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FLOOD ROUTING WITH REAL-TIME METHOD FOR FLASH FLOOD FORECASTING IN THE PLAIN BOU SALEM

Medjerda River in Tunisia

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Abstract— Flooding problem raised seriously in the watershed of Medjerda indeed flood risk factors still exists for some cities. Studies forecasting and flood management may be important to address these problems. The plain of Bou Salem had long known catastrophic floods. Sudden rain, releases of dams and tributaries flows caused historic flooding at the level of this plain. We recovered thirty floods in the station of Bou Salem during the period 1973-2013. Among the thirty floods, we distinguish mainly three Flash floods. In fact, Flash flood is a short and sudden local flood with great volume, it has a limited duration which follows within few (usually less than six) hours of heavy or excessive rainfall, rapid rain, or after a sudden release of water from a dam. This communication is designed to analyze the results of the flash floods forecasting by simple propagation models namely Muskingum and Regression. 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 satisfaction of all criteria together is not touched. The results were satisfactory with Nash coefficient ranging from 71% to 99.8%.

Index Terms— Flash flood, plain of Bou Salem, forecasting, Muskingum, Regression.

I. INTRODUCTION

When it rains in a catchment area, all the difficulty lies in the definition of rainwater division between its various possible destinations (evaporation, infiltration or streaming…) and in the definition of the concerned physical processes to realize these tasks.

The Flash flood are definite by [1] as being suddenly appear, often not easily foreseeable, fast climb time and had relatively important specific discharge. These floods are usually associated with intense rainfall events and occur in basins of moderate size. The tributary flows and dams' releases aggravate the situation. This is the case of the plain of Bou Salem which became a flood stage. It is crossed by the river Medjerda receiving water from Jendouba station, tributaries Mellegue, Tessa and Bouheurtma. Plain Bou Salem has experienced devastating floods that have caused serious human and material damage.

II. STUDY AREA

Medjerda is the most important river of Tunisia by the size of its watershed (23,500 km^2) and the importance of annual contributions which represent on average a third of the surface water resources of the country (915 million m^3 in average).

Plain Bou Salem is located in northern Tunisia and high valley of Medjerda (Fig 1). It is limited by the hydrological station of Jendouba (upstream) and Bou Salem (downstream). The plain is crossed from west to east by the Medjerda River over a length of 10 km and a catchment area of 6808 km^2.

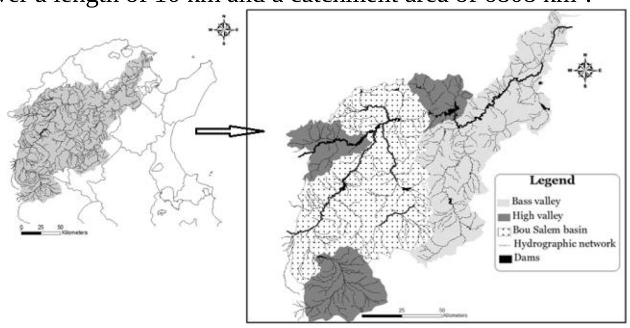

Fig. 1 **Localization of Bou Salem plain in the high valley of Medjerda**

The main tributaries which flow into Medjerda River at the plain of Bou Salem are (Fig. 2):

At the left side:

- Oued Bouhertma: it converges near Bou Salem after a course of 64 km, it drains a catchment area of 390 km².

At the right bank

- Oued Mellègue: it covers a distance of 317 km before converging just after Jendouba, it drains a catchment area of 4,497 km².
- Oued Tessa: It flows into Medjerda River just after Mellegue. It covers a distance of 143 km, it drains a watershed of 2,410 km².

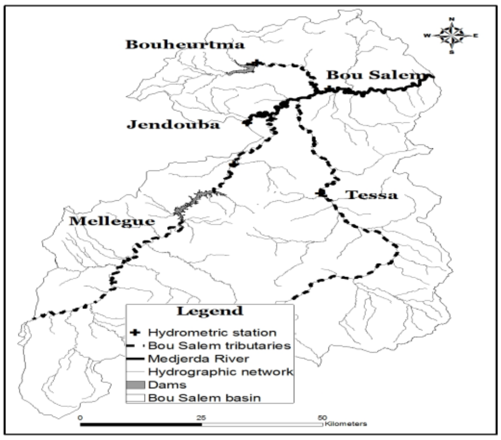

Fig. 2. **Tributaries of Bou Salem plain**

A. Climate context

At Medjerda, the average annual rainfall varies from 1,000 mm in the northern part and the southern part receives only 300 mm. Precipitation plain Bou Salem (Fig. 3) varies between 240 and 700 mm with an average of 500 mm. Rainfall is also very irregular from one year to another. The average temperature in the basin varies between 38° C in July and August and less than 6° C in January.

