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Modeling of meteorological data optimization to study hydrological behavior of watersheds: case study – MZAB basin, southeast of Algeria

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ABSTRACT

Rainfall–runoff relationship modeling is a fundamental key for a better evaluation of hydrological cycle, however, it is so difficult to achieve. This modeling is a requirement of a capital importance for a good design of hydraulic structures and well protection of towns against flooding risks. The different hydrological parameters of a watershed, such as the meteorological and hydrometric data, taken from several observation stations during a long period are highly required in the modeling. Several models were elaborated to study the rainfall–runoff relationship for ungauged basins, however, the elaborated models are not available for managers. Therefore, the propose of the present study is a new technique using coupling called: genetic algorithms – HEC-HMS. The application of the proposed technique on the MZAB basin has given perfect results with insignificant error values.

Keywords: Modeling; Optimization; Rainfall–runoff relationship; Genetic algorithm; HEC-HMS

1. Introduction

Hydrology is a science that focuses on the study of the water cycle through a qualitative and quantitative manner. The precipitation is the important variable as well as one of the main drivers of this water cycle [1–5]. Modeling the rainfall–runoff relationship is a fundamental approach for a better water resources management [6–9]. For this reason, hydrologists and water engineers have developed several hydrological models for decision-making regarding hydraulic structures sizing to protect agglomerations against natural risks [10,11]. These models can save time and money regarding their ability to make a long-term simulation of the hydrological behavior of watersheds [12]. Several studies have interested to the simulation of runoff in ungauged basins for the last 30 years in order to represent better hydrological behavior of a watershed that has no hydrometric station at its outlet [13]. Without hydrometric data, the hydrological model cannot be calibrated, therefore, regional methods are provided to connect the parameters of a rainfall–runoff model to the conditions of the studied area [14]. In this context, the use of a model for calculating flow rates and water estimate on the scale of a watershed becomes necessary [15]. There are several models in the literature to model the rainfall–runoff relationship. However, these models are still applicable for some specific cases and for quite different regions, and require an adequate data for the conduct and evaluation of their performance [16,17]. For the MZAB valley, located in the south of Algeria, no hydrometric measure is presented. Dubief worked on the floods of MZAB valley and conducted a flood frequency analysis in the period 1907–1953. This work shows that watershed located in the northeast of Brazil shared the same hydrological characteristics of MZAB basin. In these basins, the results obtained in the principle of unit hydrograph could be "regionalized", that is to say,

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it is possible to interpolate the flood characteristics, values for MZAB basin based on rainfall and physical characteristics (size, permeability, and relief). Genetic algorithms are proposed to solve complex optimization problems due to their better performance compared with other tools. After the first studies on the optimization in the middle of 1980, these algorithms have been successfully applied to various optimization problems [18,19].

Modeling of the optimization of meteorological data is very important for understanding the hydrological behavior of watersheds and controlling factor of natural risks in a particular area (arid zone). The hydrological impacts of the variation in precipitation have received a considerable amount of interest in hydrology. Since the development of empirical models, modeling the rainfall–runoff relationship has been a topic of active research for many research groups in the world. In this study, the coupling between genetic algorithms and the hydrological modeling system (HEC-HMS) is a very essential tool, which produce results to adapt some empirical models. In the present work, the coupling between genetic algorithms and the hydrological modeling system (HEC-HMS) was used to model the hydrological behavior of the MZAB basin to validate this coupling and control the adaptation of the empirical formulas used in Algeria. This coupling is applied to the watershed of Wadi MZAB through the Ghardaia city (southeastern region of Algeria).

2. Materials and methods

2.1. Model based on genetic algorithms

The genetic algorithm was originally developed and introduced in 1975 by John Holland. It is a stochastic optimization method based on the mechanism of the natural selection and genetics [19]. Genetic algorithms start with the random selection of the individuals of constant size, these individuals called the initial population, in a way that these individuals squeeze into a competition over a succession of iterations called generations. Between generations, individuals are assessed by operators called successively: crossover and mutation so that these operators will transform the population to encourage the emergence of best individuals [20,21].

2.1.1. Principle of the genetic algorithm

The genetic algorithms begin with the random generation of an initial population of constant size, then the operators: crossover and mutation are generated. A new population is created. The stopping criterion is the number of generations (Fig. 1). Individuals are permitted to survive, so that we can start a new population of individuals α. The circle is complete, and it starts with a selection phase for reproduction, a period of change, and so on. For genetic algorithms, a stopping criterion permits leaving the loop, for example, a number of iterations without significantly improving the performance of individuals [22].

