TOPMODEL: Hydrological Modelling in Tropical Regions

Case Study: Middle Magdalena Valley, Colombia

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ABSTRACT

Hydrological distributed modelling is a key point for a comprehensive assessment of the feedback between the dynamics of the hydrological cycle, climate conditions, and the land use. Aforementioned modelling results are markedly relevant within the fields of water resources management. Here TOPMODEL (Topography based hydrological MODEL) is subjected for the hydrological modelling of the zone in the Middle Magdalena Valley (MMV), a tropical basin located in Colombia. This study is set in the intertropical convergence zone and is characterized by special meteorological conditions, with fast water fluxes over the year. It has been susceptible to significant land use changes and as well, a result of intense economic activities, i.e., agriculture, energy and oil & gas production. The model procures a record of 12 years of daily precipitation database from observed gauges, daily evapotranspiration database from temperature data and streamflow database as observed data from calibration. Calibration is implemented using data from 2000 to 2008, and the validation is accomplished with data from 2009 to 2012. The Nash-Sutcliffe coefficient is used to assess the robustness of our calibration process (values of this metric being 0.74 and 0.73, respectively for model calibration and validation). The results reveal high water storage capacity in the soil, and a marked subsurface runoff, consistent with the characteristics of the soil types in the regions. The calibrated model provides relevant indications about recharge in the region, which is essential to quantify the interaction between surface water and groundwater, chiefly during the dry season, which is more relevant in climate-change and climate-variability scenarios.

KEYWORDS

Hydrologic modelling, TOPMODEL, Middle Magdalena Valley, Nash Sutcliffe efficiency.

INTRODUCTION

Recently, mathematical models have taken over the most important tasks in solving problems in hydrology [1] [2] [3]. Many discussions about modeling have appeared in the scientific literature, but the justification for the construction of the model was the complexity of the hydrological systems [4].

Hydrological models have been developed for different reasons and therefore have many different forms [5]. However, they are generally designed to meet two main objectives: i). obtain a better understanding of the hydrological phenomena that operate in a basin and how changes in the basin can affect these phenomena and ii). the generation of synthetic sequences of hydrological data for the design of the facilities or for their use in forecasting [6] [7] [8]. However, hydrological models also provide valuable information to study the potential for changes in land use or climate [9].

Currently, water supply, mainly for human consumption, food production and energy generation, has become a global priority in the economic and social sphere [10]. During the last decades, the demand for water has increased rapidly due to the growth of the population to establish economic activities such as agriculture and mining [11] [12]. Despite its importance, knowledge of the actual hydrological functioning of these ecosystems is still deficient, together with the effects of climate change on this functioning [13].

The scarcity of data is quite common in some areas of Colombia, due to the complexity of the topography that hinders the instrumentation of the basins [14]. Consequently, hydrological modeling becomes an important tool to investigate and understand the behavior of strategic ecosystems, even with scarce data and also to forecast changing climatic conditions [15] [16].

The integration of data, through modeling, has facilitated the verification of the assumptions that underlie any hydrological system, which has contributed significantly to the generation of new knowledge [8]. Through models, it has been possible to represent the dominant hydrological processes corresponding to the hydrological cycle of each ecosystem, mainly by calculating the water balances, related to hypotheses and estimated parameters, which allow to explore the validity of the representation, interactions and various levels of behavior [17].

Hydrological modeling at basin scale based on topography allows to evaluate in a simplified way the spatial variability of the hydrological response [18]. The information of the topographic index is integrated into the general structure of the model, throughout the spatial distribution of the moisture content of the water table [19].

The document presents a simplified description of the TOPMODEL model applied in the Middle Magdalena Valley area and also contains a general description of the methods used for its evaluation. The paper is organized as follows. Section 2 presents theoretical framework. Section 3 show the study area. Section 4 present the data source. Section 5 illustrates our results for the calibration and validation model, and conclusions are indicated in Section 6.

THEORETICAL FRAMEWORK

Hydrologic Model: TOPMODEL

TopModel is a semi-distributed model based on the similarities featured by the topography, as expressed through an index (Topographic Index). It can be considered as a rainfall-runoff conceptual model based on the landscapes characteristics that contains three dynamic storages: i) root zone, ii) gravity zone and iii) saturated zone [20] [21] (Figure 1). Its main assumptions are:

- dynamics of saturated zone can be approached through a steady state,
- parameters are spatially homogeneous,
- hydraulic gradient can be approached by the surface gradient,
- hydraulic conductivity decreases exponentially with depth.

