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VALIDATION OF FLOOD ROUTING TECHNIQUES IN AN ANDEAN MICRO-BASIN

Fernando Oñate-Valdivieso[1]
Arianna Oñate-Paladines
Antonio Ríos

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A B S T R A C T

Flood routing describes the process by which a river network conveys runoff downstream, considering mass balance and the speed at which the flood wave propagates. Flood routing methods are generally classified into two categories: hydraulic and hydrological methods. In this study, two hydrological methods (Muskingum and Muskingum–Cunge) and one hydraulic method (Kinematic Wave) were evaluated to model the outlet hydrograph in a section of the main channel of a micro-basin in the equatorial Andes. The evaluation was conducted by comparing the hydrographs measured at the outlet of the section with the inflow hydrograph routed to the outlet. This comparison was performed using three parameters commonly applied in hydrological engineering. Although all three methodologies demonstrated a high level of reliability, the Muskingum–Cunge method exhibited the highest efficiency. Given its computational simplicity and the fact that it requires relatively easy-to-obtain data, it becomes an attractive option for flood routing.

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1. INTRODUCTION

Flood routing describes how a river network transports runoff downstream, considering mass balance and the velocity of flood wave propagation (Mays, 2010). Flood routing methods can be classified into two main categories: hydraulic and hydrological methods (Akbari et al., 2020). Hydraulic methods, which are highly accurate, are based on the solution of continuity and momentum differential equations (Bozorg-Haddad et al., 2019). Hydrological methods, on the other hand, are relatively simple, sufficiently accurate, and require less data (Bozorg-Haddad et al., 2019).

The Muskingum model is one of the best-known and most widely used hydrological flood routing techniques. In this method, model parameters (decision variables) are estimated through optimization methods based on historical records of inflow and outflow hydrographs. The Muskingum-Cunge method (Cunge, 1969; Ponce, 1986) is a time-centered finite-difference solution to the continuity equation, which assumes a prismatic flood wave as a constitutive relation to simplify the momentum equation.

On the other hand, the kinematic wave method (Zheng et al., 2020) is a hydraulic flood routing technique based on the Saint-Venant equations. It models flow propagation in a channel by considering only the balance between bed slope and friction, neglecting inertia and pressure effects. This simplification allows for an efficient estimation of flood evolution.

[1] Corresponding author: Fernando Oñate-Valdivieso
Email: fronate@utpl.edu.ec

The present study aims to evaluate the efficiency of three flood routing methodologies in an Andean micro-basin by analyzing seven flood events recorded at two hydrometric stations located at the upstream and downstream ends of a river section. The observed hydrograph at the outlet is compared with the inflow hydrograph routed to the same location.

2. MATERIALS AND METHODS

2.1 Study area

This study focuses on the El Limón micro-watershed (10.19 km²), located in southern Ecuador, southwest of the city of Zamora (18,000 inhabitants), at coordinates 79.97º W, 4º S. It is part of Podocarpus National Park, a biodiversity hotspot (Oñate-Valdivieso et al., 2021). The area has a highly irregular relief, with an average slope of 68%, and a humid temperate subtropical climate, with annual rainfall ranging from 1,800 to 2,200 mm and an average temperature of 20 ºC. The vegetation cover consists of premontane rainforest and very humid tropical forest, along with small patches of grassland. The micro-watershed serves as the primary water source for human consumption in the city of Zamora. Its location is shown in Figure 1.

Figure 1. Location of the study area.

2.2 Hydrologic Transit Methodologies

In this study, three widely used hydrological flood routing methodologies were applied: the Muskingum, Muskingum-Cunge, and Kinematic Wave methods.
The general equation for the Muskingum method is expressed as (Moradi et al., 2023):

$$S = K[XI + (1 - X)O] \qquad (1)$$

where S is the storage in the river reach (m³), K is the storage or transit time through the reach (hours), and X is the attenuation coefficient, which is dimensionless and varies between 0 and 0.5. I represent the inflow to the reach (m³/s), and O represents the outflow from the reach (m³/s).

