



Modeling of flood generation in semi-arid catchment using a spatially distributed model: case of study Wadi Mekerra catchment (Northwest Algeria)

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Abstract

This paper aims to apply the MERCEDES distributed hydrological model with an event-based mode to simulate flood generation in the Wadi Mekerra basin situated northwest of Algeria. This catchment is characterized by a semi-arid climate, convective thunderstorms, and ephemeral flow. The input data are mainly the daily rainfall-runoff and numerical maps such as slope, flow direction, and land use. The comparison between calculated and measured runoff revealed that the MERCEDES performance to simulate flood generation in Wadi Mekerra basin is encouraging and satisfying which is justified by the Nash–Sutcliffe and observations standard deviation ratio criteria. However, the proposed model tends to underestimate peak runoff due to convective rainfall that may be much localized in space. Furthermore, the sensitivity analysis shows that the hydrological response in the Wadi Mekerra catchment depends strongly on the potential maximum retention parameter which is related to the land use type and varies significantly between seasons according to the vegetation cover dynamics, rainfall intensity, and drought.

Keywords MERCEDES model · Rainfall-runoff · Wadi Mekerra · Flood generation · Loss and routing methods · Land use

Abbreviations

A (m ²)	Cell area	ω	Fraction of the subsurface water
$C(t)$	Runoff coefficient	L_m (m)	Flow path length
CN	Curve number	V_0 (m s ⁻¹)	Transfer speed
ds (day ⁻¹)	Drainage coefficient	ATHYS	Atelier Hydrologique Spatialisé
$f(t)$	Infiltration	DEM	Digital elevation model
$i(t)$	Intensity	MERCEDES	Maillage Elémentaire Régulier Carré pour l'Etude Des Ecoulements Superficiels
I_a (mm)	Initial loss	NSE	Nash–Sutcliffe efficiency criterion
K_0	Empirical constant of proportionality	RSR	Observations standard deviation ratio criteria
$P(t)$ (mm)	The cumulative rainfall	SABY	Sidi Ali Ben Youb
RSR	Observations standard deviation ratio	SBA	Sidi Bel Abbes
$R(t)$	Runoff	SCS	Soil Conservation Service
$S(t)$ (mm)	Soil reservoir capacity (the potential maximum retention)	SRTM	Shuttle Radar Topography Mission
T_m	Propagation time		
$vid(t)$	Soil drainage		

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Introduction

The risk of flooding due to runoff is estimated as one of the most dangerous natural disasters in the world. Floods cause more than 50% of natural disasters with an average of 20,000 deaths per year (Randrianasolo 2009). Between 1900 and 1980, floods have caused more than 339 million casualties (Ballais et al. 2011). This situation became

more and more dangerous in the last years (Aroua and Berezowska-Azzag 2009).

In Algeria, the catastrophic flash floods occurring in wadis are most dangerous, although the majority of these wadis are ephemerals. In the last decade, flooding disasters affect several regions in Algeria such as the following: on October 20, 1993, in Wadi R'hiou in central Algeria; October 14, 2000, in Ain Temouchent (Western Algeria); November 10 to 11, 2001, in Bab El Oued, Algiers; April 18 to 19, 2007, in Ghardaïa southeast of Algeria; and October 9, 2008, in Aïn Defla in Central Algeria. In total, these events have provoked more than 872 dead (Bouasria et al. 2010). As a consequence, their prediction has become a necessity. Among the effective forecasting tools often used are the hydrological simulation models based on rainfall-runoff relationships.

However, the transformation processes of runoff generation due to precipitation and its transmission to the outlet are the most complicated processes (Benkaci and Dechemi 2004; Estupina 2004), knowing that the rainfall-runoff relationship strongly depended on the land surface heterogeneities and the physics of the processes (Bouvier 2004; Jain et al. 2004). In such case, the distributed modeling techniques are commonly used to describe the hydrological processes which vary in spatial scale within a given catchment (Abushandi 2011). The main advantage is the ability to provide a better representation of the physical characteristics such as soil heterogeneity, vegetation, and topography of the basin.

In the last decade, several distributed models have been developed: USDA SWAT model (Arnold et al. 1998), TOPMODEL (Beven and Kirkby 1979), HEC-HMS (Fleming and Scharffenberg 2012), MERCEDES (Bouvier et al. 1994), etc. However, most of them are separated from spatial information processing tool, which makes their use a significant challenge for hydrologists. Currently, the spatial modeling platform ATHYS (Atelier Hydrologique Spatialisé) offers the possibility of coupling the model MERCEDES (Maillage Élémentaire Régulier Carré pour l'Etude Des Ecoulements Superficiels) with spatial data processing modules.

Several evaluation studies of the MERCEDES model show that this model has been successfully applied on various types of catchments including a few semi-arid regions. For example, MERCEDES was applied in two rural basins in France such as Rognon (618 km²) (Boulay 2011) and Gardon (545 km²) (Marchandise 2007); in urban basin of Ouagadougou (610 ha) situated in Burkina Faso (Bouvier and Delclaux 1996); in two rural basins located east of Algeria such as Kissir (92 km²) and Bouhamdene (1105 km²) (Abdi and Meddi 2015).

In this work, we use the MERCEDES model applied to the Wadi Mekerra catchment. MERCEDES is a conceptual spatial model and is available for free download from <http://www.athys-soft.org>. It is integrated in the ATHYS platform which is dedicated to hydrological environment for rainfall-runoff

distributed modeling (Bouvier et al. 1996; Lequien 2003; Marchandise 2007). In this model, the watershed is discretized into regular square cells (Beven 2001). Each cell contains information about the soil characteristics, the land use, the slope, and the flow direction (Jain et al. 2004). MERCEDES combines between hydrological data (e.g., rainfall, runoff), geographical data (e.g., DEM, land use mapping), and the models (loss and routing methods) to estimate the basin's hydrological response.

In this study, the application of the MERCEDES model has two objectives: first, to simulate the runoff in the semi-arid region like Wadi Mekerra catchment, and second, to study the influence of land use change on flood generation in this wadi.

The SCS (Soil Conservation Service) loss method and the routing method (lag and route) included in the MERCEDES model are used. The SCS method is used to estimate the effective rainfall (the fraction of rainfall that contributes to runoff) for each cell. The runoff produced by each cell is then routed until the basin outlet using lag and route method. Furthermore, the proposed model is applied following the principle of event-based mode. An event-based model tends to simulate the basin response to occasional storm rainfalls without considering previous conditions (Le 2008). It is efficiently used in operational hydrological forecasting namely for extreme events (Muhammad et al. 2015).

The MERCEDES model evaluation is done using automatic calibration to check model performance and estimate optimal parameters using the Nash–Sutcliffe (NSE) and observations standard deviation ratio (RSR) criteria and rainfall-runoff observations from 21 events occurring between 2003 and 2012. Also, the sensitivity analysis is conducted to identify the parameters that significantly affect model outputs.

