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Modeling of Continuous and Extreme Hydrological Processes Using Spatially Distributed Models MERCEDES, VICAIR and VISHYR in a Mediterranean Watershed

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ABSTRACT

Hydrological modeling predicts flood discharge and diminishes the danger by minimizing the environmental damages downstream. This study aimed to investigate the application of the ATHYS Models platform for simulating the rainfall-runoff relationship in Oued Laou Watershed (940 km^2). The study area is characterized by strong storms associated with the highest rainfall in Morocco, as well as renowned for its regular water supply and historical flooding; for these reasons, it is classified as a vulnerable area during a rainfall event. The models of the ATHYS platform have been implemented in continuous time during (2004–2012), and in four hourly rainfall extremes recorded in March 2018 at the Kodiat Khorireen station. The VICAIR model was used to visualize, analyze and spatially adjust the input data in raster format (land use, soil numerical map, slope, and flow direction). The VISHYR model, on the other hand, was used for corrections, calculations, management, and visualization of local hydro-climatic data in the FTS63 format. Under the MERCEDES model, the combination of the Soil Conservation Service (SCS) production function and the Lag and Route (L&R) transfer function has produced satisfactory results for continuous simulation periods and for the extreme scenarios. The modeling of the flow process in the Oued Laou by the ATHYS platform produced a reasonable performance with an average NSE of 0.70, R2 of 0.73, PBIAS of 13% and RMSE of 0.46. The research results reveal that the storage parameters, soil type, land use, and vegetation are the most important factors affecting the sensitivity of the hydrological response in the Oued Laou watershed. Moreover, the results indicate that the MERCEDES model is an appropriate tool for modeling floods and flow volumes associated with specific rain events and could be used by managers and decision-makers as a tool for flood forecasting in Morocco.

Keywords: ATHYS, VICAIR, VISHYR, MERCEDES, Oued Laou watershed, Morocco.

INTRODUCTION

The Mediterranean coasts have experienced significant climate changes in recent years, accompanied by fairly heavy rains that led to flooding risks [Jonkman 2005; Guy Delrieu *et al*. 2005; Drobinski *et al*. 2018]. Mediterranean Moroccan watersheds often suffer from catastrophic floods (Chefchaouen – September 2007, Tangier – October 2008, Martil plain – 2008, Nador, Mdiq and Fnidek – 2014). Over the past ten years, the floods in the Oued Laou watershed area caused by heavy rains have damaged rural schools, cut roads, collapsed dikes and led to power outages that affected large parts of the population. The prediction of flood in this watershed has become a priority; the effective prediction tools often used include the hydrological simulation models based on the relationships between precipitation and runoff.

The hydrological modeling of river watershed is an increasingly challenging task for the water resources research due to its complexity in collecting and handling of both spatial and non-spatial data such as rainfall, gauge-discharge data, vegetation, soil heterogeneity, topographic and hydrologic parameters [Rao *et al*. 2011; Gichamo *et al*. 2012; Vema *et al*. 2017; Aqnouy *et al*. 2018; Brouziyne *et al*. 2018; Aqnouy *et al*. 2019; Bouadila A *et al*. 2019; Bouadila A *et al*. 2020]. One of the important problems in hydrological modeling is to recognize the initial conditions of the watershed such as climate, land use and base flow. In such case, it is necessary to use a distributed hydrological model, for this reason several kind of these models have been developed: ATHYS [Bouvier and Delclaux 1996], HEC-HMS [Skhakhfa I.D., Ouerdachi L. 2016; Guohua Fang *et al*. 2018], SWAT [Arnold and Fohrer 2005], HBV model and TOPMODEL [Seibert 1999]. This approach of modeling was the subject of several studies over the world [Cong *et al*. 2015; Madsen 2003; Muthuwatta *et al*. 2009; Wi *et al*. 2015]. Nowadays, the ATHYS (spatial modeling platform) offers the possibility of coupling the MERCEDES model (Regular Square Elementary Mesh for the Study of Surface Flows) with VICAIR (Processing of spatialized geographical data) and VISHYR (Processing of stationary hydro-climatic data) spatial data processing models.

MERCEDES is based on the spatial discretization of the watershed into regular square meshes, which allows the spatial variability of the main factors that determine flows to be easily taken into account. The required data are hydroclimatic (rainfall, flow, temperatures, etc.) or geographical (soil, relief, geology, etc.) [Bouvier and Delclaux 1996].

The aims of this article were threefold:

1) Determine the effectiveness of the VICAIR, VISHYR and MERCEDES model structures in modeling continuous hydrological series and prevent flooding in the Oued Laou watershed.
2) Identify the most important parameters affecting the sensitivity of the hydrological response in the Oued Laou watershed.
3) Validate the application of the ATHYS hydrological platform in the Oued Laou watershed.

The MERCEDES model was evaluated using manual and automatic calibration. The SCS production function was used to calculate the amount of rain that contributes to runoff given its simplicity and robustness [Soulis *et al*. 2009]. The transfer methods (Lag and Route) were used because they enable conveying the volume of runoff produced at each mesh to the outlet of the watershed [Koussis and Mazi 2015], these two loss and routing methods are included in MERCEDES.

Study area

The Laou watershed is located in the northern region of Morocco (Fig. 1), in the central part of the Rifaine chain. It is bounded by the Jebel Kelti peaks (1928 m) to the west, Jebel Soukna (1800 m) and Tissouka (2180 m) to the Southeast, Jebel Tazoute (1800 m) to the Northeast and the Mediterranean Sea to the north. The watershed is known by its sloping topography with altitude that varies between 0 and 2123 m a.s.l.. It extends over an area of 940 km²; more than 60% of this area is covered with forest and moderately cultivated land. In terms of hydrology, the Oued Laou watershed is drained mainly by the Laou River.

The geological units in this watershed essentially consist of impermeable or low permeability facies, only the limestone chain, the plains, the alluvial valleys, benefit from the infiltration of rainwater. The most significant feature is the presence of a limestone chain dominated by the peaks of Jbel Kelti and Jbel Tissouka. The limestone chain constitutes an important aquifer in the regulation of the water resources of the watershed.

