Research article

http://www.revistas.unal.edu.co/index.php/refame

Revista Facultad Nacional de Agronomía

Hydrological modelling with TOPMODEL of Chingaza páramo, Colombia

UNIVERSIDAD NACIONAL DE COLOMBIA

Modelación hidrológica con TOPMODEL en el páramo de Chingaza, Colombia

doi: 10.15446/rfna.v69n2.59137

Eydith Girleza Gil[1]* and Conrado Tobón[1]

ABSTRACT

Key words:
Ecohydrology
Modelling
Páramos
The Chucua basin
Topmodel

Páramo ecosystems are located on the upper parts of the tropical mountains, below the snow line areas or in isolated areas where no glacier ecosystems occur. These ecosystems are considered important for their biodiversity, but mainly because they are permanent source of water for populations located at the upper and middle parts of the Andes. Recent studies indicate that ecosystems located at high altitudes, are more vulnerable to climate change and to changes in land use, which threatens the ecosystem services derived from them. There are very few studies in these ecosystems, within which, studies on the hydrological functioning are even scarcer, which seems to be related to their position in the top of the mountains and difficulties associated with the access to them. This implies that there is a need to create tools that allow us to study these ecosystems, overcoming the current difficulties. Hydrological TOPMODEL is used to investigate the hydrological functioning of the páramo of Chingaza, through a case study in La Chucua basin. For this, we calibrate and validate the model using two data sets of climate and the hydrology of the basin (climate and discharge from 2008 and 2009, respectively). Through the calibration procedure we obtain a high efficiency value of 0.76 model (coefficient Nash - Sutcliffe), which adequately represents the hydrological behavior of the páramo. Simulations with better adjustment between measured and predicted values of discharge, have low values of surface infiltration excess runoff, indicating high water storage capacity on the soils. This agrees with the predominance of subsurface flow in studied ecosystem, given the special characteristics of soils. Results also show the large influence of factors represented in the model (topography and soils), on water basin response to rainfall events. This is significant evidence of exceptional hydrological behavior of the páramos, mainly related to the presence of soil with high organic matter content. These results imply that TOPMODEL is a robust tool, able to represent in a precise manner the hydrological functioning of the basin La Chucua, and consequently it is expected that TOPMODEL can also represent hydrological conditions of Chingaza páramo.

RESUMEN

Palabras claves:
Ecohidrología
Modelación
Páramos
Cuenca La Chucua
Topmodel

Los páramos son ecosistemas localizados hacia las partes altas de las montañas, por debajo de las zonas de nieves perpetuas o en áreas aisladas, donde no hay glaciar. Estos ecosistemas son considerados importantes, tanto por su biodiversidad, como por ser fuente permanente de agua para poblaciones ubicadas hacia las partes medias y altas de las montañas andinas. Estudios recientes indican que ecosistemas localizados en altitudes altas, son más vulnerable al cambio climático y cambios en el uso del suelo, lo que pone en peligro los servicios ecosistémicos que se derivan desde estos. Son muy pocos los estudios realizados en estos ecosistemas, dentro de los cuales, estudios sobre su funcionamiento hidrológico son aún más escasos, lo que parece estar relacionado con las dificultades asociadas con el acceso a los mismos. Esto implica que existe una necesidad de generar herramientas que nos permitan estudiar estos ecosistemas, sobreponiéndose a las dificultades actuales. En este sentido en la presente investigación, se utilizó el modelo hidrológico TOPMODEL con el fin de investigar el funcionamiento hidrológico del páramo de Chingaza, a través de un estudio de caso en la cuenca La Chucua. Para esto se calibró y validó el modelo, mediante dos series de datos del clima y la hidrología de la cuenca (clima y caudales de los años 2008 y 2009, respectivamente), obteniéndose un valor alto de eficiencia del modelo de 0.76 (coeficiente Nash-Sutcliffe), el cual representa adecuadamente el comportamiento hidrológico del páramo. Las simulaciones de mayor ajuste presentaron bajos valores de escorrentía superficial por exceso de infiltración, lo que indica alta capacidad de almacenamiento de agua en el suelo, y coincide con la predominancia de la escorrentía subsuperficial, dadas las características especiales de los suelos allí presentes. Se comprobó la influencia que tienen los factores representados en el modelo (topografía y suelos), sobre la respuesta hídrica de la cuenca. Esto constituye evidencia significativa del comportamiento hídrico excepcional de los páramos, debido a sus suelos. Estos resultados implican que TOPMODEL es una herramienta robusta, capaz de representar de una manera precisa el funcionamiento hidrológico de la cuenca La Chucua, y por ende se espera que pueda representar igualmente las condiciones del páramo de Chingaza.

[1] Facultad de Ciencias Agrarias. Universidad Nacional de Colombia. A.A. 1779, Medellín, Colombia.
* Corresponding author <dailesol@gmail.com>

Received: March 6, 2016; Accepted: June 6, 2016
Rev. Fac. Nac. Agron. Medellín 69(2): 7919-7933. 2016 ISSN 0304-2847 / e-ISSN 2248-7026

Water supply, mainly for human consumption, food production and hydropower generation, has become a worldwide priority in the economic and social level (Buytaert *et al.*, 2011). The provision of this service in Andean region, is mainly attributed to the high mountain ecosystems, specifically to páramos and cloud forests (Tobón, 2009), considered strategic ecosystems, given the multiplicity of the environmental services offered, in which stand out the water storage in soil and water regulation (Buytaert and Beven, 2011). During the last decades, water demand has increased rapidly due to population growth to establish economic activities such as agriculture and mining, very recurrent in páramos (Buytaert and Breuer, 2013). Despite its importance, the knowledge of the actual ecohydrological functioning of these ecosystems is still poor, along with the effects of climate change on this functioning.

