

Modeling the Rainfall–Runoff Relationship with TOPMODEL in the Wadi El Kebir Watershed

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Abstract

The rainfall–runoff relationship was studied in the Wadi El Kebir watershed, located in Northeastern Algeria, using TOPMODEL (topography based hydrological model). This is a geomorphological and semi-distributed model which is used to predict the hydrological behaviour of watersheds, and to calculate the water storage deficit of an aquifer in any location. It uses topographic information of the watershed to predict the extent of contributing areas in the production of runoff.

TOPMODEL was applied with event-based rainfall–runoff modeling where 13 hourly rainfall series were used to predict the discharge at the basin outlet. A digital elevation model (DEM) was also used to define the contours of the basin and to map out the drainage directions and the topographic index.

TOPMODEL was calibrated and validated using the measured discharges and various objective functions such as Nash (Nash-Sutcliffe) and coefficient of determination (R^2).

The TOPMODEL results showed a high-performance level. Indeed, after the calibration and validation procedure, the performance of the model oscillates between satisfactory and very good. For the calibration, Nash varied between 0.59 and 0.91, and R^2 between 0.66 and 0.91. However, the values of these criteria coefficients were slightly reduced during the validation phase, Nash (0.53 to 0.84) and R^2 (0.59 to 0.87). Also, the proposed model shows the weak contribution of groundwater flows in the hydrological response of the study area.

1 Introduction

The increased demand for water resources in the world and the improvement in decision-making in terms of flood protection have recently led to the development of hydrological models, in particular those based on rain and flow processes (Perrin 2002; Buytaert et al. 2011). This modeling type has become especially important in developing countries such as Algeria, which lacks sufficient hydrometric stations to control stream flows (Belloum 1993; Touazi and Laborde 2004; Chabour 2012). To develop this modeling type, it is necessary to master the factors affecting hydrological processes (Nourani et al. 2011). Among the factors that govern the generation of streamflow is the watershed topography (Beven and Kirkby 1979; Garambois 2012).

The topography is the main element that controls the hydrological response of the watershed (Lane et al. 2009; Gil and Tobón 2016). It determines the gross drainage area (Wagener and Kollat 2007), the hydraulic characteristics of the soil, (Raghavendra and Mohanty 2012), and many other parameters. The

influence of topography on flows has many utilities in hydrological modeling (Beven 2012). In fact, in a hydrological system, soil saturation is reached more easily in zones with low slopes. This allows runoff to be generated more quickly (Kessasra 2017).

Distributed models such as TOPMODEL can directly use the topography to simulate the flow in the catchment (Maréchal 2004). This model aims to reproduce the hydrological behaviour of watersheds in a semi-distributed manner; in particular, the dynamics of areas contributing to surface and subsoil flows (Beven and Kirkby 1979). Therefore, TOPMODEL is able to simulate soil moisture and flow rates which are not only governed by precipitation, but also by the watershed topography (Vincendon et al. 2010). TOPMODEL is the most widely semi-distributed and conceptual model used to simulate runoff in the hydrological system (Beven 1997; Mendicino and Sole 1997). It is one of the first models to use the topographic data explicitly in the model formulation (Beven and Kirkby 1979). It allows extracting topographic information related to the runoff generation (Devi et al. 2015).



Compared with other conceptual hydrological models, the popularity of TOPMODEL comes from its simplified, modifiable, and flexible structure (Beven et al. 2021). It reduces both the data requirements and the number of input parameters (Jeziorska and Niedzielski 2018). These advantages have favoured the application of TOPMODEL to a wide range of watersheds (Nourani et al. 2011). For example, TOPMODEL has been successfully tested in:

- Mediterranean basins: such as Gardond’Anduze (Sempere-Torres 1990), Mont-Lozère (Durand et al. 1992), Avic and Teula (Pinol et al. 1997);
- Temperate wetlands and sub-humid climate: we cite the Buro-borotu watershed in Ivory Coast (Quinn et al. 1991) and Heihejinpen reservoir (China) (Hao et al. 2018); and
- In semi-arid zones, TOPMODEL has been applied to the Karoon Basin in western Iran (Nourani and Mano 2007).

In addition, there are some comparative studies of hydrological models against TOPMODEL which have shown that TOPMODEL is suitable for rainfall–runoff modeling at event or even daily scale (Nourani et al. 2011). These studies have confirmed that despite the few input parameters, TOPMODEL is able to reproduce time series of flows with good accuracy (Saulnier and Datin 2004).

TOPMODEL is based on the concept of variable contributing zones (Ambroise 1999), where the flow occurs from surface flows generated mainly by precipitation (variable contributing area) and also from hypodermic flow from shallow saturated zones according to Darcy’s law (Bireche 2017). The contributing areas are temporarily saturated where precipitation can no longer infiltrate due to subsoil saturation (Lardet and Obled 1994; Taha et al. 1997). In TOPMODEL, the flow modeling at the catchment downstream is based on the theory of hydrological similarity (Xiong and Guo 2004). Topography is expressed quantitatively by the topographic index (or topographic humidity index) (Jeziorska and Niedzielski 2018). This index determines the geographic areas that have similar hydrological behaviour; it mainly depends on the topography (Beven and Kirkby 1979; Obled and Zin 2004; Kessasra 2017). TOPMODEL uses as inputs rainfall data, the DEM of the basin, and a few sets of parameters representing the hydraulic properties of the soil such as the hydraulic conductivity and water reserve in the soil. The advantage of TOPMODEL is that it requires few elements (Beven et al. 1984; Ambroise et al. 1996). Therefore, the model outputs are the discharges at the basin outlet as well as the topographic index map which present the hydrologic similarity classes (Beven 1997).

TOPMODEL software was chosen for this work for several reasons. This work represents the first application of TOPMODEL on an Algerian watershed. Thus, the assessment of water resources in our country suffers from the lack of data regardless of the climatic, hydrological, and hydrogeological data (Belloum 1993; Bouaïchi et al. 2006). This challenge makes it very difficult to apply overly parametric hydrological models such as SWAT (Soil Water Assessment Tool) or moderately parametric models like HEC-HMS (Hydrologic Modeling System). For this, we adopted TOPMODEL as

a model that does not require many parameters to study the process of streamflow generation and water storage at groundwater level.

In this study, TOPMODEL was used to simulate the rainfall–runoff relationship and to examine its performance on the Wadi El Kebir basin (Northeastern Algeria), subject to a Mediterranean climate and temporary flow. The simulation was performed with event hydrologic modeling which allows simulating the response of the basin to occasional torrential rains without considering pre-vios conditions, such as antecedent soil moisture and reservoir levels. (Le 2008). Event-based rainfall–runoff modeling is effective in operational flood forecasting (Muhammad et al. 2015). This study also aims to explore the topographic index map to show the spatial distribution of the hydrological response in the study area. The model parameters are calibrated using 7 observed time series of hourly discharges as well as evaluation criteria (Nash and R^2). The performance of TOPMODEL on the Wadi El Kebir basin is determined in the validation phase using 6 other observed events.

2 Data and methods

2.1 Study area

The study area was the Wadi El Kebir basin, which is part of the Kebir Rhumel basin (Northeast of Algeria) (Figure 1 (a)). It is located between latitudes 36°11’10.03” and 36°32’52.62” North and longitudes 5°25’10.78” and 5°54’50.66” East. Wadi El Kebir is over 53 km in length and drains into an area of about 932 km².