The Muskingum-Cunge method (Bindas et al., 2024) improves upon the classical Muskingum method by dynamically estimating the parameters K and X as functions of the hydraulic characteristics of the flow. Its general equation is expressed as:

$$O_t = C_0 I_t + C_1 I_{t-1} + C_2 O_{t-1} + C_3 O_t \qquad (2)$$

where O is the outflow from the reach, and I is the inflow. The coefficients Ci depend on flow and channel properties such as velocity, slope, roughness, and the calculation time interval (Δt). These coefficients are determined from hydraulic parameters, including the Courant number (λ) and the weighting coefficient (θ), which typically has a value of 0.5.

The general kinematic wave equation for flood routing (Zheng et al., 2020) is derived from the continuity equation and the flow resistance equation and is expressed as:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad (3)$$

where Q is the flow rate (m³/s), A is the cross-sectional area of the flow (m²), x is the distance along the channel (m), and t is the time (s).

2.3 Evaluation of Methodologies

The hydrographs of seven flood events recorded at hydrometric stations at the beginning and end of a section of the main river of the El Limón micro-basin (1912.53 m long, with an average width of 4.41 m, an average depth of 0.26 m, an average slope of 13%, and a Manning's n of 0.04) were used. The peak flows of the seven events ranged from 2.5 to 6.0 m³/s.

The inflow hydrograph at the reach inlet was routed using the methodologies described in section 2.2 and compared to the hydrograph observed at the basin outlet using the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and root mean square error (RMSE) (Oñate-Valdivieso & Bosque Sendra, 2007).

3. ANALYSIS OF RESULTS

Figures 2 and 3 show the first and third events studied respectively, in which the measured inflow hydrograph (Inflow), the measured outflow hydrograph (Outflow), and the hydrograph routed using the different methods analyzed can be observed. The graphical fit between the outflow hydrograph and the routed hydrographs is quite acceptable, which supports the efficiency of the methodologies used.

Table 1 shows the values of R^2, NSE, and RMSE for each of the seven events and the three methodologies applied.