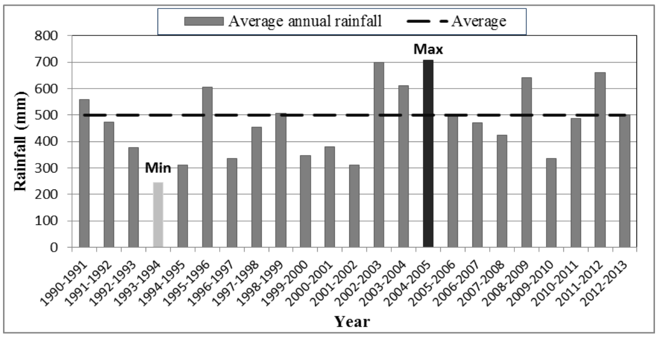

Fig. 3. **Annual average precipitation of Bou Salem**

B. Historic flooding in Bou Salem

We recovered thirty flood of the station Bou Salem during the period 1973-2013. These floods occur mainly during the spring and winter seasons. From these floods, we noted the existence of five major floods where the runoff volume for a few days can reach the average annual volume. The following table summarizes some characteristics of main floods:

TABLE I. **HISTORIC FLOODING**

Flood	**Peak flow (m^3/s)**	**Precipitation (mm)**	**Rain duration (day)**	**Specific flow ($l/s/km^2$)**
March 1973	3220	123	6	473
Mai 2000	977	67	4	143
January 2003	1020	187	3	150
November 2004	529	83	4	77
April 2009	550	55	2	81
February 2012	882	50	2	129

The flood of March 1973 is characterized by a single high peak inflow and considerable rainfall in the entire basin during 6 days. The volume spilled from Mellegue dam, Jendouba basin and Tessa tributary reached 155, 259 and 75 million m^3 respectively.

The flood of Mai 2000 had a high speed entering with a single point, and localized rainfall. Precipitation focused on the sub-basins Tess and Mellegue. The volume spilled reached from Mellegue dam 93 10^6 million m^3 and Jendouba basin 56 million m^3.

The flood of January 2003 had unique inflow and sudden rainfall peak. The dam releases Mellegue (82 million m^3) and Bouheurtma (36 million m^3) and contribution of Jendouba basin (108 million m^3) and Tessa tributary (18 million m^3) participated in the aggravation of this flood.

The flood of November 2004 had a flat unique inflow. The precipitation was located at Mellegue dam with moderate intensities for 4 days. The dam releases Mellegue (3.6 million m^3) and Bouheurtma (12 million m^3) and contribution of Tessa tributary (5 million m^3) and Jendouba basin (42 million m^3) caused this flood.

The flood of April 2009 caused by sudden and significant rainfall, releases from the dams of Mellegue (14 million m^3) and Bouheurtma (69 million m^3) and contribution of Tessa (15 million m^3 and Jendouba basin (54 million m^3).

The flood of February 2012 provoked by sudden and significant rainfall, releases from Bouheurtma dams (68 million m^3) and contribution of Jendouba watershed (196 million m^3).

C. Choice of flash floods in Bou Salem

Several definitions of flash floods have been found in the literature. Table 2 presented the selection of flash floods in Bou Salem according to the characteristics defined by [2].

Based on this characteristic we identified three flash floods: the one of January 2003, April 2009 and February 2012. In the next chapter, we will precede to the prediction of these three floods with the models of Muskingum and Regression.