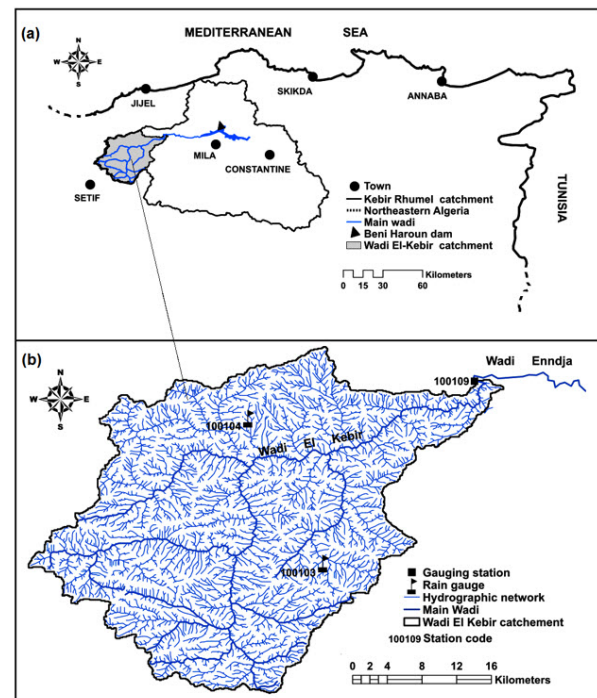


Figure 1 Location map of the Wadi El-Kebir watershed: (a) General location; (b) Rainfall and gauging stations.

Wadi El Kebir ends at the Beni Haroun dam (Figure 1(a)) which is a very important hydraulic structure in Africa. This dam can store 1 km³ water and ensures the supply of potable water and irrigation for six counties (Chebbah and Kabour 2018). Vegetation in the watershed consists mainly of market gardening and cereal crops with fallow (Figure 2). However, forests represent only 19% of the basin's surface, the majority of which is cedar and oak. The relief is of the order of 765 m at its highest point and 400 m at the outlet. The average slope of Wadi El Kebir is about 0.6%.

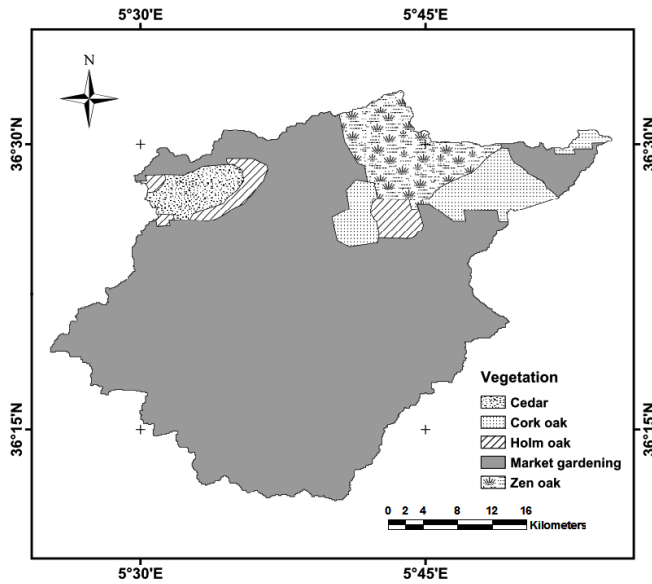


Figure 2 Vegetation map of Wadi El-Kebir catchment.

The Wadi El Kebir basin is subject to a Mediterranean climate, characterized by a hot and dry summer and a mild and humid winter. However, analysis of the annual rainfall and discharge measurements between 1995 and 2013 (Figure 3) shows an irregularity in these two parameters from year to year. The annual average rainfall is around 379 mm, producing about 110 mm of runoff which corresponds to an annual volume about of 102.67 hm³.

The flow in Wadi El Kebir is temporary; it is often dry but can flow from a few days to a few months. The runoff in this wadi is very irregular (Figure 3) and occurs during intense rainfall events. This flow regime characterizes the majority of wadis in Algeria and North Africa (Achite and Ouillon 2007; Maref and Seddini 2018). The interannual variation in discharge (Figure 3) shows that the flow of Wadi El Kebir is not always associated with precipitation. We observe many years of heavy rain (e.g. 1979, 2003, 2004) which generate less flow and vice versa (e.g. 2006 and 2007). The small runoff can be explained by overexploitation of water from the wadi for crop irrigation. However, the high flows

come from exceptional floods which are rapid and are characterized by heavy rains (Kerdoud 2006).

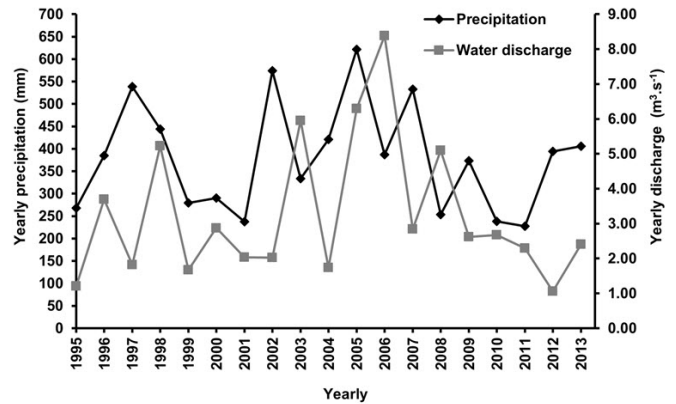


Figure 3 Annual variability of total rainfall and runoff in Wadi El-Kebir catchment.

2.2 Model structure

TOPMODEL is a semi-distributed hydrological model used to simulate the rainfall–runoff relationship. This model was presented the first time by Beven and Kirkby (1979). The version used in this work is associated with the ATHYS platform (<http://www.athys-soft.org>) (HydroSciences Montpellier 2022). It is based on the hydrological similarity principle. It is used to predict the spatial distribution of the water content within the different points of the considered watershed. Hydro-logical similarity is determined by the topographic index, which is derived from the topography of the basin (Xiong and Guo 2004). It stipulates that all the points on the watershed having the same value of the topographic index present an identical hydrological behaviour in terms of soil moisture and surface saturation (Nourani et al. 2011; Beven 2012). Therefore, TOPMODEL presents the topographic effects on the hydrology of the watershed through a topographic index

(Seibert 1999). TOPMODEL is based on three main assumptions:

1. The topography contributes to runoff production;
2. Rainwater is intercepted at the start of the event in the root zone; and
3. The transfer of infiltrated water is done from the unsaturated zone to the saturated zone according to Darcy's law.

As presented in Figure 4, TOPMODEL conceptualizes the soil column as a set of three reservoirs: root zone, unsaturated zone, and saturated zone (Nourani et al. 2011; Beven 2012; Jezior-ska and Niedzielski 2018).