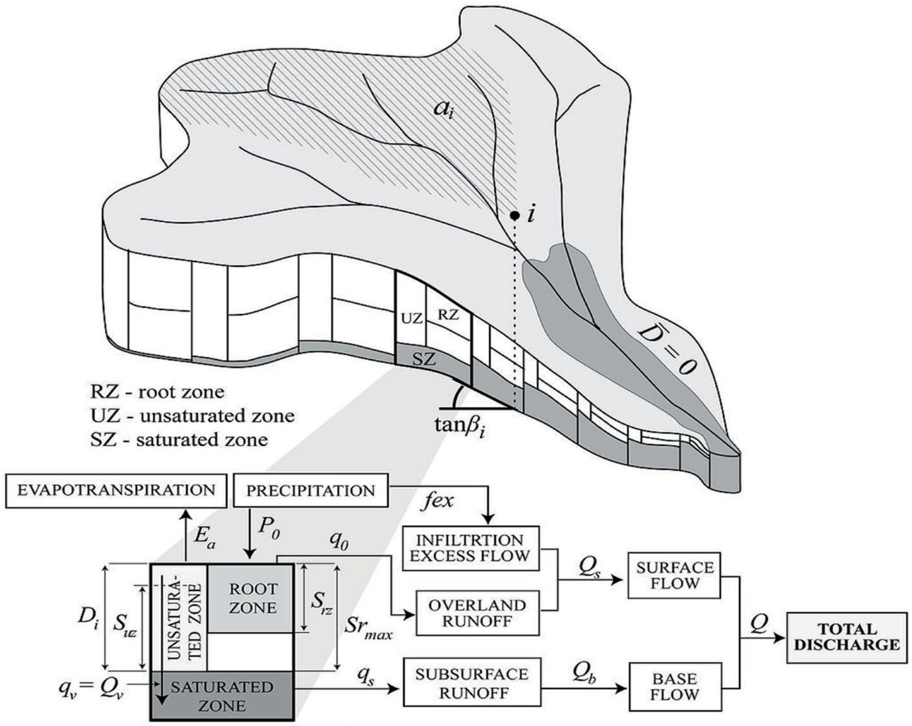


Figure 1. TOPMODEL model description

Source: [22].

The theory assumes that the local hydraulic gradient is equal to the local surface slope and implies that all points with the same value of the topographic wetness index (TWI) have the same hydraulic properties [23] [19] [24]. Its value is computed from the basin topography using equation 1.

$$TWI_i = ln\frac{a_i}{Tan\beta_i} \qquad (1)$$

where: a_i is the upslope contributing area of i-th basin, $Tan\beta_i$ is slope of the ground surface of this basin. Upslope contributing area [25]. In the raster representation of the terrain, it should be replaced by the upslope drainage area per unit of contour length [26], which is equivalent to DEM grid cell size [27]. Areas associated with high TWI values tend to saturate first and will therefore constitute potential subsurface or surface contributing areas [24].

TWI refers to variable source area concept of runoff generation [19] and is based on the following three simplifying assumptions regarding the hydrologic system [18]: a.) dynamics of the saturated zone can be approximated by successive steady-state representations b.) hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope (), thus the groundwater table and saturated flow are parallel to the local surface slope, and c.) distribution of downslope transmissivity with depth is an exponential function of storage deficit or depth to the water table.

This approach implies that all points with the same value of TWI respond in the same way [28]. Calculations need to be performed only for representative values of the index, what greatly simplifies the procedure and reduces the computational cost while maintaining the capability of the identification of water table levels and soil moisture within the catchment [29]. The results may be mapped back into space using knowledge of the pattern of TWI derived from a topographic analysis [30].