TABLE II. CHOICE OF FLASH FLOODS IN BOU SALEM

Flash flood characteristic	**1973**	**2000**	**2003**	**2004**	**2009**	**2012**
Sudden onset and evolution (rapid hydrological response, rise time of rapid flood, violence)			X		X	X
Torrential rains that are origin			X	X	X	X
Importance des débits dans les rivières	X	X	X	X	X	X
Local inundation (geographically)			X		X	X
Difficulty of predicting the flow and possibly damage they generate	X	X	X		X	X

III. APPLIED METHODS

A. Forecasting methods

The method used in this study for flow forecasting is based on the coefficients resulting from the reconstruction of flood hydrographs with propagation models. These coefficients will be taken, for each method and for each period of prediction, from a previous flood haven same degree of humidity and same season like the flood to be predicted. Prediction delay varies from 2 to 8 hours with a pitch of 2 hours.

B. Reconstitution methods

The reconstitution is an operation consisted to calculate the simulation coefficients of each flood, by each method and for each calculation period. In this study, we will use the results of reconstitution of 26 flood of Bou Salem station in Medjerda River [3].

Two models were used to predict the flash flood of Bou Salem:

- Muskingum model,
- Regression model.

1) Muskingum model

Since its development in 1939 [4], this model is widely used in hydrological engineering. Cunge [5] 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 [6]:

$$Q_s(t+d) = a_1 Q_a(t) + a_2 Q_a(t+d) + a_3 Q_s(t) \quad (1)$$

Where 'Qa' and 'Qs' are the upstream and downstream flow (expressed in cubic SI), 't' is the calculation time, 'd' represent the calculation delay and 'a1, a2, a3' are the coefficients of Muskingum model can be calculated by least squares' method.

2) Regression methods

Through two downstream data and information well before the upstream taken at time t-τp, we can write [6]:

$$Q_s(t+d) = b_1 Q_a(t+d-\tau_p) + b_2 Q_s(t) + b_3 Q_s(t-d) \quad (2)$$

Here 'τp' is the propagation times between the two upstream and downstream stations and 'b1, b2, b3' are the regression model coefficients can be calculated by the least squares method.

We note that the upstream flow has both Jendouba and Tessa flows and outgoing Mellegue and Bouheurtma dams.

C. Performance Measures

Graphic criteria used to optimize the results are observed and simulated hydrographs, Error and correlations between observed and calculated rates.

Numeric criteria chosen to test the effectiveness of the models are:

The peak relative error (PRE):

$$PRE = \frac{Q_{cal\,max} - Q_{obs\,max}}{Q_{cal\,max}} \quad (3)$$

Where 'Q_{calmax}' is the maximum rate calculated and 'Q_{obsmax}' represent the maximum observed flow.

Nash coefficient (Nash):

$$CNash = 1 - \frac{\sum_{i=1}^{n}(Qoi - Qci)^2}{\sum_{n=1}^{n}(Qoi - Qm)^2} \quad (4)$$

Where Q_{oi} is the observed flow, Q_{ci} is the calculated flow and Q_m is the average observed flow.

The peak time error: difference between the time of calculated 't_{Qcal}' and observed 't_{Qobs}' peak:

$$PTE = t_{Qcal} - t_{Qobs} \quad (5)$$

IV. Results & discussions

We present in this part the results of each flood forecasting.

A. Flash flood of 11 January 2003

For predicting the flood, we used the coefficients of the flood 13/12/1990.

We summarize in Table 3 the values of various evaluation criteria.

TABLE III. Flood forecasting of 11 January 2003

	Muskingum model			Regression model		
Prediction delay (h)	***PRE (%)***	***Nash (%)***	***PTE (h)***	***PRE (%)***	***Nash (%)***	***PTE (h)***
2	1.1	99.6	0	2	99.8	0
4	6	98.6	4	6	98	-3
6	12	97	4	16	94	-2
8	14	95	4	26	87	0

After this application, we note that:

- The peak relative error (PRE) is lower for the period of two hours for both models and it increases with time forecast. It is lower for Muskingum model.
- The Nash decreases with increasing delay of prediction for both models.
- The peak time error (PTE) is the same for a period of two hours for both models and it is lower for other periods for the regression model.

We can conclude that the satisfaction of the three numerical criteria at once is not possible to predict the flood January 2003. Nash is more important with the regression model for the period of two hours with the model Muskingum for other periods.

We present the results of forecasting the flood in January 2003 with the regression model for a period of two hours.