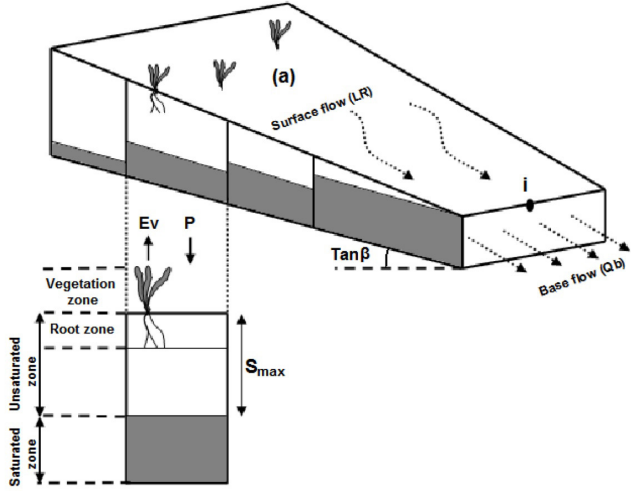


Figure 4 Conceptual diagram of TOPMODEL.

In TOPMODEL we consider that the outlet flow is equal to the sum of the basic flow, which depends on the state of the groundwater and the rapid flow, which depends on the extension of saturated surfaces (Saulnier 1996). The principle is to discretize the basin into elementary surfaces (meshes) using DEM. Each cell is characterized by the drained surface (a_i) and the slope ($\tan \beta_i$).

The inflow (m^2/s) for mesh i at time t is given by:

$$LE_i^t = a_i \cdot R_i^t \quad (1)$$

where:

LE = inflow (m^2/s),

t = time,

R_i^t = elementary recharges average received by cell i ,
and

a_i = drained area per unit of contour length.

Thus, the outflow (m^2/s) is expressed by the following formula:

$$LR_i^t = T_i^t \cdot \tan \beta_i \quad (2)$$

where:

LR = outflow (m^2/s), and

T_i^t = transmissivity of the soil column given by:

$$T_i^t = T_0 \cdot \exp(-z_i^t \cdot f) \quad (3)$$

$$T_0 = \frac{K_0}{f} \quad (4)$$

where:

T_0 = transmissivity,

z = water deficit (m),

f = parameter of exponential decrease of the hydraulic conductivity (m^{-1}), and

K_0 = hydraulic conductivity of the soil at surface saturation.

K_0 controls both the rate of water infiltration into the soil and the percolation of the unsaturated zone towards the water table (Obled and Zin 2004). The water deficit of cell i at time t

is z_i^t , and f is the exponential decrease of hydraulic conductivity. We can consider $1/f$ as a hydrodynamic efficient soil thickness through which the rapid water transfer takes place (Saulnier 1996). In terms of the topographic index τ_i , the water deficit on cell i at time t is given by:

$$z_i^t = \bar{z}^t - \frac{\tau_i - \bar{\tau}}{f} \quad (5)$$

where:

\bar{z}^t = average of water deficits (m), and

$\bar{\tau}$ = topographic index over the entire watershed.

The topographic index τ_i is given by:

$$\tau_i = \ln \left(\frac{a_i}{\tan \beta_i} \right) \quad (6)$$

During a timestep Δt , the evolution of the average water deficit is subjected to the fluctuation of the quantity of rainfalls on the unsaturated meshes (R^t), evapotranspiration (Ev^t), base flow at the outlet (Q_b), and the basin area A (km^2) as follows:

$$z^{t+\Delta t} = \bar{z}^t + \frac{Q_b^t - (R^t - Ev^t)}{A} \cdot \Delta t \quad (7)$$

where:

$$Ev^t = S \cdot (1 - \exp(-ds \cdot \Delta t)) \quad (8)$$

$$S = S^t + \min(P^t, S_{max} - S^t) \quad (9)$$

$$S^{t+\Delta t} = S - Ev^t \quad (10)$$

where:

Q_b = base flow at the outlet (m^3/s),

S = retention capacity of the soil tank (mm),

S_{max} = maximum water retention capacity of the soil tank; this parameter is in a way the volume of water needed to wet the soil before the event begins (Obled and Zin 2004),

ds = tank emptying coefficient ($days^{-1}$), and

P^t = rainfall intensity.

The base flow at the basin outlet is given by the following equation:

$$Q_b^t = A \cdot T_0 \cdot \exp(-\bar{\tau}) \cdot \exp(-f \bar{z}^t) \quad (11)$$

All these equations are used to calculate the flow rate at the basin outlet and the state of the soil saturation as a function of four parameters: S_{max} (mm), K_0 (m/h), f (/m) and ds (/d). TOPMODEL has the ability to make distributed predictions without using a large number of parameters (Abhishek 2008).

2.3 Topographic index

The topographic index represents a parameter of the spatial distribution of the excessive runoff generation in the watershed (Nourani et al. 2011). The topographic index helps to determine the effect of topography on the rainfall-runoff process and indicates the spatial distribution of soil moisture and surface saturation (Nourani et al. 2011). To calculate the topographic

index, TOPMODEL applies the multiple flow direction algorithm (MD8) developed by Quinn et al. (1991) using DEM. This algorithm can represent the convergence or divergence of the flow path according to geomorphological variation in the basin. Calculation of the topographic index using the MD8 algorithm is therefore very associated with the DEM resolution (Franchini et al. 1996) and it can reproduce more realistic spatial flow models than the D8 algorithm developed by Jensen and Dominique (1988).

The MD8 algorithm is characterized by the distribution of the contributing area to all adjacent cell downslopes (Peng et al. 2008). Figure 5 shows the multiple flow direction algorithm. It suggests that the contour length (L1, L2, and L3) is perpendicular to the flow directions and the flow is shared to adjacent cells by weighting (0.5 weighting for cardinal directions and 0.35 for a diagonal weighting).

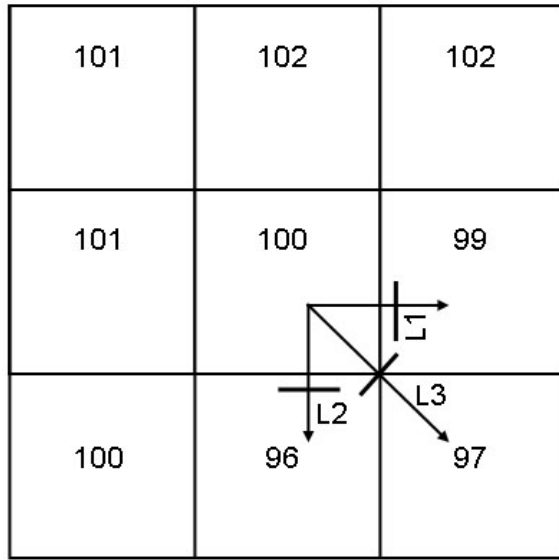


Figure 5 Illustration of the multiple flow direction algorithm MD8.

2.4 Model calibration and validation

The purpose of the calibration is to adjust the values of certain parameters to better simulate the hydrological behaviour of the watershed (Madsen 2000). Validation also makes it possible to assess the robustness of the model in the operational domain (Marchandise 2007). Observed data is used in calibration; new observed data, which were not used for calibration, are used in validation of the model (Coustau 2011).