2.1.2. Objective function

The empirical model calculates flow value for different return periods. The performance of the model is validated by the convergence indicators to obtain the minimum value of the objective function "Error". Therefore, the problem to minimize the following quadratic criterion:

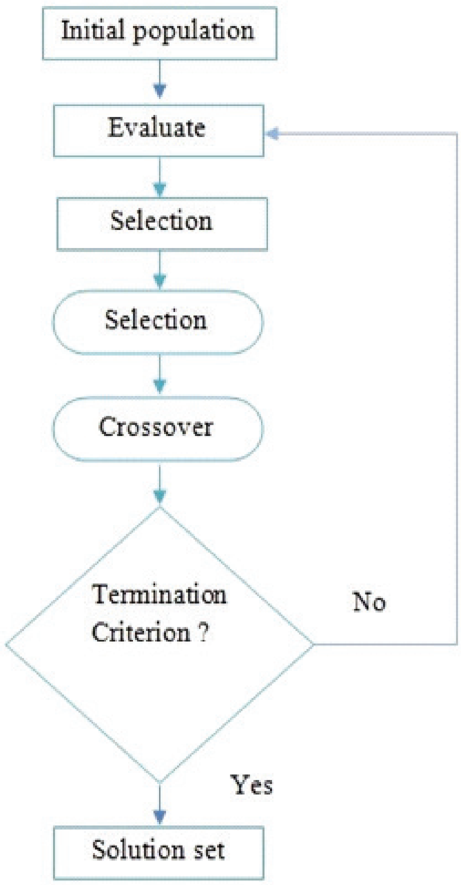

Fig. 1. Operating principle of a genetic algorithm.

$$\text{OBJFUN} = \sum_{i=1}^{n} \left(Q_{\text{sum}} - Q_{\text{pro}}\right)^2 \quad (1)$$

where Q_{sum}, simulated flow by genetic algorithms; Q_{pro}, the project flow.

2.2. Empirical models

Many flow prediction tools are empirical models, and these based on a very schematic representation of the functioning of a watershed. The predetermination of the exact values of the projected flows in the absence of the hydrometric data is based on the empirical models.

There are several formulas that calculate the projected flow rates, which are distinguished as: the formula of Mallet-Gauthier (Q/MG), the formula of Sokolovsky (Q/SOK), the formula of Giandotti (Q/GIA), the formula of Possenti (Q/MW).

$$\text{Q/MG} = 2.K.\log(1+20.P_{\text{moy}})\frac{S}{\sqrt{L}}.B \quad (2)$$

$$\text{B} = \sqrt{1+4.\log(T)-\log(S)} \quad (3)$$

$$Q/SOK = \frac{0,28.(P_t - H_o).\alpha p\%.F.S}{T_c} \quad (4)$$

$$Q/GIA = \frac{C.S.(H_{moy} - H_{min})^{\frac{1}{2}}}{4.(S)^{\frac{1}{2}} + 1,5.L}.P_t \quad (5)$$

$$Q/PO = \frac{\mu.Pj_{max}.S}{L_p} \quad (6)$$

where Q/MG the flow value is estimated by using the formula Mallet-Gauthier; Q/SOK the flow value is estimated by using the formula of Sokolovsky; Q/GIA the flow value is estimated by using the formula Giandotti; Q/PO the flow value is estimated by using the formula Possenti.

2.3. HEC-HMS model

The hydrological model HEC-HMS is a universal model to simulate the rainfall–runoff processes in a wide variety of watershed types [23,24]. To study the hydrological behavior of watersheds, the HEC-HMS consists of three flow valuation methods of flood, each of which uses one or more parameters as data, for example, the meteorological data. The three methods are: specified hyetograph, frequency storm, and the SCS (soil conservation service) method.

2.3.1. Specified hyetograph method

The specified hyetograph method allows the user to specify the exact time-series to use for the hyetograph at sub-basins. This method is useful when precipitation data will be processed externally to the program and essentially imported without alteration. This method is also useful when a single precipitation gauge can be used to represent what happens over a sub-basin [24].

2.3.2. The frequency storm method

The frequency storm method is designed to produce a synthetic storm from statistical precipitation data. This method is designed to use the data collected from the maps along with other information to compute the hyetograph for each sub-basin. This method uses the same parameter data for all sub-basins in the meteorologic model. Each storm has a single exceedance probability which must be selected from the list of available choices. The choices range from 0.2% to 50% and generally match the precipitation maps that are commonly available [25].

2.3.3. SCS method

This method uses the same rainfall data for all the sub-basins in HEC-HMS model [26]. Each storm has only one time distribution type which must be selected from the list of available choices. The available types are Type 1, Type 1a, Type 2, and Type 3 (Fig. 2). The simulation must have a duration of at least 24 h long [25].

Fig. 2 shows the different types of precipitation distribution. The type that corresponds to the MZAB region is Type 1.