Table 1. Main physiographic parameters of the Oued Laou watershed

Parameters of the watershed	Unit	Value
Watershed area	km²	940
Perimeter of the watershed	km	175.2
Length of the main Oued	km	70
Gravellus index	-	1,59
Horton's Index	-	0,19
Maximum elevation	m	2123
Minimum elevation	m	0
Mean elevation	m	680
Mean slope gradient	$m \cdot km^{-1}$	28,28
Drainage density	$km \cdot km^{-2}$	0.31
Concentration Time	h	8.04
Runoff velocity	$km \cdot h^{-1}$	8.71

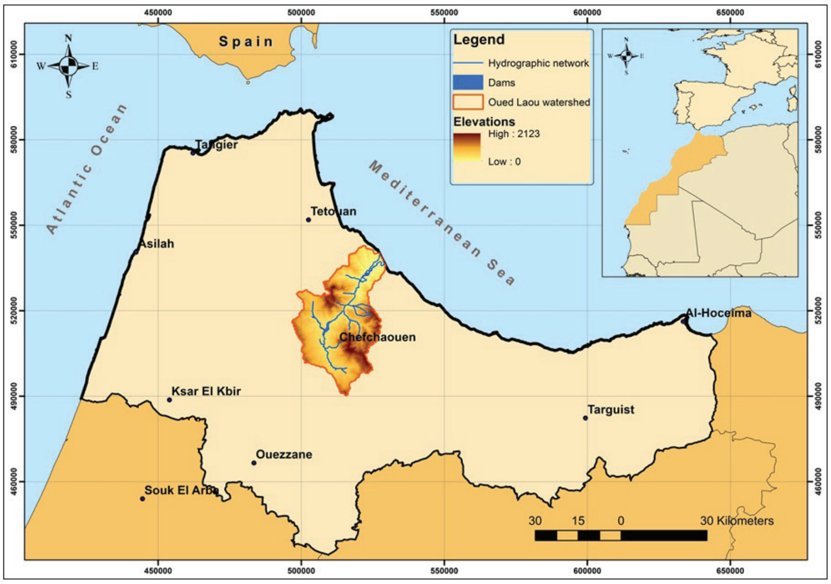

Fig. 1. Location of the study area

Climatically, the watershed is characterized by a sub-humid Mediterranean climate with high winter precipitation and dry hot summers. Precipitation increases from north (the Kodiet Kouriren station) to south (the Bab Taza station) of the watershed during the all months. The average annual rainfall ranges from 473 mm recorded at the Kodiet Kouriren station to 1361 mm at the Bab Taza station. The temperature of the study area is relatively high within the watershed and decreases downstream, especially during warm months.

Long-term (1970–2018) monthly rainfall data from two rain gauges were collected and analyzed. The distribution of the mean monthly rainfall for this period shows that the major events of precipitation occur generally in autumn and winter; flooding is often violent in these seasons. In March 2018, the gauge station (Kodiet Kouriren) recorded a dangerous event that reached 1200 m^3/s; due to abundant precipitation, such an event can cause human casualties and material damage on the trajectory of the Laou River. These hydrological events data are used to test the performance of the MERCEDES model structures to prevent the extreme hydrological events in the Laou watershed.

The daily data from 2004 to 2012, which is equivalent to 2920 days, were selected to test the performance of the MERCEDES model structures to prevent the continuous hydrological events in the Laou watershed. The climate data used in this modeling approach mainly consisting of flow and precipitation series recorded at three rainfall stations (Kodiet Kouriren, Timezouk, Bab Taza) and a hydrometric station (Kodiet Kouriren). The climate data has prepared in VISHYR model and has used to simulate the hydrological behavior in the watershed scale.

RESEARCH METHODS

Data collection

The metrological data used are daily and hourly precipitation, the distribution of these precipitations in the ATHYS platform is done by the Thiessen polygon method (Fig. 2). Flow measurements are also available in the Kodiet Kouriren station.

The watershed has a contrasted topography, the altitudes range between 0 and 2123 m a.s.l., the slopes are very steep (Fig. 3), reaching 28.28 m/km^{-1} in average. DEM with a spatial resolution of 12.5 m, obtained from the Alaska Satellite Facility website was used to conduct the geographical analysis. In the VICAIR model, the topography is reconstructed by the assembly of DEM, which helps define the drainage network, slope classes, and the drainage directions (Fig. 3).

The land use map of the Oued Laou watershed is required in order to be used for the inputs to the model. The land use map is based on the supervised classification method [Briottet *et al.* 2016], and is divided into seven classes: cultivated land, dam, bare soil, forests, rural and urban areas, pasture (Fig. 4). Regarding the soils

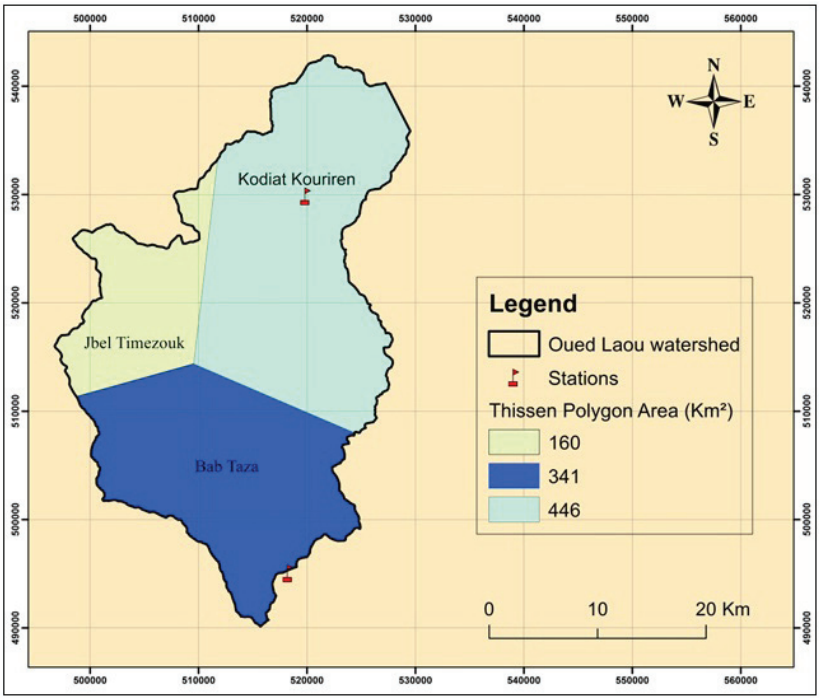

Fig. 2. Thiessen's polygons of the Oued Laou watershed

characteristics, two types of soils (Combisol and Arenosol) are presented in the Oued Laou watershed.