In this work, four parameters are subject to calibration, namely: K_o , f , S_{max} and ds , by applying both an automatic optimization technique based on the simplex iterative method (Rao 1978) and the objective functions such as Nash and coefficient of determination (R^2):

1. Nash parameter

$$Nash = 1 - \frac{\sum (X_i - Y_i)^2}{\sum (Y_i - \bar{Y}_i)^2} \quad (12)$$

2. Coefficient of determination (R^2)

$$R^2 = \left[\frac{\sum (X_i - \bar{X}_i) \times (Y_i - \bar{Y}_i)}{\sqrt{\sum (X_i - \bar{X}_i)^2} \times \sqrt{\sum (Y_i - \bar{Y}_i)^2}} \right]^2 \quad (13)$$

where:

X_i = calculated N discharge values,

Y_i = observed N discharge values, and

\bar{X}_i, \bar{Y}_i = averages of N calculated and observed discharge values, respectively.

The Nash and R^2 coefficient are the most widely used objective functions to determine the performance of the hydrological forecasting model (Marchandise 2007; Buytaert and Beven 2011; Ferraz et al. 2021). The optimal values of Nash and R^2 are both 1. Moriasi et al. (2007) and Thiemig et al. (2013) qualified the criteria of performance level of the hydrological model according to the Nash and R^2 values (Table 1).

Table 1 Different performance levels depending on the limits of Nash and R^2 .

Coefficient	Unsatisfactory	Satisfactory	Good	Very Good
NSE	Nash ≤ 0.50	$0.50 < \text{Nash} \leq 0.65$	$0.65 < \text{Nash} \leq 0.75$	$0.75 < \text{Nash} \leq 1$
R^2	$R^2 \leq 0.5$	$0.50 < R^2 \leq 0.70$	$0.70 < R^2 \leq 0.80$	$R^2 > 0.80$

The calibration and validation procedures were carried out using the observed values of the discharges. Overall, 13 events (rainfall–runoff) were used (Table 2). Seven events were used for model calibration and 6 other events were used for model validation.

Table 2 Main characteristics of the investigated rainfall–runoff events in Wadi El Kebir basin.

Event	Max discharge (m ³ /s)	Max rainfall intensity (mm/h)	Flow duration (h)
Calibration			
1995-12-01	45.3	10.11	2.27
1996-03-09	107.2	8.68	69
1998-01-20	7.71	2.9	95
2000-12-24	17.24	1.13	31
2010-01-10	35.8	7.96	69.5
2013-12-13	14.89	2.24	22
2015-05-12	43.6	9.3	22
Validation			
1985-11-17	15	1.97	36.5
1988-04-25	10.3	7.79	43
1999-04-07	82.9	16.13	116
2015-11-28	14	3.67	35
2017-11-25	97.2	16.44	182
2018-02-24	52.86	19.13	93.5

2.5 Simulation steps

The input data necessary for the operation of TOPMODEL are the hydrological data (rainfall and runoff), topographic data (DEM), and parameters. The rains have been recorded in the two rain gauge stations (100104: Beni Aziz and 100103: Boumalek) and the discharges were observed at the outlet of the basin through a gauging station (100109: Douar Tassadane) (Figure 1 (b)). The time step of the rainfall and discharge data varies between 30 min and 1 h (Bouilloud et al. 2010; Nourani et al. 2011; Hao et al. 2018).

Generally, for a TOPMODEL application, the DEM used is 50 m resolution (Figure 6). This spatial resolution was used in several studies (Quinn et al. 1991; Nourani et al. 2011).

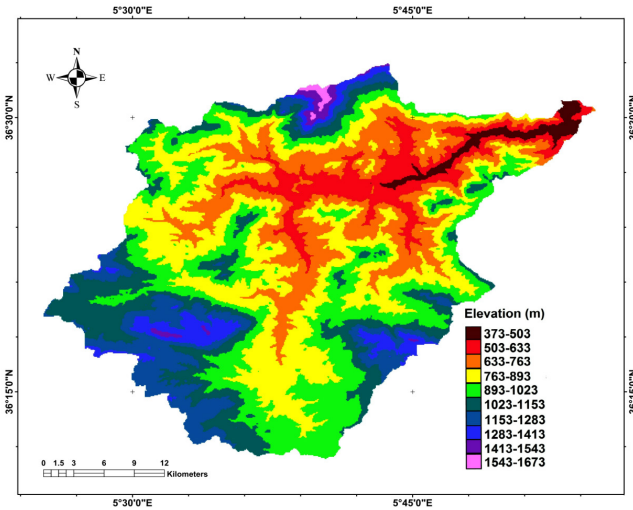


Figure 6 DEM of study catchment (using Athys v5.0).

The different stages of the TOPMODEL simulation begin by integrating the DEM of the basin. Using the ATHYS platform, we can delimit the contour of the watershed, discretize the basin into meshes, and derive the drainage directions map (Figure 7).

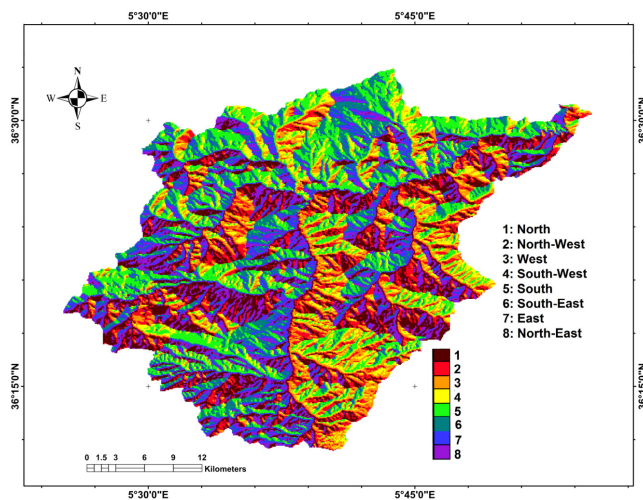


Figure 7 Drainage direction map of the study catchment (using Athys v5.0).

In the second step, we start with the calibration phase where we used the 7 sets of observed rainfall–runoff data and the initial values of the parameters to be calibrated. The simulation was carried out with event-based rainfall–runoff modeling. This type of modeling is particularly used for the study of storm events such as floods (Gerard 2010) and for understanding detailed hydrologic processes. Thus, a small temporary scale is useful when long term intensive monitoring data is not available, or data are incomplete (Chu and Steinman 2009). As such, we must fix the variation range of each parameter and the number of iterations for the calibration (maximum 500 iterations). However, in the validation phase, the parameter values were fixed, and we used 6 other observed rainfall–runoff datasets. TOPMODEL provides the hydrograph of the calculated discharges and the map of the topographic index, which is used to classify the hydrological similarities, and to deduce the extension of the contributing zones to the runoff production (Maréchal 2004).

3 Results and discussion

In terms of calibration, the performance of TOPMODEL can be evaluated using a numerical comparison (Table 3) or graphs (Figure 8). The results indicate that the model has adequately reproduced the studied events. Encouraging efficiency values were obtained during the calibration phase (Table 3), where the Nash varies between 0.59 and 0.91, and R^2 was between 0.66 and 0.91. This result indicates that the performance of the model oscillates between satisfactory and very good.

Table 3 TOPMODEL results with the calibrated parameters and efficiency criterion values.