Data scarcity is quite common in the Andean mountains, due to the complexity of topography which hinders the instrumentation of the basins (Buytaert and De Bièvre, 2012). Accordingly, hydrological modelling becomes an important tool to investigate and understand the behavior of strategic ecosystems, even with data scarce and also to make predictions of climate changing conditions (Buytaert *et al.,* 2006a; Almeida *et al.,* 2013).

Hydrological models are useful simulation tools to describe the behavior of ecosystems, mainly at basin scale (Albek *et al.,* 2004), but also to predict the potential hydrological impacts of climate and land use changes (Croke *et al.,* 2004). Integration of data, through modelling, has facilitated the verification of the assumptions underlying any hydrological system, which has contributed considerably to the generation of new knowledge. Through models it has been possible to represent the dominant hydrological processes corresponding to hydrological cycle of each ecosystem, mainly by computing water balances, related with hypotheses and estimated parameters, allowing to explore the validity of representation, interactions and several behavioral levels (Buytaert and Beven, 2011). These models also provide relevant information for scientists and decision makers in the framework of conservation policies, management and efficient use of water resources (Viviroli *et al.,* 2009). One possibility for modeling at basin scale is the hydrological model TOPMODEL (TOPography based hydrological MODEL) a semi-distributed model that represents a simplified version on the spatial variability of the hydrological response, in which topography is spatially considered (Beven *et al.,* 1984). In this case, the information of the topographic index is integrated into the overall structure of the model, throughout the spatial distribution of moisture content of the water table (Güntner *et al.,* 1999). The advantage of TOPMODEL is that it requires values of few variables and parameters, which are easily determined in the field, overcoming limitations associated to data acquisition and the restrictions on computers capacities to perform simulations (Beven *et al.,* 1984). Recently, TOPMODEL has been used to study páramos at a basin scale, and also, to test different climate change scenarios, including changes in land uses (Franchini *et al.,* 1996; Dietterick *et al.,* 1999; Da Silva and Kobiyama, 2007a).

Despite the lack of hydrological and climatological data that is required to model the hydrological functioning of a páramo ecosystem, the hydrological model has been applied at a basin scale (Buytaert *et al.,* 2009). The advantage of TOPMODEL is its simple structure contrary to other models with more rigid structure and greater difficulties for its programming. Additionally TOPMODEL is available in a free programming language access, with libraries that facilitate code domain (Buytaert *et al.,* 2008).

Páramos are considered important ecosystems in the tropical montane, given their large contribution to water supply (Tobón, 2009; Hofstede, 1995; Buytaert *et al*., 2010), their biodiversity (Myers *et al*., 2000) and carbon storage, mainly in the soil. Despite this importance, they are among the most susceptible ecosystems in the tropics, both to land use and climate change (Foster 2001; IDEAM 2002). Moreover, páramos, among other tropical mountain ecosystems, are considered unique areas for detection and assessment of impacts related to climate change (Vuille *et al.,* 2008), thus nowadays there is a growing interest to understand it ecohydrological behavior.

According to the lack of knowledge, the associated difficulties to generate field data for most páramos, and the needs for hydrological information regarding the effects of climate change, we propose a modelling approach to characterize the hydrology of Chingaza páramo at a basin scale, through the hydrological processes modelling using TOPMODEL.

MATERIALS AND METHODS

Study area

The study area is the Chucua basin, located in the Natural National Park Chingaza (4°40'6.38''N to 4°41'00''N and 73°49'5.27''W to 73°50'19.5''W), La Calera, Cundinamarca, Colombia. The area of the Chucua basin is 2.59 2.59 km^2, tributary (Figure 1), of Blanco and Negro rivers basins located at its greatest extent in the Forest Reserve Protected Area of Chingaza Park. This basin provides the drinking water to Bogotá city and for electric power generation (Guavio Dam). Average annual rainfall is around 3300 mm, with low intensity and long duration events (0.185 mm h^{-1}). The distribution of rainfall is relatively homogeneous for the whole year, presenting their minimum values between December-February (98-170 mm per month) and maximum around May. The daily average air temperature ranges from 7.5 to 12.3 °C; however ranges are more abrupt, from -2 to 24 °C. The basin receives moisture from two fronts: in the south side, from Sumapaz and in the eastern side, from the Amazon. The area is frequently covered by low clouds (insolation equal to 2.5 to 3.5 h of sunshine per day), air humidity is high, values are maintained in the range of 89.5 and 91% and an annual evapotranspiration approximately of 289 mm, characterizing the páramo as perhumid with water effective surplus (water yield between 0.68 - 0.70).