Model Development in ATHYS software

The application of a hydrological model would be an effective hypothesis [Savenije 2009; Gaagai *et al.* 2020] for flood forecasting in the Oued Laou watershed, which is characterized by high spatial variability in both rainfall and surface properties. For this purpose, the hydrological response of Oued Laou was simulated using a hydrological model based on the spatially distributed approach. ATHYS is a software consisting of complete processing chain which allows using these models (MERCEDES, VISHYR and VICAIR) to carry out a rainfall-runoff modeling [Bouvier, 1994]. The MERCEDES model offers a variety of production and transfer functions that enabled to select the coupling of two simple SCS-Lag and route functions in spatial mode for applying it to the study area [Bouvier, *et al* 1994]. The model was selected takes into account the subhumid climate prevailing the region and the rural nature of the watershed.

Under the ATHYS platform, the hydrological response of Oued Laou watershed was simulated by following these steps:

1. The data must first be archived in a matrix map type, point or vector under the VICAIR model. These files can be created by importing or from standard formats. This process is started by transforming DEM to ASCCI under ARC GIS 10.3; then, the ASSCI file is viewed in VICAIR, and the correction manager of the drainage model is run; after the loop correction, the drainage map, the slope map (Fig. 3) and the sub-watersheds are extracted.
2. In the VISHYR model, the data must be previously archived in a file in FTS62 or FTS63 format by importing it from an ASCII file type CSV containing all data. Once the file has been created, it is opened, while the characteristics of the stations (Bab Taza Timezouk, and Kodiet Kouriren) and the episodes contained in the file are presented in the main menu.
3. MERCEDES is designed for the analysis and prediction of flows the predominant component of which is of surface origin. So far, MERCEDES has been applied in very diverse watersheds: urban watersheds from a few hectares to a few tens of square kilometers, small mountain watersheds from a few tens to a few hundred square kilometers, medium and large watersheds of more than a few thousand square kilometers. The MERCEDES applications include flood forecasting, water resource management, impact studies related to the

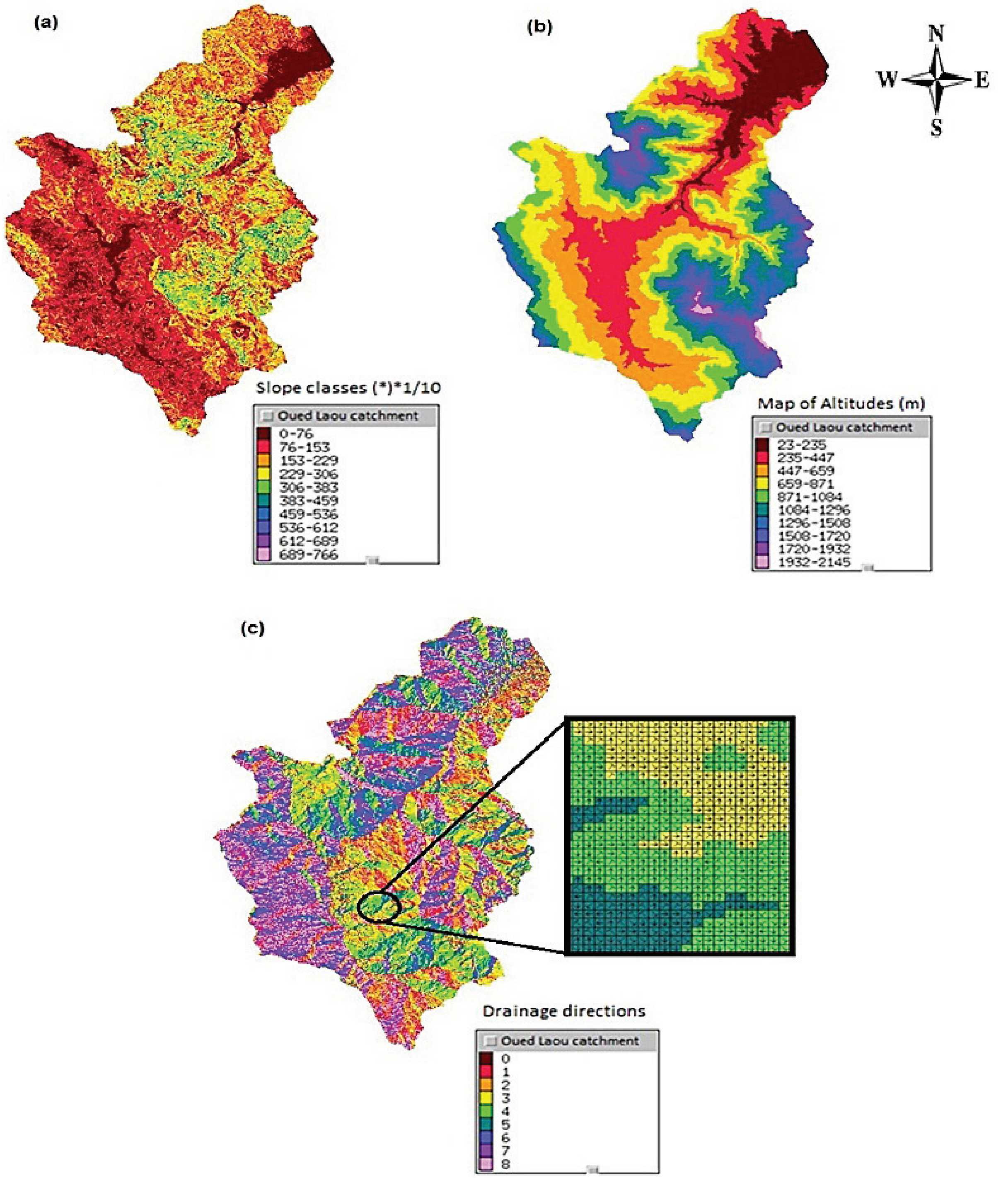

Fig. 3. (a) Slope classes of the Oued Laou watershed, (b) Elevation map, (c) Drainage map discretized on grid cells and extraction of flow direction

geographical or anthropogenic changes. MERCEDES is based on the concept of the soil storage system (Fig. 6) considering that rainfall fills a reservoir in the ground, in this model we have found several productions functions (SCS, Green and Ampt, Smith and Parlange, TOPMODEL, and Girard) and transfers functions (lag and route, kinematic wave, etc.) [http://www.athys-soft.org]. The production function developed by the USDA Soil Conservation Service (SCS) [Gaume et al. 2004] and the routing function Lag & Route [Bentura and Michel 1997], were used for this study.