Events	$Q_{max,obs}$ (m^3/s)	$Q_{max,cal}$ (m^3/s)	S_{max} (mm)	K_0 (m/h)	f (/m)	ds (/d)	Nash	R^2
1995-12-01	45.3	44.59	1.31	0.17	1.85	1.27	0.61	0.68
1996-03-09	107.2	74.78	1.57	0	3.74	0	0.76	0.77
1998-01-20	7.71	7.77	1.17	0	0.07	0.77	0.59	0.68
2000-12-24	17.24	14.58	0	0	1.49	2.42	0.91	0.91
2010-01-10	35.8	25.01	0.13	0.06	2.41	1.02	0.66	0.66
2013-12-13	14.89	13.7	1.37	0.01	1.01	1.26	0.88	0.89
2015-05-12	43.6	27.95	1.41	0.09	2.29	0.93	0.75	0.75

Notes:

$Q_{max,obs}$ maximum observed discharge;

$Q_{max,cal}$ maximum calculated discharge.

The graphical comparison between the observed and the calculated hydrograph illustrates only events with extreme values of Nash (min and max) (Figure 8). This comparison shows a good correlation between the two hydrographs. Abhishek (2008) demonstrated that TOPMODEL is relevant in understanding and predicting the hydrological behavior of watershed. Durand et al. (1992) showed in their study that TOPMODEL can successfully simulate discharges in drier catchments. Devi et al. (2015) revealed

the capability of TOPMODEL for hydrological modeling in a watershed characterized by shallow soil and moderate topography, as is the case in the study basin.

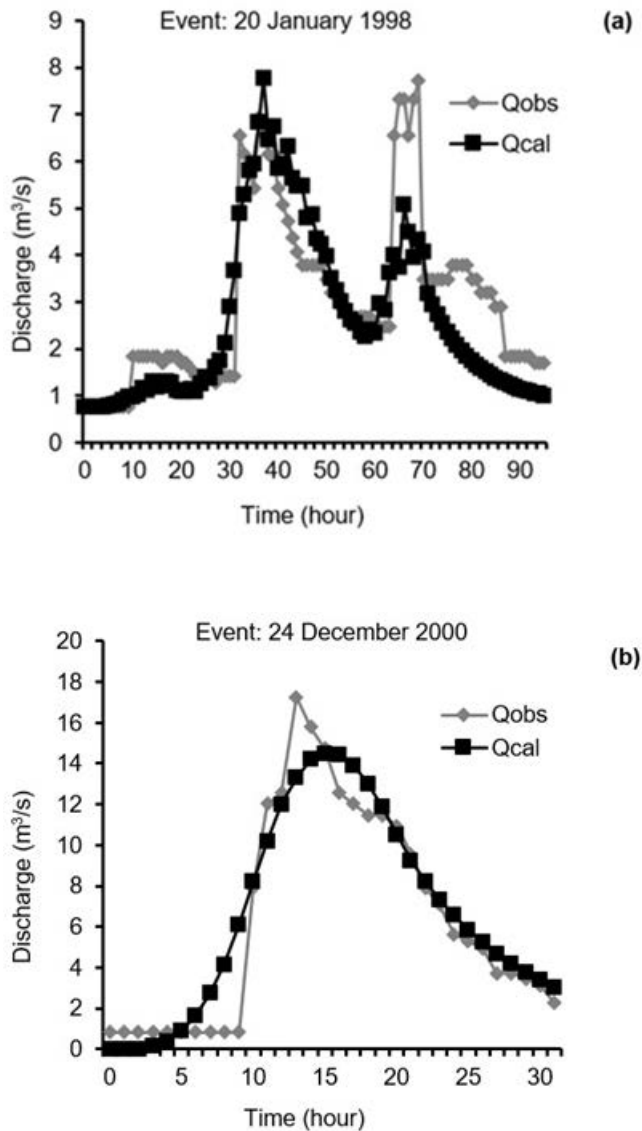


Figure 8 Comparison between observed and calculated discharge using calibration parameters: (a) Nash = 0.59, and (b) Nash = 0.91.

Table 3 and Figure 8 show that all the maximum discharges calculated by TOPMODEL remain underestimated. In fact, an accurate prediction of runoff requires an accurate recording of precipitation (Beven 2001). The underestimation of peak flows is based on the neglect of the spatial variability of rainfall (Sangati et al. 2009; Maref and Seddini 2018). This is evident in the Wadi El Kebir basin where the rainfall data used in the simulation is provided by only 2 rain gauge stations. This number of stations is

insufficient to properly represent the spatial distribution of rainfall in comparison with the area of the study basin (932 km²).

The runoff distribution in the watershed is not only based on topographic information, but also on the spatiotemporal variability of the rainfall over the watershed (Vincendon et al. 2010). The high sensitivity of TOPMODEL to the distribution of precipitation has already been demonstrated (Zehe et al. 2005; Le Lay and Saulnier 2007). The calibration of the parameters indicates that the values of S_{max} and K_0 have the same order of magnitude (Table 3) except for the S_{max} parameter in the events of 2000-12-24 and 2010-01-10. The average values of these two parameters were 0.99 and 0.05 respectively.

Also, except for the events of 1996-03-09 and 1998-01-20, we can observe small variations in the parameters f and ds where the mean values were 1.84 and 1.10 respectively. The relatively low values of hydraulic conductivity (K_0) characterize low soil permeability; the soil in the study basin consists mainly of clay or marl (Kerdoud 2006). This reveals that the runoff generation over the Wadi El Kebir watershed is a Hortonian type (Infiltration Excess Overland Flow). It occurs when the precipitation intensity exceeds the infiltration capacity of the soil (Horton 1933; Coustau 2011). Albergel et al. (2003) revealed that the Hortonian runoff process dominates in Mediterranean basins, especially in flood generation. In general, the hydrological response of the watersheds in these regions is rapid and is directly related to the rainfall intensity (Audard-Vincendon 2010).

Also, the hydraulic conductivity of the soil influences the maximum retention capacity which is determined by the parameter S_{max} . Thus, Table 3 shows quite low values of S_{max} which reflects a slow movement of the water in the soil (Buytaert et al. 2003). Low hydraulic conductivity implies rapid runoff and insignificant subsurface flow, while large conductivity values reflect high infiltration, resulting in a low water volume at the outlet (Sigdel et al. 2011). Marchandise (2007) found that retention capacity is controlled by the hydraulic conductivity of the soil. Therefore, this parameter has a decisive effect on the surface and subsurface flow and the shape of the flow hydrograph (Gil and Tobón 2016).

The topographic index map of the Wadi El Kebir basin is shown in Figure 9. It indicates that the maximum class is around 16.28 to 17.61 and the minimum class is between 4.26 and 5.59. However, the dominant class of the topographic index is between 5.59 and 6.93 (Figure 9). Equal index values of the topographic index characterize areas of similar soil moisture conditions. This indicates that their saturation degree is similar (Burt and Butcher 1985) and in this case they have the same hydrological response characteristics (Fisher and Beven 1996; Xue et al. 2018). The topographic index map (Figure 9) also shows that the high values are associated with flow paths (streams) while the low classes relate to high altitudes (slope). Obviously, the index values gradually increase as the slope decreases.

