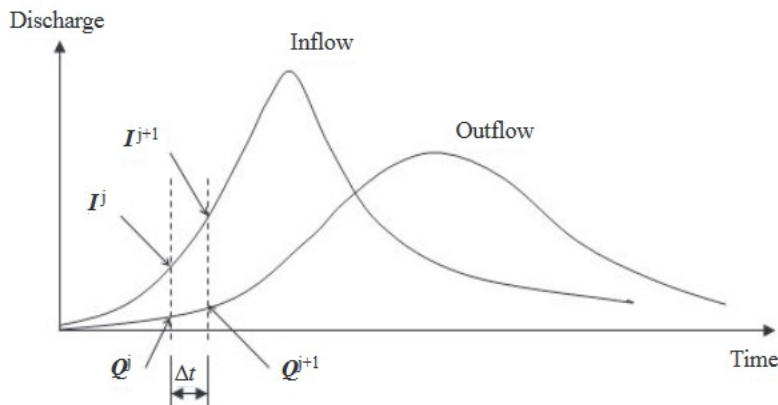


Figure B. Schematic diagram of upstream (I) and downstream (O) flood hydrograph at the beginning (j) of a time step and at the beginning of the next time step (j+1).

$\Delta t$  is the length of the time step.

The places of Inflow and Outflow are at a certain distance.

The rate of change of storage during a time interval  $dT$  of water between the upstream and downstream end of the river reach (section) is:

$$(1) \quad dS / dT = I - O$$

while the amount of water stored is

$$(2) \quad S = K * [R * I + (1 - R) * O]$$

where  $S$  = storage;  $I$  = inflow;  $O$  = outflow;  $T$  = time;  $K$  = storage time constant for the river reach (stretch) and  $R$  = dimensionless weighting factor representing the inflow outflow effects on storage.  $R$  ranges between 0 and 0.5 for reservoir storage and 0 and 0.3 for stream channels

Equation (2) is known as the Muskingum Equation (Reference: Chow V. T. 1959 Open Channel Hydraulics. McGraw-Hill Book Company, New York, NY).

The outflow ( $O_p$ ) over the time step  $dT$  is written as:

$$O_p = C_1 * I_p + C_2 * I_v + C_3 * O_v$$

where  $I_p$  is the inflow over the present time step,  $I_v$  is the inflow over the foregoing time step and  $O_v$  is the outflow over the foregoing time step, while:

$$C_1 = (0.5 * dT - K * R) / [K - K * R + 0.5 * dT]$$

$$C_2 = (0.5 * dT + K * R) / [K - K * R + 0.5 * dT]$$

$$C_3 = [K - K * R - 0.5 * dT] / [K - K * R + 0.5 * dT]$$

$$C_1 + C_2 + C_3 = 1$$

Application of the Muskingum model involves a calibration phase to determine the values of  $K$  and  $R$  and a prediction phase applying these values.