The simple SCS function:

The SCS production function, commonly used because of its simplicity and robustness, has been

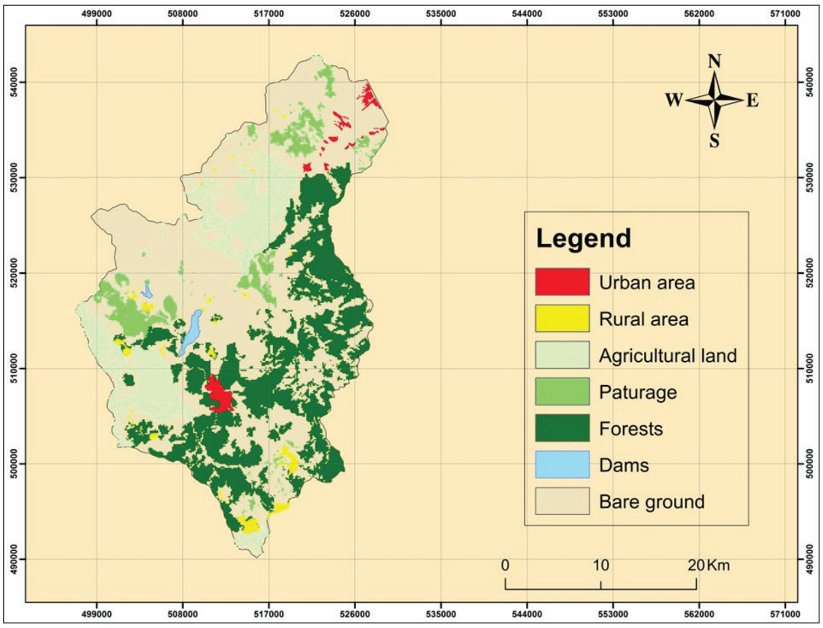

Fig. 4. Land use Map of the Oued Laou watershed

chosen to calculate the amount of rain that contributes to runoff; this model is used to estimate the runoff volume R(t) based on the maximum soil retention capacity S (mm), net rainfall P_e, gross rainfall P_b, and initial losses P [Chow et al. 1988]:

$$\mathrm{P_e} = \left(\frac{(P_b - I_a)^2}{(P_b - I_a) + S}\right) \quad (1)$$

Where la [L] refers to the losses at the beginning of the event and S [L] to the maximum water retention capacity of the soil (water deficit at the beginning of the episode). The model expresses the evolution of the runoff coefficient from 0 when the gross rainfall accumulation is less than I_a in 1 when the gross rainfall accumulation tends towards infinity (Fig. 5).

The adjustment parameters of the model are I_a and S. It is generally assumed that I_a and S are linked by the relationship:

$$\mathrm{I_a} = 0.2\,\mathrm{S} \quad (2)$$

S expressed in mm, can also be linked to the SCS Curve Number by the relationship:

$$\mathrm{S} = \frac{25400}{CN} - 254 \quad (3)$$

It represents the transformation of the gross rain into net rain on each mesh. In MERCEDES, the expression of the instantaneous runoff coefficient is used in the following form [Gaume *et al.* 2004]:

$$\mathrm{P_e(t)} = \mathrm{P_b(t)} - \left(\frac{\mathrm{P(t) - 0.2\,S}}{\mathrm{p(t) + 0.8\,S}}\right)\left(2 - \frac{\mathrm{p(t) - 0.2\,S}}{\mathrm{P(t) + 0.8\,S}}\right) \quad (4)$$

where: $P_e(t)$ – the intensity of the net rain at the instant t, P(t) – the intensity of precipitation at time t, $P_b(t)$ – the gross intensity at time t, S – the maximum capacity of soil retention, mm.

Runoff

$$\mathrm{R(t)} = \mathrm{C(t).\,i(t)} \quad (5)$$

with:

$$\mathrm{C(t)} = \left(\frac{\mathrm{P(t) - 0.2\,S}}{\mathrm{p(t) + 0.8\,S}}\right)\left(2 - \frac{p(t) - 0.2\,S}{P(t) + 0.8\,S}\right) \quad (6)$$

where: P(t) is the cumulative rainfall at time t [L] since the beginning of the episode, C(t) the runoff coefficient at time t [–], i(t) the rainfall intensity at time t, equal to dP(t)/dt [$L \cdot T^{-1}$], R(t) the runoff at time t [$L \cdot T^{-1}$].

Supply of the ground reservoir

$$f(\mathrm{t}) = \left(1 - \mathrm{C(t)}\right).\mathrm{i(t)} \quad (7)$$

Where *f*(t) corresponds to the infiltration intensity at time t [$L \cdot T^{-1}$], it also depends on the spatial variability of the soil properties such as soil layer depth, heterogeneity, porosity, hydraulic conductivity etc. (Fig. 6).

Discharging the ground reservoir

$$Vid(t) = d_s.S(t) \quad (8)$$

Where S(t) denotes the level of the ground reservoir at time t [L], Vid(t) the intensity of the emptying at time t [$L \cdot T^{-1}$] and ds the proportionality

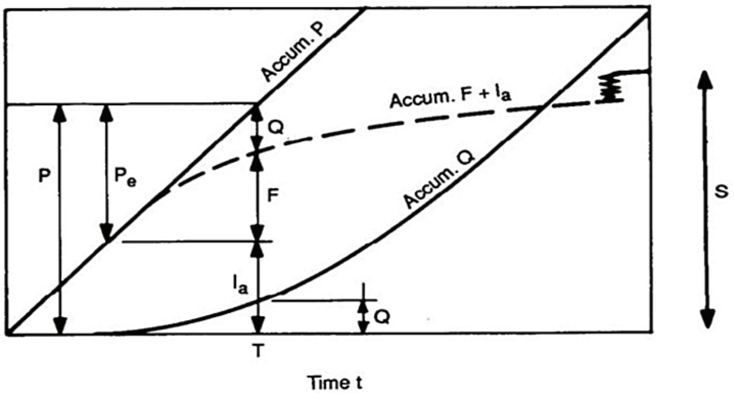

Fig. 5. Rainfall and cumulative produced volumes during a constant intensity rainfall [http://www.athys-soft.org]