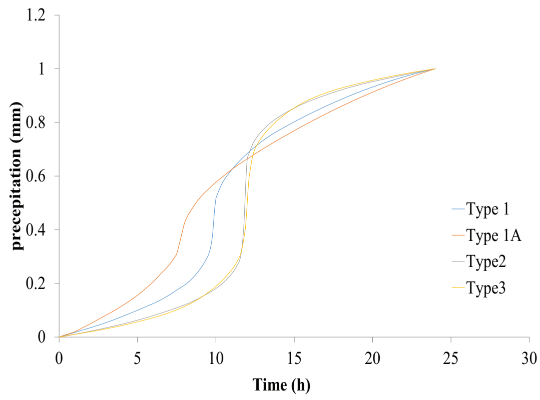

Fig. 2. Types of precipitation distribution.

This type is used in cases where the percentage distribution of precipitation is equal to 25%.

3. Study area

3.1. Presentation of the study area

The MZAB basin is a part of the northern Sahara which covers an area of 600,000.00 km^2. The MZAB basin is characterized by an area of 1,653.65 km^2 and a main talweg of 38.8 km and average annual rainfall of 130.15 mm. MZAB basin is crossed by four valleys draining trays Dayas and dorsal of Mozabite, its natural outlet is constituted by Sebkha of Sefioune, which is near a Ouargla city (Fig. 3).

The basin delineation is performed on a digital elevation model (DEM) with a ArcGIS tool. The Oued MZAB crosses the Basin from the west to east (Fig. 4). It is fed by the left Rive by contribution to the capital of Ghardaia city (632 km south of Algiers). The result is an elongated and symmetrical basin whose the right and left Rives play a major hydrological role for the reason of the occupation of the majority of the basin of the urban area. The MZAB basin is composed of a mesh of several sub-basins oriented from north to south, the dividing line between the sub-basins is on the red line (Fig. 5).

3.1.1. Hydrometric data

For the MZAB basin, there is no hydrometric measurement exists except for the summary and qualitative observation, but very useful floods that have passed through the agglomeration of Ghardaia. Dubief worked in the floods of the MZAB valley, and carried out a frequency analysis of floods for the period 1907–1953.

In the case of the absence of hydrometric stations where there is a lack of hydrometric data, it is necessary to evaluate the characteristics of floods using precipitation of short duration. The observations made by Dubief were exploited by engineers of the design office (The BG group) located in Switzerland to use its data for the design of three large dams upstream from the town of Ghardaia. Dubief also shows that watersheds located in the northeast of Brazil, whose hydrological characteristics are similar to that of MZAB basin, so hydrography should be rationalized with the possibility of interpolation of flood characteristic values for the basin MZAB depending on rainfall and physical characteristics (size, permeability, and relief).

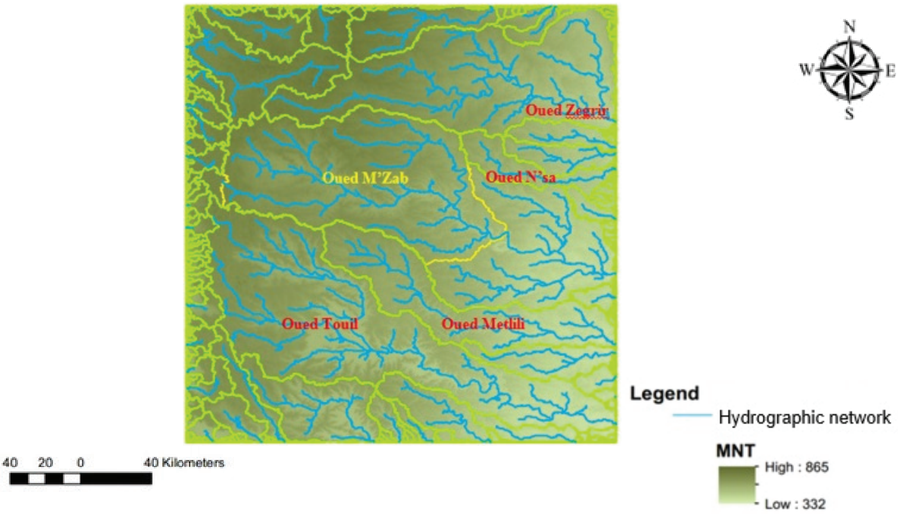

Fig. 3. The limits of the watershed MZAB. Fig. 3 shows the river system and the limits of MZAB basin. MZAB basin is marked by a large network of Wadis such as: Oued Metlili, Oued N'SA, and Oued Zegrir.