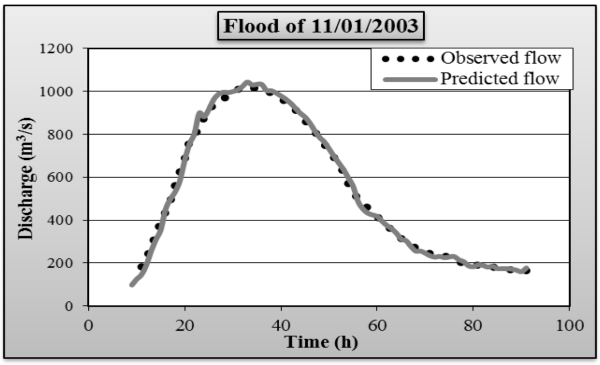

Fig. 4. **Flow hydrograph forecasting of 11/01/2003 flood by Regression model in 2 hours**

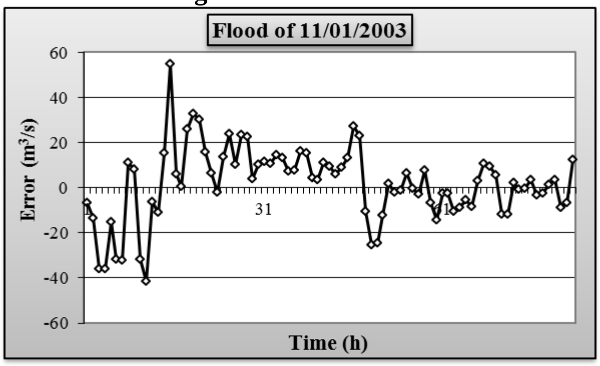

Fig. 5. **Prediction error of 11/01/2003 flood by Regression model in 2 hours**

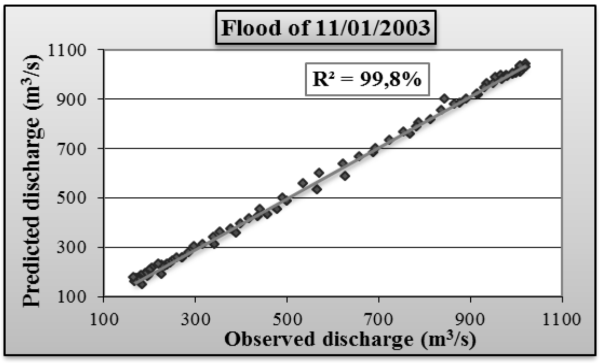

Fig. 6. **Flow correlation of 11/01/2003 flood by Regression model in 2 hours**

The prediction results of flood 11/01/2003 in 2 hours are satisfactory. In fact, the shape of the hydrograph is reproduced and the observed one is superposed with the calculated. The maximum flow is reproduced by its shape, its value with a small error (2%) and its time. The flow error varied from -42 to 55 m^3/s. The Nash coefficient is high, equal to 99.8%.

The prediction results of flood 11/01/2003 in 2 hours are satisfactory. In fact, the shape of the hydrograph is reproduced and the observed one is superposed with the calculated. The maximum flow is reproduced by its shape, its value with a small error (2%) and its time. The flow error varied from -42 to 55 m^3/s. The Nash coefficient is high, equal to 99.8%.

B. Flash flood of 16 April 2009

For predicting this flood, we used the coefficients of the flood 25/05/2000. The results are summarized in the following table:

TABLE IV. **FLOOD FORECASTING OF 16 APRIL 2009**

	Muskingum model			Regression model		
Prediction delay (h)	***PRE (%)***	***Nash (%)***	***PTE (h)***	***PRE (%)***	***Nash (%)***	***PTE (h)***
2	-0.1	97.5	2	2.7	99.6	-2
4	-0.2	91	4	4.3	97	0
6	-0.5	81	6	5	89	2
8	-1.2	71	8	4.2	80	4

The values of the performance criteria are variable from one model to another. We do not have complete satisfaction for all criteria. For the peak relative error (PRE), the Muskingum model gives the best results. For the Nash coefficient and the peak time error (PTE), the regression model prevails.

For both models and for all delay, Nash varies between 71 and 99.6%, which proves the good prediction of the flood of April 2009 at Bou Salem.