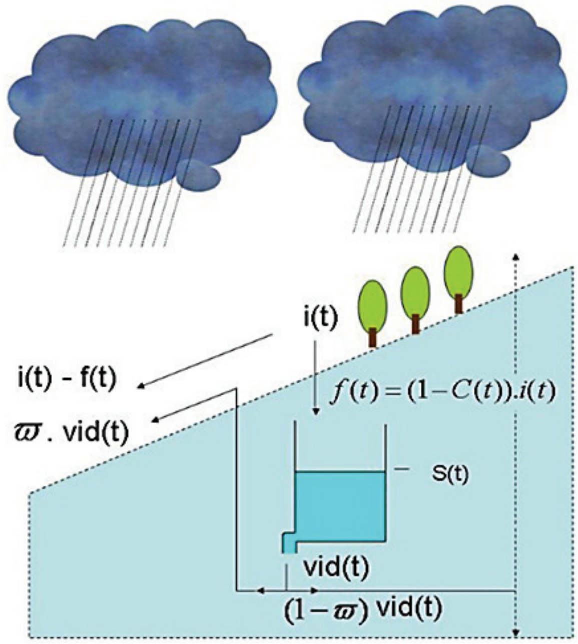

Fig. 6. Schematic representation of the MERCEDES model structure (http://www.athys-soft.org)

coefficient between the level of the reservoir and the intensity of the emptying [T^{-1}]. The reservoir level is calculated by combining the previous equation with the continuity equation:

$$\frac{dp(t)}{dt} = f(t) - Vid(t) \tag{9}$$

From version 5.2.1 onwards, evapotranspiration has been introduced in the calculation of the emptying of the soil reservoir. The evapotranspiration values must be read from the hydro-climatic data file (rainfall, flow rates, etc.), and stored in a station the type of which must be declared as "Ev" (type 5). The change in inventory is calculated by:

$$\frac{dp(t)}{dt} = i(t) - Vid(t) - Ev(t) \tag{10}$$

Where Ev(t) represents the intensity of evapotranspiration [$L \cdot T^{-1}$]

Draining the rain reservoir

For the consistency of the scheme, the draining applied to the ground reservoir must also be applied to the cumulative rainfall, so that the runoff coefficient C(t) is equal to 0 when the ground reservoir is empty. The accumulation of precipitation P(t) must therefore be reduced in relation to the emptying of the ground tank. This is achieved by introducing a Vid_2 drain [$L \cdot T^{-1}$] applied to rain accumulation:

$$\frac{dp(t)}{dt} = i(t) - Vid_2(t) \tag{11}$$

with:

$$Vid_2(t) = \frac{p(t)}{S(t)}.Vid(t) \tag{12}$$

Finally, we consider that an exfiltrated quantity, Ex f(t) [$L \cdot T^{-1}$], which corresponds to a fraction of the drained volume is put back into gravity flow:

$$Exf(t) = \omega.Vid(t) \tag{13}$$

The total runoff R to t(t) [$L \cdot T^{-1}$] produced by a mesh at time (t) is therefore equal to:

$$R_{tot}(t) = i(t) - f(t) + Exf(t) \tag{14}$$

Note: The differential equations are solved by explicit schemas on the calculation time step t_0, $t_0+\Delta_t$.

The transfer model Lag & Route

The simple Lag & Route transfer model is a conceptual model. It enables to convey the volume of runoff produced at each mesh m to the outlet for a definite time step t_i, as shown in the following equation [Tramblay *et al.* 2011] :

$$\text{If } t < t_0 + T_m \text{ so } q_m(t) = 0 \tag{15}$$

$$q_m(t) = \frac{p_e(t_0)}{K_m}\, exp\left(-\frac{t-(t_0-T_m)}{K_m}\right) * A \quad (16)$$

where: Pe(t) designates the effective rain produced by the mesh m over time, T_m – the transfer time of the mesh, t_0 – the initial time, K_m – the storage capacity of the tank, A – the area of the mesh m^2.

The parameter T_m is calculated from the following relation:

$$T_m = \sum \frac{L_m}{V_m} \quad (17)$$

L_m and V_m respectively represent the length and the flow velocity of the meshes between the mesh m and the outlet. In the simple version of the Lag & Route function, the speed is considered constant: $V_m = V_o$ the K_m parameter is calculated with the following relation:

$$K_m(t) = K_0 * T_m \quad (18)$$

The total flow is obtained at the outlet by summation of the elementary flow rates of all the meshes at all the time steps. According to the hydrological studies already performed [Jin *et al.* 2015] on sub-humid climate watersheds characterized by the presence of groundwater sources, which are manifested in the form of springs, it was recognized that the deep flow contributes considerably to the runoff, so the modelers must take into account the base flows as a determining factor in the reproduction of outfall flows, especially during the periods without precipitation.

The base flow under ATHYS is calculated according to the following equation:

$$Q(t) = Q_0 \exp(-a(t-t_0)) \quad (19)$$

Several possibilities are offered in MERCEDES, to fix Q_0 and α:

- Q_0 and α are derived from the same event observed at a reference station.
- Q_0 and α are imposed constant for all events.
- Q_0 and α are deduced from the previous event.

Process of simulations

The main procedure of simulation in the ATHYS platform is described in (Fig. 7). It is structured according to the following steps :

- On the basis of the DEM, the watershed area is divided into cells (cf. Fig 3(c)). In the presented case, the cell size is 12.5×12.5 m corresponding to an area of 156.25 m^2. The cells are therefore geographically characterized by altitude, direction of flow, and land use;
- The model provides an estimate of the total rainfall received by each at multiple time points using the interpolation of the Thiessen polygon method (Fig. 2);
- Total rainfall is transformed into effective rainfall using the SCS loss methodology Eq (1);
- The contribution of each cell in terms of the elementary hydrograph is then routed at the outlet, using the Lag and Route transfer model Eq (15) and (16);
- Finally, the complete hydrograph at the outlet of the watershed is generated by addition of all provided elementary hydrographs of all cells during each event (Fig. 7).

Evaluation methodology

In order to judge the quality of the model and their ability to reproduce the flows at the outlet of the Oued Laou watershed, the flow are assessed using four indices; the Nash and Sutcliffe efficiency, the root mean square error (RMSE), the relative bias (BIAS), and the linear correlation coefficient (R^2).The equations for these indices are as follows.

Nash and Sutcliffe

The efficiency proposed by Nash and Sutcliffe [Nash and Sutcliffe 1970] is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. It is calculated as:

$$\text{Nash} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right] \quad (20)$$

Where Y^{obs}, Y^{sim}, Y^{mean} are the observed and simulated flows over a time step and the average of the observed flows, respectively. Practically, it is estimated that the simulation is of poor quality when the Nash criterion is low (<0.5), it is acceptable when it is greater than (> 0.7), perfect when it is equal to (1).