Methods and models

Modeling principle with MERCEDES

MERCEDES developed by Bouvier (1994) and Bouvier et al. (1994) is a spatial hydrological tool to study the rainfall-runoff relationship. This model is implemented in the ATHYS platform (<http://www.athys-soft.org>). ATHYS is a computing tool dedicated to the spatially distributed hydrological modeling type (Bouvier et al. 1996). It is developed by the IRD (Institut de Recherche pour le Développement) in Montpellier (France).

The homogeneous ATHYS platform contains three main modules.

- a) VICAIR (Visualization des Cartes et Images Raster) is a preprocessor for geographical data. This module allows extracting hydrologic system properties of the watershed

- (convexity, slope, drainage areas, etc.) from the DEM (digital elevation model);
- b) VISHYR (Visualization des données Hydrologiques) is a preprocessor for storing and managing hydrological data. It displays, selects, and stocks the data and the chronological series such as rainfalls and discharges;
- c) MERCEDES is a conceptual spatial model based on square grids adapted to the surface runoff. It combines a large range of production functions such as (SCS, Green and Ampt, Smith and Parlange, TOPMODEL, and Girard) with transfer functions (lag and route, kinematic wave, etc.) that are applicable in a homogeneous and user-friendly environment.

The MERCEDES model structure is based on the soil reservoir concept (cf. Fig. 1) where it is considered that the rainfall fills a soil reservoir. The reservoir level $S(t)$ is calculated using a balance between the infiltration $f(t)$ and the runoff $R(t)$ by the following relation:

$$R(t) = i(t) - f(t).$$

In our case, we use the SCS production method with four parameters ($S, I_a/S, ds,$ and ω) and lag and route routing method with two parameters (V_0 and K_0).

Runoff generation processes

In terms of runoff, the contribution of each cell in the catchment is computed by the SCS model that permits the transformation of the total rainfall into effective rainfall which is estimated as a function of the cumulative precipitation, soil type, land use, and antecedent moisture condition (Chow et al. 1988; Ayenew 2008; Feldman 2000).

This model has been commonly used for flood modeling because of its simplicity and use of a reduced number of parameters (Tramblay et al. 2011; Halwatura and Najim 2013).

To calculate the runoff $R(t)$, the MERCEDES model links the runoff coefficient $C(t)$ to the rain intensity $i(t)$ by:

$$R(t) = C(t) \times i(t) \tag{1}$$

$C(t)$ is calculated through

$$C(t) = \left(\frac{P(t) - 0.2S}{P(t) + 0.8S} \right) \times \left(2 - \frac{P(t) - 0.2S}{P(t) + 0.8S} \right) \tag{2}$$

Where $P(t)$ (mm) is the cumulative rainfall computed from the beginning of the event. $S(t)$ (mm) is the soil reservoir capacity (the potential maximum retention). This parameter depends on land use and soil

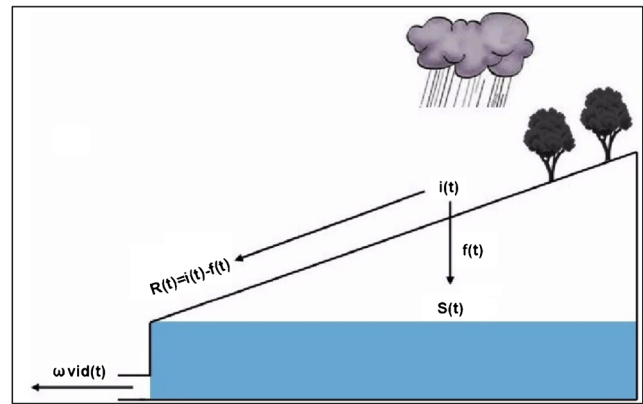


Fig. 1 Schematic diagram of the MERCEDES model structure

characteristics in the catchment. It can be obtained from the SCS CN (curve number) by:

$$S = \frac{25400}{CN} - 254 \tag{3}$$

Generally, S is calculated using the equation:

$$S = \frac{I_a}{0.2} \tag{4}$$

Where I_a (mm) is the initial loss at the beginning of the event.

The soil reservoir filling

The soil reservoir is filled by infiltration which is governed by this relation:

$$f(t) = (1 - C(t)) \times i(t) \tag{5}$$

Where $f(t)$ is the infiltration capacity at the time t . It also depends on the spatial variability of the soil properties such as soil layer depth, heterogeneity, porosity, hydraulic conductivity, etc.

The soil reservoir draining

The drainage of soil reservoir is computed by the following formula:

$$vid(t) = ds \times S(t) \tag{6}$$

Where $vid(t)$ is the drainage of soil reservoir at the time t and ds (day^{-1}) is the drainage coefficient which is a function of the evaporation, percolation, and interflow. The ds values range from 0 (no drainage) to ∞ (complete drainage).

Depending on the soil type, a fraction of infiltrated water returns up to the surface in the form of the exfiltration and promotes the runoff. It is the subsurface runoff which is expressed by:

$$Exf(t) = \omega \times vid(t) \tag{7}$$

Where the adimensional parameter ω represents the fraction of the subsurface water.

Flow routing

MERCEDES provides two transfer methods: kinematic wave (interactive meshes mode) and lag and route (independent meshes mode) which have been commonly used (Bentura and Michel 1997; Trambly et al. 2011) and applied in this study too.

In independent mesh mode, each cell m produces an elementary hydrograph and transfers it to the watershed outlet at each time interval, without taking into account the neighboring cell contributions. Thus, the propagation time from the cell to the outlet is:

$$T_m = \frac{L_m}{V_0} \quad (8)$$

Where T_m is the propagation time, L_m (m) is the flow path length from the cell m to the outlet, and V_0 (m s^{-1}) is the transfer speed.

The equation of the elementary hydrograph associated with the cell contribution between instants t_0 and $t_0 + \Delta t$ is therefore written in terms of the specific discharge:

$$q(t) = 0 \quad \text{if} \quad t < t_0 + T_m \quad (9)$$

$$q(t) = \frac{R(\Delta t)}{K_m} \times \exp\left(-\frac{t-(t_0 + T_m)}{K_m}\right) \cdot A \quad t > t_0 + T_m \quad (10)$$

With,

$$K_m = K_0 \times T_m \quad (11)$$

Where q ($\text{m}^3 \text{s}^{-1}$) is the specific discharge, A (m^2) is the cell area, and K_0 is an empirical constant of proportionality fixed at $K_0 = 0.7$.

Calibration and optimization of the model

MERCEDES provides an optimization and sensitivity analyses that can calibrate automatically certain model parameters in order to reduce their uncertainty. The automatic calibration procedure is based on the comparison between the observed and the calculated discharges using available efficiency criteria such as observations standard deviation ratio (RSR) (Moriassi et al. 2007) and Nash–Sutcliffe efficiency (NSE) criterion (Nash and Sutcliffe 1970) which is mostly used in hydrology as an objective function (Ardoin 2004; Gerard 2010). Both of these criteria are used in this study.

