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A Real-Time Flow Muskingum Forecasting Model for Three Main Stations of the Medjerda River (Tunisia)

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ABSTRACT: Flooding problem raised seriously in the watershed of Medjerda in Tunisia indeed flood risk factors still exists for some cities. Studies forecasting and flood management may be important to address these problems. In this context, the axis "Flood Mapping and modeling" of the project "Improving of water resources management and adaptation to climate change - Tunisia", funded by the GEF - World Bank, coordinated by the Regional Centre for Remote Sensing of North Africa States, supported by NASA and conducted jointly by the Ministry of Agriculture, the National Centre for Cartography and Remote Sensing and the National Institute of Meteorology, aims to establish a reliable model for flood forecasting of Medjerda major hydrometric stations. Following the parsimonious concept of parameters, simplified models for flood forecasting based only on flood routing have been developed for flood-prone sites located downstream of a gauged station and at a distance allowing an appropriate forecasting lead-time. In this context, the Muskingum model can be a useful tool. A model for real-time flood forecasting in river systems with large drainage areas has been developed. Flow variations between upstream and downstream stations are interlinked and are typically governed by reach properties. The reach of Ghardimaou-Bou Salem (upstream basin of Medjerda) had long known catastrophic floods. We recovered twenty four floods in the upstream basin during the period 1973-2013. This communication is designed to analyze the results of the floods forecasting by simple propagation model namely Muskingum. The method of forecasting depends on the upstream station flow and models coefficients of antecedent floods. Forecast periods range from 2 to 8 hours, with a pitch of 2 hours. We used numerical criteria, such as Nash coefficient, peak relative error and time separating observed and calculated pic, to evaluate the results. We noted that the results were satisfactory with Nash coefficient ranging from 20% to 99.8%.

Keywords: Flood forecasting, upstream basin of Medjerda, Muskingum

1 INTRODUCTION

Channel flooding is a complex dynamic process characterized by spatial and temporal variation in the flow parameters. Generally, information on water levels is collected at critical locations, as well as at existing stream gauging stations, for analyzing flood movement. Development of flood forecasting model characteristics based on only an observed stage is a difficult task because of recharge over the reach, spatial variability of rainfall, and varying channel characteristics influence river flow in a highly nonlinear manner. These issues become more complicated for large river systems, thus, requiring detailed distributed information for routing the flood along the river reach.

Deterministic flood forecasting models can be divided into two general categories: flood routing models and real-time rainfall– runoff models. Models of flood routing are varied; there are a big number of algorithms from simple statistical receipt to the partial differential equations of Saint-Venant (Bentura, 1996). The Muskingum model is numerically equivalent to the Saint-Venant equations via the diffusion equation of a wave. It is a classical flood routing method. However, the representation of lateral inflow contributions, as well as the discharge forecasting at the outlets of upstream sub-catchments cause problems. Muskingum model is improved to incorporate multiple sources of inflows and single outflow to route the flood in the reach.

In Tunisia, the flood problem arise the only perennial river, Medjerda, in particularly the reach of Ghardimaou-Jendouba- Bou Salem. During the work of my Masters memory, we applied Muskingum model to reconstitute flood hydrographs of the main stations of Medjerda River in the upstream Sidi Salem dam and the results were satisfactory (Abidi, 2011). In this paper we will use Muskingum model for flood forecasting using the results of flow reconstitution. The consideration of lateral flow in the hydrograph reconstitution ameliorated the results (Abidi, 2014). We decide in this paper to enter lateral flow in the upstream discharge for the forecasting.

The first part of the paper presents the models and the performance criteria, the second section illustrates the study area and in the third part we present the results.

2 MATERIALS & METHODS

2.1 *Methods*

The methods of flood routing are broadly classified as empirical, hydraulic, and hydrological (Fread, 1981). A number of soft computing related techniques were used for flood forecasting in addition to Muskingum method.