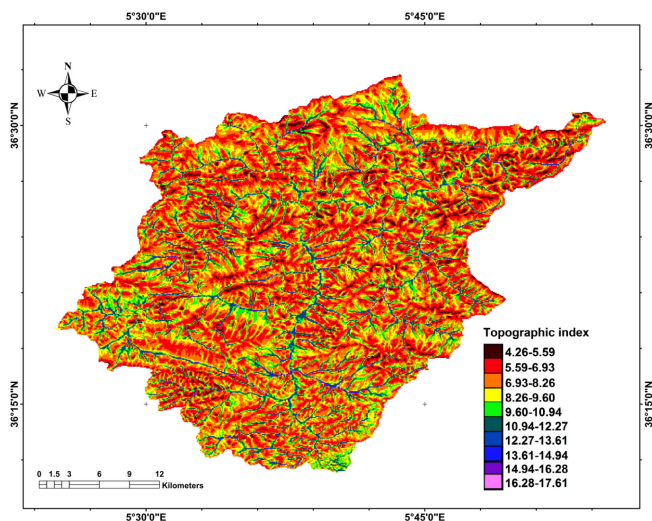


Figure 9 Topographic index map of Wadi El Kebir catchment.

The high values of the topographic index are associated with low slopes and topographically converging locations, especially downstream of the drainage network (Beven 1997, Seibert 1999, Gil and Tobón 2016). These areas are characterized by a low evacuation capacity and a high saturation capability (Bouilloud et al. 2010). Areas associated with high topographic index tend to be saturated first and then constitute zones that potentially contribute to subsurface and surface runoff (Beven 1997, Gumindoga 2010). Therefore, we can see that the trend of the topographic index of the study basin towards low values reflects a limited contribution of groundwater flow to the runoff generation in the Wadi El Kebir watershed.

The performance of the model in the validation phase is illustrated in Table 4 and Figure 10. It is acceptable, although there is a slight decrease in Nash values (0.53 to 0.84) and R^2 values (0.59 to 0.87). However, the model performance is still between satisfactory and very good. In terms of discharge, the model maintained the underestimation of peak flows during the validation.

Table 4 Results of TOPMODEL with efficiency criterion values in the validation phase.

Events	$Q_{max,obs}$	$Q_{max,cal}$	Nash	R^2
1985-11-17	15	8.81	0.76	0.76
1988-04-25	10.3	8.78	0.72	0.72
1999-04-07	82.9	88.07	0.75	0.80
2015-11-28	14	12.44	0.84	0.85
2017-11-25	97.2	42.54	0.53	0.59
2018-02-24	52.86	57.53	0.81	0.87

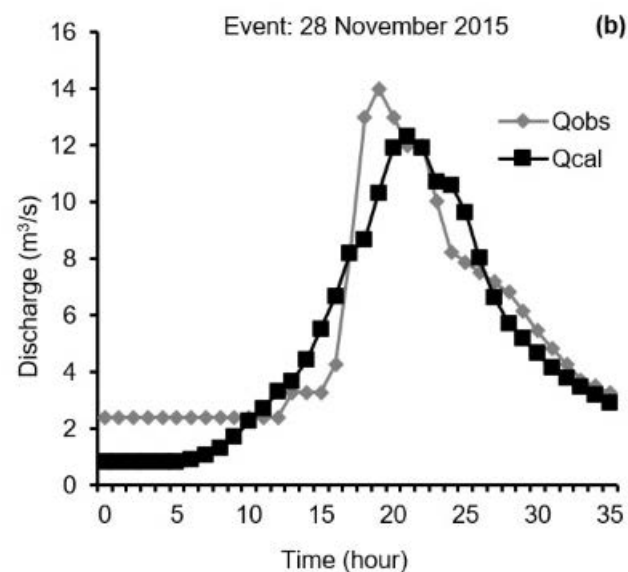
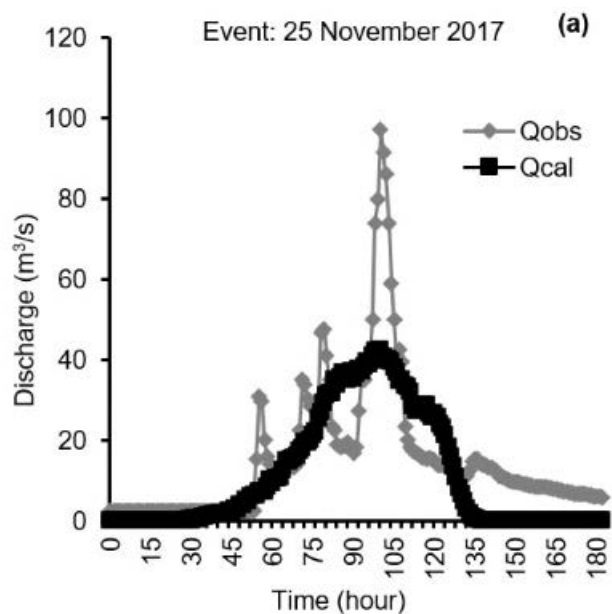


Figure 10 Comparison between observed and calculated discharge in validation phase of TOPMODEL: (a) Nash = 0.53, and (b) Nash = 0.84.

4 Conclusions

The performance of TOPMODEL to reproduce the hydrological response in a Mediterranean zone has been investigated in this work. TOPMODEL simulates the rainfall–runoff relationships using the variable contributing zones approach to derive the topographic index map with event-based rainfall–runoff modeling.

TOPMODEL has been successfully applied in Wadi El Kebir basin (Northeastern Algeria) where the values of the efficiency criteria (Nash and R^2) have indicated that the performance level of this model oscillates between satisfactory and very good in both calibration and validation phases. However, the model systematically underestimates the peak flows because of the spatial heterogeneity of rainfall.

The model parameters remain relatively stable from event to event. In addition, the low values of hydraulic conductivity indicate low soil permeability. This characteristic illustrates that the generation of the runoff over the Wadi El Kebir catchment is directly linked to rainfall intensity. This flow generation is a Hortonian type.

The spatial representation of the topographic index in the study area revealed that high values are associated with stream channels, while low values characterize slopes. Most areas in the Wadi El Kebir basin have a topographic index between 5.59 and 6.93. In addition, areas with the same topographic index are characterized by a similar hydrological response and the degree of soil saturation. Furthermore, the predominance of lower classes in the topographic index indicates a low contribution from groundwater flow.

TOPMODEL can also be applied to identify the mechanism of groundwater flow processes and groundwater level fluctuations. This helps us to properly exploit and mobilize groundwater resources.

Finally, it is recommended to use TOPMODEL in future research and confirm its reliability and relevance for hydrological studies in other Algerian watersheds, as well as in North Africa.

