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Flood Routing Using the Muskingum-Cunge Method and Genetic Algorithm

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ABSTRACT

Flooding remains one of the most catastrophic natural hazards, often causing widespread human casualties and extensive economic damage. Nonetheless, the severity of its consequences can be significantly mitigated through precise modeling, thorough analysis, and the implementation of effective flood management strategies. A deep understanding of flood behavior and trends is crucial for improving forecasting accuracy and enabling timely preventive actions in flood-prone areas. When integrated with early warning systems, flood control infrastructures, and coordinated emergency responses, reliable flood forecasting can dramatically reduce the risk to human life and infrastructure. This study adopts a documentary and library-based research methodology to gather and analyze relevant data, with the objective of enhancing the accuracy of flood modeling techniques. Specifically, the study evaluates the effectiveness of the Maskingham-Cunge method in conjunction with genetic algorithms for modeling flood behavior. The integration of these approaches allows for the dynamic adjustment of parameters, replacing static inputs with variable ones to better reflect real-world conditions. Additionally, incorporating one-dimensional kinematic wave theory to compute wave speed improves the precision of output hydrograph estimation. The findings demonstrate that this combined approach significantly enhances the predictive performance of flood models. As a result, it offers a robust tool for informed decision-making in flood management, contributing to more efficient disaster preparedness and risk reduction efforts in vulnerable regions.

1. INTRODUCTION

Flooding is one of the most important natural events that causes significant damage worldwide every year. Rainfall, soil permeability, and land slope play a fundamental role in the occurrence of floods. Rainfall causes floods within a specific period. Storm floods also occur frequently and have complex characteristics in dry and mountainous regions. In dry and mountainous areas where rainfall is intense, the soil structure can quickly convert precipitation into runoff, leading to greater risks [13]. Flooding is a natural disaster caused by excessive rainfall and the climatic and geographical conditions during the monsoon season. Although the problems caused by floods cannot be eliminated, flood forecasting models, as a critical aspect of flood warning services, can help reduce flood losses by providing timely warnings. Flood routing methods are commonly used as flood forecasting models. Therefore, the effects of floods can be minimized through appropriate modeling, analysis, and management methods [14]. Floods

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result from the sudden runoff of surface water into previously dry land areas. This phenomenon is considered one of the most dangerous natural disasters worldwide due to its impact on economic, social, and environmental sectors. Floods also have significant political consequences and threaten both emerging and developed economies. The analysis of flood risk forecasting indicates that climate change and poor preparedness in many areas are likely to lead to flood-related damages. Globally, flooding is a crucial hydrological issue, and the environment, national policies, and economies are particularly affected by flooding. Recently, flood forecasting has made significant progress in terms of technique and capacity, enabling policymakers to achieve more accurate predictions and identify flood-prone and affected areas [15]. Flood routing calculations in rivers are essential for flood control studies, both structural and non-structural, and the accuracy of their results is crucial for designing and implementing river flood control structures [1]. Generally, flood routing methods can be divided into two categories: hydraulic routing and hydrological routing. Hydraulic methods are based on solving the numerical equations of Saint-Venant governing the non-steady, non-uniform flow in open channels. Although the results of this method are acceptable, it involves complex computations and requires extensive information, such as slope, topography, river path changes, roughness, and cross-section characteristics. To overcome the complexity and time consumption of hydraulic methods, hydrological methods are particularly important. Hydrological routing methods use the principle of flow continuity and the relationship between flow discharge and temporary water storage along the path. These methods are simple and yield reasonably accurate results. The Muskingum method is one of the most well-known and widely used hydrological routing methods [2].