2.1.1 *Muskingum model*

Since its development in 1939 by McCarthy, this model is widely used in hydrological engineering. Cunge (1969) showed that the Muskingum model is numerically equivalent to the Saint-Venant equations via the diffusion equation of a wave. Muskingum model proposes a relationship between the inflow Qa (t) and outflow Qs (t) of type (Habaieb, 1992):

$$Q_s(t+d) = a_1 Q_a(t) + a_2 Q_a(t+d) + a_3 Q_s(t) \tag{1}$$

Where 'Qa' and 'Qs' are the upstream and downstream flow (expressed in m^3/s), 't' is the calculation time, 'd' represent the calculation delay and 'a_1, a_2, a_3' are the coefficients of Muskingum model calculated by least squares' method.

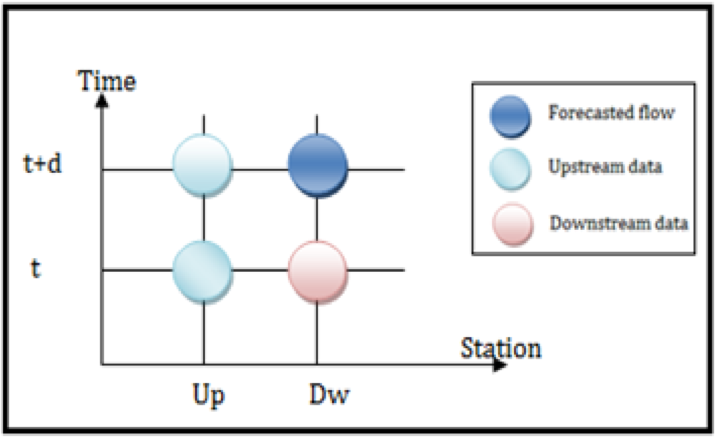


Figure 1. Muskingum model technic of reconstitution

2.1.2 *Forecasting model*

After dressing the Muskingum coefficient of flow reconstitution, we regrouped flooding by season. To forecast a flooding by Muskingum model, the coefficient (a_1, a_2, a_3) are taken from a simulated flooding that had a previous date, belong to the same season and had a near humidity index.

2.1.3 *Performance measures*

Graphic criteria used to optimize the results are observed and simulated hydrographs, peak flows observed and simulated correlations between observed and calculated rates. Numeric criteria chosen to test the effectiveness of the models are the Nash–Sutcliffe model efficiency coefficient "Equation (2)", the peak relative error "Equation (3)" and the peak time error "Equation (4)".

$$CNash = 1 - \frac{\sum_{i=1}^{n}(Qo - Qc)^2}{\sum_{n=1}^{n}(Qo - Qm)^2} \tag{2}$$

$$PRE = \frac{Qc\,max - Qo\,max}{Qc\,max} \tag{3}$$

$$PTE = t_{Qc} - t_{Qo} \tag{4}$$

Where '*Qo*' is the observed flow, '*Qc*' is the calculated flow, '*Qm*' is the average observed flow, '*Qc*max' and '*Qomax*' are the maximum calculated and observed flow, t_{Qc} and t_{Qo} are the calculated and observed peak time.

2.2 *Study area*

The Medjerda, the major Tunisian river, originates in the semi-arid Atlas Mountains of eastern Algeria. In Tunisia, the western part of the catchment is delimited by the south facing slopes of the Tell region and in particular the Kroumir Mountains, and at the south by the north facing slopes and piedmonts of the semi-arid Dorsal Mountains. The river then flows east, through the tectonic depression of the Ghardimaou basin, characterized by an 8–10 m thick Holocene floodplain sediments. The Medjerda catchment covers approximately 24,000 km², of which 16,100 km² located in Tunisia and extends for 460 km including 350 in Tunisia (Zielhofer, 2002).

The area under study covers partially the Medjerda river basin and is defined as the area draining between the gauging subwatershed of Ghardimaou and Bou Salem, just before reaching the Sidi Salem Dam (Figure 1), the largest dam in North Africa.

The area of the studied basin is about 4645 km². The basin is drained by a series of rivers of varying sizes (table 1) which two tributaries are conducted by dams.