Correlation coefficient (R^2)

R^2 is widely used in hydrological modeling studies, thus serving as a benchmark for performance evaluation.

$$R^2 = \left\lfloor \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \right\rfloor \quad (21)$$

More R^2 is close to 1, more the result of simulation is close to the observation [Garba and Chukwujama 2016].

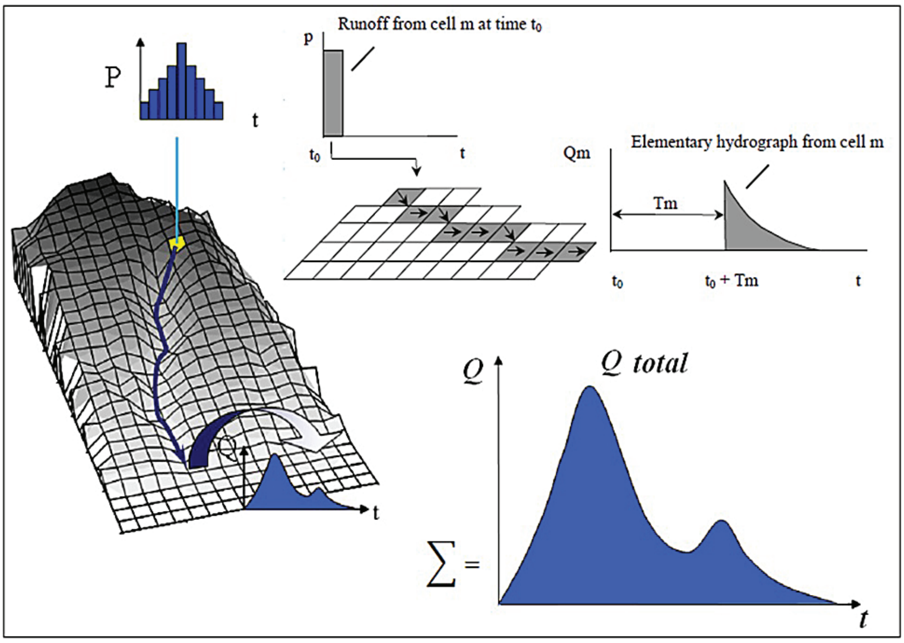

Fig. 7. Diagram of simulation procedure by MERCEDES and routing method with Lag and Route mode [Tramblay *et al.* 2011; M. Coustau *et al.* 2012]

Observations standard deviation ratio (RMSE)

This indicator is frequently used and its definition is given by:

$$RMSE = \left[\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2} \right] \qquad (22)$$

Where Y_{obs} and Y_{sim} represent the sample (of size n) containing the observations and the model estimates, respectively. It ranges from 0 to 1, where RMSE = 0 indicates a perfect fit [Ritter and Muñoz-Carpena 2013].

Percent Bias coefficient (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than the observed counterparts [Yen *et al.* 2015]. It also measures the over- and under-estimation of bias and expresses it as a percentage. Percent stream flow volume error [Yen *et al.* 2015], prediction error [Fernandez *et al.* 2007], and percent deviation of stream flow volume [Moriasi *et al.* 2015], are calculated in a similar manner as PBIAS:

$$PBIAS = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) \times (100)}{\sum_{i=1}^{n} \left(Y_i^{obs} \right)} \right] \qquad (23)$$

Where PBIAS is the deviation of data being evaluated, expressed as a percentage. The PBIAS coefficient can be used to determine how well the model simulates the average magnitudes for the output response of interest, is useful for continuous long-term simulations, and can help identify the average model simulation bias (over-prediction vs. under-prediction); and can incorporate measurement uncertainty [Herzel 2005].

Calibration and validation of continuous and extreme event

After preparing the data in the VICAIR and VISHYR models, the simulation process under MERCEDES model is performed in continuous mode with a daily time step over a period of eight years, subdivided as follows: five years (from 2004 to 2009) to manually calibrate the model, which was tested by changing the parameters of the two functions (Production and Transfer) to obtain a better agreement between the simulated and observed flow rates. The applicability of the model to the study area using the values of the calibration parameters that gave the best fit in simulation to model three hydrological years (from 2009 to 2011) was validated.

In order to simulate extreme events with an hourly time step, four events were chosen, subdivided as follows: in the calibration period, two events (2 and 5 March 2018) were used to calibrate the model. In the validation period, the applicability of the model to the study area was validated using two events (8 and 18 March 2018).

RESULTS AND DISCUSSION

Once the simulations have been completed, the MERCEDS output results were compared with the observed flows recorded at the Kodiet Kouriren station. The evaluation criteria (Nash, R^2, Bias [%], RMSE) has indicated appropriate findings (Table 2). The results show that the ATHYS platform which combined the Vicair, Vishyr, and MERCEDES models, performs well in the Oued Laou watershed. The correlation between DEM, initial land use status and soil and MERCEDES hydrological models indicates that the spatial distribution method provides a better estimate of the simulation of continuous and extreme events.

The sensitivity analysis carried out during the calibration process showed that the effectiveness of the MERCEDES model in modeling runoff at the Oued Laou watershed area depends essentially on the S, d_s and V_0 parameters, the performance of MERCEDES depends mostly on the S parameter, compared to the other parameters. It shows that the S parameter varies considerably from one event to another on the same type of land use in a range from 82.18 to 91.25 mm, similarly to the V_0 parameter which also varies from 2.13 to 1.80 m/s. A large number of hydrological modeling studies using the MERCEDES model have found fluctuations in these parameters [Maref and Seddini 2018; Tramblay *et al*. 2011]. The low S values are mainly due to the soil potential nature of the watershed; the possibility of an error in the soil type and corresponding soil properties in the region, which could create some uncertainty about the simulated result (underestimated of the runoff), cannot be excluded. Another problem is soil erosion, which affects the structure, infiltration capacity and other soil properties, since the model does not take into account the effect of soil erosion on runoff predictions can be uncertain [Shimelis *et al*. 2014]; in addition, the retention capacity significantly depends on the nature of land use and seasons, S (Soil reservoir capacity) takes high values in vegetated areas (forests, rangeland and agricultural land) because a higher fraction of rainfall does not reach the ground, but is still stored on the leaves as an interception [Halwatura and Najim 2013], while in the non-vegetated areas, the water retention capacity is significantly reduced; this also occurs in the urban areas where the retention capacity has been reduced due to the extension of the building and the concrete roof.

The land use changes can lead to high modifications in the hydrological parameters of a watershed area and then produce a variable flow. It was noted that the high temperatures during the summer seasons (which can increase up to 35°C) reduce the retention capacity in the Oued Laou watershed area.