The Muskingum method is a hydrological routing technique that is widely applied due to its simplicity in flood routing and was introduced by McCarthy in 1938. Research by Kanze (1969) showed that the equation of the Muskingum method closely resembles the transfer-dispersion equation, and its results are similar to those of the kinematic wave method. By discretizing the kinematic wave equation and matching numerical dispersion with physical dispersion, he modified the Muskingum method. Therefore, the parameters of the Muskingum-Kanze method are calculated based on the physical characteristics of the river [16]. Optimization methods are an appropriate choice for determining optimal parameters in the Muskingum-Kanze model to enhance computational speed. The parameters of this model are optimally calculated using a genetic algorithm [17]. Mohan (1985) proposed a model based on the genetic algorithm for estimating the nonlinear Muskingum parameters. The results showed that the flow hydrograph derived from the GA method has a higher match with the observed hydrograph compared to methods presented by other researchers [3]. Karimi and colleagues (2012) compared the accuracy of the kinematic wave and Muskingum-Kanze methods in flood routing through a case study on the Doab Samsami River. The RMSE values for the kinematic wave method were 0.845, and for the Muskingum-Kanze method, it was 1.401, showing that the kinematic wave method provided more accurate results. Qalani and Ebrahimi (2012) evaluated direct search and genetic algorithms in optimizing the nonlinear Muskingum model parameters for a flood from the Karun River. The results of flood routing with the direct search algorithm showed that the sum of squared errors and the absolute error between the routed and observed flow rates were 62.65 and 29.48 cubic meters per second, respectively. The smallest difference between the observed and routed peak flow rates was 0.29 cubic meters per second. The results of flood routing in the Karun River using the direct search algorithm indicated that the sum of squared errors, sum of absolute errors, and the difference in peak flow rate were 0.420, 7842.10, and 9.7 cubic meters per second, respectively. Therefore, although the direct search algorithm did not outperform other algorithms in some parameters, it showed reasonable accuracy for optimizing the nonlinear Muskingum model parameters. Samani and colleagues (2013) applied hydrological flood routing using the Muskingum method in a multi-branch river system optimized by a genetic algorithm. In this study, a method was proposed where calibration (parameter determination) was performed using a genetic algorithm, which is capable of solving complex problems with more parameters. The proposed method was applied to both single-branch and multi-branch rivers, as well as rivers lacking hydrological data in intermediate watersheds. In all cases, the computational results showed satisfactory agreement with real data. Norouzi and Bazargan (2020) examined the accuracy of the Muskingum-Kanze method in the stretch between the Malasani hydrometric station upstream and the Ahvaz hydrometric station downstream of the Karun River. The study indicated that by using three different values for the Muskingum-Kanze parameters, rather than a fixed value, and employing one-way wave relations for calculating kinematic wave speed, the accuracy of the Muskingum-Kanze method in estimating the output hydrograph improved.

2. FLOOD ROUTING

One of the important issues in hydrology engineering is predicting how a flood will rise and subside, or the rise and fall of the hydrograph of a river at a specific point along its path. This issue can be studied using the flood routing method. As the flow discharge increases, the river's level rises, and concurrently, the volume of water that temporarily accumulates along the river also increases. During the recession of the flood, an amount of water equal to the accumulated volume is released from the storage area, causing the base time of the flood wave, which is moving downstream, to appear longer and its height to decrease. Generally, flood routing refers to determining the output flow hydrograph using known input flow values upstream of a river. In other words, flood routing refers to the set of operations that is used to determine the time and magnitude of a flood wave at a point along the river, using hypothetical or real data at one or more upstream flow points. Figure 1 illustrates the classification of common flood routing methods. Multiple definitions of flood routing include:

- Flood routing is a method that engineers use with mathematical methods to calculate the effect of river storage or reservoirs on the shape and movement of a flood wave.
- Flood routing includes the set of operations through which the output hydrograph can be determined, assuming that the input hydrograph is known or hypothetical.
- Flood routing is the series of steps by which the temporal and spatial progress of a flood wave is determined at consecutive points along the river.
- Flood routing is a method based on mathematical operations, where the flow characteristics downstream can be calculated by knowing or assuming the flow at an upstream point and using the flood routing method [8].

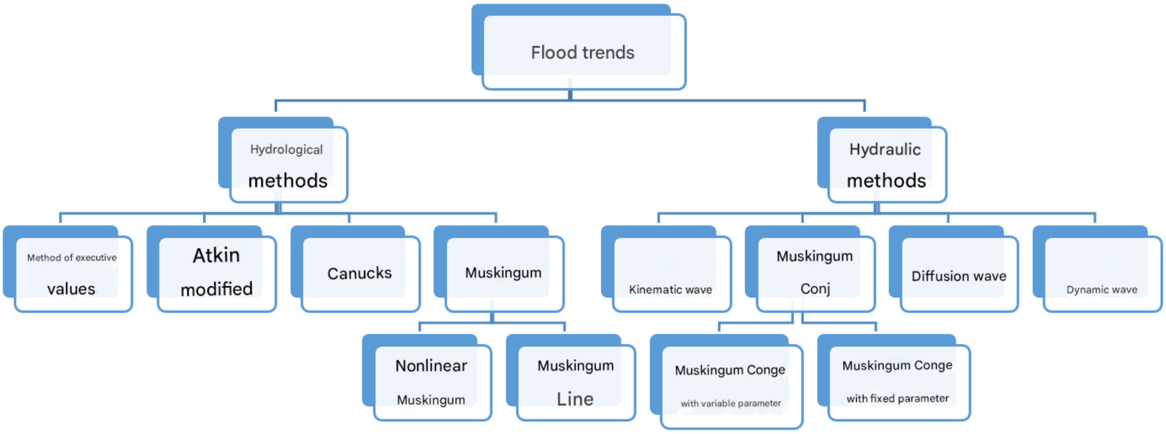

Fig. 1. Classification of Common Flood Routing Methods [8].