According to the TOPMODEL concept, there are two main factors that account for runoff generation, namely the catchment topography and the transmissivity that diminishes with depth [31]. A soil column in TOPMODEL is defined as a set of three stores: root zone, unsaturated zone and saturated zone. They behave like three interdependent repositories (Figure 1). Rainfall infiltrates the superior layer, root zone, until its storage capacity is reached. An additional component, the interception storage, needs to be added, where the surface is covered by the forest canopy. The root zone can be depleted at the linear rate by the actual evapotranspiration from the surface, described by equation 2.

$$E_a = E_p\left(1 - \frac{Sr_z}{Sr_{max}}\right) \qquad (2)$$

where: E_a is actual evapotranspiration,E_p is potential evapotranspiration, Sr_{max} is maximum root zone deficit and Sr_z is root zone deficit.

After infiltration, the excess water reaches the unsaturated zone with a delay, fills this reservoir and recharges the saturated zone – the water table rises, reducing the distance between ground and the saturation zone. According to the first TOPMODEL assumption, the local water table depth is represented by local storage deficit (D), which can be calculated for each TWI class using the equation 3.

$$D_i = D + m\left(\alpha - ln\frac{a_i}{Tan\beta_i}\right) \qquad (3)$$

where: D_i is mean storage deficit (catchment average water table depth), α is average TWI, and m is scaling parameter.

The water table touches the ground surface when the storage deficit D=0. Thus, the value of average TWI for which $D_i=0$ constitutes the threshold for maximum storage capacity and each point that has greater TWI value is considered to be in the saturated condition. Any further rainfall falling onto these saturated surfaces cannot infiltrate and the excess water is directly transferred into saturated overland runoff.

The other process that accounts for the total surface flow Qs is the infiltration excess flow FEX that is generated when the precipitation intensity exceeds the infiltration capacity [32], and Qs and FEX are interrelated as show in equations 4 to 6:

$$Q_s = q_0 + FEX \qquad (4)$$

$$q_0 = Max(0, S_{uz}) - D \qquad (5)$$

$$FEX = P_0 - P_i \qquad (6)$$

where: q_0 is overland runoff, P_0 is precipitation per unit width, is precipitation infiltrated into the soil in the i-th unit, S_{uz} is local water storage in the unsaturated zone.

The water storage deficit is reduced by the recharge water flux from the unsaturated zone to groundwater, and its rate can be calculated using equation 7:

$$q_v = \frac{S_{uz}}{D_l T_d} \qquad (7)$$

where: D_l is the local storage deficit (local water table depth), T_d is the mean residence time in the S_{uz}.

Therefore, the total recharge rate q_v is expressed (Equation 8) q_v as the sum of all values of multiplied by the upslope area A_i representing a set of hydrologically homogenous points, associated with topographic index class of the i-th location [21].

$$Q_v = \sum_{i=1}^{\square} \square\, q_{v_i} * A_i \qquad (8)$$

where: Q_v is total flux, q_{v_i} is the flux of water entering the water table locally (per unit area), A_i is area associated with topographic index class.

The base flow Qb is represented as the subsurface saturated zone flux q_s, and can be defined by equation 9:

$$Q_b = q_s = Q_0 * e^{\left(\frac{-D}{m}\right)} \qquad (9)$$

where: Q_0 is the hydrological flux for the entire catchment area when D = 0. Both above described components: surface flow Q_s and base flow Q_b account for the total discharge.

Thus, following the TOPMODEL concept, the total runoff at the river outlet of the catchment, expressed as the sum of surface and base flow, can be calculated for each time step [33]. The downslope transmissivity (T) (Equation 10), according to the third TOPMODEL assumption, diminishes with depth following the negative exponential law versus saturation deficit D with m being a recession parameter [34].

$$T = T_0 * e^{\left(\frac{-D}{m}\right)} \qquad (10)$$

Where:T_0 is the local saturated transmissivity.

Calibration and Validation

Calibration is the procedure for obtaining a set of optimal parameters and initial values, adjusted to the particular characteristics of each basin [35] and use the Nash Sutcliffe objective function (Equation 11) [36] is considered a test of goodness of fit of the hydrological prediction model, by comparison between observed and simulated discharges [35]. Measured discharge was used as indicative variable, to be compared with model predictions of discharge, through the studied period.

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \hat{O}_i)^2} \qquad (11)$$

where: NSE represents the efficiency in fractional terms, O_i represents the hydraulic head of S_i observations and $\hat{O}_i$ of simulations and represent the average of hydraulic head of observations.