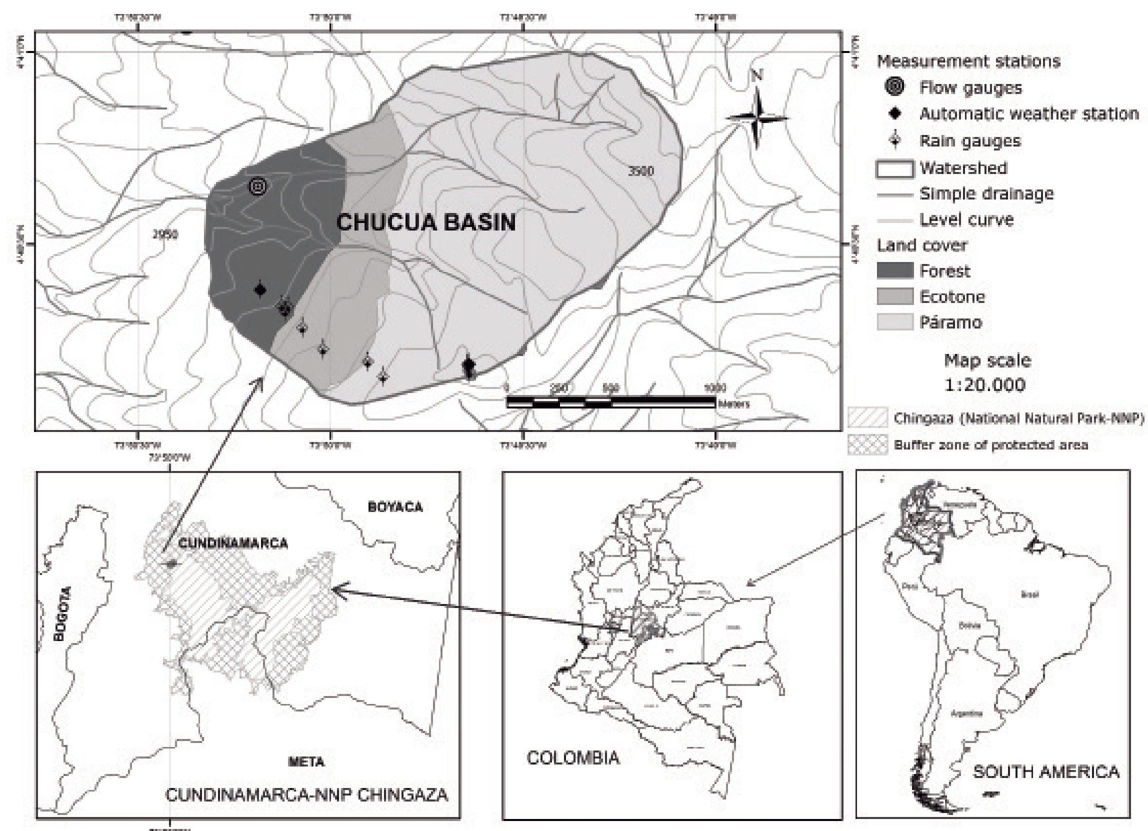


Figure 1. General location of the study area and measurement stations.

The area was formed from Devonian sedimentary rocks containing limestone, silt stone and sandstone, determining an abrupt topography with slopes higher than 30%, and altitude around 3800 m. Soils derived from volcanic ashes, with an effective depth down to 1.2 m, moderately well-drained and belong to the order of Inceptisols (USDA, 2014). They have very high organic matter content, up to 38% and high water storage capacity (90% in saturation conditions, a high porosity of 80% and a rate infiltration around 20 – 60 mm h^{-1}) (Tobón, 2009). Vegetation is dominated by dominated by giant rosettes of the genus *Espeletia*, and grasses as *Calamagrostis*, and small patches of upright sclerophyllous shrubs and puyas (Sklenár, 2000).

Hydrological modelling

TOPMODEL is a conceptual model in which the predominant factors determining the formation of runoff are represented by the topography of the basin and a negative exponential tend line, linking the transmissivity of the soil with the saturated zone belowground. This model is frequently described as a physically based model in the sense that its parameters can be measured directly in situ (Franchini *et al.,* 1996). See more details regarding to model structure in Beven and Kirkby (1979). The model requires the following data input: digital elevation model, hydrometeorological data, cumulative delay function and parameters.

Data input for the model

Digital elevation model (DEM) was derived from the SRTM data (2000) -zone u03_n004w074 available at 1-arc second resolution (approximately 30 m at the equator), and projected to a local coordinate system Colombia-Bogotá-Zone. The contour of the basin was delineated using the program GRASS GIS version 6.4. For the generation of topographic index map by class brands, the DEM was exported to TOPMODEL by library *spgrass6* of R as an array of type ASCII data, with altitude information and using a flow direction algorithm called D8, which allows generating raster files of direction and accumulation flows. Hydrological similarity units were generated from the pixels grouping into categories based on the index function (Campling *et al.,* 2002).

Hydrometeorological data was gathered through field monitoring of climate and hydrological variables, distributed along the altitude range of the Chucua basin, between 2007 and 2010 within the framework of the research project *"Ecohydrology of the páramos in Colombia III: Páramo Chingaza"*, led by researchers from Universidad Nacional de Colombia. The instruments were installed in a transect of the basin by type of coverage (forest, ecotone and páramos) and altitude gradient from 2500 to 3550 m, in order to consider the spatial and temporal variability of the monitored variables.