Using the Simplex iterative method (Rao 1978), the optimization procedure consists of determining the parameters associated with the optimal values (0 for RSR

criterion, 1 for Nash). The better performance of the model is associated with the following ranges: 0 to 0.5 for RSR and 0.75/0.8 to 1 for NSE (Varado 2004; Fourmigue and Lavabre 2005; Khattati et al. 2016).

The RSR criterion is given by:

$$\text{RSR} = \frac{\sqrt{\sum_{i=1}^n (Q_{\text{obs},i} - Q_{\text{cal},i})^2}}{\sqrt{\sum_{i=1}^n (Q_{\text{obs},i} - \overline{Q_{\text{obs}}})^2}} \quad (12)$$

NSE criterion is based on the sum of the quadratic errors as:

$$\text{NSE} = 1 - \frac{\sum_{i=1}^n (Q_{\text{obs},i} - Q_{\text{cal},i})^2}{\sum_{i=1}^n (Q_{\text{obs},i} - \overline{Q_{\text{obs}}})^2} \quad (13)$$

Where $Q_{\text{obs},i}$ and $Q_{\text{cal},i}$ represent the observed and simulated discharges, respectively, at time i ; $\overline{Q_{\text{obs}}}$ is the mean of n observed discharges.

In addition, the relative error (RE) is used in order to estimate the model accuracy in terms of peak discharge. It is given by:

$$\text{RE}(\%) = \frac{Q_{\text{p.computed}} - Q_{\text{p. observed}}}{Q_{\text{p. observed}}} \times 100 \quad (14)$$

Where Q_p is the peak discharge.

Simulation process

The general MERCEDES simulation procedure is described in Fig. 2. It is based on the following steps:

1. From the DEM, the watershed is divided into cells (cf. Figure 7(b)). In our case, the cell size is $90 \text{ m} \times 90 \text{ m}$ corresponding to an area of 8100 m^2 . The cells are hence geographically characterized by altitude, flow direction, and land use;
2. The model estimates the total received rainfall by each cell at different times using the Thiessen polygon interpolation method;
3. The total rainfall is transformed into effective rainfall using the SCS loss method;
4. The contribution of each cell in terms of the elementary hydrograph is then routed at the outlet, using the Lag and Route routing model;
5. Finally, the complete hydrograph at the catchment outlet is obtained by adding all the elementary hydrographs provided from all cells during the event.

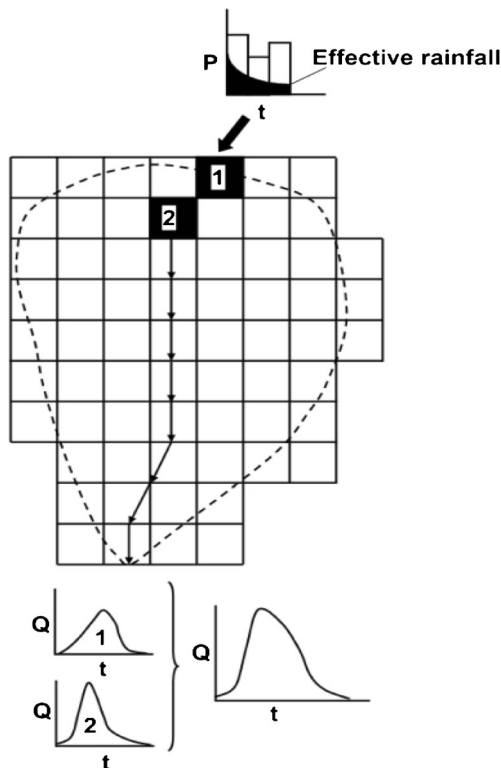


Fig. 2 Diagram of simulation procedure by MERCEDES and routing method with Lag and Route Mode

Description of the study catchment

Geographic location and general characteristics

The Wadi Makerra watershed is part of the large Macta basin (cf. Fig. 3). It is located in the northwestern part of Algeria. The geographical location of the watershed is between $0^{\circ} 20' 34.8''$ W and $1^{\circ} 10' 15.6''$ W longitudes and $34^{\circ} 18' 10.8''$ N and $35^{\circ} 22' 34.8''$ N latitudes. It covers approximately 3574.8 km^2 .

This basin is drained by the Wadi Makerra along 142.4 km approximately and takes its source from the highland in the basin south. The Wadi Makerra crosses many cities such as Ras El Ma, El Haçaiba, Sidi Ali Ben Youb (SABY), and Sidi Bel Abbes (SBA) to reach the Cheurfa Dam.

The main morphological parameters of the basin are listed in Table 1. It shows that the form of the basin is elongated with very rugged relief. The basin topography can be generally divided into three areas: highland in the south (1640–750 m), middle elevation area (750–493 m), and the plain of SBA in the north (493–350 m).

The land use (cf. Fig. 8) types of Wadi Mekerra catchment are classified as agricultural land (44.7%), rangelands (35.8%), forests (18.7%), and urban areas (0.85%). The agricultural areas are dominated by wheat

crops which form the principal permanent cultures. The soil of the cultivated land consists mainly of silt which can be considered as a less permeable soil. The rangeland is characterized by sparse vegetation cover and permeable soil.

Climate, rainfall, and runoff

The climate of Wadi Makerra basin is Mediterranean in northern parts but the dominant southern zones are semi-arid. The precipitation decreases from north to south where the mean annual rainfall ranges from 319 mm (measured in Sidi Bel Abbès station) in the downstream to 198 mm (measured in Ras El Ma station) in the upstream.