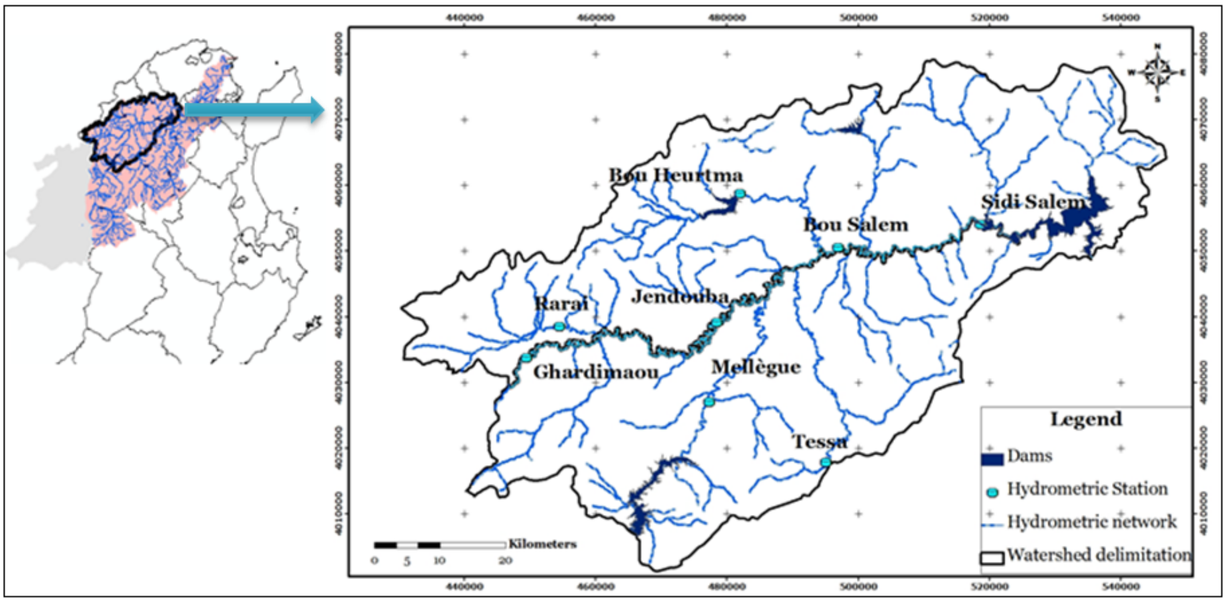


Figure 2. Study area

Table 1. Tributaries characteristics

Tributaries	Area (km²)	Length (km)
Rarai	750	14
Mellegue	10700	317
Tessa	2450	143
Bouheurtma	550	30

The rugged terrain overlooking the plain on the north side and south side slopes are generally high, which promotes surface runoff.

The catchment lies in the sub-humid to Mediterranean humid bio-climatic region. The rainy season extends from September to May, with intense precipitations in autumn.

3 RESULTS AND DISCUSSION

25 floods were reconstituted by Muskingum model. The model coefficients were used to forecast these floods. Forecast periods range from 2 to 8 hours, with a pitch of 2 hours.

The flow of Jendouba upstream is the sum of Ghardimaou and Rarai flow. The flow of Bou Salem upstream is the sum of Jendouba flow and the tributaries flows (Mellegue, Tessa, Bouheurtma).

To analyze the results we draw the distribution functions of the different criteria in each section.