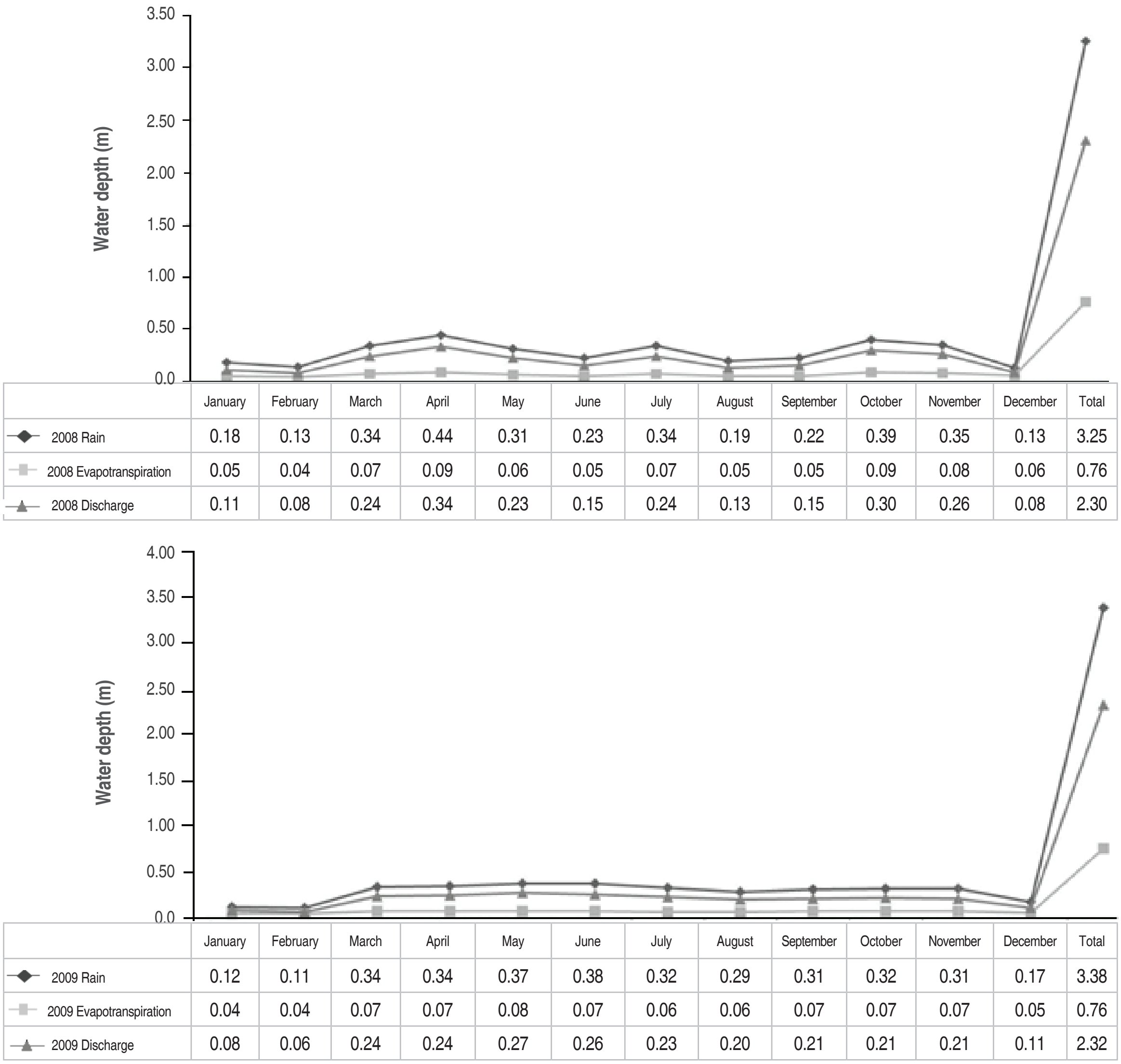
Precipitation was measured with six automatic rain gauges, located every 200 m in the altitude gradient (between 2800 and 3800 m). The average precipitation in the basin was estimated by the method of kriging. Climatic variables, as temperature, air humidity, solar radiation, wind speed and wind direction, were measured with two automatic weather stations located at an altitude of 3000 and 3600 m within the basin. Horizontal precipitation was measured at two sites (by the weather stations) and soil moisture, at different soil depths was measured through the TDR technique, in four sites, located at within the range altitude of 2800 and 3800 m.

Evapotranspiration was calculated from climatic variables, by the Penman-Monteith method (1965) previously applied by Tobón (1999) and was developed in Stella version 8.0 to this work.

The discharge was continuous measured by installing a limnigraph in a rectangular weir, located at the close of the basin, at an altitude of 3034 m. The measurements of the water column above the bed of the creek, and the canal area was measured, were used to calculate discharge amounts through the measured period.

Thirty minutes data on precipitation, evapotranspiration and discharge were used as input data entered into TOPMODEL in a text file as a water depth (m) for each variable. Data from 2008 is used for the calibration of the model and total data from 2009 was used to validate the model (Figure 2).

Cumulative delay function of the basin represents the residence time on the drainage network that takes the generated surface and subsurface flow over time in each sub-basin to be driven to the output (Topmodel, 2011). To represent this function, a matrix type data distributed in two columns: one represents a cumulative fraction of the area of the basin, which is divided according to the morphological characteristics (Da Silva and Kobiyama, 2007a), and the other represents the cumulative distance measured on the main channel, from the output, to each specific area,



	January	February	March	April	May	June	July	August	September	October	November	December	Total
2008 Rain	0.18	0.13	0.34	0.44	0.31	0.23	0.34	0.19	0.22	0.39	0.35	0.13	3.25
2008 Evapotranspiration	0.05	0.04	0.07	0.09	0.06	0.05	0.07	0.05	0.05	0.09	0.08	0.06	0.76
2008 Discharge	0.11	0.08	0.24	0.34	0.23	0.15	0.24	0.13	0.15	0.30	0.26	0.08	2.30

	January	February	March	April	May	June	July	August	September	October	November	December	Total
2009 Rain	0.12	0.11	0.34	0.34	0.37	0.38	0.32	0.29	0.31	0.32	0.31	0.17	3.38
2009 Evapotranspiration	0.04	0.04	0.07	0.07	0.08	0.07	0.06	0.06	0.07	0.07	0.07	0.05	0.76
2009 Discharge	0.08	0.06	0.24	0.24	0.27	0.26	0.23	0.20	0.21	0.21	0.21	0.11	2.32

Figure 2. Precipitation and discharge recorded, and evapotranspiration estimated for The Chucua basin during 2008 to 2009.

in relation to the cumulative area of the drainage network in each fraction (Topmodel, 2011). In that way the basin is divided into three homogeneous areas (Table 1), which assumes that in hydrological terms, its functioning is different in the area of wetlands, near the outlet and in the remaining area.