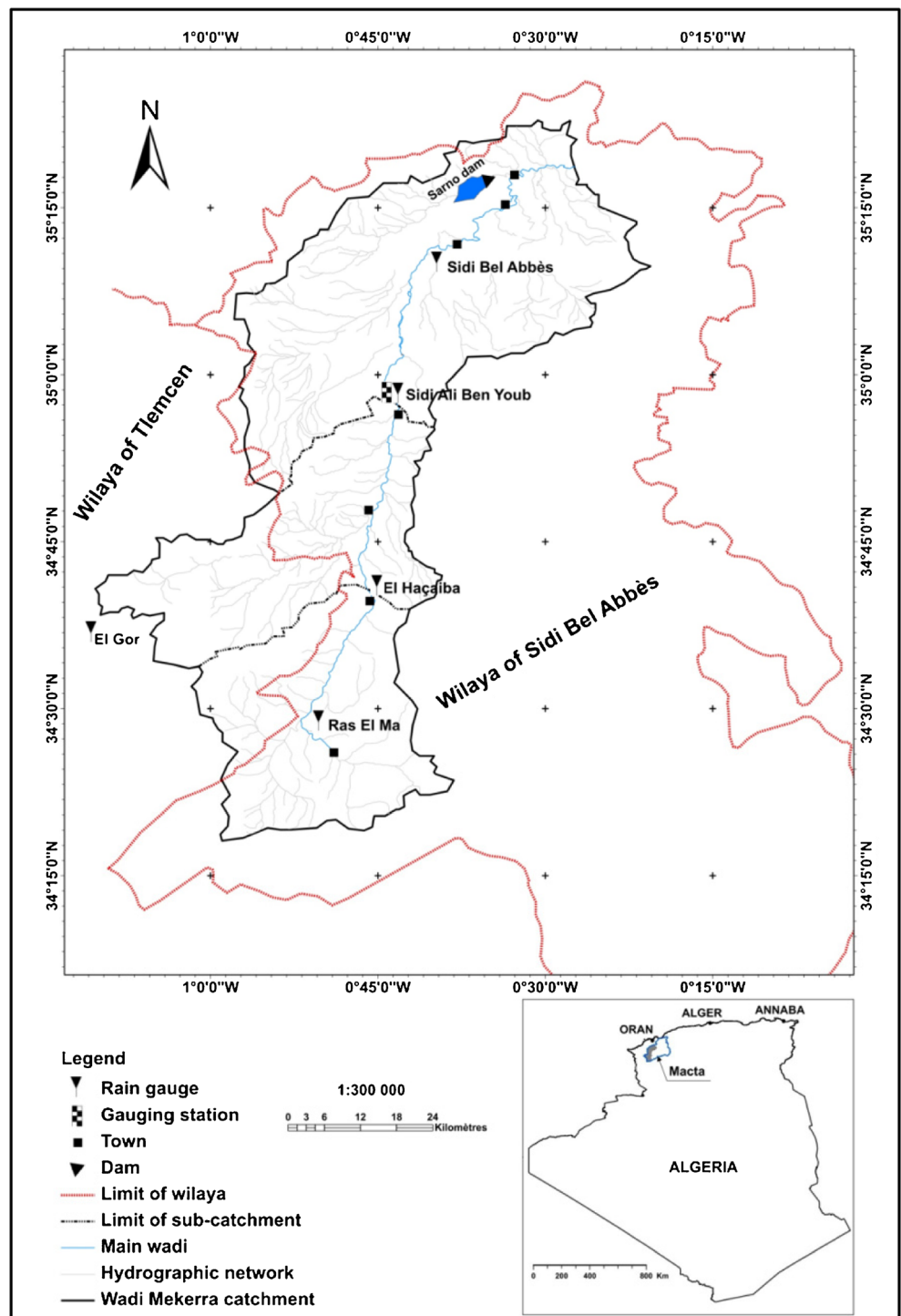
In the watershed of Wadi Mekerra, the rainfall variability from 1978 to 2009 was highly irregular (cf. Fig. 4). It is also characterized by an alternation of wet and dry periods. The total annual rainfall in the dry period may decrease less than 50 to 80% of the average annual rainfall.

The monthly rainfall distribution from the same period is presented in Fig. 5. It reveals three periods which can be distinguished during the hydrological year: the first one is mainly centered on winter (December to February) where rainfall exceeds about 38% of the total annual rainfall, the second one is the thunderstorm season that may dominate during autumn (October to November) and contributes about 26%, and the third period is the spring rains (March to April) which represents only 22% of the annual rainfall.

In terms of annual runoff, the flow regime of Wadi Mekerra fluctuates greatly from year to year, as shown in Fig. 4. The mean annual discharge was very low ($0.51 \text{ m}^3 \text{ s}^{-1}$ observed at Sidi Ali Ben Youb station) and the exceptional floods are able to reach more than $750 \text{ m}^3 \text{ s}^{-1}$. It is also noted that high annual rainfall does not necessarily generate high discharge. For example, total annual rainfall between 2007 and 2008 (660.2 mm) was higher than that recorded between 2008 and 2009 (611.3 mm) in which the mean annual discharges were 0.34 and $1.36 \text{ m}^3 \text{ s}^{-1}$, respectively.

Figure 5 shows the monthly discharges observed at SABY gauging station. In general, the contribution of the precipitations on the Wadi flow during winter was less compared to that during the autumn and spring seasons. Hence, the regime flow in the basin is distinguished by two periods: the flood season where the high runoff values observed in autumn and spring are generated by important floods (Borsali et al. 2005; Oufella and Touaibia 2005) and the low-flow season in winter and summer.

Fig. 3 Location map of Wadi Mekerra basin with the rain gauges and gauging station



The distribution of the mean daily discharges for the period 2003–2012 (cf. Fig. 6) shows that the major flood events occur generally in autumn and more specifically in late September until late November. This period is characterized by high flood frequencies which are often violent and generally lasts 1 to 2 days only.

The floods’ second period is recorded in the middle spring. It commonly starts in the middle of April and ends in early June. These floods are often less severe and spread out over several days.

According to the river classification, the rivers can be considered as ephemeral if its daily flow rate is less than

Table 1 Main physiographic parameters of the Wadi Mekerra catchment

Parameter	Unit	Value
Basin area	km ²	3574.8
Perimeter of the basin	km	406.5
Gravellus index	–	1.9
Maximum elevation	m	1640
Minimum elevation	m	350
Mean elevation	m	1297
Mean slope gradient	m km ⁻¹	4.5
Length of the main wadi	km	142.4
Drainage density	km km ⁻²	0.37

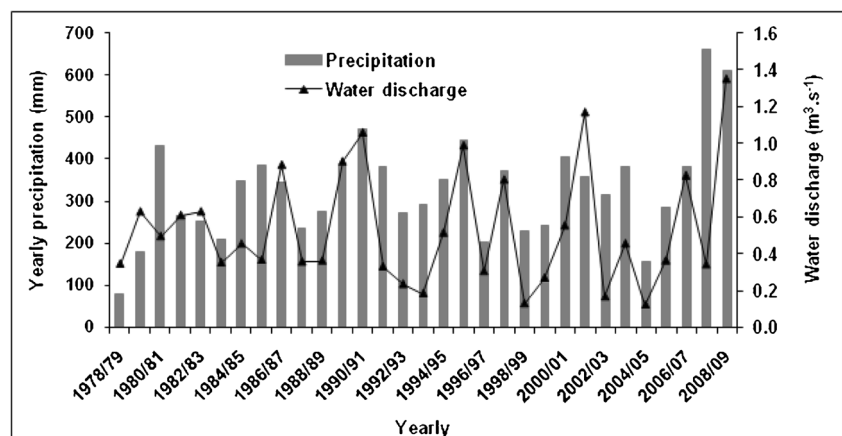
20% (Matthews 1998). Like the majority of the Algerian wadis (Achite and Ouillon 2007), the Wadi Mekerra is considered as an ephemeral stream. It is characterized by the short flowing periods with an average daily flow rate of about 12% per year; otherwise, it is dry.

Required data

Hydrological data

The used hydrological data consists of the daily rainfall and the mean daily discharge from the period (2003–2012). A total of 21 rainfall-runoff events, which is equivalent to 639 days, were selected (Table 2). The choice of this period is based on the availability of data. Rainfall records were collected from five rain gauging stations (El Gor, Ras El Ma, El Haçaiba, SABY, and SBA). Also, the discharge measurements are provided in the SABY gauging station (cf. Fig. 3).