Validation is the final step of the calibration-validation process, and permit to determine how accurate the model reproduces or imitates independent information using the values of the parameters found during calibration [6] [37] [38].

STUDY AREA

The MMV (Figure 2) is located geomorphologically along the central part of the valley, crossed by the Magdalena River, between the Eastern and Central mountain ranges of the Colombian Andes, covering an area of 32.000 km2. The Middle Magdalena region is divided between the departments of Antioquia, Bolivar, Boyacá Cesar, Santander, and to a lesser extent between Caldas, Cundinamarca, and Tolima (Agencia Nacional de Hidrocarburos. (ANH), 2012).

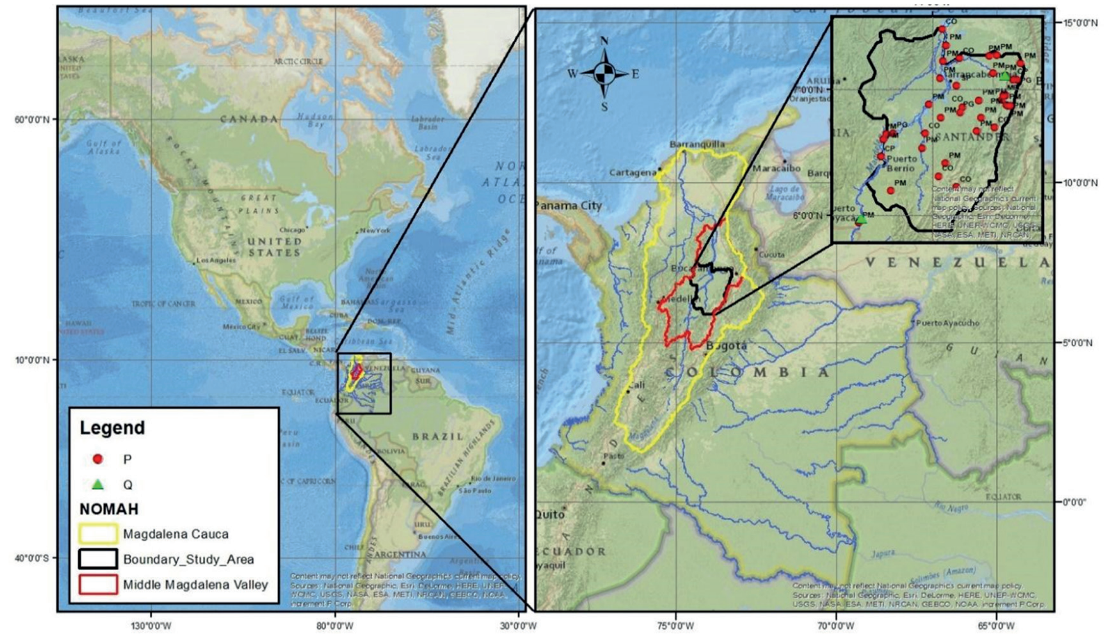


Figure 2. Location Study Area in Magdalena-Cauca Basin and Middle Magdalena Valley

Source: authors.

The MMV is located in the warm termal floor that start on the south of the Huila to a height superior to the 400 meters above sea level and descends until approximately 75 meters in the area of Barrancabermeja. The annual average temperature is above 24°C throughout the territory. In this area, the rains are distributed in two periods: the first is between March and June and the second between October and December; the other months of the year is dry. The MMV is a wet province and has an intermediate area between region north of Puerto Berrio and Barrancabermeja, with a very wet climate. In the departments of Cesar and Bolívar, the north sector of Middle Magdalena the climate is transitional to dry. In the wet area, rainfall is more than 2.000 mm/year and the river has an annual average flow of 2.361 m3/s and high flows (Q5) of 4.298 m3/s and low (Q95) of 1.578 m3/s.

DATA SOURCES

The data which become inputs to TOPMODEL can be divided into two groups: hydrometeorological time series (temporal variability) and terrain characteristics (spatial variability). The next two subsections correspond to this classification.

Terrain characteristics

Digital elevation model (DEM) was derived from the SRTM data with 30 meters resolution (Figure 3a). The contour of the basin was delineated using the program ArcGIS version 10.0. For the generation of topographic index map by class brands, the DEM was exported to TOPMODEL by library Sp, Raster and Topidx of R [21] as an array of type ASCII data, with altitude information and using a flow direction algorithm, which allows generating raster files of direction and accumulation flows [24]. Hydrological similarity units were generated from the pixels grouping into categories based on the index function [39].