3. HYDROLOGICAL ROUTING

In hydrological routing, the dynamic effects of the wave are assumed to be negligible, and the acceleration of the water surface and momentum are ignored. In flood routing based on hydrological principles, the approach relies on the continuity equation, input hydrographs, peak flood discharge, flood velocity, cross-sectional flow area, the relationship between downstream discharge and flood data from past events. Typically, in flood routing, the main focus is on the relationship between the water level, storage volume, or discharge of the storage volume. Determining the storage volume is usually done by analyzing flood statistics, and the assumptions and relationships for future floods are also valid. The necessary data for this comes from upstream and downstream flood statistics at hydrometric stations. When a flood occurs at the junction of a stream branch, it causes backflow, and when it is controlled by a dam, a wave is created. The effect of backflow waves cannot be accurately estimated using hydrological methods.

3.2 Hydraulic Routing

The basis of hydraulic routing methods involves the continuity equation, motion equation, and unsteady flow equations, which are differential equations used for routing non-permanent flows. This type of routing is precise, but the main challenges are the difficulty in solving the associated equations, making the use of computers indispensable, and requiring large amounts of data. The difference between the two systems of routing is that, in a hydrological model, flow is calculated only as a function of time at a specific location, whereas in a hydraulic model, flow is considered as a function of both time and space. Some researchers divide flood routing into three branches: 1. Reservoir routing, 2. River routing, 3. Watershed routing (runoff routing) [9].

4. MASKINGAM - CONG

Cong's (1969) studies show that the equation related to the Maskingam method is very similar to the equation of dispersion transport and that its results are close to the kinematic wave method. By separating the equation related to the kinematic wave and adjusting the numerical dispersion with physical dispersion, Cong modified the Maskingam method. Thus, the parameters related to the Maskingam-Cong method are obtained based on the physical characteristics of the river. The Maskingam-Cong method is widely used in flood routing. The differences between this method and the Maskingam method include the modification of the basic Maskingam method by determining its parameters in a specific way by Cong and colleagues, based on dispersion, and the ability to consider lateral flows. In most natural channels, inertia and acceleration, compared to the bed slope, can be neglected in the momentum equation [7]. Therefore, the Maskingam-Cong method is an extension of the Maskingam method. Cong used the fact that the Maskingam method is a special case of solving the kinematic wave equation using the finite difference approximation method and derived the following relationships for calculating xx and kk.

$$\mathrm{k} \approx \frac{\Delta x}{c_k} \tag{1}$$

$$\mathrm{x} = \frac{1}{2}\left(1 - \frac{Q_0}{C_k\ \Delta x\ T_0\ S_0}\right) \tag{2}$$

Where:

Q_0 =Peak discharge, equal to the maximum or average discharge of the input hydrograph

T_0 =Water surface width corresponding to the base discharge in the river

S_0 =River bed slope

C_k =Kinematic wave velocity, which is derived from the following relation:

$$C_k = \frac{dQ_0}{dA} = \frac{1}{T_0}\frac{dQ_0}{dy} \tag{3}$$

With the input hydrograph and the geometric characteristics of the channel, the output hydrograph can be obtained from the following relation:

$$Q_{i+1} = C_1 I_i + C_2 I_{i+1} + C_3 O_i \tag{4}$$

$$C_1 = \frac{0.5\ \Delta t + \alpha \frac{\Delta x}{c_k}}{0.5\ \Delta t + (1-\alpha)\frac{\Delta x}{c_k}} \tag{5}$$

$$C_2 = \frac{0.5\ \Delta t - \alpha \frac{\Delta x}{c_k}}{0.5\ \Delta t + (1-\alpha)\frac{\Delta x}{c_k}} \tag{6}$$

$$C_3 = \frac{-0.5\ \Delta t + (1-\alpha)\frac{\Delta x}{c_k}}{0.5\ \Delta t + (1-\alpha)\frac{\Delta x}{c_k}} \tag{7}$$

In the above equations, \(\alpha \) is a weighting factor used in the partial derivatives of time in the finite difference form of the kinematic wave equations. It should be noted that although the form of the routing equations in the Maskingam-Conge method is similar to the Maskingam method, these two methods are fundamentally different. The Maskingam method is a hydrological routing method, while the Maskingam-Conge method is a hydraulic method based on an approximation of the Saint-Venant kinematic wave equations.