Fig. 4 Variability of total annual rainfall and mean annual discharge at Sidi Ali Ben Youb station



DEM and numerical maps

The DEM is obtained from the Shuttle Radar Topography Mission (SRTM) data with approximately 90-m spatial resolution as shown in Fig. 7(a).

The DEM is used to divide the catchment surface into many meshes or cells (cf. Fig. 7(b)) and hence extract spatial information required by the model. The flow direction of each mesh is oriented following the D8 algorithm (Jenson and Dominique 1988). The principle of this algorithm is the flow direction from one cell can be oriented to eight other neighboring cells, as shown in Fig. 7(b). The flow path is established following the direction of the steepest slope.

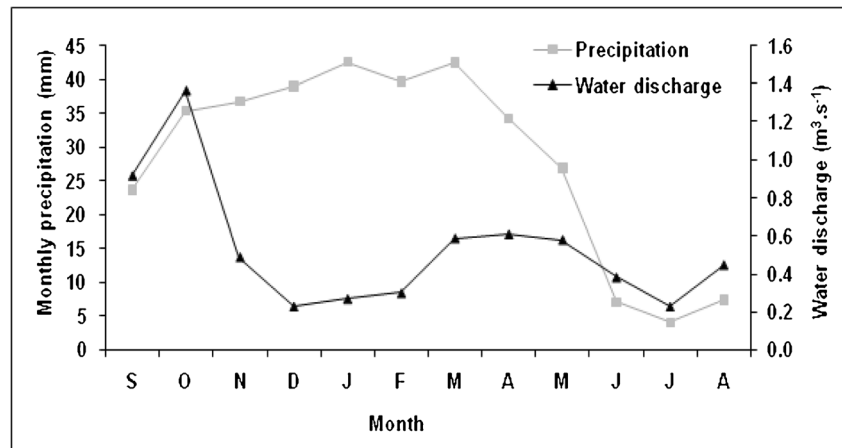
Also, the land use map of the catchment is needed for model inputs and its classification is provided through digitized maps (scale 1/200,000). It is divided into four classes: agricultural land, rangelands, forests, and urban areas (cf. Fig. 8). This numerical map is prepared using Global-Mapper software.

Results and discussion

The results of MERCEDES simulations for the selected events are depicted in Figs. 9, 10, and 11. They show, respectively, the comparisons of the computed and the observed hydrographs, the evaluation criteria (NSE and RSR), and relative error (RE).

Furthermore, the comparison between computed and observed hydrographs shows a good agreement (cf. Fig. 9). In terms of the model efficiency, the NSE ranges from 0.46 to 0.99 for 21 studied events in which 14 events (about 66% of events) have the NSE criterion greater than or equal to 0.80 (cf. Fig. 10). Likewise, the RSR criterion varies between 0.11 to 0.74 of which 15 events (about 71% of events) have the RSR less or equal to 0.5. It can also be noted that RSR values

Fig. 5 Variability of monthly average rainfall and water discharge at Sidi Ali Ben Youb station (hydrological year begins from September until August)



below 0.5 coincide with NSE values greater than or equal to 0.8.

Concerning the relative error, the computed peak run-offs are underestimated for the majority of the events, where the relative error values range from -60 to 0% with an average of -17.7%. However, there is no proportionality between the observed discharge and the model uncertainty (cf. Fig. 11). For example, an observed discharge of $20.2 \text{ m}^3 \text{ s}^{-1}$ is underestimated by 18.82%, while the underestimation of $1.8 \text{ m}^3 \text{ s}^{-1}$ reaches 50%.

The source of this underestimation can be related to the rainfall underestimation which is characterized by high spatial

heterogeneity and it represents the major difficulties to quantify rainfall in semi-arid zones.

The rainfall heterogeneity has been proven from the observations of Kedem et al. (1990), who found that the intense rainfall affects frequently a smaller area over a large catchment. Zhao et al. (2013) have confirmed that the runoff generation and also the hydrologic process in a catchment are strongly affected by the spatial rainfall variability.

Convective thunderstorms are frequently local storms with diameters less than 14 km (Renard and Keppel 1966; Diskin and Lane 1972). It is accompanied by highly concentrated local rainfall events (Sharon 1972;

Fig. 6 Daily flows for Wadi Mekerra from 2003 to 2012 at Sidi Ali Ben Youb gauging station

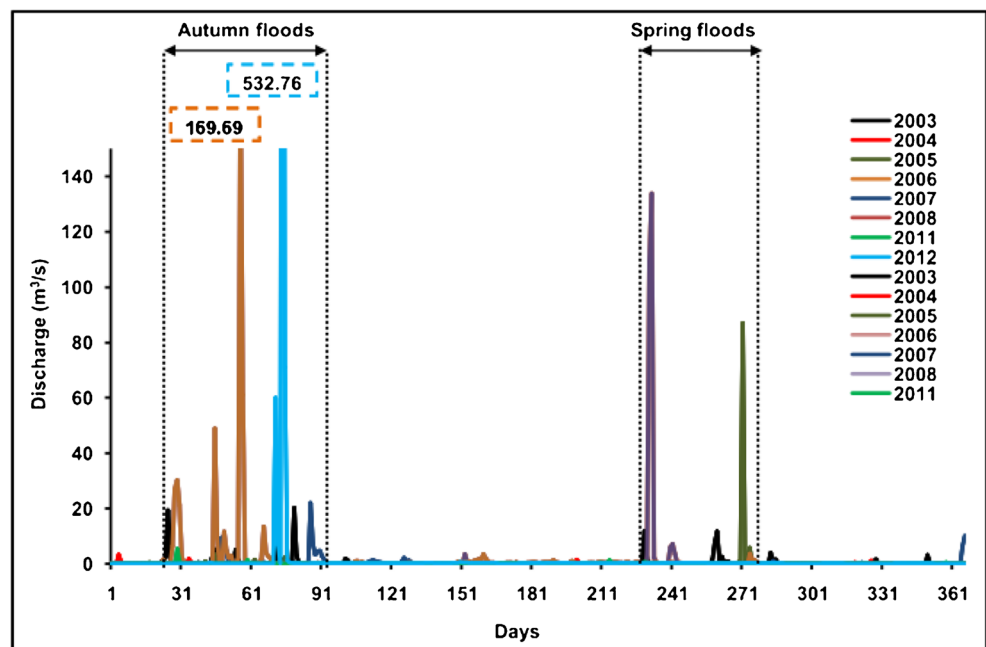


Table 2 Characteristics of the selected rainfalls and discharges used for simulation