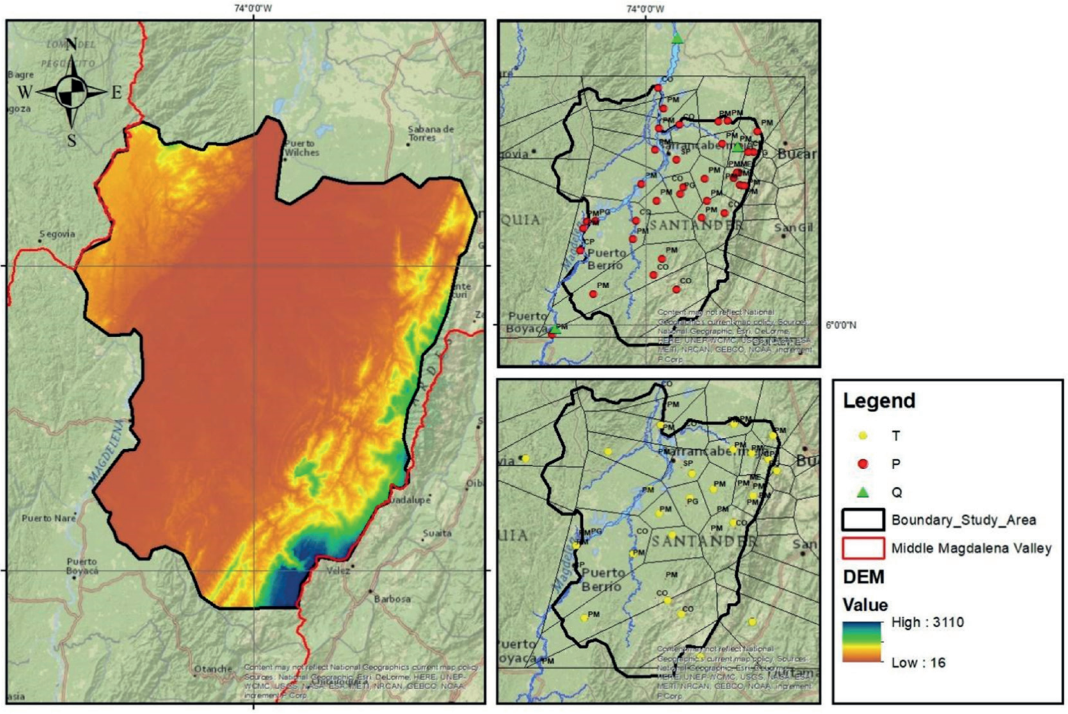


Figure 3. Data source in MMV for use TOPMODEL. (A). Digital elevation model (DEM), resolution 30 m, (B). distribution of hydrometeological stations in the area and (C). distribution of climatological stations in the area.

Source: authors.

Hydrometeorological time series

TOPMODEL needs time series of discharge, rainfall and potential evapotranspiration in m/km2 per time step. The observed river flow and precipitation data, sampled every 24 hours, are obtained from the IDEAM. However, potential evapotranspiration is modelled empirically, and the same 24 hours time step is kept.

The daily precipitation data was obtained from 37 hydrometeological stations in the study area (17.000 km2) between 2000 and 2012. Since no continuous information on precipitation field is provided, we applied the Thyssen polygons to relate rainfall to a given contributing basin (Figure 3b) [40] [41].

Potential evapotranspiration has been computed empirically, through constructed an averaged time series which is assumed to be valid for every year. Evapotranspiration was calculated from climatic variables, by the Hargreaves method [42], which used observed mean temperature from 24 stations; its distribution on the basin was estimated by the method of Thiessen with correction based on elevation (Figure 3c) [42] [43]. Discharge was obtained from Puerto Berrio and San Pablo stations. Data from 2000 to 2008 was used for the model calibration data from 2009 to 2012 was used to validate the model. The time series of P, Q and ET are shown in the Figure 4.