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References

- Abhishek, K. 2008. *Hydrological Modelling Using TOPMODEL in Karso Watershed*. Dissertation, Indian Institute of Remote Sensing (NRSA), Andhra University, India.
- Achite, M., and S. Ouillon. 2007. "Suspended sediment transport in a semi-arid watershed, Wadi Abd, Algeria." *Journal of Hydrology* 343: 187–202.
- Albergel, J., R. Moussa, and N. Chahinian. 2003. "Les processus hortonien et leur importance dans la genèse et le développement des crues en zone semi-arides: genèse des crues et des inondations: compréhension actuelle des phénomènes physiques (1^{re} partie)." *La Houille Blanche* 6: 65–73.
- Audard-Vincendon, B. 2010. *Apport des modèles météorologiques de résolution kilométrique pour la prévision des crues rapides méditerranéennes: vers une prévision d'ensemble des débits en région Cévennes–Vivarais*. Dissertation, University of Toulouse III, France.
- Ambrose, B. 1999. "La dynamique des cycles de l'eau dans un bassin versant Processus, Facteurs, Modèles." Bucarest: HGA.
- Ambrose, B., K. Beven, and J. Freer. 1996. "Toward a generalization of the TOPMODEL concepts: topographic indices of hydrological similarity." *Water Resources Research* 32: 2135–45.
- Belloum, A. 1993. "Hydrologie agricole en Algérie—une double problématique." *Hydrological Sciences Journal* 38: 479–95.
- Beven, K.J. 1997. "TOPMODEL: A critique." *Hydrological Processes* 11: 1069–85.
- Beven, K.J. 2001. "How far can we go in distributed hydrological modelling?" *Hydrology and Earth System Sciences* 5: 1–12.
- Beven, K.J. 2012. *Rainfall–runoff Modeling*. Chichester: Wiley-Blackwell.
- Beven, K.J., and M.J. Kirkby. 1979. "A physically based, variable contributing area model of basin hydrology." *Hydrological Sciences Journal* 24: 46–69.
- Beven, K.J., M.J. Kirkby, J.E. Freer, and R. Lamb. 2021. "A history of TOPMODEL." *Hydrology and Earth System Sciences* 25: 527–49.
- Beven, K., M.J. Kirkby, N. Schoffield, and A. Tagg. 1984. "Testing a Physically Based Flood Forecasting Model TOPMODEL for Three U.K. Catchments." *Journal of Hydrology* 69: 119–43.
- Bireche, M. 2017. *Comparaison de modèles hydrologiques sur le bassin du Rhône*. Dissertation, University of Pierre et Marie Curie, Paris, France.
- Bouilloud, L., K. Chancibault, B. Vincendon, V. Ducrocq, F. Habets, G-M. Saulnier, S. Anquetin, E. Martin, and J. Noilhan. 2010. "Coupling the ISBA Land Surface Model and the TOP-MODEL Hydrological Model for Mediterranean Flash-Flood Forecasting: Description, Calibration, and Validation." *Journal of Hydrometeorology* 11: 315–33.
- Bouaïchi, I., B. Touaïbia, and F. Dernouni. 2006. "Approche méthodologique de calcul du débit pluvial en cas d'insuffisance de données: Cas de la région de Tipaza, Algérie." *Le Journal de l'Eau et de l'Environnement* 5: 7–18.

- Burt, T.P., and D.P. Butcher. 1985. "Topographic controls of soil moisture distributions." *Journal of Soil Science* 36: 469–86.
- Buytaert, W., and K. Beven. 2011. "Models as multiple working hypotheses: Hydrological simulation of tropical alpine wetlands." *Hydrological Processes* 25: 1784–99.
- Buytaert, W., R. Celléri, B. Bièvre De, J. Deckers, and G. Wyseure. 2003. "Modelando el comportamiento hidrológico de micro-cuencas de paramo en el sur del Ecuador con TOPMODEL." In *Biblioteca Hernán Malo González*, 249–64.
- Buytaert, W., F. Cuesta, and C. Tobón. 2011. "Potential impacts of climate change on the environmental services of humid tropical alpine regions." *Global Ecology Biogeography* 20: 19–33.
- Chabour, N. 2012. "Caractérisation des aquifères karstiques en zone aride et semi-aride, sous contexte de forte hétérogénéité structurale dans la région des Ziban." 1st International Colloquium on "Water resources in the arid and semi-arid regions: Challenges and prospects. Case of the African continent. Morocco."
- Chebbah, L., and A. Kabour. 2018. "Impact de la retenue d'un barrage sur le régime climatique local cas de Beni Haroun (Est Algérien)." *Larhyss Journal* 33: 51–69.
- Chu, X., and A.M. Steinman. 2009. "Event and Continuous Hydrologic Modeling with HEC-HMS." *Journal of Irrigation and Drainage Engineering* 135: 119–24.
- Coustau, M. 2011. *Contribution à la prévision des crues sur le bassin du Lez: modélisation de la relation pluie-débit en zone karstique et impact de l'assimilation de débits*. Dissertation, University of Montpellier II, France.
- Devi, G.K., B.P. Ganasri, and G.S. Dwarakish. 2015. "International conference on water resources, coastal and ocean engineering (icwrc 2015)." *Aquatic Procedia* 4: 1001–7.
- Durand, P., A. Robson, and C. Neal. 1992. "Modeling the hydrology of submediterranean montane catchments (Mont Lozère, France) using TOPMODEL: initial results." *Journal of Hydrology* 139: 1–14.
- Ferraz, F.T., S.S. Zanetti, R.A. Cecílio, D. De Carvalho, and F.R. De Oliveira. 2021. "Method for the analysis of the relationship between forest cover and streamflow in watersheds." *iForest – Biogeosciences and Forestry* 4: 344–52.
- Fisher, J.I., and K.J. Beven. 1996. "Modeling of streamflow at Slapton Wood using TOPMODEL within an uncertainty estimation framework." *Field Study* 8: 577–84.
- Franchini, M., J. Wendling, C.H. Obléd, and E. Todini. 1996. "Physical interpretation and sensitivity analysis of the TOPMODEL." *Journal of Hydrology* 175: 293–338.
- Garambois, P.A. 2012. *Étude régionale des crues éclairées de l'arc méditerranéen français; élaboration de méthodologies de transfert à des bassins versants non jaugés*. Dissertation, University of Toulouse, France.
- Gerard, L. 2010. *Sensibilité des performances d'un modèle de prévision des crues au critère de calage*. Dissertation, National Polytechnic Institute of Toulouse, France.
- Gil, E.G., and C. Tobón. 2016. "Hydrological modelling with TOPMODEL of Chingaza páramo, Colombia." *Revista Facultad Nacional Agronomía*. 69: 7919–33.
- Gumindoga, W. 2010. *Hydrologic impacts of land use change in the Upper Gilgel Abay River Basin, Ethiopia: TOPMODEL Application*. Dissertation, University of Twente, Netherlands.
- Hao, G., J. Li, L. Song, H. Li, and Z. Li. 2018. "Comparison between the TOPMODEL and the Xin'anjiang model and their application to rainfall runoff simulation in semi-humid regions." *Environmental Earth Sciences* 77: 279.
- Horton, R.E. 1933. "The role of infiltration in the hydrologic cycle." *Transactions of the American Geophysical Union* 14: 446–60.
- HydroSciences Montpellier. 2022. "ATHYS". <http://www.athys-soft.org/>
- Jenson, S.K., and J.O. Dominique. 1988. "Extracting topographic structure from digital elevation data for geographic information system analysis." *Photogrammetric Engineering Remote Sensing* 54: 1593–600.
- Jeziorska, J., and T. Niedzielski. 2018. "Applicability of TOPMODEL in the mountainous catchments in the upper Nysa Kłodzka river basin (SW Poland)." *Acta Geophysica* 66: 203–22.
- Kerdoud, S. 2006. *Le bassin versant de Beni Haroun eau et pollution*. Dissertation, University of Mentouri, Constantine. Algeria.
- Kessasra, F. 2017. *Cours de modélisation en hydrologie et hydrogéologie*. University of Jijel, Algeria.
- Lane, S.N., S.M. Reaney, and A.L. Heathwaite. 2009. "Representation of landscape hydrological connectivity using a topographically driven surface flow index." *Water Resources Research* 45: W08423.
- Lardet, P., and C. Obléd. 1994. "Real-time flood forecasting using a stochastic rainfall generator." *Journal of Hydrology* 162: 391–408.
- Le, X. 2008. *Variabilité des processus hydrologiques entrant dans le mécanisme de la genèse des crues sur les bassins à cinétique rapide*. Dissertation, National Polytechnic Institute of Toulouse, France.
- Le Lay, M., and G.M. Saulnier. 2007. "Exploring the signature of climate and landscape spatial variabilities in flash flood events: Case of the 8-9 September 2002 Cévenne-Vivarais catastrophic event." *Geophysical Research Letters* 34: L13401.
- Madsen, H. 2000. "Automatic calibration of a conceptual rainfall-runoff model using multiple objectives." *Journal of Hydrology* 235: 276–88.
- Marchandise, A. 2007. *Modélisation hydrologique distribuée sur le Gardon d'Anduze; Étude comparative de différents modèles pluie-débit, extrapolation de la normale à l'extrême et tests*