The results show that the SCS-LR model under MERCEDES can simulate the continuous and extreme hydrological event; however, an underestimation of runoff has been noted, which can be related to rainfall distribution on the Oued Laou watershed. Studies confirmed that Hydrological modeling is strongly influenced by the distribution of precipitation, which is directly reflected in runoff production [Hans-Reinhard Verworm and Lars Stuecken 2001; Zhao *et al*., 2013]. An underestimated precipitation can produce a significant underestimation of runoff in hydrological modeling; It was noted that rainfall variability dominates the uncertainty of the runoff prediction, while parameter variations have only a minimal effect [Bahat *et al*. 2009], This result is consistent with that of [Arnaud et al. 2002] who found that the calibration of the rainfall-runoff model is impacted when using a uniform average of precipitation. Unfortunately, the measurement of precipitation

Table 2. Parameter results of the spatio-temporal modeling at the level of the Laou watershed

Specification			S [mm]	W	ds [1/day]	V_O [m/s]	k_O	Q Bias [%]	RMSE	Nash	R^2
Extreme events	Calibration	02/03/2018	82.18	0.61	0.17	2.13	0,70	15%	0.59	0.63	0.65
		05/03/2018	82.18	0.61	0.17	2.13	0,70	11%	0.35	0.78	0.80
	Validation	08/03/2018	82.18	0.61	0.17	2.13	0,70	13%	0.42	0.74	0.77
		18/03/2018	82.18	0.61	0.17	2.13	0,70	10%	0.34	0.79	0.81
Continuous events	Calibration	01/01/2004 to 31/12/2008	91.25	0.58	0.12	1.80	0,75	14%	0.51	0.67	0.68
	Validation	01/01/2009 to 31/12/2011	91.25	0.58	0.12	1.80	0,75	16%	0.53	0.61	0.66

in the Oued Laou watershed area is provided by two stations located at the outlet and upstream of the watershed area, which supports this hypothesis. In order to better control precipitation in this watershed and to obtain improved hydrological modeling, it seems necessary to establish other stations in the Oued Laou watershed area. This is coherent with the fact that a significantly higher number of rain gauges could improve the model performance, i.e. more precipitation data would help the model become more predictive [Son Nguyen and Christophe Bouvier 2019], Likewise, the findings from [Cole and Moore 2008] suggest that a model using different spatial resolutions of rainfall may require recalibration of the model parameters.

The underestimation of the simulated flow in the Oued Laou watershed may also be reflected in the collection of runoff from dams, reservoirs and other water collection systems used by the population in the region (Metfia, Gdira).

The enhanced precipitation will affect the runoff and alter the hydrological behavior within the watershed. Similarly to climate, groundwater has an important role in understanding the runoff generation processes and for predicting the water quantities, including floods and basal flows [Gonzales *et al*. 2009; Liu *et al*. 2015]. For this reason, the groundwater in the Oued Laou watershed has a very significant impact on the runoff, mostly during the dry season.

The Nash coefficients, the linear correlation and the relative bias and RMSE on runoff volume and peak flow of the continuous simulations with the different rainfall inputs (calibration and validation) confirm that the MERCEDES model provides a better prediction of the surface runoff in continuous mode (Fig. 8). The results of the modeled flows simulated from the four scenarios are summarized in (Fig. 9). All simulations of extreme events have a Nash coefficient greater than 0.63. The event (1) has the lowest Nash values, below 0.7 with all the different rainfall inputs, probably indicating some inadequate rain estimation. A significant improvement in flood simulations is observed for the event (4) during the validation period, with Nash coefficients increasing from 0.63 to 0.79. These results for the efficiency of the simulation should be considered as the fact that 2 precipitation gauges are available in the watershed, allowing an underestimation of precipitation at the watershed scale.

Considering the results above, the efficiency of the VICAIR, VISHYR and MERCEDES model structures in the simulation of continuous hydrological series and flood prevention

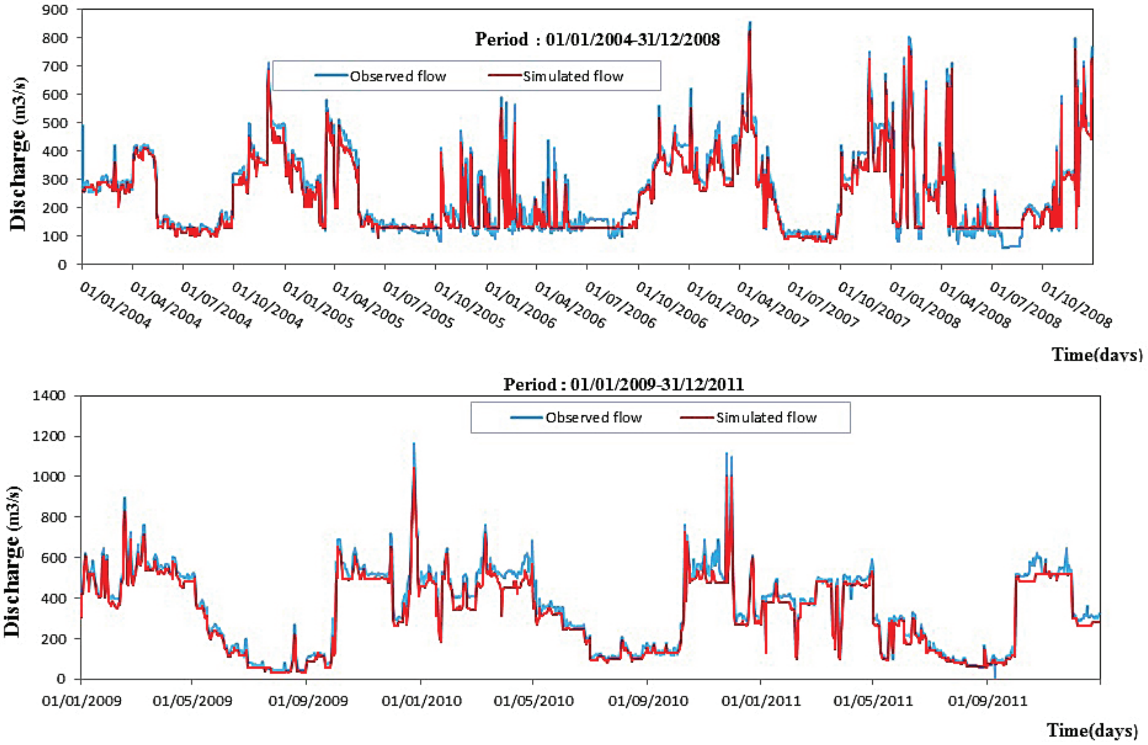

Fig. 8. Simulated and observed Hydrographs throughout the five years (2004–2008) for the calibration and three years (2009–2012) for the validation period