Table 1. Cumulative delay function of Chucua basin.

Polygon	Area (km^2)	Accumulative area	Distance from the channel for each polygon (km)	Cumulative distance to output (km)
0 (River outlet)	0	0	0	0
1	0.53	0.30	0.61	0.61
2	1.41	0.80	1.10	1.71
3 (wetlands and water birth)	0.65	1	0.74	2.45
Total	2.59		2.45	2.45

The values of the *model parameters* were initially established from reported literature values (Buytaert and Beven, 2011) (Table 2), and then were adjusted the ranges by the method of calibration (by inputting the information into the model as a set of data in matrix array organized into a text file) (Topmodel, 2011).

The values were settled at appropriate intervals to the páramo, also considering field data taken in 2008.

Table 2. Initial interval of the parameters based on literature.

Parameter	Description	Unit	Set range	
qs0	Initial subsurface flow	[m]	0	0.00006
LnTe	Transmissivity (log transformed)	[m^2 h^{-1}]	0.5	3
m	Shape of the transmissivity curve		0	0.005
Sr0	Initial root zone storage deficit	[m]	0	0.1
Srmax	Maximum root zone storage deficit	[m]	0.1	0.2
td	Unsaturated zone time delay	[h m^{-1}]	0	3
vch	Overland flow velocity	[m h^{-1}]	1000	1000
vr	Channel flow velocity	[m h^{-1}]	1500	2300
K0	Surface hydraulic conductivity	[m h^{-1}]	0	1
CD	Capillary drive	[m]	0	5
dt	Time step	[h]	0.5	0.5

Baseline simulation: calibration and validation

The baseline includes hydrological modelling of the basin by applying a water balance with TOPMODEL version 0.7.2-2 available in R library (Topmodel, 2011). The model was implemented for field data during the 2008-2009 period, with a time scale of 30 minutes. Data from 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 study basin. Data from 2009 was used for the validation of the calibrated model for the Chucua basin.

Calibration is the procedure for obtaining a set of optimal parameters and initial values, adjusted to the particular characteristics of each basin (Blasone *et al.,* 2008). Calibration was started in a sensitivity analysis of the parameters, to establish an order for its calibration and thus restrict the valid ranges for the parameters and to increase the number of subsequent simulations with higher efficiency during application of GLUE procedure (Generalized Likelihood Uncertainty Estimation).

During the calibration procedure, 10000 to 50000 iterations were performed to set final model parameter values. The predictions were considered acceptable when the coefficient of Nash and Sutcliffe (1970) presented an efficiency value [$E(\theta)$] greater than 0.65 converged to the same result (Buytaert *et al.,* 2008). The Nash - Sutcliffe objective function is considered a test of goodness of fit of the hydrological prediction model, by comparison between observed and simulated discharges (Buytaert and Beven, 2011). Measured discharge was used as indicative variable, to be compared with model predictions of discharge, through the studied period.

The most sensitive parameters were found by graphical analysis that allowed detecting for each parameter variation range, the efficiency values that were reached. In these graphs, if apparent homogeneity that does not reveal a maximum efficiency value for a given parameter is observed, it is considered that there is little sensitivity and low influence on runoff response.

The parameters lay down a set of acceptable values, through an appropriate physical interpretation of them (Blasone *et al.,* 2008). The parameter values were presented graphically as uncertainties associated with the model (Beven and Freer, 2001). It was therefore found based on initial simulations and in field data taken in 2008, the valid range of each parameter used in the general model calibration, product of the initial setting parameters reported in the literature. Finally, a recalibration was performed, in which the ranges of the tightest parameters, according to the maximum and minimum values found for the sets of parameters, with the best efficiencies (Nash-Sutcliffe) were selected.

The evaluation of the efficiency of the model and the uncertainties associated with the hydrological forecasting, considers the equifinality principle (Beven, 2001), which states that there are different sets of parameters that have acceptable adjustments to the observed flows. In that sense, it was carried out an adaptation on the GLUE (Beven and Binley, 1992) to restrict the values of the parameters. That method rejects the hypothesis of the existence of a unique set of optimum parameters, and instead, uses a large sample sets associated parameters for the same behavior model indicated that can be used in later predictions. GLUE is a package that integrates with TOPMODEL to generate a complete routine of hydrological modelling (Topmodel, 2011).

As indicated below, the decision criteria used in this phase was a value of $[E(\theta)] \geq 0.65$ on the sets of simulated parameters. This means that parameter sets with efficiencies above this value, were considered as behavioral parameters. The selection of the best simulations was also performed using a physical criterion: the value produced by infiltration excess overland flow (FEX). This criterion along with the components of the dominant hydrological processes to the ecosystem greatly facilitates the understanding of the páramos and contributes to note the definition of the line base of hydrological simulation. Given the computational limitations for simultaneous simulation and calculation of all components of the model for thousands of set of parameters, only five sets of parameters were selected, which showed relatively high efficiencies (>70%) and low FEX values.