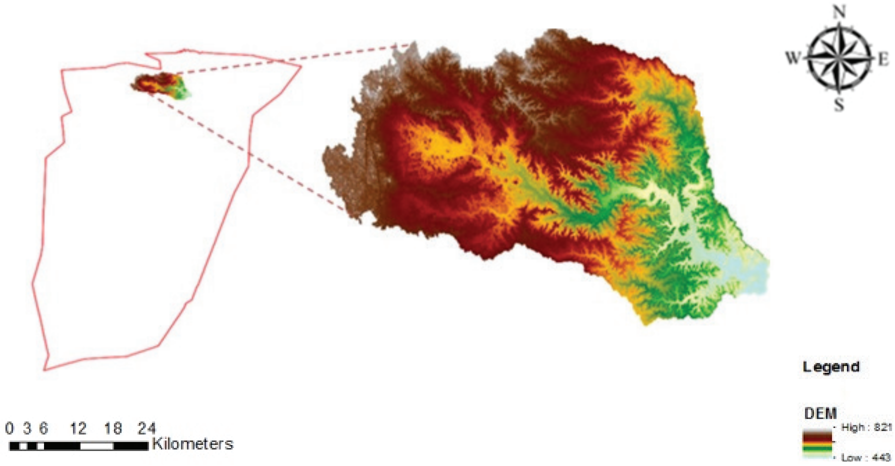

Fig. 4. Hypsometric map MZAB basin.

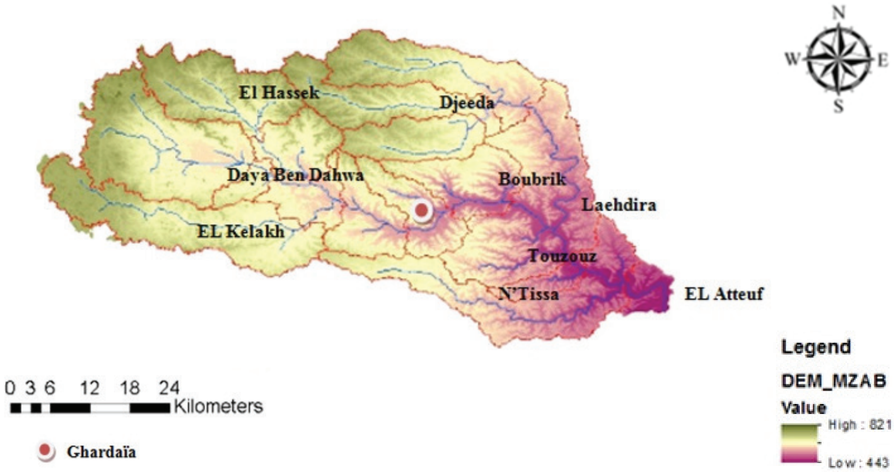

Fig. 5. Sub-basins belonging to MZAB basin.

3.1.2. Predetermination of MZAB flows

The flow predetermination is generally based on a statistical study of chronic observed flow or on modeling the rainfall in runoff. This predetermination requires hydroclimatic information that is only available for gauged watersheds [27]. In this study, the regional method established by Rodier and Auvray is used. The mathematical expression of the design of the discharge value is given by the following equation:

$$Q_{\max} = \alpha \times Q_{\text{moy}} = \propto \times 277 \times \frac{V}{T_b} \quad (7)$$

where α is the tip of coefficient given by the following equation:

$$\alpha = 0.24 \times \text{Ln}(A) + 2 \quad (8)$$

The volume of raw V is calculated by the following equation:

$$V\ (10^6 \text{m}^3) = Pj \times \text{Ka} \times \text{Kr} \times A\ (\text{km}^2)/1000 \quad (9)$$

Such as: Pj is the height of the maximum daily rainfall, Ka and Kr are, respectively, the coefficient of abatement and runoff given by the following equations:

$$\text{Ka} = 1.1943 - 0.0604 \times \text{Ln}(A) \quad (10)$$

$$\text{Kr} = 110 \times A^{-0.186} \quad (11)$$

T_b base time is given by the following equation:

$$T_b = 2.146 \times A^{0.368} \quad (12)$$

T_m rise time is given by the following equation:

$$T_m = 0.24 \times \text{T}_b \quad (13)$$

The centennial rate value is shown in Table 1.

The calculated value of the project flow is used as a reference rate value.

3.1.3. Climate appearance

Fig. 6 shows the time evolution of the monthly average rainfall of Ghardaia station during the period 1970–2014, the study of precipitation in the case of our study covers a long period to learn more about the temporal variation in precipitation. During this period, alternating between dry months and rainy months is observed.

For the graphical representation of monthly average precipitation (Fig. 6), we remark that the hydrological year in the MZAB basin is divided into two rainfall periods:

(1) A dry period corresponding to the months May, June, July, and August;
(2) A relatively dry period corresponding to the months December, January, and February.

On the other hand, the rainiest months are September, December, and March, and the driest month is represented by July.

Fig. 7 shows that in the whole of the MZAB basin, the rainy seasons are autumn and winter. The driest season is summer. The autumn and spring seasons are characterized by stormy and intense rains that cause flooding in the MZAB basin.