Event	SABY			Ras El Ma		El Haçaiba		El Gor		SBA	
	$Q_{j,max}$	$P_{j,max}$	P_{Tota}	$P_{j,max}$	P_{Tota}	$P_{j,max}$	P_{Tota}	$P_{j,max}$	P_{Tota}	$P_{j,max}$	P_{Tota}
Sep/2003	19.5	16.5	16.5	5	11.6	8.8	21.8	23.3	26.1	0	0
Nov/2003	20.2	23.1	59.1	27.6	42.7	22.5	53.2	22.5	63.4	6.9	34.3
Dec/2003	1.80	24.1	53	13.6	22.7	14.8	49.2	0	0	23.6	51.9
March/2004	0.4	6.4	19.7	0	0	10.2	15.7	3.3	9.7	8	15.2
April/2004	11.8	25.5	38.6	27	56.6	18.6	39.2	8.2	21.8	27.5	33.9
June/2004	4	1	1.5	20	20	0.9	1.3	5.5	10.1	8.5	9.9
Aug/2004	3.2	11	13	14	39	18.6	28.2	6.6	20	11.6	11.7
Oct/2004	1.8	16	37.8	9.5	11.4	8.5	27.2	5.7	23	14.5	45.5
July/2005	1.1	0	0	9.8	10.3	0	0	0.7	0.7	4	4
Oct/2005	3.4	14.9	41.3	16.4	42.9	32.6	64.3	15.4	48.7	7.6	29.2
Nov/2005	2.3	21.3	49.8	23	42.7	20.1	63.1	25.5	67	16.1	78.2
May/2006	87	8.3	26.9	20.5	29	25.6	34.3	11.5	24	9.7	22.9
March/2007	0.2	25.9	98	15	24.4	22.6	51	22.5	57.3	42.8	98.7
Nov/2007	21.9	16.2	47.9	0	0	12.8	32.4	15	31.2	22.7	55.7
Jan/2008	2.2	14.2	30.8	0	0	10.8	13.3	9.1	23.7	8	21.7
Feb/2009	3.5	17	34.3	0.2	9.7	18.6	21.6	38	64.9	7.5	27.5
May/2009	3.7	0	0	0	0	4.6	5.9	3.6	4	0.2	0.3
Oct/2011	1.3	23.3	38.3	0	7.3	22.8	49.1	15.8	37.7	16.1	26.7
Nov/2011	0.3	27.5	72.2	5.3	15	31.2	65.5	7.8	40.6	33.1	108
April/2012	0.6	10.3	41.8	17.8	49.1	18.5	72.6	17.6	37.6	19.2	41.4
Aug/2012	0.4	0	0	0	0	2	3.5	8.7	18.4	0.7	0.7

$Q_{j,max}$, daily maximum discharge ($m^3 s^{-1}$); $P_{j,max}$, daily maximum rainfall (mm); P_{Tota} , total monthly rainfall (mm)

Thornes 1994). In practice, it is particularly difficult to measure the rainfall using conventional rain-gauge network in arid and semi-arid zones (Şen 2008). Lange et al. (2000) have revealed that the intense flood events cause measurement problems which reduce the quality of the data. Andreassian et al. (2007), Collier (2007), and Moulin (2007) have noted that the modeling errors are often associated with the uncertainty on the input rainfall. Also, Bahat et al. (2009) have confirmed that the effect of uncertainties in rainfalls is dominant comparing to the other model parameters who have a limiting effect.

Furthermore, the uncertainty in discharge data is an additional obstacle to the applications of hydrological models in basins, particularly during calibration procedure (Bessière 2008). It is important to note that the lack of high-quality measurements is currently the major challenge to hydrologists working in semi-arid regions (Abushandi 2011).

According to the above results, one can judge that the MERCEDES model performance is generally encouraging and can be considered as satisfactory.

However, the sensitivity analysis revealed that the MERCEDES performance for modeling runoff mostly depends on the S parameter comparing to the other parameters. The sensitivity analysis of S parameter, for the best correlated events (14 events), is presented in Fig. 12 which shows that the parameter S varies from 0 to 18.28 mm in forests, 0 to 9.6 mm in rangelands, 0 to 7.01 mm in cultivated areas, and 0 to 5.73 mm in urban areas. It reveals that the S parameter varies widely from event to event on the same land use type with a variation coefficient that ranges from 0.82 to 1.32.

In general, the water retention capacity of each land use type in Wadi Mekerra basin varies significantly between seasons. The high values of S depend greatly on the vegetation cover (forests, rangelands, and agricultural areas) while in areas devoid of vegetation, the water retention capacity decreases significantly. That is observed at urban areas where the water retention capacity has decreased from one year to another due to the asphalt expansion and concrete cover.

As well, it can be confirmed that the water retention capacity in the cultivated areas increases during the

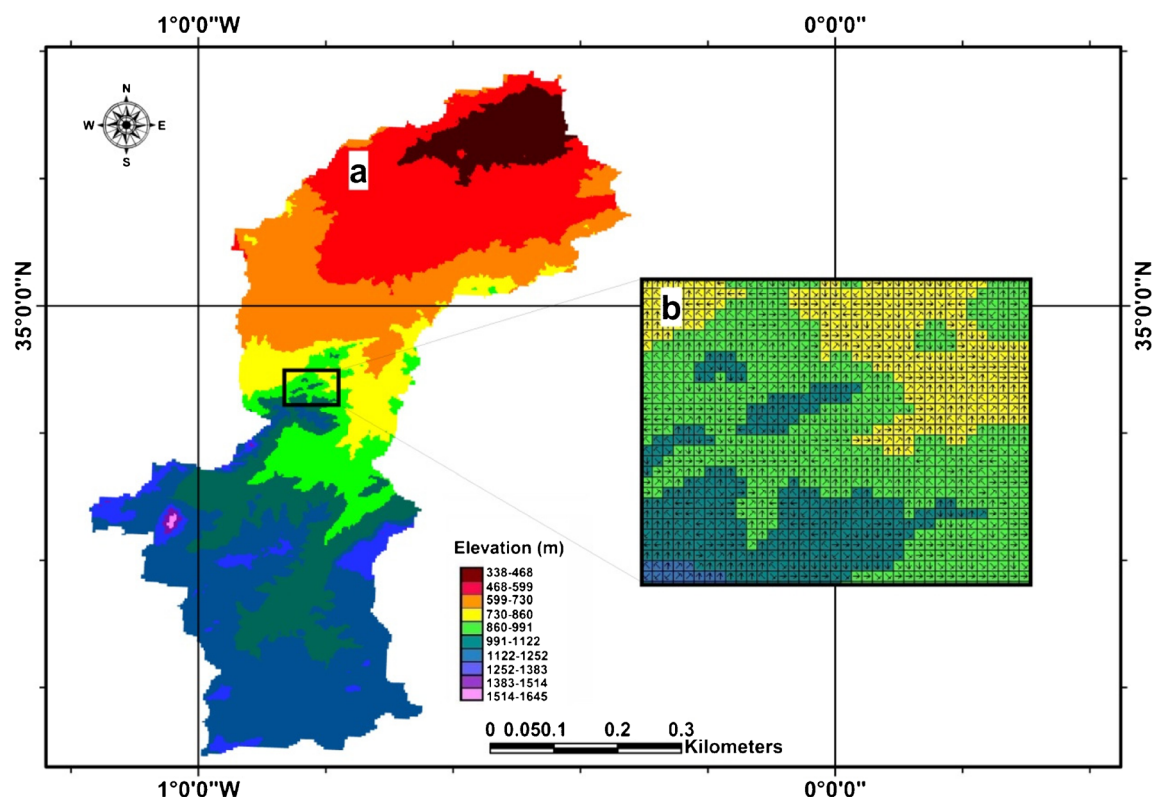


Fig. 7 DEM of Wadi Mekerra catchment discretized on grid cells and extraction of flow direction, (a) DEM; (b) grid cells and flow directions

seasonal cultivation such as wheat cultivation from November to May while it is reduced after harvest season (June, July, and August), where the cultivated soil mainly consists of silt which is less permeable. In fact, seasonal cultivation plays an important role in terms of decreasing runoff and consequently the floods. This is because a greater fraction of precipitation does not reach the soil but remains as interception storage on the leaves (Halwatura and Najim 2013).