3.1 *Section Ghardimaou - Jendouba*

The following figures show the repartition function of the Nash coefficient, the Pic relative error and the pic time error for all forecasted time:

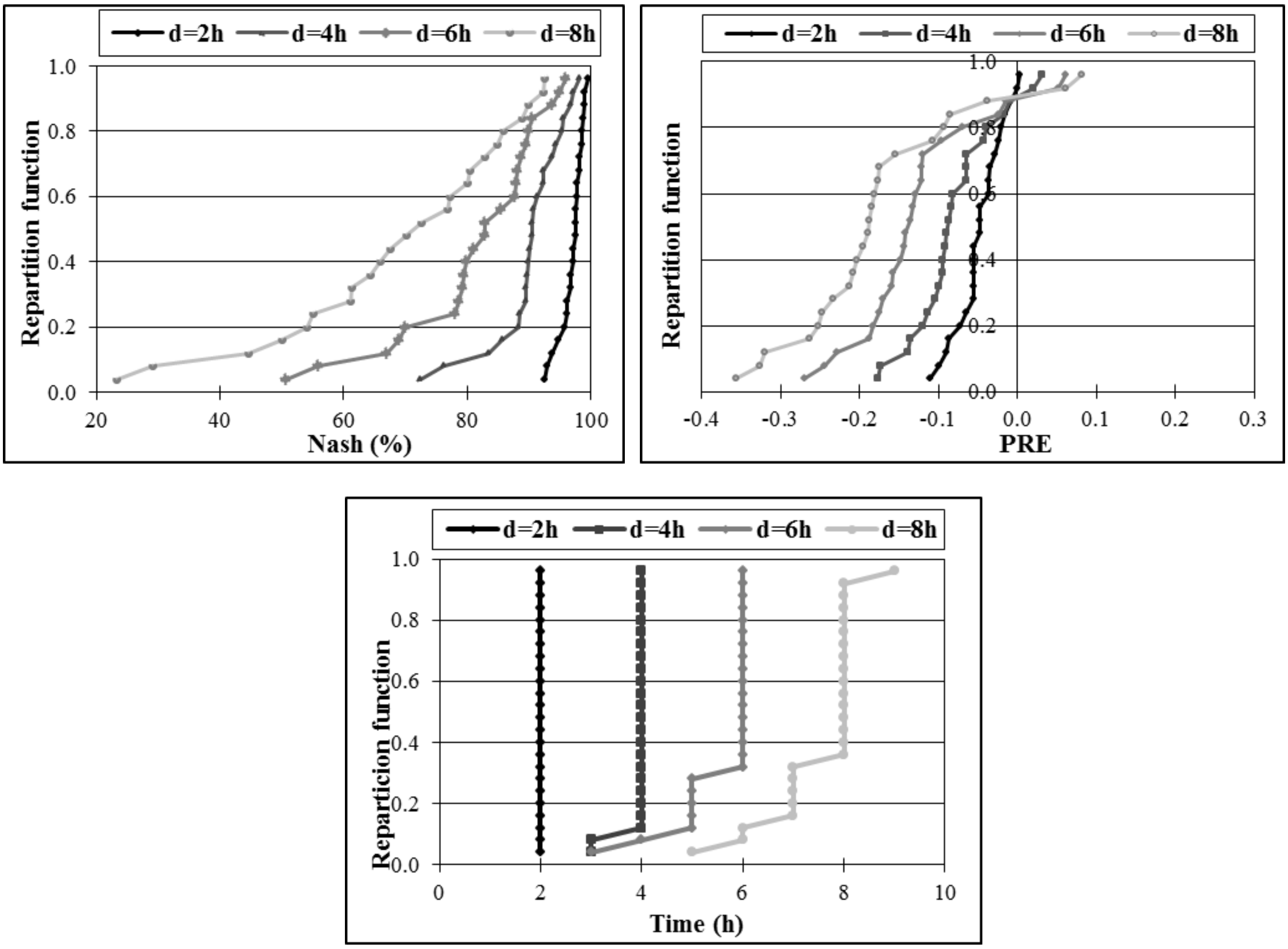


Figure 3. Repartition function of Nash coefficient, Pic relative error and pic time error of forecasting Jendouba flow.

The variation of three criteria is proportional to calculated time: the criteria value increase with the forecasting delay.

The Nash coefficient varies between 23 and 92.6% for the forecasting delay of 8 hours, between 50 and 96 for the forecasting delay of 6 hours, between 72.5 and 98 for the forecasting delay of 4 hours and between 93 and 99.6 for the forecasting delay of 2 hours. So the highest value is found by forecasting delay of 2 hours.