4.1. Parameter Estimation Using Genetic Algorithm Optimization

Various optimization methods have been developed for engineering problems, with the genetic algorithm (GA) emerging as one of the most effective approaches. Initially introduced for solving nonlinear equations, GA gained prominence across other disciplines with advances in microprocessors. As a nonlinear search method, GA draws inspiration from natural evolution and genetic traits of organisms.

This algorithm starts the search process with a set of random solutions referred to as the population. After randomly generating the initial population, the chromosomes in this generation are evaluated. Based on the fitness of each chromosome, the next generation is formed in a way that guides the problem toward an optimal solution. In other words, individuals with better fitness are more likely to appear in the next generation. The values of XX and KK are determined such that the objective function is minimized.

4.2. Genetic Algorithm (GA)

The Genetic Algorithm is a nonlinear search and optimization method inspired by the biological processes of natural selection and survival of the fittest. It relies on relatively few assumptions and does not depend on mathematical properties like differentiability or continuity, making it highly versatile and efficient.

GA has recently found extensive applications in water resource engineering, flood forecasting, and rainfall-runoff modeling. It can minimize (or maximize) an objective function under specified constraints. For example, GA can optimize model parameters by minimizing the Mean Absolute Error (MAE) or maximizing the Nash-Sutcliffe Efficiency (NS) coefficient.

GA is a subset of evolutionary algorithms, utilizing techniques from evolutionary biology such as inheritance and mutation. It implements search strategies inspired by Darwin's principle of natural selection and the survival of the fittest. Commonly used in optimization, research, and machine learning problems, GA begins with a population of random solutions evaluated using a fitness function. Key components of the algorithm include crossover, mutation, and selection. A flowchart illustrating GA-based optimization is shown in Figure 2.

4.3. Advantages of Genetic Algorithm Over Other Optimization Methods

1. Capable of optimizing in continuous or discrete spaces.
2. Does not require information about the derivative of the function.
3. Can handle a large number of decision variables.
4. Efficient for optimizing complex objective functions.
5. Uses a population of potential solutions rather than a single value to start.
6. Allows for encoded variables
7. instead of using the variables directly.
8. Compatible with numerical, experimental, or analytical data.
9. Guides the search process using probabilistic rules instead of deterministic rules.

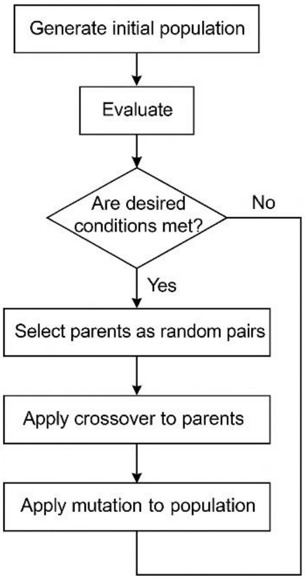

Fig. 2. Flowchart of Optimization Using Genetic Algorithm [10]

5. FINDINGS

Among various flood routing models, Muskingum models require calibration and validation using parameter estimation methods and recorded hydrological data. If the river's physical characteristics align with the simplifications imposed by the derivation of the Muskingum-Cunge model, this method proves more reliable in unmanaged catchments. One of the key advantages of the Muskingum-Cunge model is that routing parameters are best estimated without a calibration process, utilizing direct numerical techniques. Additionally, this model avoids estimating multiple parameters for routing across several sub-reaches, considering the entire river as a single unit. Compared to other simplified routing methods (e.g., kinematic wave models), Muskingum-Cunge is more reliable given similar input data and computational costs.

When a river reach has moderate values of bed slope and roughness coefficient, Muskingum-Cunge schemes are particularly accurate for designing unmanaged catchment projects. Using the (X, K) method for each reach enhances the precision of the Muskingum-Cunge model, especially in estimating the peak section of the flood hydrograph, which is crucial for designing flood control structures. Incorporating geometric characteristics of the cross-section and flood flow dynamics over time improves the model by utilizing monoclinal wave equations for calculating kinematic wave velocity.