3.2. Calculation by empirical mode

The characteristics of the basin are used to calculate the maximum flood value for different return periods. We use a number of empirical models to estimate the centennial flood

Table 1
The 100-year flood flow estimated by the method of Rodier and Auvray

	MZAB
A (km^2)	1,653.65
T_m (h)	8.16
T_b (h)	32.86
Kr	27.7
Ka	0.75
V (10^6 m^3)	61.6
Q_{moy} (m^3/s)	520
α	3.8
$Q_{\max}$ (m^3/s)	1,967

Fig. 6. Average monthly precipitation (mm) of rainfall station of Ghardaia (period 1970–2014).

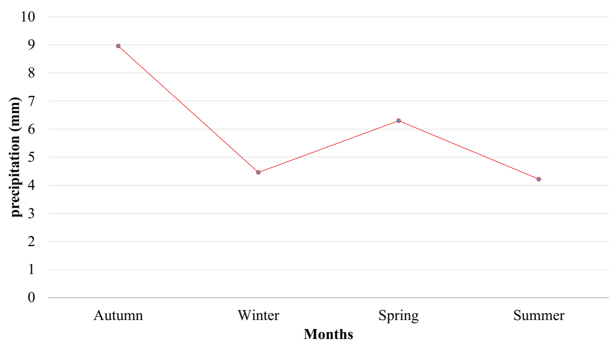

Fig. 7. Seasonal variation in precipitation in the MZAB basin.

for the MZAB basin. The results of the calculation of the various models are summarized in Table 2.

Fig. 8 shows the design flood hydrographs for different empirical models. We find that the formula of Possenti is not applicable in the MZAB basin.

3.3. Results and discussion

The performance of genetic algorithms is conditioned and validated by the stability of the error during generation and the number of tests in order to give a chance to select the best individuals as shown in Table 3.

Table 3 represents the values of the objective function (OBJFUN). For each method (M-G; SKOLOV; GIAN; POSS) the objective function corresponding to the minimum of the quadratic error OBJFUN which is calculated by the equation (Eq. (1)) is better appreciated for simulated flood values which permits these results to be quite satisfactory. For these values, genetic algorithms must be stable (Fig. 9). After the use of genetic algorithms, year flood values are summarized in Table 4.

Fig. 9 shows changes in the objective function along the generations in different methods. From the analysis of the results obtained, it can be seen that there is a fast enough convergence from 500 generations, noise fluctuations are mainly due to genetic operators (crossover and mutation). Further, we note that a considerable improvement in a dynamic performance was obtained with flood rates. This flood is optimized by a genetic algorithm with a high robustness for estimating and optimizing precipitation values.

Table 2
Summary of flood flow results

Method	Q (m^3/s)
Mallet-Gauthier	1,421.6
Sokolovsky	1,320.16
Possenti	2,936.93
Giandotti	994.89
Q project	1,967

Fig. 10 shows an overlap between the observed flows and modeled flows. The single-objective calibration was used by an objective function (OBJFUN). For this reason, genetic algorithms were used as an optimization algorithm. The correct choice of genetic algorithm parameters (crossover and mutation) gives a good agreement with the quadratic criterion and consequently can yield very usual results.

Fig. 11 shows the cloud between the projected flow and the flow rate values simulated by genetic algorithms. After the values of the correlation coefficients (r = 0.999) for each method (M-G; SKOLOV; GIAN; POSS), we note that there is a very good agreement and the results are very satisfactory. From this analysis and depending on the behavior of point cloud that gives a priori best estimate of rates, the results can be further improved if we increase the number of generations and tests and if we better adjust the parameters of the genetic algorithm.

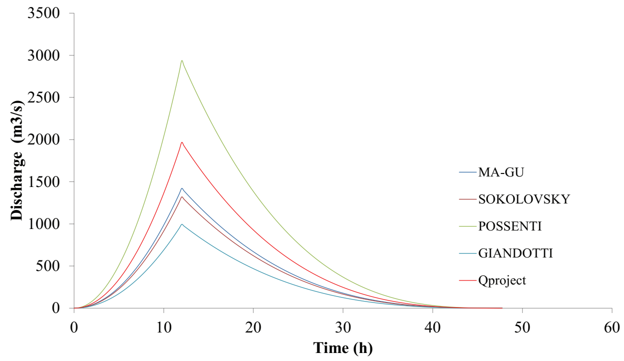

Fig. 8. Centennial flood hydrographs for different models.