The values of the pic relative error (PRE) are very low: the lowest absolute values are found by forecasting delay of 2 hours (0 and 11%). The pic flow is underestimated for 22 flow.

The pic time error varies from 2 to 9 hours, but the lowest values are given by the forecasting delay of 2 hours.

We conclude that forecasting results depend on the applied time; over time decreases more than the forecast will be best. The highest values are given by the flow forecasting in two hours.

These criteria show that the Muskingum model provided adequate Jendouba flow forecasting.

3.2 *Section Jendouba – Bou Salem*

We present for this section the repartition function of the Nash coefficient, the Pic relative error and the pic time error for all forecasted time:

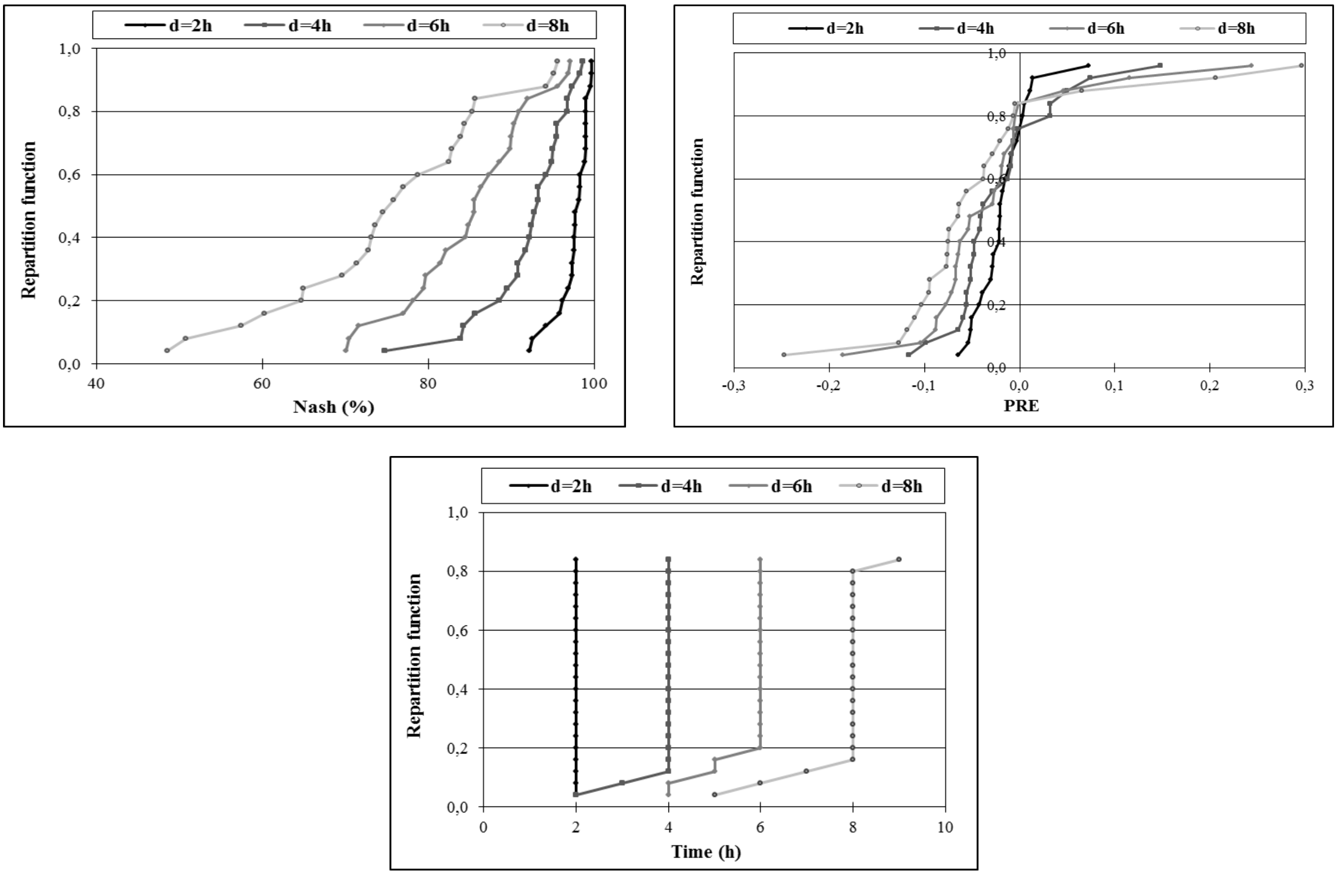


Figure 4. Repartition function of Nash coefficient, Pic relative error and pic time error of forecasting Bou Salem flow.

We note that all the criteria increase when the forecasting delay increases.

For the forecasting delay of 8 hours, the Nash coefficient range from 50 to 95.6%, the pic relative error (PRE) varies between -24 to 29% and the pic time error is in average equal to 8 hours.