The following figures show the results of forecasting flood of April 2009 with the Muskingum model with a delay of 4 hours.

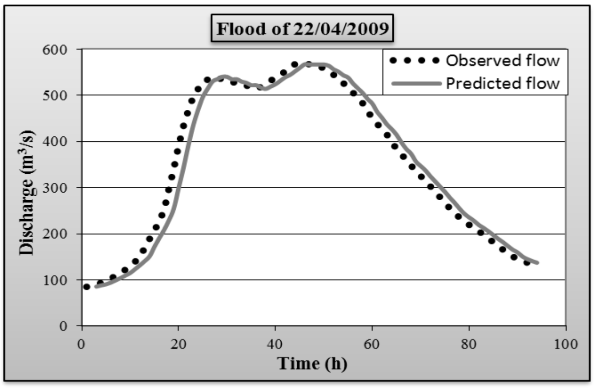

Fig. 7. **Flow hydrograph forecasting of 22/04/2009 flood by Muskingum model in 4 hours**

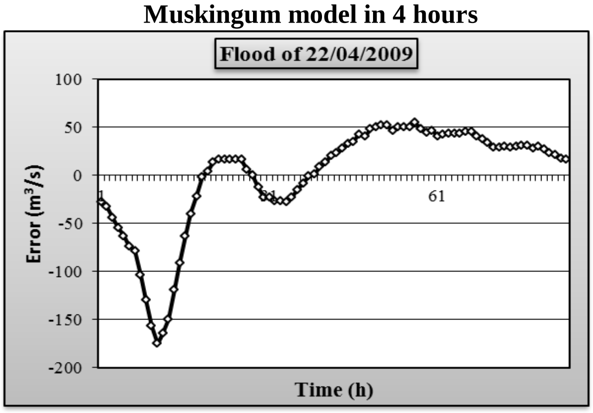

Fig. 8. **Prediction error of 22/04/2009 flood by Muskingum model in 4 hours**

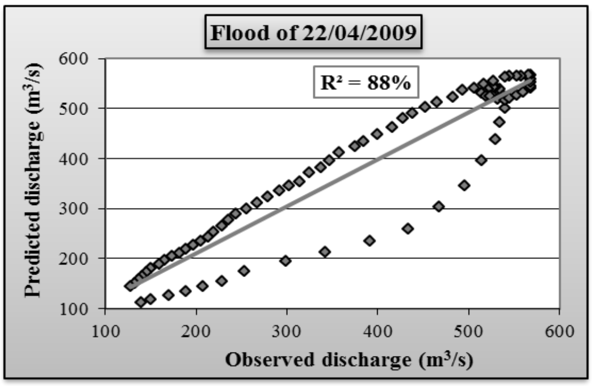

Fig. 9. **Flow correlation of 22/04/2009 flood by Muskingum model in 4 hours**

The model reproduces the hydrograph shape: the rising limb is underestimated and the receding limb is overstated. The peak is reproduced by its form and value with a very low error of -0.1% and it appeared ahead two hours. The variation of the flow error varied between -175 m3/ s and 50 m^3/ s.

C. Flash flood of 22 February 2012

By coefficients calculated during the reconstruction of the flood 01/02/2003, we made the prediction of the flood of February 2012 using both models Muskingum and Regression. Performance criteria are summarized in Table 5.

TABLE V. FLOOD FORECASTING OF 22 FEBRUARY 2012

	Muskingum model			Regression model		
Prediction delay (h)	***PRE (%)***	***Nash (%)***	***PTE (h)***	***PRE (%)***	***Nash (%)***	***PTE (h)***
2	-0.9	98	2	0.7	99	2
4	-1.9	96	4	1.3	97	1
6	-3.1	92	6	1.8	93	0
8	-4.5	88	8	9.6	82	2

This table shows also the relative error of the peak (PRE) is smaller in absolute value for the regression model. For both models, this error increases with delay prediction. For both models, the value of Nash is inversely proportional to the time of forecast. The peak time error (PTE) is lower for the regression model for all forecasting delay.