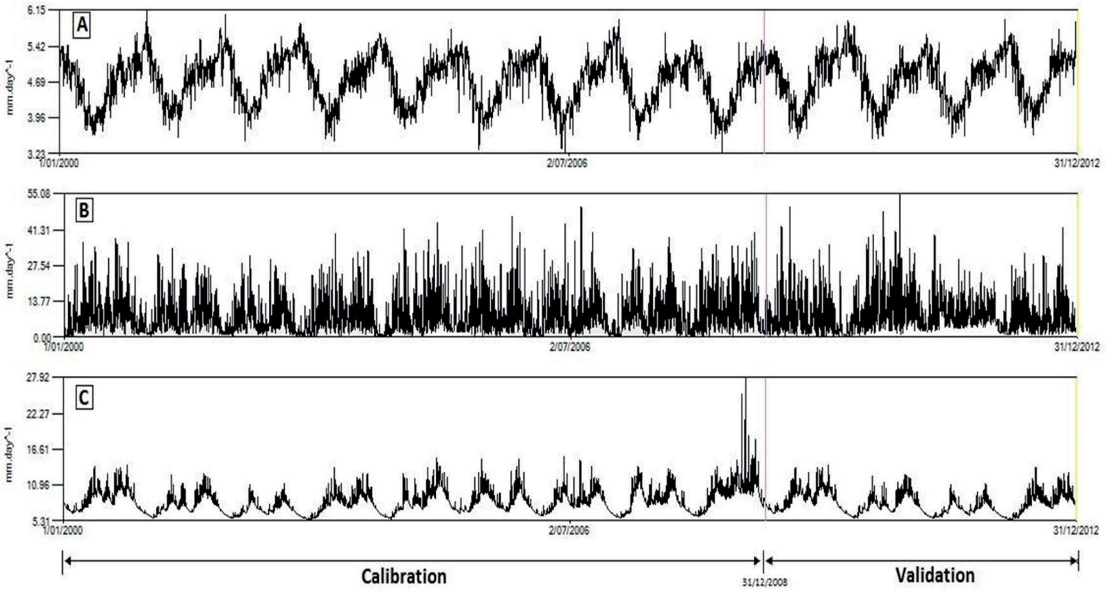


Figure 4. Time series section in MMV. (A). ET, (B). Precipitation and (C). Flow

Source: authors.

RESULTS

Simulation

TWI map of the basin is presented in (Figure 5), indicating a correspondence between the highest values of the index and the drainage network. Areas with values between 12 to 16 correspond to the level where the drainage network occurs. High values of the topographic index are related to contributing areas which generate discharge and return flows, associated with topographically convergent places or smooth slopes [44], and they are characterized by low transmissivity, thus the water table reaches the surface. These areas in the basin may generally correspond to valleys [45], in which, the saturation condition causes a decrease in the amount of subsurface flow and leads to fully development saturated areas.

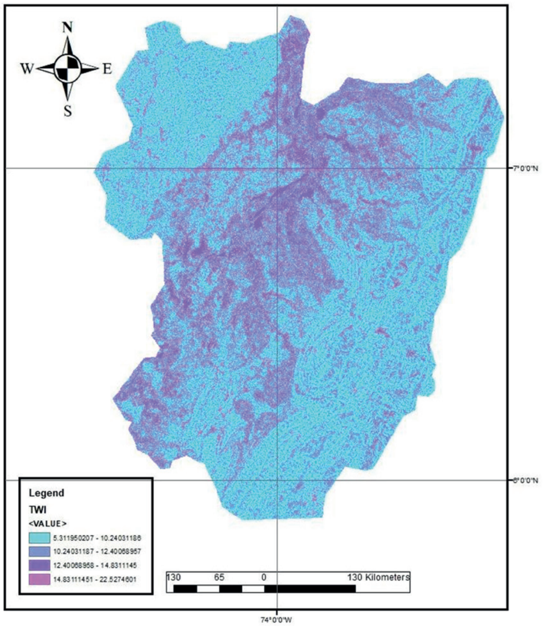


Figure 5. Topographic Wetness Index for the study area

Source: authors.

The average value of the TWI for the basin was 10.3. The distribution of these values by class-mark, showed that the category where most of the pixels were grouped on the map have a value between 12 and 14. Values of the index between 6 and 8, are associated with areas of higher slopes [19], which are very common in the border of the study area for being among the mountains ranges.