In arid and semi-arid areas, the lack of vegetation cover is one of the main causes of soil degradation due to absence of soil protection from raindrop impact which leads to the soil crusting and consequently to a large reduction in infiltration capacity for bare soil conditions (Morin and Benyamini 1977).

It is worth noting that the deforestation contributes significantly to an increase in the probability of flood events, which leads to an increase in peak flows (Beschta et al. 2000; Jones 2000; Göttle 2012).

Nevertheless, the retention capacity decreases significantly during intense rainstorm such as the event in May 2006 where in a single day, 52.2 mm of rainfall occurred and the peak flow was $396.5 \text{ m}^3 \text{ s}^{-1}$.

The intensity and duration of rainfall have a large influence on the infiltration capacity of the soil. The

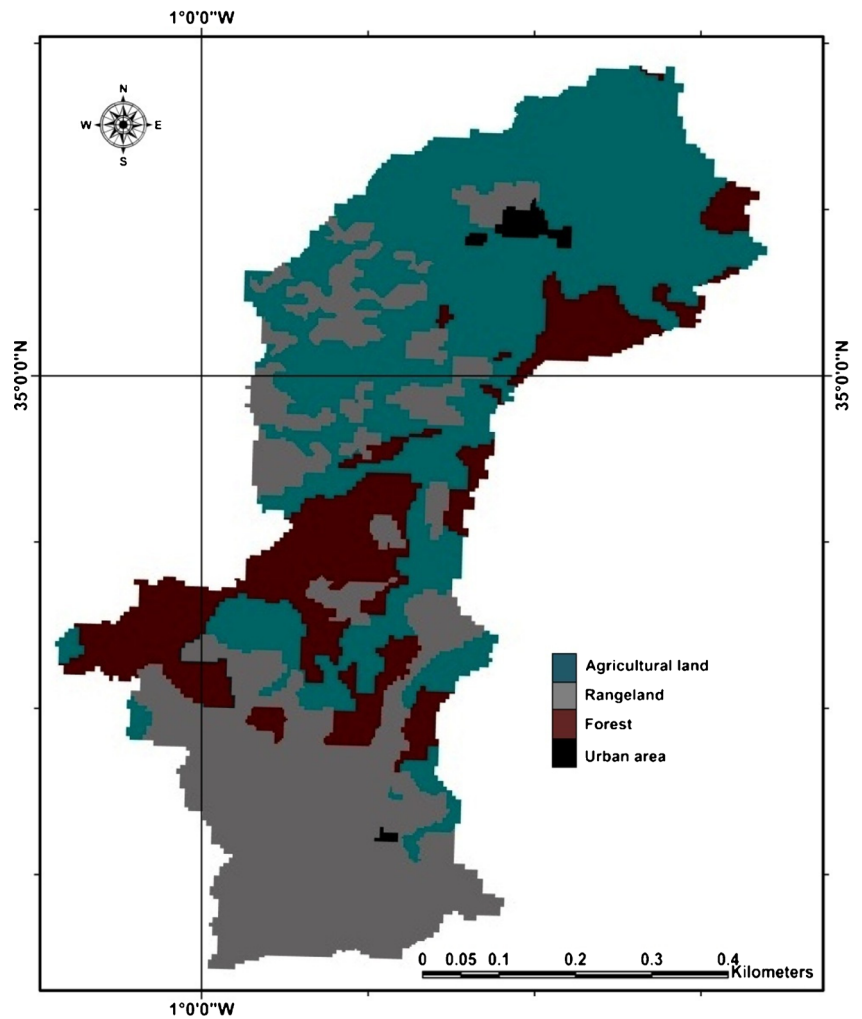
infiltration capacity of the soil is reduced namely in case of the high intensity with short duration rainfall which results in overland flow (Tarboton 2003).

It can also be noted that the high temperature during the summer seasons (June, July, and August) decreases the retention capacity in the forests and rangelands. This can be explained by the prolonged drought which compacts the soil crust.

However, at the spatial scale, the water retention capacity in rangelands can exceed that of the forests such as that observed in October (cf. Fig. 12). This is explained by the thunderstorms which generally occur in the large rangeland areas situated in the south part of Wadi Mekerra catchment, whereas from November the thunderstorms occur in the center of the basin which is mostly covered by forests and cultivated areas.

It is evident that the runoff potential within the watershed depends strongly on the hydrological characteristics of the soil (Feldman 2000; U.S. Army Corps of Engineers 2008; Cunderlik and Simonovic 2007; Duan 2011; Fleming and Scharffenberg 2012). The variations in the hydrological parameters of a watershed are primarily associated with land use change (Ayenew 2008). The flow generation depends highly on several factors such

Fig. 8 Land use map of Wadi Mekerra catchment



as rainfall quantity, intensity and duration, permeability of the soil, and even the catchment relief, geometry,

vegetation, and soil cover (Dubrueil 1985, 1986). Thus, the urbanization and agricultural activity have a great

Fig. 9 Comparison between observed and computed flood hydrographs in SABY gauging station of Wadi Mekerra catchment (using SCS loss function model)