As for validation, at this stage it is determined in what degree of accuracy the model reproduces or imitates independent information, using the values of the parameters found during calibration (Beven, 2001). For this purpose, we used field data from 2009, for which the efficiencies parameter $[E(\theta)] > 0.755$ were used to validate the model performance. The ranges of values obtained for each parameter in the calibration step were adjusted again in subsequent simulations to ensure greater efficiencies. Therefore it was obtained a new set of parameters whose values and efficiency is coincident with the found in 2008. The method used to validate the information was useful to incorporate the best set of parameters found and their subsequent application in the validation phase.

RESULTS AND DISCUSSION

Baseline simulation

Topographic index map of the basin is presented in Figure 3, indicating a correspondence between the highest values of the index and the drainage network; where areas with higher values (9 to 12) correspond to the level where the drainage network occurs. These differences between values are attributed to the quality of the DEM (Pan *et al.,* 2004). Although this may influence the spatial distribution of saturation zones, it does not affect the prediction of flows. 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 (Beven, 1997), and they are characterized by low transmissivity, thus the water table reaches the surface. These areas in the basin may generally correspond to narrow valleys and/or holes or circles originated in Pleistocene (Güntner *et al.,* 1999), in which, the saturation condition causes a decrease in the amount of subsurface flow and leads to fully development saturated areas.

The average value of the index for the basin was 8.10, which is relatively high; however the distribution of these values by class-mark, showed that the category where most of the pixels were grouped on the map (17.7% of basin area), has a lower value (5.19). Values of the index between 3 and 6, are associated with areas of higher slopes (Campling *et al.,* 2002), which are very common in Chingaza páramo.

Topography has a strong influence on the hydrological response of a basin, and this is represented in the model

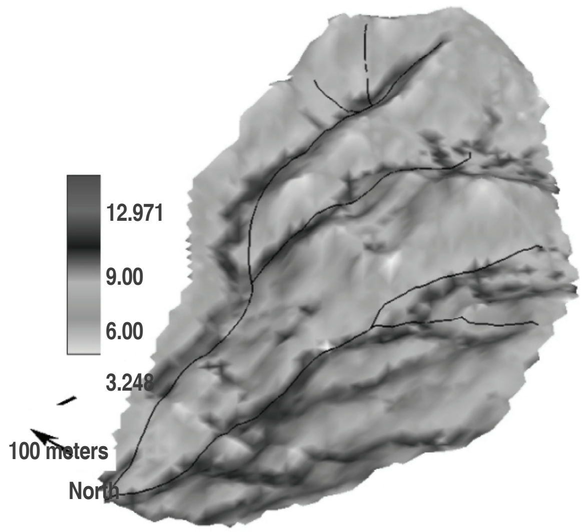


Figure 3. Spatial distribution of the topographic index in The Chucua basin.

with the topographic index. Local depressions and flat areas where drainage accumulates frequently generate saturated conditions. At the same time, the high porosity and infiltration capacity of the soils in páramos, in combination with the typical low rainfall intensity, virtually eliminate infiltration excess overland flow (Buytaert *et al.,* 2006b). As a result, the dominant process to generate surface runoff is saturation excess overland flow, which is expected not to occur in studied páramo. In that sense TOPMODEL provides a more complex representation of the basin according to the functioning of the páramo (Buytaert and Beven, 2011).

Sensitivity analysis

Initial simulations with iterations between 10000 and 50000 for 2008 data were made, in which no significant differences in values of $E(\theta)$ and FEX were found. Therefore a maximum of 10000 iterations was selected to optimize the capacity of the computer in the execution of calibration and validation processes. From the 10000 simulations for 2008, 3065 simulations obtained $E(\theta) \geq 0.65$, which would be considered acceptable (Buytaert *et al.,* 2008). The results of the sensitivity analysis (Figure 4) showed that the parameters of lower sensitivity are those who did not reveal any optimum value over the range of possible values. Thus, the sensitive analysis showed that the order at which the model is more sensitivity to changes in parameter values is: *Sr0*, *k0*, *CD*, *qs0*, *Srmax*, *td*. This coincides with the sensitivity analysis performed in a páramo in Ecuador (Buytaert *et al.,* 2003), where lower sensitivity parameter was *Srmax*.

Moreover, soil parameters *m*, *vr* and *LnTe*, results to be the most sensitive ones, since they showed their maximum values in the respective ranges 0 - 0.005, 1500 - 2300 and 0.5 - 3, which supports the importance premise of these three parameters in the hydrological response of the basin (Campling *et al.,* 2002). Ranges of these parameters were adjusted, due to the fact they present an incidence on the discharge magnitude and thus in the efficiency, by 31.4%, 8.9% and 2.7%, respectively.

Parameter *m* represents the hydraulic conductivity of the páramo soils. A very small value of this parameter indicates a slow movement of water in the soil, and soil water flow drops at soil moisture below saturation point (Buytaert *et al.,* 2003). This parameter is related to subsurface flow control and the deficit of local storage, which is important in the case of water regulation of the páramos, because it is common to attribute to páramos soils high buffering capacity. This condition is positively correlated with the continuous base flow in páramo ecosystems (Buytaert and Beven, 2011). Therefore, this parameter has a significant effect on the calculation of the local storage deficit, contributing areas (distribution of surface and / or subsurface flow) and the shape of the curve in the hydrograph recession.