For the forecasting delay of 6 hours, the Nash coefficient range from 70 to 97%, the pic relative error (PRE) varies between -19 to 24% and the pic time error is in average equal to 6 hours.

While, for the forecasting delay of 4 hours, the Nash coefficient range from 75 to 98.6%, the pic relative error (PRE) varies between -13 to 15% and the pic time error is in average equal to 4 hours.

Finally, for the forecasting delay of 2 hours, the Nash coefficient range from 92 to 99.6%, the pic relative error (PRE) varies between -6 to 7% and the pic time error is constant equal to 2 hours.

The pic relative error is underestimated for 19 floods for the forecasting delay 2 and 4 hours and for 21 floods for 6 and 8 hours.

We conclude that the forecasting in two hours had the best value of the three criteria. The Muskingum model provided satisfactory forecasting of Bou Salem flow.

We present as an example of forecasting of Jendouba flow, the predicted flood of November 2010 at the calculated delay of 2 hours. This flood is classified 24 by Nash coefficient and 20 by pic relative error.

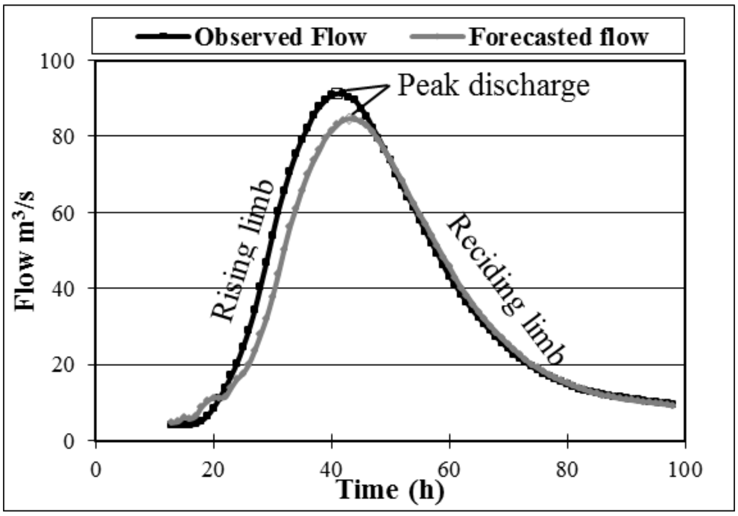


Figure 5. Observed and forecasted hydrograph of the flood November 2010 at 2 hours