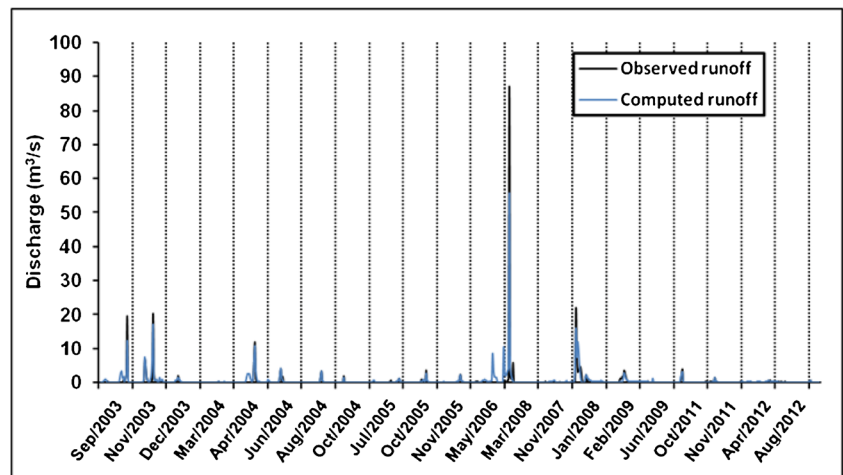
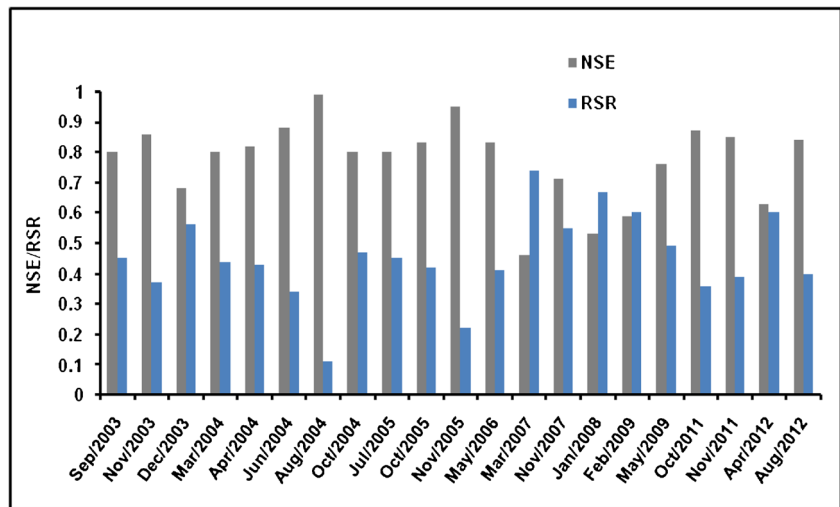


Fig. 10 NSE and RSR values for each studied events



affect on the quality and quantity of streamflow (Abushandi 2011).

Conclusions

The present paper investigates flood generation in an ephemeral wadi using the spatially distributed approach based on DEM, land use mapping, and MERCEDES model. This study shows that the MERCEDES model can adequately simulate runoff in Wadi Mekerra catchment and indicates that both methods (SCS and lag and route) are successfully applied to simulate the runoff generation mechanisms.

The comparison of the observed and simulated results indicates that more than 66% of the events are well reproduced by the model, where both efficiency criteria Nash-Sutcliffe (NSE) and observations standard deviation ratio (RSR) are optimal ($NSE \geq 0.8$ and $RSR \leq 0.5$).

However, the model underestimates peak flows by – 60 to 0%. Indeed, in most rainfall-runoff models, the maximum discharges are underestimated. The majority of hydrologists agreed that the underestimation of rainfall measurements is the main factor inducing uncertainty on the model results.

The analysis of these results indicates that the flood generation mechanisms in Wadi Mekerra basin depend mainly on the water retention capacity (maximum potential retention) of each land use type. Generally, in the

Fig. 11 Relative error (RE) values and discharges observed for studied events

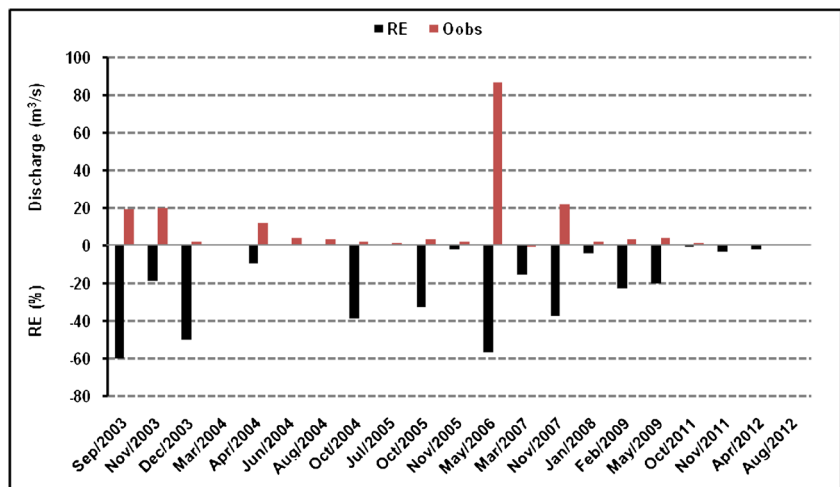
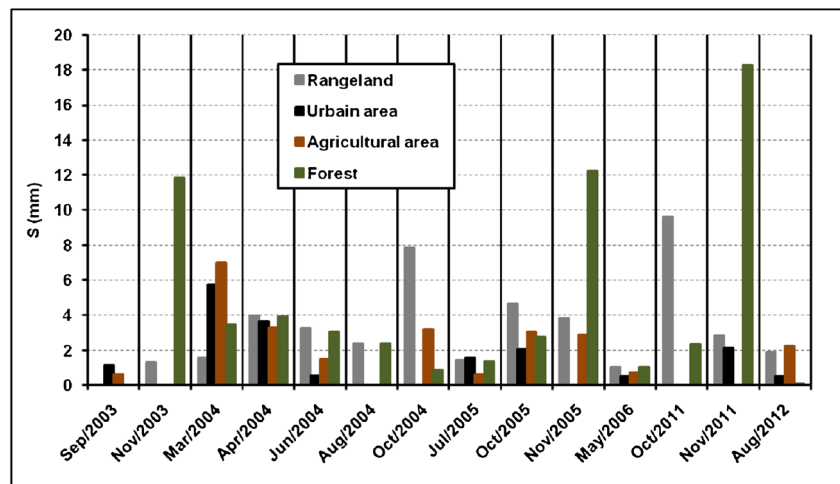


Fig. 12 Values of maximum potential retention (S) parameter for each land use type (only events with its NSE criterion values greater than or equal to 0.80)



semi-arid catchment, the water retention capacity is mostly associated with the vegetation cover dynamics (e.g., seasonal changes in agriculture), rainfall intensity, and drought.

Contrary to the intense rains and the drought, the vegetation cover contributes to the reduction in the runoff production by increasing the water retention capacity. Therefore, the flood generation will be limited. The high-intensity rainfall can exceed the infiltrability of the soil, which generates significant amounts of runoff resulting in severe flood. Also, the drought contributes to the soil compacting which reduces the infiltration capacity of the land surface.

Therefore, it is necessary to reforest a large area of land in Wadi Mekerra catchment to increase the water retention capacity and therefore decrease the flood probability.

This solution type has become one of the sustainable approaches to managing floods. It is also proposed for use (rainfall radar) as an alternative solution to capture localized rainstorms, especially in the semi-arid region.

Finally, the paper concludes that the MERCEDES model can be considered as an important tool to study the rainfall-runoff relationship especially in semi-arid catchment. Moreover, the spatially distributed approach plays an extremely important role in modeling the effects of land use changes on catchment response. However, it is interesting to note that the efficiency of this kind of modeling requires, on the one hand, the use of both high-quality and high-quantity input data and, on the other hand, it should be taken into account the different factors contributing to the runoff generation such as vegetation cover, rainfall intensity, and drought.

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