To further enhance accuracy, plotting the width and depth of the flow against time and using a weighted average of flow widths instead of a fixed value—considering changes in depth and width—can refine the peak hydrograph estimation in the Muskingum-Cunge method.

Two approaches exist for estimating routing parameters in Muskingum-Cunge:

- **Linear Approach**: The routing parameters (K and X) remain constant throughout computations.
- **Nonlinear Approach**: The routing parameters are allowed to vary with flow.

The Muskingum method, in both linear and nonlinear forms, is widely used for river flood routing due to its simplicity and stepwise computation of outflow discharge from river reaches. The strength of the Muskingum-Cunge model lies in its theoretical basis as an analog of the diffusion wave equation. Cunge observed that both the Muskingum method and kinematic wave models share the same theoretical foundation.

Moreover, Cunge quantified the first-order numerical scheme error (i.e., Muskingum method) and linked it to the hydraulic diffusion of the diffusion wave, enabling routing parameters to be computed directly from geometric and hydraulic variables. This eliminated the need for expensive and impractical field measurements. The Muskingum-Cunge method is highly accurate due to its solid theoretical foundation. Its numerical properties, including stability and convergence, are extensively documented in theory and practice.

The Muskingum-Cunge method is highly stable and has excellent convergence properties for Courant number values near 1. It is the only numerical analog of the diffusion wave equation that offers network independence while being computationally explicit and straightforward. Currently, no other flood routing method boasts these properties. Genetic algorithms (GAs) and the Muskingum-Cunge model are highly effective in determining the magnitude and timing of peak discharges. However, GAs offer ease and speed in optimizing coefficients for nonlinear Muskingum models, avoiding trial-and-error approximations and extensive data collection required for traditional Muskingum and Muskingum-Cunge models. Therefore, using GAs is recommended for flood routing.

6. CONCLUSION

Flood routing in rivers is a mathematical process for determining the flow hydrograph at any point along a river. One routing approach involves solving the complete Saint-Venant equations for unsteady flow, which, due to its complexity, requires computers and advanced models. Alternatively, simpler methods with adequate accuracy have been developed, providing acceptable results from a hydrologist's perspective.

The Muskingum-Cunge model is one such method, where the precision in parameter estimation significantly influences the routed hydrograph, particularly for maximum flood control. Studies indicate that genetic algorithms are also an effective option for optimizing the Muskingum-Cunge model's parameters.

The Muskingum-Cunge method calculates flood routing parameters without relying on historical or previously recorded flood data. Additionally, this method performs rapid computations to effectively route flood hydrographs with fixed coefficients, making it easy to program. Therefore, the Muskingum-Cunge method and genetic algorithms are recommended for flood routing.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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REFRENCESS

[1] Zahiri, A. R., Asghari, S., & Dehghani, A. A. (2016). Trending of river floods by multi-interval Muskingum method. Journal Name, 4(1), 81–88.

[2] Raisi, A., & Yazidi, S. (2021). Flood trending using multi-interval linear Muskingum method and sea hunters algorithm. Iranian Journal of Soil and Water Research, 52(10), 2693–2707.

[3] Khalifa, S., Khodashenas, S. R., & Esmaili, K. (2021). Estimation of the nonlinear parameters of the Muskingum model in the flood trending model with the new dragonfly algorithm. Sharif Civil Engineering Journal, 2(37), 3–10.

[4] Karimian, R., Hanrabakhsh, A., Sadatinejad, S. J., & Abdollahi, K. (2011). Flood trends in rivers using kinematic wave model and Muskingum-Cunge (Case study: Doab Samsami river). Iranian Water Research Journal, 6(10), 57–65.

[5] Mohammadi Ghaleni, M., & Ebrahimi, K. (2013). Evaluation of direct search and genetic algorithms in optimization of Muskingum nonlinear model parameters—a flooding of Karoun River, Iran. Water and Irrigation Management, 2(2), 1–12. jwim.ut.ac.ir+3آکادمیا+3jwim.ut.ac.ir+3

[6] Samani, H., Haghigi, A., & Farhadi, S. (2012). Flood hydrological trending using the linear Muskingum method in the system of multi-branch rivers with optimization by genetic algorithm. Scientific Research Journal, 8(1), [Page numbers].

[7] Nowrozi, H., & Merchant, J. (2019). Investigating the selection of different trending parameters on the accuracy of flood trending in rivers using the Muskingum-Cunge method. Journal of Irrigation and Drainage, 1(14), 181–192.