Topography has a strong influence on the hydrological response of a basin, and this is represented in the model with the topographic index. Local depressions and flat areas where drainage accumulates frequently generate saturated conditions. At the same time, the porosity and infiltration capacity of the soils in Middle Magdalena Valley, in combination with rainfall intensity, increase the possibility of infiltration excess overland flow [10]. As a result, the process to generate surface runoff is saturation excess overland flow.

Parameter estimation

Although the TOPMODEL assumptions require relatively small number of parameters that need to be estimated, the difficulty of the calibration is caused by the uncertainty of the parameters [46]. Additionally, as [44] stress out, a diverse set of possible parameter values can produce a similar modeling results.

TOPMODEL can automatically implement a Monte Carlo simulation, which was used to estimate a set of parameters that offer the best model performance. Random sampling was performed in the specified parameter range is performed, assuming the same probability of sampling each element (uniform distribution). Table 1 shows the ranges applied for each parameter based on the reported literature [47] [48] and manual calibration. In order to enhance the certainty, the number of simulations was set to 10.000. Further increase of this number did not improve the final result and required a more time-consuming computation.

Table 1. Initial interval of parameters used.

Parameters	Description	Unit	Range
Qs_0	Initial subsurface flow per unit area	m	0-0.00005
LnTe	Log of the areal average of Transmissivity	m^2/h	-7 - 6
m	Model parameter controlling the rate of decline of transmissivity in the soil profile		0-3
Sr0	Initial root zone storage deficit	m	0-3
Sr_max	Maximum root zone storage deficit	m	0-3
Td	Unsaturated time zone delay per unit storage deficit	h/m	20-50
Vch	Channel flow outside the catchment	m/h	1200-10800
Vr	Channel flow inside the catchment	m/h	50-2500
K0	Surface hydraulic conductivity	m/h	0-2
Cd	Capilary drive	m	0-5
Dt	Time step	h	24

Source: authors.

Each parameter is equally important during the Monte Carlo sampling, although the manual calibration showed, that four of the parameters – m, LnTe, Srmax and qs0 – are more meaningful, i.e. variation in their values influences the model performance and the shape of the simulated hydrograph most significantly.

The m parameter represents the change in the saturate hydraulic conductivity with depth. Small values of m imply the quick flow and insignificant subsurface runoff, while large values indicate that more rainfall can infiltrate the soil, thus less water reaches the outlet via surface route [49]This parameter is related to subsurface flow control and the deficit of local storage, which is important in the recharge case of water [17]. Therefore, this parameter has a significant effect on the calculation of the local storage deficit, contributing areas and the shape of the curve in the hydrograph recession.

LnTe parameter influences directly the shape of hydrograph. The quick recession is associated with small values of the LnTe parameter, while low values result in gradual fall of the hydrograph limb after the peak, as a result of increasing saturated transmissibility that may cause runoff delay.

The value of the maximum root zone deficit (Srmax) indicates the influence of evapotranspiration on the hydrological behavior of the catchment. Low Srmax value allows less water to be stored in the root zone and hence available for evapotranspiration what can lead to the increased runoff [20].