To analyze the results of forecasting flood 22/02/2012, we have chosen the results given by Regression model for delay of 6 hours:

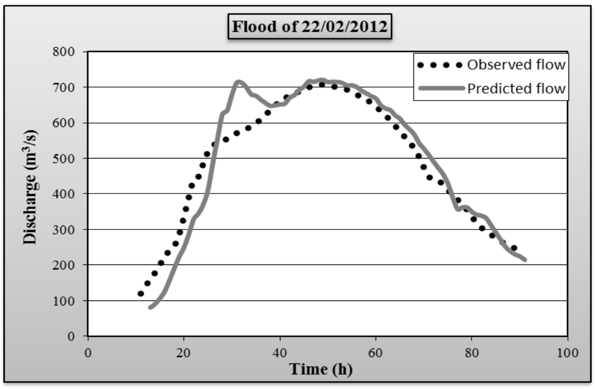

Fig. 10. **Flow hydrograph forecasting of 22/02/2012 flood by Regression model in 6 hours**

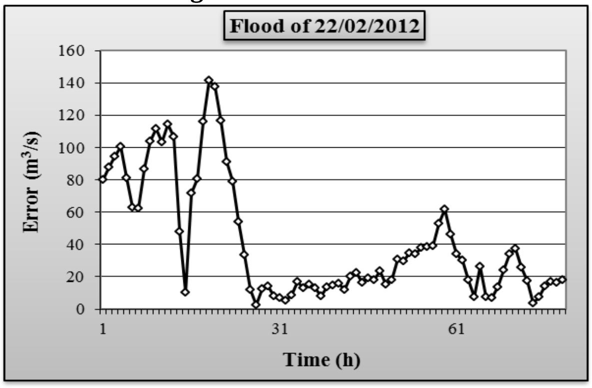

Fig. 11. **Prediction error of 22/02/2012 flood by Regression model in 6 hours**

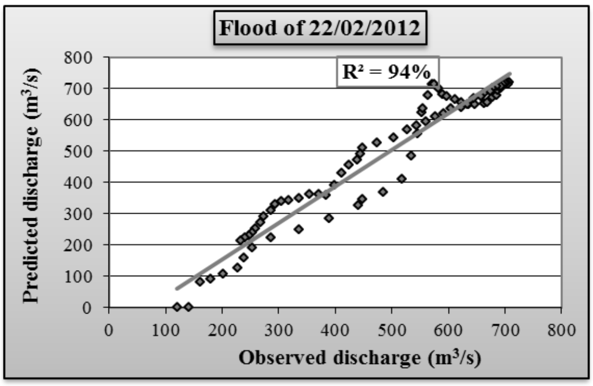

Fig. 12. **Flow correlation of 22/02/2012 flood by Regression model in 6 hours**

Predicting the flood hydrograph of 22/02/2012 to six hours with the regression model gave birth to a second peak in advance of the observed peak. Raising limb is underestimated and the receding limb is gently overestimated. The peak is reproduced by its form and the value is overestimated by 1.8%. The error on the flow varies entre 2.5 m3/s and 141 m3/s. the cloud points given by the flow correlation are close to the first bisector.

V. Conclusion

The characteristic location of Bou Salem, which lies in a low plain where the confluence of Medjerda tributaries (Mellègue, Tessa and Bouheurtma) provoked a braking fairly important to the flow of Medjerda toward the plain.

From historical floods Bou Salem (period 1973-2013), we identified three flash floods: January 2003, April 2009 and February 2012.

Two propagation models are challenged to predict flows at Bou salem: Muskingum model and Regression model. For these two models, we considered upstream flows: Jendouba (at the main course Medjerda) and flow rates of 3 tributaries (Mellègue, Bouheurtma and Tessa) which flow into the section Jendouba-Bou Salem. The forecasting delay is varied from 2 to 8 hours with a pitch of 2 hours. To judge the validity of predictive models, we took three numerical criteria: relative error peak, Nash coefficient and peak time error.

Floods forecasting by both models and for all forecasting delay showed that the satisfaction of three numerical criteria at once is not possible. But generally forecast results were satisfactory. The models reproduced well the shape of the hydrograph, the peak and the flood. Taking into account three criteria, we argued that it is the Regression model prevails.

The flash flood forecasting is a step in risk management, which required the implementation of flood warning systems. This system provides information when water levels rise rapidly to cause flooding within hours.

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