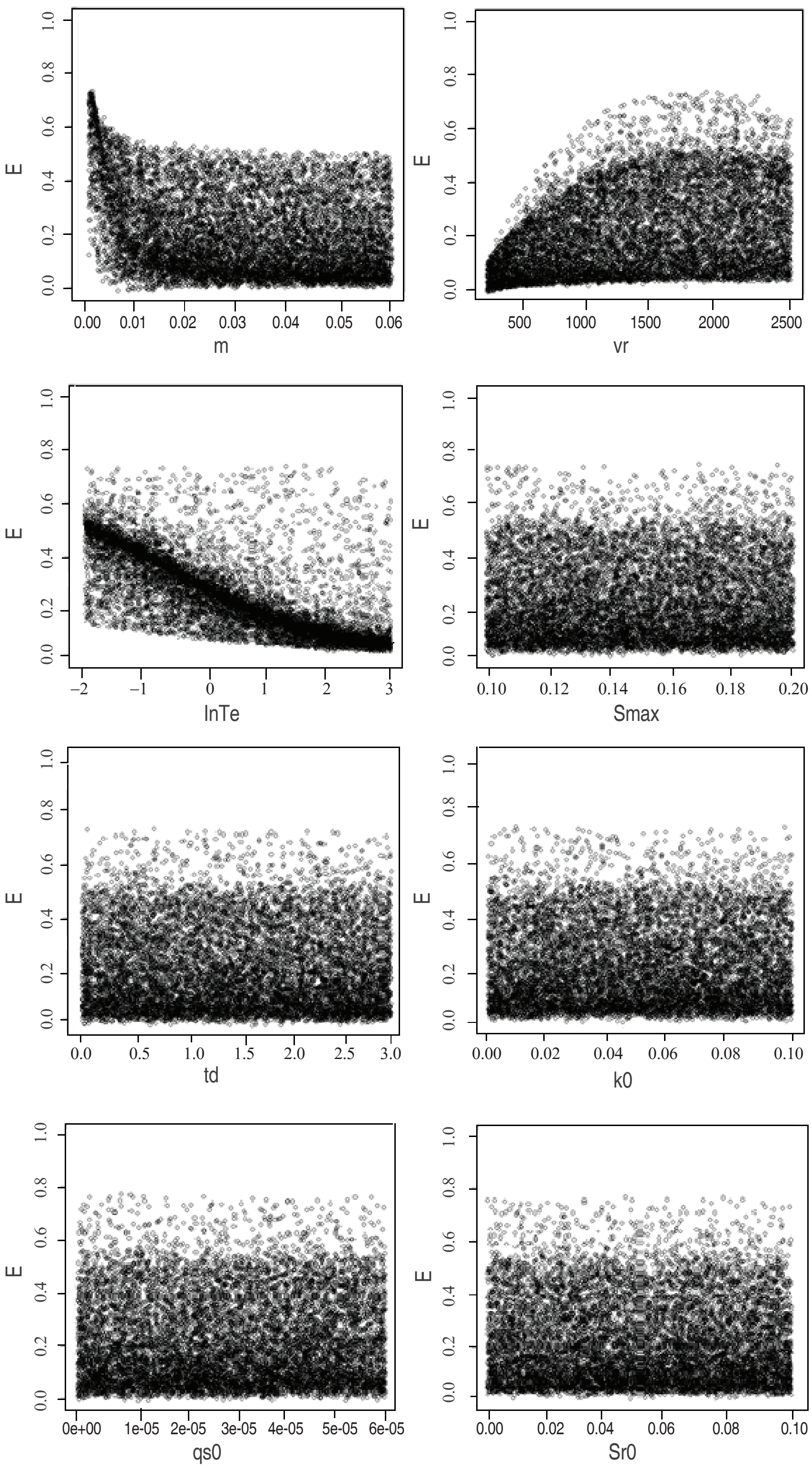


Figure 4. Scatter plots of behavioral parameter sets run through the 2008 time series.

Low values of *m* (as in our case 0.00065, see Table 4, parameter set 3) indicate an effective minimum depth of the water table, associated to a high transmissivity under saturation conditions (2.02 m^2 h^{-1}), which indicates a dominance of subsurface runoff generation in the soil. Moreover, smaller values of parameter *m* implies higher values of rainfall infiltration, which in fact occurs in studied páramo, as in most undisturbed páramos (Tobón, 2009). This, in time, explains the negligible infiltration excess overland flow found in this study, as most of the water is stored in the soil.

The *vr* parameter is related to transit time in basins, which is assumed aggregated in the model. This parameter, together with the delay function of the basin is related to the representation of flows, especially the peaks, because the movement of water in the channel is a function of time that each area within the basin reversed to gauging point (Buytaert *et al.,* 2003).

Model calibration

From the sensitivity analysis, the tightest range of each parameter was used in the overall calibration of the model (Table 2). Further, during the process of recalibration, the values of model parameters were selected (Table 3), and maxima and minima corresponding to the parameter sets with the highest values of efficiencies (>0.755) obtained in the simulations performed from table 2 values.

Table 3. Final ranges selected for calibration.

Parameter	Range	
qs0	2.81×10^{-7}	5.52×10^{-5}
LnTe	0.664	2.132
m	2.64×10^{-4}	6.20×10^{-4}
Sr0	6.99×10^{-5}	6.95×10^{-2}
Srmax	0.106	0.196
td	0.083	2.986
vch	1000	1000
vr	1575.2	1894.7
K0	0.0289	0.961
CD	0.556	4.825
dt	0.5	0.5

The results from GLUE calibration, (Table 4) generates the sets of parameters with the best efficiency of the objective function [$E(\theta)$], and a physical meaning for the hydrological functioning of the basin. Four sets (named 2, 3, 4 and 5) showed the lowest value of infiltration excess overland flow (FEX), with efficiencies greater than 0.755. For this series of calibration data, set one in table 4 yielded the highest efficiency [$E(\theta)$ = 0.7610]; however, 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 ecosystem.