[8] Karimi, V. (2019). Investigating the accuracy of different flood forecasting methods in rivers using different hydrological methods (Master's thesis, Zanjan University).

[9] Rezavandi, L. (2021). Investigating flood trends in prismatic composite channels with rough walls (Case study: Barandooz River-Sediqabad region) (Master's thesis, Urmia University).

[10] Mirzazadeh, P. (2012). Investigating flood trending methods in reservoirs and rivers (Master's thesis, University of Sistan and Baluchestan).

[11] Majidipour, A., & Efros, A. (2018). Approximate prediction of improvement of erosion and sedimentation pattern at the intersection of channels by optimizing geometric and hydraulic parameters with the help of genetic algorithm. Scientific and Specialized Journal of Water Engineering, 7(1), 61–82.

[12] Maithami, A. (2011). Optimization of nonlinear Muskingum model parameters for flood trending using genetic algorithm (Master's thesis, Shahid Chamran University, Ahvaz).

[13] Sarıgöl, M., & Yesilyurt, S. E. F. A. (2022). Flood routing calculation with ANN, SVM, GPR, and RTE methods. Polish Journal of Environmental Studies, 31(6), [Page numbers]. https://doi.org/10.15244/pjoes/151542

[14] Bharali, B., & Misra, U. K. (2022). Numerical approach for channel flood routing in an ungauged basin: A case study in Kulsi River Basin, India. Water Conservation Science and Engineering, 7(4), 389–404. https://doi.org/10.1007/s41101-022-00149-w

[15] Antwi-Agyakwa, K. T., Afenyo, M. K., & Angnuureng, D. B. (2023). Know to predict, forecast to warn: A review of flood risk prediction tools. Water, 15(3), 427. https://doi.org/10.3390/w15030427

[16] Norouzi, H., & Bazargan, J. (2022). Flood routing using the Muskingum-Cunge method and application of

different routing parameters. Sādhanā, 47(4), 282. https://doi.org/10.1007/s12046-022-02049-0

[17] Shayannejad, M., Akbari, N., & Askari, K. O. A. (2015). Determination of the nonlinear Muskingum model coefficients using genetic algorithm and numerical solution of the continuity equation. International Journal of Sciences: Basic and Applied Research (IJSBAR), 21(1), 1–14. gssrr.org

[18] Orouji, H., Bozorg Haddad, O., Fallah-Mehdipour, E., & Mariño, M. A. (2014). Flood routing in branched river by genetic programming. Proceedings of the Institution of Civil Engineers - Water Management, 167(2), 115–123. https://doi.org/10.1680/wama.12.00006

[19] Fevzi, O., & Safak, O. O. (2017). Flood routing model using genetic expression programming. In 7th International Scientific Forum, ISF 2017 (Vol. 2004, p. 481).

[20] Prawira, D., Soeryantono, H., Anggraheni, E., & Sutjiningsih, D. (2019). Efficiency analysis of Muskingum-Cunge method and kinematic wave method on the stream routing (Case study: Upper Ciliwung watershed, Indonesia). IOP Conference Series: Materials Science and Engineering, 669(1), 012036. https://doi.org/10.1088/1757-899X/669/1/012036

[21] Akbari, R., Hessami-Kermani, M. R., & Shojaee, S. (2020). Flood routing: Improving outflow using a new non-linear Muskingum model with four variable parameters coupled with PSO-GA algorithm. Water Resources Management, 34, 3291–3316. https://doi.org/10.1007/s11269-020-02613-5

[22] Mirzazadeh, P., Akbari, G. H., & Ghodsi, M. (2022). Investigating Muskingum-Cunge method application of different schemes in flood routing. Journal of Hydrosciences and Environment, 6(11), 42–48.

[23] Zucco, G., Tayfur, G., & Moramarco, T. (2015). Reverse flood routing in natural channels using genetic algorithm. Water Resources Management, 29, 4241–4267. https://doi.org/10.1007/s11269-015-1058-z

[24] Azizipour, A., Kashefipour, S. M., & Haghighi, A. (2021). Reverse flood routing in an open channel using genetic algorithm. Preprints. https://doi.org/10.20944/preprints202102.0364.v1

[25] Barati, R., Akbari, G. H., & Rahimi, S. (2013). Flood routing of an unmanaged river basin using Muskingum–Cunge model; Field application and numerical experiments. Caspian Journal of Applied Sciences Research, 2(6), 8–20.

[26] Ponce, V. M. (2019). The Muskingum-Cunge method. Journal of Hydrologic Engineering, 24(10), 1-10. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001842