Table 3
The objective function for the various methods

Method	M-G	SKOLOV	GIAN	POSS	PROJECT
Q (m^3/s)	1,421.36	1,320.16	994.89	2,936	1,967.00
OBJFUN	735.8	2.26	733.86	293.06	–

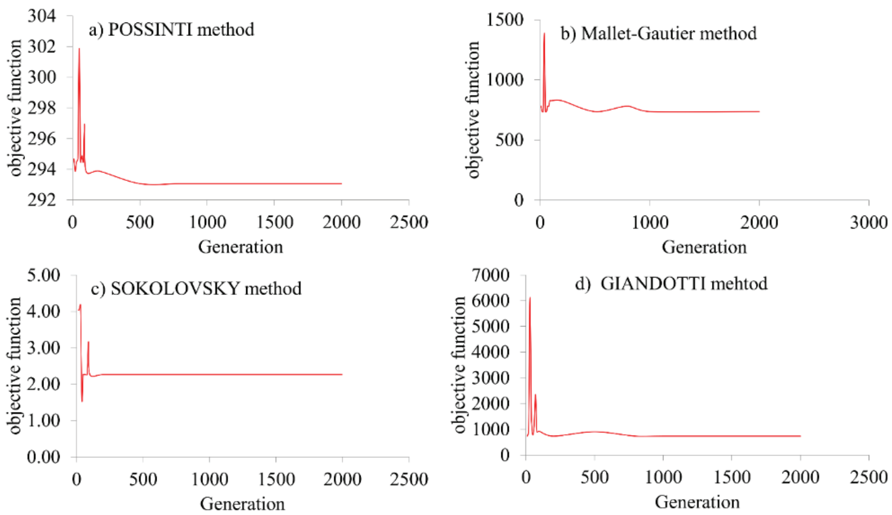

Fig. 9. Fluctuation of the objective function along the generations.

3.4. Coupling between genetic algorithms and HEC-HMS

Genetic algorithms were used in optimization. These algorithms give very satisfactory results in different fields of optimization research (economics, mechanics, electricity, hydraulics, hydrology, etc.). For the modeling of the hydrological behavior of the MZAB basin, genetic algorithms give acceptable values of flood calculated by various empirical models. This point deals with a coupling between genetic algorithms and the hydrological model HEC-HMS. In this step, the precipitation values simulated by genetic algorithms are used in different methods of HEC-HMS model (specified hyetograph, frequency storm, and the SCS method). The results obtained by the different methods are included in Table 5.

SCS STORM is the method: soil conservation service; SPSF HYTO is the specified hyetograph method; FRQ STORM is the frequency of showers method.

The values of the rates listed in Table 5 are centennial flow values estimated by the methods of hydrological model HEC-HMS.

It is found that a high degree of difference between the flow rate values estimated by the three methods of the HEC-HMS model and the project flow rate such that the value of α (the ratio between the project flow rate and the simulated flow rate) ranging from 0.29 to 0.36 which allows the values to be very large by adding the project rate value.

Fig. 12 shows the flood hyetograph, which is drawn by the flow rate values calculated in the case where precipitation is not simulated by the use of genetic algorithms.

The results obtained from the use of simulated rainfall by genetic algorithms give acceptable flow values. These values are summarized in Table 6.

Table 4
The flow values obtained by the use of genetic algorithms

Method	M-G	SKOLOV	GIAN	POSS	PROJECT
Q (m³/s)	1,421.36	1,320.16	994.89	2,936	1,967.00
Q/AG	1,987.4	1,940	1,985.2	1,694.2	–

The performance of hydrological models is validated by statistical parameters. The statistical parameter used in this study is the Nash–Sutcliffe coefficient of efficiency (E) [28,29]. This parameter is defined as:

$$E = 1 - \frac{\sum_{i=1}^{N}\left(Q_p - \hat{Q}_m\right)^2}{\sum_{i=1}^{N}\left(Q_p - \bar{Q}_p\right)^2} \quad (14)$$

where Q_p is observed discharge, $\hat{Q}_m$ is modeled discharge, $\bar{Q}_p$ is the mean of observed discharges, and N is the number of data. The results obtained by these different methods are summarized in Table 7.

These results show the good performance of the coupling between the genetic algorithms and the HEC-HMS model. This performance can be explained by the fact that the genetic algorithm gives a minimum value of the error during generation and its operators (mutation and crossover) are powerful tools for representing its evolution over time, and consequently a best estimate of flows.

Several studies published for deferent fields, these studies used the Nash–Sutcliffe coefficient of efficiency (E) to test the performance of model such as, combined hydrological, rainfall–runoff, hydraulic and sediment transport modeling in Upper Acheloos River catchment [29], and the adaptive neural fuzzy inference systems for the daily flow forecast in Algerian coastal basins [9], and comparison of the performance of stochastic models in forecasting daily dissolved oxygen data in dam-Lake Thesaurus [11].

All these researches explains the validity of the results obtained by the Nash–Sutcliffe coefficient of efficiency (E).