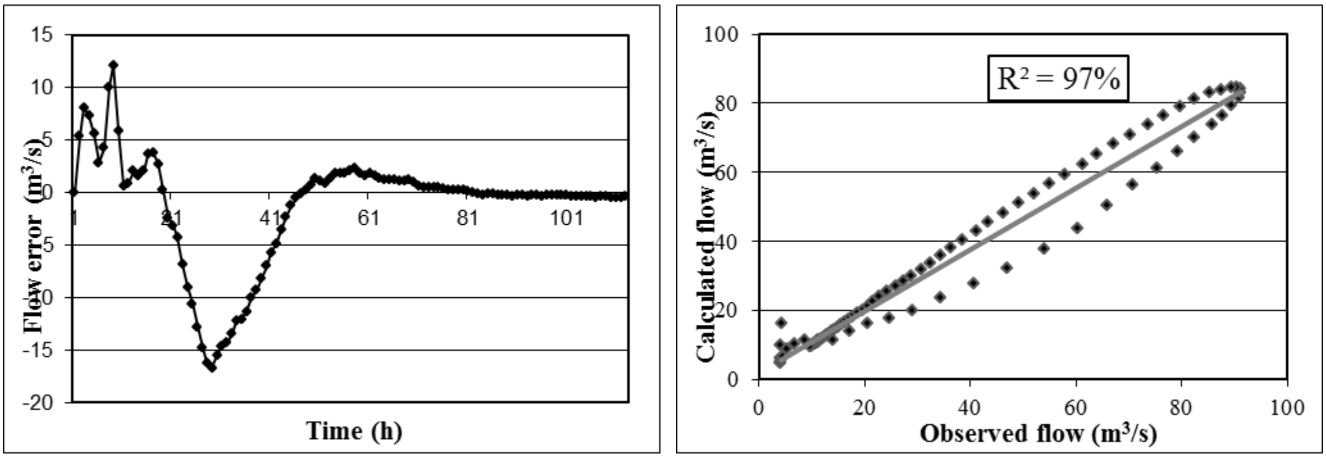


Figure 6. The error and the correlation between observed and forecasted flow of the flood November 2010 at 2 hours

The shape of the hydrograph is reproduced, the rising limb is underestimated and the receding limb is confused with the observed hydrograph. The form of the pic is reproduced; it appears after 2 hours with an error of its value of -7%. The error differences between observed and calculated flows are low, between -16 and 12 m^3/s. The scattered point is close to the first bisector with a coefficient of correlation equal to 97%.

We conclude that the routing model of Muskingum give satisfactory results of forecasting of the flow of Jendouba at 2 hours with a Nash of 96%.

We present also an example of forecasting of Bou Salem flow, the predicted flood of February 2011 at the calculated delay of 4 hours. This flood is classified 14 by Nash coefficient and 12 by pic relative error.

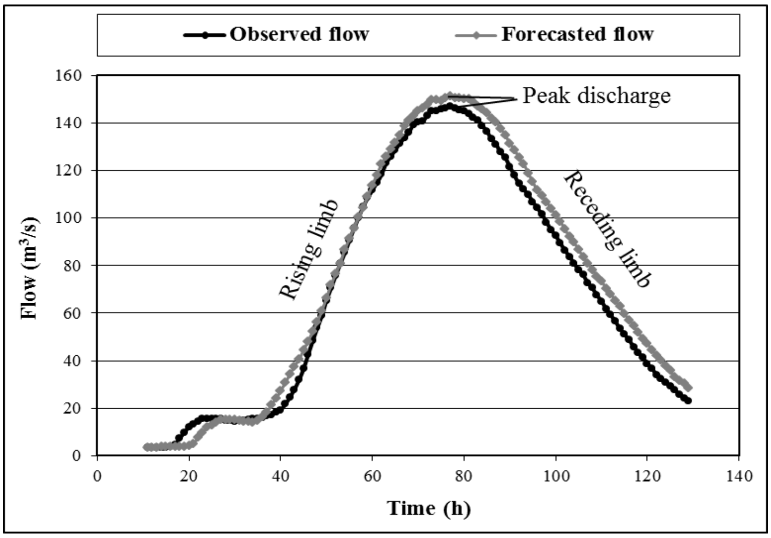
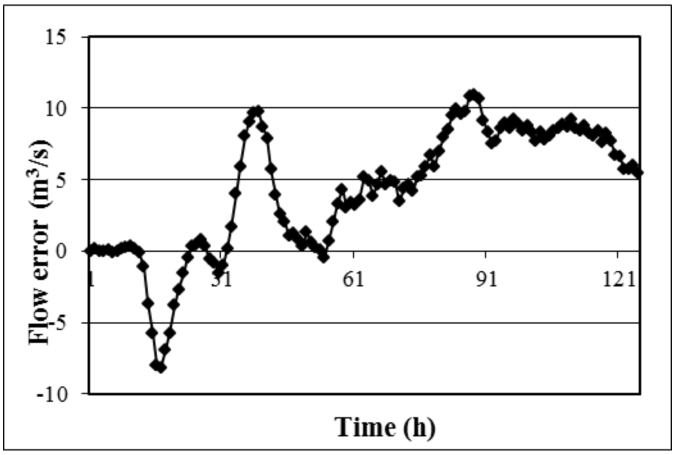