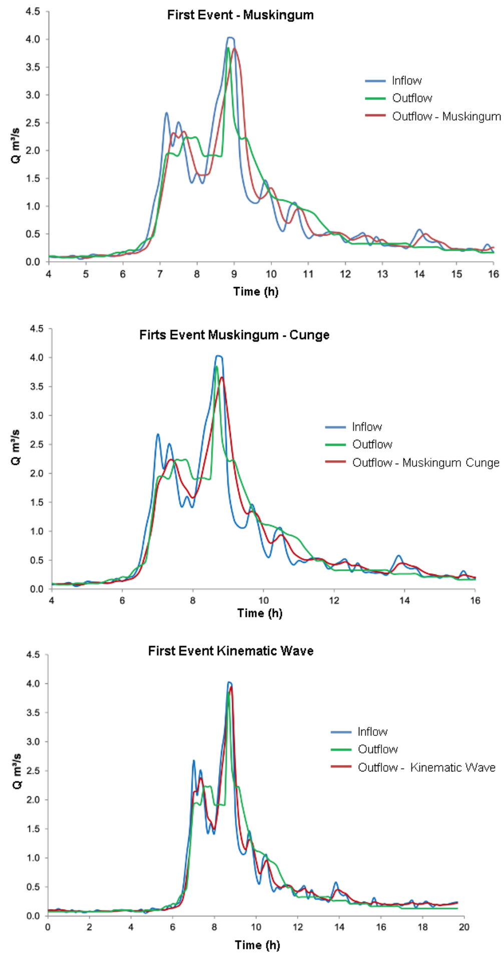

Figure 2. Hydrographs of the first event

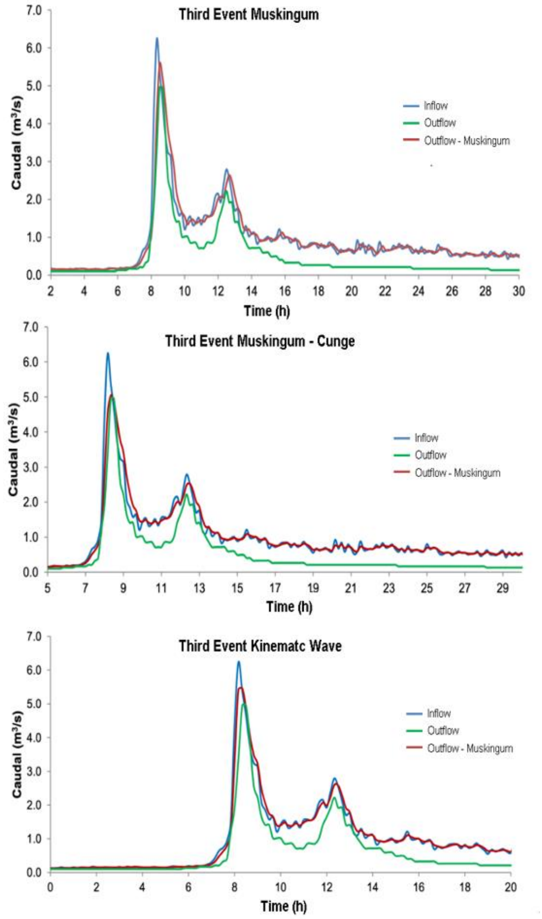

Figure 3. Hydrographs of the third event

Table 1. Validation coefficient values

Event	Muskingum			Muskingum - Cunge			Kinematic Wave		
	R^2	NSE	RMSE	R^2	NSE	RMSE	R^2	NSE	RMSE
1	0.95	**0.90**	0.24	**0.97**	**0.93**	**0.19**	0.95	**0.91**	0.23
2	0.95	0.84	**0.20**	0.95	0.83	0.20	0.95	0.84	0.20
3	**0.97**	0.66	0.44	0.96	0.64	0.44	**0.96**	0.65	0.44
4	0.96	0.84	0.31	0.96	0.84	0.31	**0.96**	0.84	0.31
5	0.92	0.76	0.31	0.93	0.76	0.31	0.90	0.71	0.34
6	0.89	0.73	0.23	0.91	0.78	0.20	0.87	0.69	0.24
7	0.79	0.62	0.33	0.81	0.66	0.31	0.78	0.60	0.34
Mean	0.92	0.76	0.29	**0.93**	**0.78**	**0.28**	0.91	0.75	0.30
S.D.	**0.06**	**0.10**	**0.08**	0.06	0.10	0.09	0.07	0.12	0.08

Table 1 indicates that the coefficient of determination (R^2) value is acceptable in all cases, exceeding 0.7. A similar trend is observed for the NSE, although the minimum values are somewhat lower, reaching a minimum of 0.6. The RMSE values are less than 0.3 in most cases, except for event 3, which has a high value of 0.44. In general, it can be observed that the three methodologies perform well in simulating the outflow hydrograph, with the Muskingum-Cunge method yielding the best average values and showing the best performance for event 1. Event 3 presented the greatest limitations in being modeled by all three methods, as the recession curve in the observed outflow hydrograph was significantly lower than that of the routed hydrograph. This could be attributed to the fact that the model assumed greater storage in the channel than was observed.

4. CONCLUSIONS

Three flood transit methodologies were evaluated by comparing them with observed hydrographs from seven events, using three validation parameters commonly applied in hydrological engineering. The three hydrologic transit methodologies evaluated successfully modeled the outflow hydrograph, with the Muskingum-

Cunge method demonstrating the best performance. Considering its simplicity in calculation and the fact that it requires relatively easy-to-obtain data, it presents an attractive alternative for modeling flood transit.

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Fernando Oñate-Valdivieso
Universidad Técnica Particular de Loja,
Loja,
Ecuador
fronate@utpl.edu.ec
ORCID 0000-0002-2400-0510

Arianna Oñate-Paladines
Universidad Técnica Particular de Loja,
Loja,
Ecuador
ayonate@utpl.edu.ec
ORCID 0000-0001-5175-8450

Antonio Rios
Universidad Técnica Particular de Loja,
Loja,
Ecuador
amrios@utpl.edu.ec