A comparison was made with the Rodier and Auvray method to evaluate the performance of coupling between the genetic algorithms and the HEC-HMS model. Fig. 13 shows the results obtained by this coupling. These results show the performance, the originality, and the adaptation of the coupling. This performance reflects the feasibility of the coupling and the precision of their results, in order to favor to obtain and to make the right decisions and to avoid situations of hesitation.

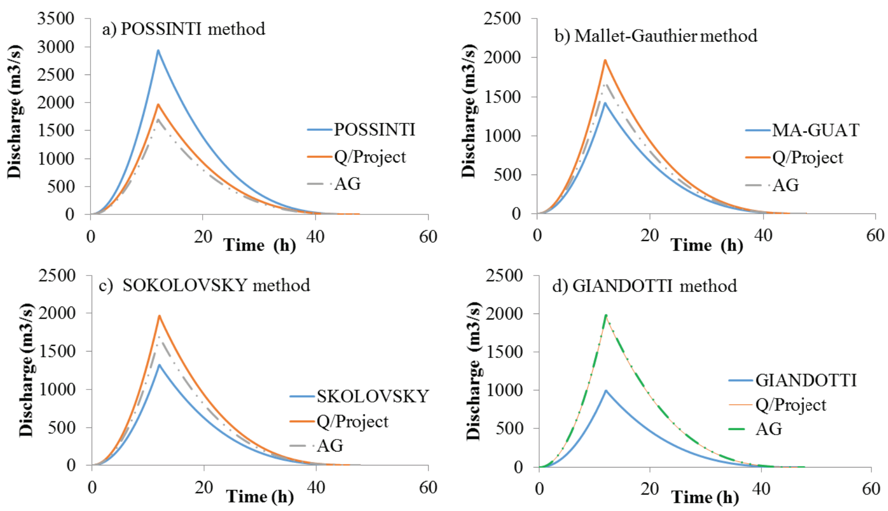

Fig. 10. Hydrographs flood, different rates calculated using different empirical models and simulated using the genetic algorithm.

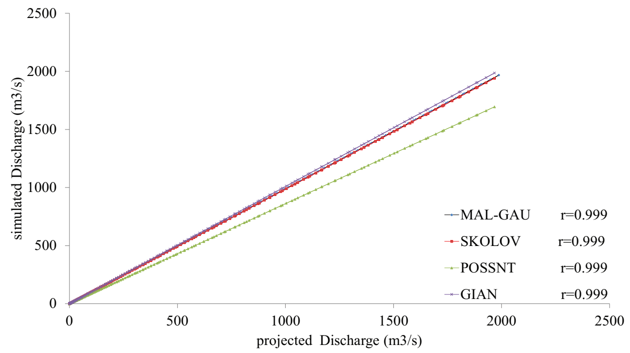

Fig. 11. The relationship between projected and simulated flows.

Table 5
The flow values obtained using the HEC-HMS model

Method	*Q* (m³/s)	*A*
SCS STORM	6,778	0.29
FRQ STORM	5,400	0.36
SPSF HYTO	5,583	0.35
Q PROJECT	1,967	–

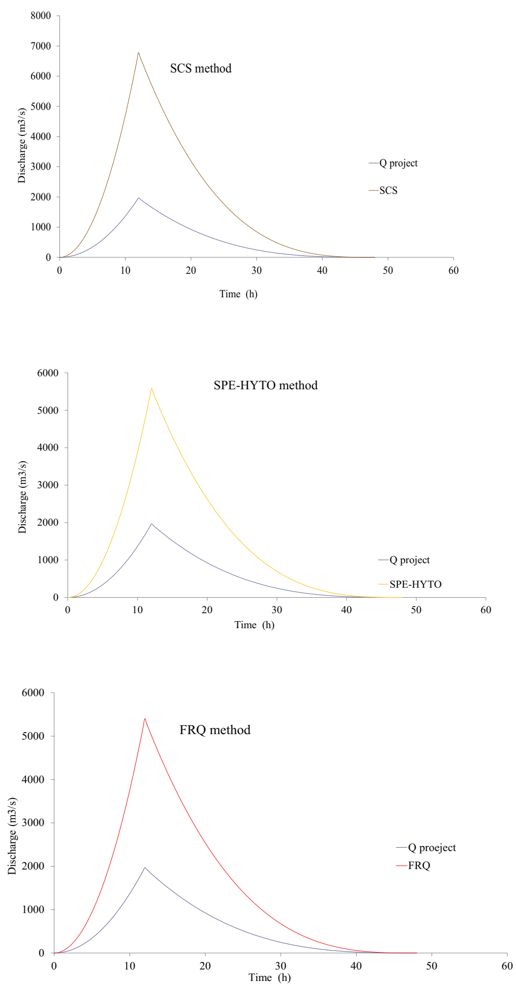

Fig. 12. Flood hydrographs, different rates calculated using different methods: SPE-HYTO, SCS, and FRQ.