Figure 7. Observed and forecasted hydrograph of the flood February 2011 at 4 hours



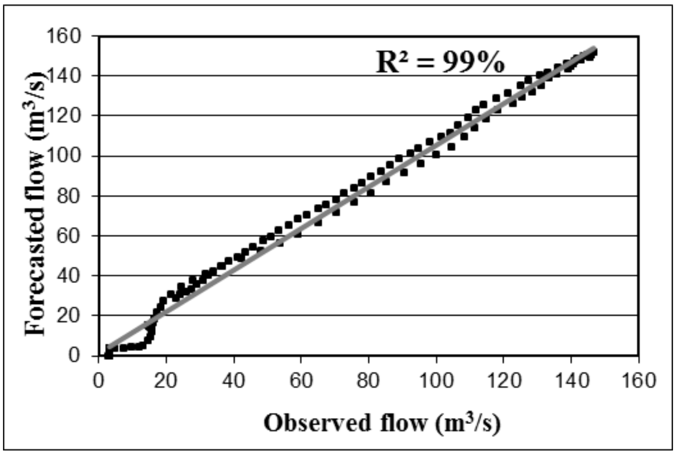


Figure 8. The error and the correlation between observed and forecasted flow of the flood February 2011 at 4 hours

For this flooding, we note that Muskingum model reproduces the shape of the hydrograph. The rising limb is confused with the observed hydrograph and the receding limb is overestimated. The model reproduces also the form of the pic; which appears after 2 hours with an error of its value of 3%. The difference between observed and calculated flows is low, between -16 and 12 m^3/s. The scattered point is close to the first bisector with a coefficient of correlation equal to 99%.

We conclude that the routing model of Muskingum give satisfactory results of forecasting of the flow of Jendouba at 2 hours with a Nash of 96%.

4 CONCLUSION

The Muskingum method is examined in this study for its applicability as flood forecasting method for the case study of three main station of Medjerda River in Tunisia. Twenty four floods from 1973 to 2013 are analyzed for this purpose. Mean squared method is employed to determine the values of the coefficients required for the Muskingum method. The method of forecasting depends on the upstream station flow and models coefficients of antecedent floods. Forecast periods range from 2 to 8 hours, with a pitch of 2 hours. So 192 operation of flow forecasting are analyzed.

It is observed that Nash coefficient, pic relative error and pic time error decreases systematically with decrease forecasting delay. In addition, it is observed that the pic flows predicted by Muskingum method are underestimated for 22 floods (for all forecasting delay) in the section Ghardimaou-Jendouba and 19 floods (for 2 and 4 hours) and 21 floods (for 4 and 6 hours) in section Jendouba-Bou Salem.

From these results it can be concluded that the Muskingum model can be explored for similar watershed such as Medjerda.

Future directions of the present study are: the integration of rain in flow forecasting and the test of regression method.

NOTATION

Q_a	upstream flow (cubic meter per second)
Q_b	downstream flow (cubic meter per second)
t	calculation time
d	calculation delay
a_1, a_2, a_3	model coefficients
Q_o	observed flow
Qc	calculated flow
Q_m	average observed flow
Q_{cmax}	maximum calculated
Q_{omax}	maximum observed flow
t_{Qc}	calculated peak time
t_{Qo}	observed peak time.

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