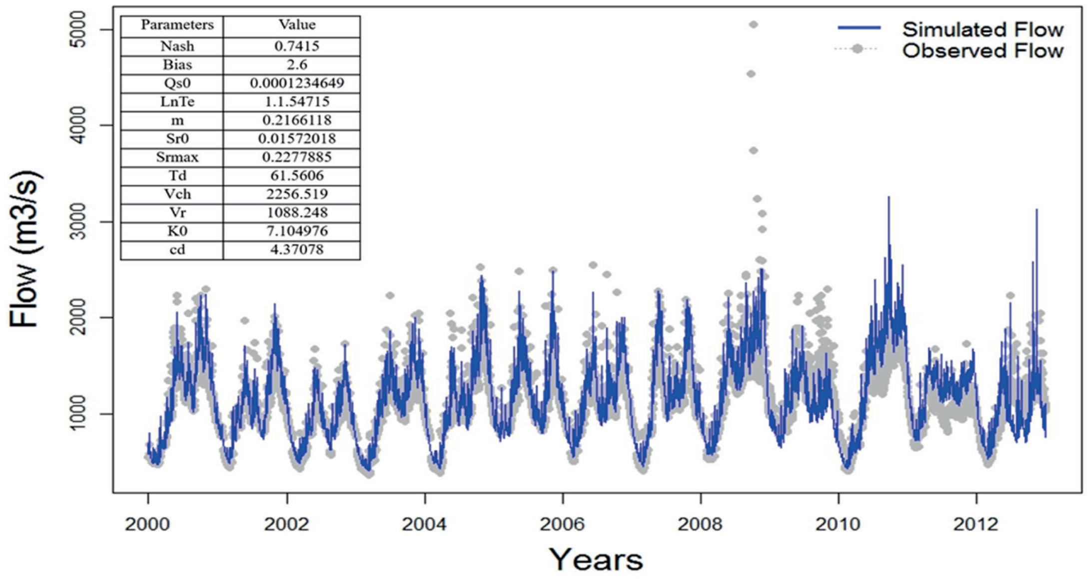
Model performance

The model was implemented for 2000-2012 period, with a time scale of 24 hours. Data between 2000 and 2008 was used for the calibration of the model, by verifying site conditions adjusted to the structure and model assumptions and the establishment of a set of initial parameters which adequately describes the hydrological behavior of the basin study. Data from 2009 to 2012 was used for the validation of the calibrated model.

During the process of calibration, the highest values of model parameters were selected and these corresponding to the parameter sets with the highest values of efficiencies obtained (i.e. NSE values) in the simulations performed. Initial simulations with iterations between 10.000 and 35.000 for data were made, in which non-significant differences in values of efficiency were detected when comparing best parameter sets performance.

The results from calibration generated a set of parameters with efficiency of 0.74 for the objective function. The differences in the efficiencies of the parameter sets were very low, so the overall performance of all simulations can be considered very similar, despite small variations in the values of all parameters that generate these efficiencies. This is associated with the sensitivity of the parameters and their impact on the representation of hydrological processes in the studied basin.

This set of parameters (Figure 6) was used to calculate the simulated flows by TOPMODEL during the period studied, presenting an under estimation of the maximum flows. For the process of validation of the model results generated from the calibrated parameters, the values of efficiency were near to 0.73 and its simulated flows are shown in the Figure 6.



Parameters	Value
Nash	0.7415
Bias	2.6
Qs0	0.0001234649
LnTe	1.1.54715
m	0.2166118
Sr0	0.01572018
Srmax	0.2277885
Td	61.5606
Vch	2256.519
Vr	1088.248
K0	7.104976
cd	4.37078

Figure 6. Observed (gray) and simulated flows (blue) in the calibration and validation process for the study area in MMV

Source: authors.

The efficiencies were classified according to the methodology reported by [50].The NSE values found are close to the values obtained for a proven model in Ecuador and Colombia with efficiency values near to 0.67 and 0.7 respectively [51] [52]. However, it is possible that longer periods of time could help ensure better simulations and adjustments, because to the extent that more data is added to model, the variability increases. Additionally, it is widely known that TOPMODEL has problems to accurately represent low flows during droughts [20]. For periods where precipitation exceeds evapotranspiration, the wide range of parameters provide acceptable simulations for basin discharge, although base flow is less accurately simulated, as it happens in other sites (42).

CONCLUSION

TOPMODEL was able to reproduce the main pattern of the hydrograph with acceptable accuracy for the case-study. A low performance to simulate some patterns (baseflow) can be attributed to input data error, calibration inaccuracy, parameter uncertainty and model structure. The most probable cause of those results is linked to the uncertainty of the data series analyzed. Low accuracy of the model can also be an effect of the model inability to represent distributed rainfall pattern.

Complicated environment and lack of soil data makes the calibration of parameters challenging. The Monte Carlo simulation produces the most suitable parameter sets, but they may not correspond to the actual conditions of the basin.

The application of hydrological model, developed in this research contributes to national efforts and the availability of results for the development of comparative studies in Middle Magdalena Valley at basin scale. This work constitutes a sample of the advantage of applying a widely used semi-distributed model that is freely accessible to the scientific community, contrary to the limitations of using a model that depends on the singularity of the study area. The results obtained here will be used as input data in the hydrogeological analysis of the area.

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