Table 6
The flow values obtained by using the hydrological model HEC-HMS

Method	*Q* (m³/s)
SCS STORM	1,984.8
FRQ STORM	1,388
SPSF HYTO	1,978.3
Q PROJECT	1,967

Table 7
The values of Nash–Sutcliffe coefficient for different methods: SPE-HYTO, SCS, and FRQ

Method	Nash–Sutcliffe coefficient
SCS STORM	0.999
FRQ STORM	0.838
SPSF HYTO	0.999

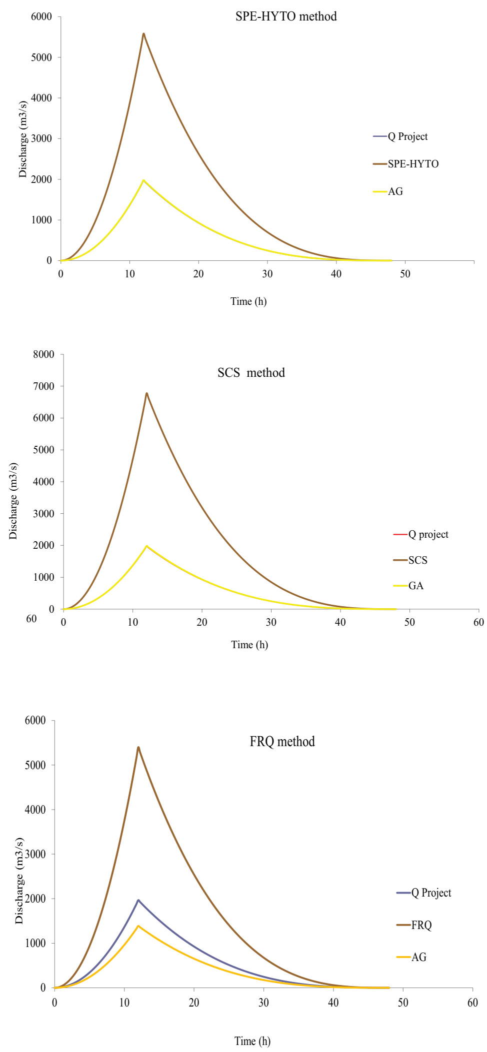

Fig. 13. Flood hydrographs, different rates calculated using different methods: SPE-HYTO, SCS, and FRQ. These flows were simulated using the genetic algorithm.

4. Conclusion

The coupling between genetic algorithms and the hydrological modeling system HEC-HMS is effective for modeling the hydrological behavior of the MZAB basin. The accuracy of the value of maximum flow rates is dependent on the quality of observed data on the installed weather station. The quality of results depends strongly on the right choice of parameters of the genetic algorithm (generation number, the number of tests, crossover, mutation, selection mode, etc.). Frequent use of empirical models is the lack of hydrometric data. These models provide acceptable levels of project flows necessary for the design and management of hydraulic structures (deviation of main watercourses, dam, etc.). However, there are other empirical models that need be used. The models used in this study (formula of Mallet-Gauthier, Sokolovsky formula, the formula of Giandotti, and the formula of Possenti) should be tested in the MZAB basin under the condition of optimizing the meteorological data by using the genetic algorithms. This work is based on an optimization technique for the study of the hydrological behavior of a watershed. This technique is a coupling between the genetic algorithms and the hydrological modeling system (HEC-HMS). This study on the hydrological modeling of ungauged catchments is of paramount importance because several difficulties are encountered in this research. The major problem is the collection of hydrometric data. These data are provided by different weather services (the National Agency for Water Resources, the National Meteorological Office, etc.). The main advantage of using these observed data is the calibration of hydrological models used. Finally, the coupling between the genetic algorithms and the hydrological modeling system (HEC-HMS) is a good method and an effective technique for optimization. In this regard, we mention that this technique requires precise and reliable data. It is believed that the application of coupling between the genetic algorithms and hydrological modeling system (HEC-HMS) in the field of hydrology should be popularized and tested on various other strong cases.

Symbols

Q_{sum}	—	Simulate flow by genetic algorithms
Q_{pro}	—	The project flow
Q/MG	—	The flow value is estimated by using the formula Mallet-Gauthier
Q/SOK	—	The flow value is estimated by using the formula Sokolovsky
Q/GIA	—	The flow value is estimated by using the formula Giandotti
Q/PO	—	The flow value is estimated by using the formula Possenti
α	—	The tip of coefficient
V	—	The volume of raw
Pj	—	The height of the maximum daily rainfall
Kr	—	The coefficient of runoff
Ka	—	The coefficient of abatement
T_b	—	Base time
Q_p	—	Observed discharge
$\widehat{Q}_m$	—	Modeled discharge
$\bar{Q}_p$	—	The mean of observed discharge

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