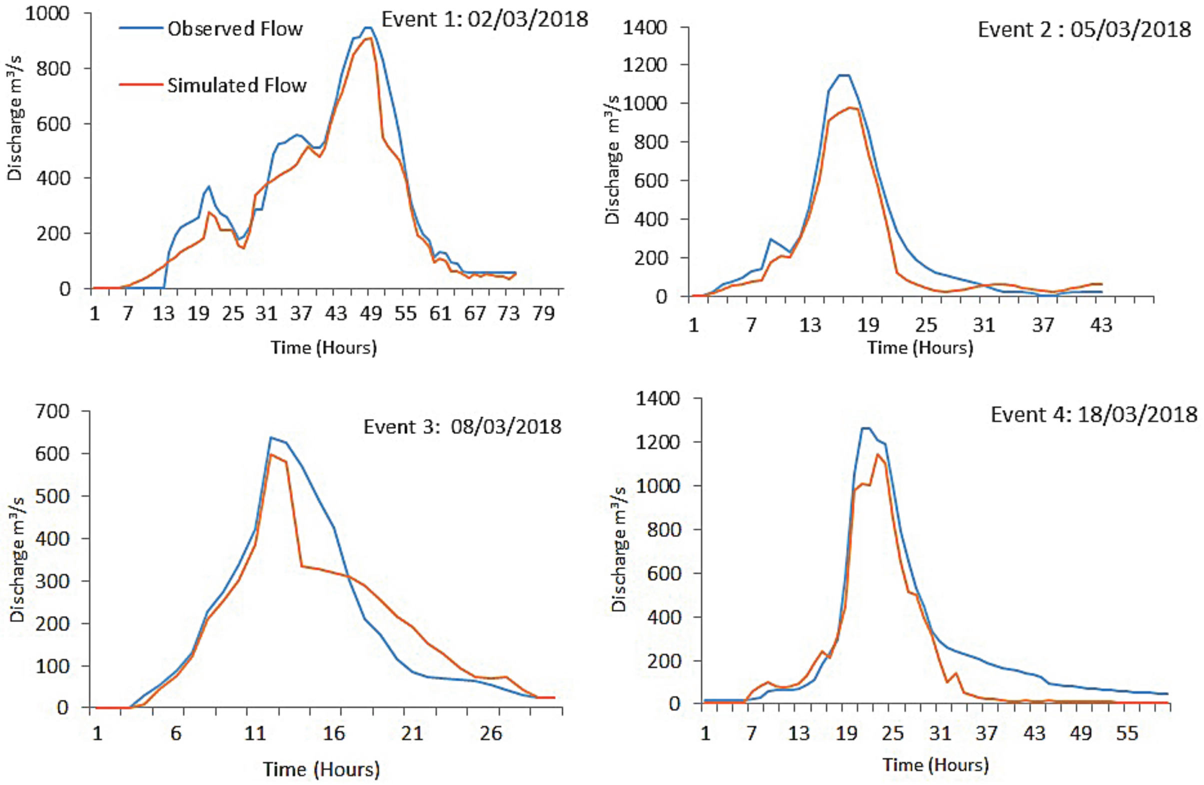

Fig. 9. Simulations results of four flood events used with an hourly time step

in the Oued Laou watershed can be confirmed. If the extreme hydrometeorological event had occurred in the presence of warning and prevention systems in the Oued Laou watershed, the material damage would probably have been less significant.

New nature conservation guidelines based on the protection of the forest as water regulation areas proposed by scientists [Wegehenkel 2009; Yang *et al*. 2011] can assist in controlling runoff, because the modeling and scenarios of the Oued Laou watershed case clearly express the importance of vegetation cover as a factor in flow regulation. Since the forest ecosystem protects only half of the Oued Laou watershed, with forest masses located in the eastern half of the watershed, if the deforestation trend continues for a few decades, the water flow control through flood warning systems will be a necessity because the existence of high slopes will increase the intensity of floods. Understanding the land use parameter in the Oued Laou watershed is useful for hydrological modeling, because it is an indication of the roughness of the land area, which has a significant influence on the patterns of runoff and water flows on the opposite side.

CONCLUSIONS

On the basis of the findings, it can be judged that the performance of the ATHYS platform is generally encouraging and can be considered satisfactory. The rainfall-runoff relation was tested in the MERCEDES model, the employed evaluation criteria give a good agreement with a mean of (Bias = 13%, RMSE = 0.46, Nash = 0.70, R^2 = 0.73).

An analysis of the parameter-hydrology interaction reveals an undeniable complexity of the issue; the more conceptual the model is, the more it feeds on the parameters that have more intrinsic at least physical meaning. Thus, it was noticed that the knowledge of spatial distribution becomes essential for modeling flood generation.

The research results reveal that the storage parameters, soil type, land use and vegetation are the most important factors affecting the sensitivity of the hydrological response in the Oued Laou watershed.

According to the results obtained, the ATHYS platform models are appropriate tools for modeling floods and flow volumes associated with specific rainfall events and could be used by managers as well decision-makers as a tool for flood forecasting in northern Morocco, to take the emergency measures such as evacuating people, so that their lives can be saved and the loss of property can be minimized.

Table 3. Abbreviations used

ATHYS	Spatial Hydrological Platform	i(t)	Intensity
VICAIR	Processing of specialized geographical data	SCS	Soil Conservation Service
VISHYR	Processing of stationary hydro-climatic data	I_a (mm)	Initial loss
MERCEDES	Spatial modeling platform	R(t)	Runoff
A (m^2)	Area	(t)	Soil drainage
f(t)	Infiltration	DEM	Digital elevation model
C(t)	Runoff coefficient	L_m (m)	Flow path length
P(t) (mm)	The cumulative rainfall	T_m	Propagation time vid
S(t) (mm)	Soil reservoir capacity (the potential maximum retention)	RMSE	Observations standard deviation ratio
d_s (day^{-1})	Drainage coefficient f(t) Infiltration	R^2	Linear correlation coefficient
K0	Empirical constant of proportionality	NSE	Nash–Sutcliffe efficiency criterion
ω	Fraction of the subsurface water	PBIAS (%)	Percent Bias coefficient
V_0 (m·s^{-1})	Transfer speed		

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