d'hypothèses sur les processus hydrologiques.
Dissertation, University of Montpellier II, France.

- Maréchal, D. 2004. *A soil-based approach to rainfall–runoff modeling in ungauged catchments for England and Wales.* Dissertation, University of Cranfield, United Kingdom.
- Maref, N., and A. Seddini. 2018. "Modeling of flood generation in semi-arid catchment using a spatially distributed model: case of study Wadi Mekerra catchment (Northwest Algeria)." *Arabian Journal of Geosciences* 11: 1–15.
- Mendicino, G., and A. Sole. 1997. "The information content theory for the estimation of the topographic index distribution used in TOPMODEL." *Hydrological Processes* 11: 1099–114.
- Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith. 2007. "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations." *American Society of Agricultural and Biological Engineers* 50: 885–900.
- Muhammad, A., W. Muhammad, A. Jae-Hyun, and K. Tae-Woong. 2015. "Improved runoff estimation using event-based rainfall-runoff models." *Water Resources Management* 29: 1995–2010.
- Nourani, V. and A. Mano. 2007. "Semi-distributed flood runoff model at the subcontinental scale for southwestern Iran." *Hydrological Processes* 21: 3173–80.
- Nourani, V., A. Roughani, and M. Gebremichael. 2011. "TOPMODEL capability for rainfall–runoff modeling of the Ammameh watershed at different time scales using different terrain algorithms." *Journal of Urban and Environmental Engineering* 5: 1–4.
- Obled, C. and I. Zin. 2004. "TOPMODEL: Principes de fonctionnement et application." *La Houille Blanche* 90: 65–77.
- Peng, D., L. Zhijia, and X. Fan. 2008. "Application of TOPMODEL in Buliu River Basin and comparison with Xin'anjiang model." *Water Science and Engineering* 2: 25–32.
- Perrin, C. 2002. "Vers une amélioration d'un modèle global pluie-débit au travers d'une approche comparative." *La Houille Blanche* 6/7: 84–91.
- Pinol, J., K.J. Beven, and J. Freer. 1997. "Modeling the hydrological response of Mediterranean catchments, Prades, Catalonia. The use of distributed models as aids to hypothesis formulation." *Hydrological Processes* 11: 1287–306.
- Quinn, P.F., K.J. Beven, P. Chevallier, and O. Planchon. 1991. "The prediction of hillslope flow patterns for distributed hydrological modelling using digital terrain models." *Hydrological Processes* 5: 59.
- Raghavendra, J., and B. Mohanty. 2012. "On topographic controls of soil hydraulic parameters scaling at hillslopes scales." *Water Resources Research* 48: W02518.
- Rao, S.S. 1978. *Engineering optimization: theory and applications.* Hoboken, NJ: John Wiley.
- Sangati, M., M. Borga, D. Rabuffetti, and R. Bechini. 2009. "Influence of rainfall and soil properties spatial aggregation on extreme flash flood response modelling: An evaluation based on the Sesia river basin, North Western Italy." *Advances in Water Resources* 32: 1090–106.
- Saulnier, G.M. 1996. *Information pédologique spatialisée et traitements topographiques améliorés dans la modélisation hydrologique par TOPMODEL.* Dissertation, Grenoble INPG.
- Saulnier, G.M., and R. Datin. 2004. "Analytical solving of a bias in the TOPMODEL framework water balance." *Hydrological Processes* 18: 1195–218.
- Seibert, J. 1999. "Regionalisation of parameters for a conceptual rainfall–runoff model." *Agricultural and Forest Meteorology* 98–99: 279–93.
- Sempere-Torres, D. 1990. *Calcul de la lame d'eau ruisselée dans les modèles pluie-débit: Limitations des approches globales et introduction de manière simplifiée de la topographie et de la variabilité spatiale des pluies: application aux bassins versants du Gardon d'Anduze et du Réal Collobrier.* Dissertation, University of Grenoble, France.
- Sigdel, A., R. Jha, D. Bhatta, R.A.I. Abou-Shanab, V.R. Sapireddy, and B-H. Jeon. 2011. "Applicability of TOPMODEL in the catchments of Nepal." *Geosystem Engineering* 14: 181–90.
- Taha, A., J.M. Gresillon, and B.E. Clothier. 1997. "Modelling the link between hillslope water movement and stream flow: Application to a small Mediterranean forest watershed." *Journal of Hydrology* 203: 11–20.
- Thiemig, V., R. Rojas, M. Zambrano-Bigiarini, and A. Roo. 2013. "Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin." *Journal of Hydrology* 499: 324–38.
- Touazi, M., and J.P. Laborde. 2004. "Modélisation pluie-débit à l'échelle annuelle en Algérie du nord." *Journal of Water Science* 17: 503–16.
- Vincendon, B., V. Ducrocq, G.M. Saulnier, L. Bouilloud, K. Chancibault, F. Habets, and J. Noilhan. 2010. "Benefit of coupling the ISBA land surface model with a TOPMODEL hydrological model version dedicated to Mediterranean flash-floods." *Journal of Hydrology* 394: 256–66.
- Wagener, T., and J. Kollat. 2007. "Numerical and visual evaluation of hydrological environmental models using the Monte Carlo analysis toolbox." *Environmental Modelling & Software* 22: 1021–33.
- Xiong, L., and S.H. Guo. 2004. "Effects of the catchment coefficient on the performance of TOPMODEL in rainfall–runoff modeling." *Hydrological Processes* 18: 1823–36.
- Xue, L., F. Yang, Y. Changbing, W. Guanghui, L. Wenqian, and H. Xinlin. 2018. "Hydrological simulation and uncertainty analysis using the improved TOPMODEL in the arid Manas River basin, China." *Scientific Reports* 8: 452.
- Zehe, E., R. Becker, A. Bardossy, and E. Plate. 2005. "Uncertainty of simulated catchment runoff response in the presence of threshold processes: Role of initial soil moisture and precipitation." *Journal of Hydrology* 315: 183–202.