For a better fit in the values of the parameters to the conditions of the studied páramo, it was necessary to sacrifice efficiency in estimating the set of parameters, ie, slightly higher values of FEX resulted in a better fit between the model predictions and field measurements. Accordingly, we select parameter set number 3 (Table 4), although it has a low value of FEX, but with the highest efficiency (0.7558). This set of parameters was used to calculate simulated discharge by TOPMODEL during 2008 (Figure 5).

Model validation

From the processes of validation of the model results obtained from the calibrated parameters, the values of efficiency and FEX are shown in table 5, with the best five sets of parameters. The assembly which had the highest efficiency value in the validation stage was the set number 6 with a [$E(\theta)$] value near 0.7618.

The overall efficiency of the model slightly increase during the validation process, which means that the model efficiently predicts the hydrological functioning of the Chucua basin,

Table 4. Selected sets parameters for calibration (10000 iterations).

Parameter	Unit	Parameter set				
		1	2	3	4	5
qs0	[m]	4.44×10^{-5}	9.82×10^{-6}	1.37×10^{-5}	3.37×10^{-5}	4.27×10^{-5}
LnTe	[m^2 h^{-1}]	1.656	1.871	2.029	1.891	1.855
m		4.91×10^{-4}	6.53×10^{-4}	6.53×10^{-4}	6.38×10^{-4}	5.91×10^{-4}
Sr0	[m]	6.87×10^{-5}	1.51×10^{-3}	1.23×10^{-3}	5.20×10^{-3}	6.33×10^{-3}
Srmax	[m]	0.140	0.193	0.197	0.119	0.182
td	[h m^{-1}]	1.598	2.378	1.900	2.322	2.921
vch	[m h^{-1}]	1000	1000	1000	1000	1000
vr	[m h^{-1}]	1737.2	1777.5	1808.6	1873.7	1711.8
K0	[m h^{-1}]	0.945	0.447	0.451	0.901	0.802
CD	[m]	2.466	3.513	3.267	2.689	3.474
dt	[h]	0.5	0.5	0.5	0.5	0.5
FEX	[m]	0.3550	0.2277	0.2294	0.2306	0.2610
***E*(*θ*)**		0.7610	0.7557	0.7558	0.7557	0.7555

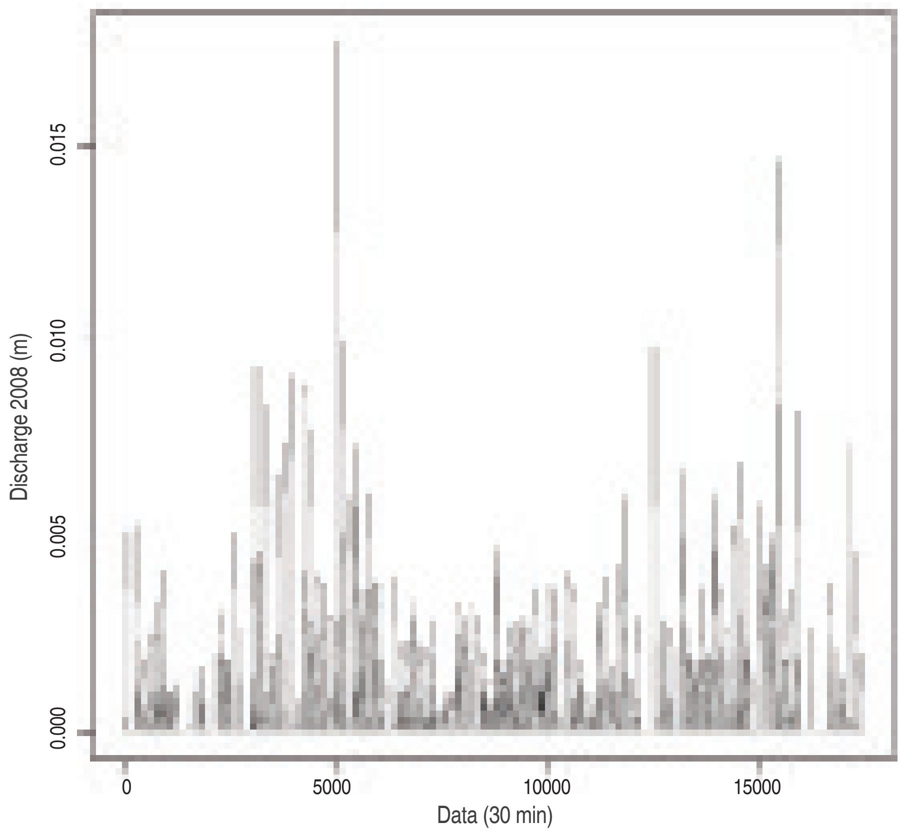


Figure 5. Observed (black) and simulated (gray) discharge from The Chucua basin during 2008.

not only for 2008, but also for 2009, with calibrated values of parameters.

According to the results, it appears to be a direct relationship between the FEX and efficiency associated with the parameter sets, suggesting that a gain on the predictive power of the model means a better ability to adequately represent the behavior of the páramo; so by choosing the sets that result in greater efficiency, meaning the increase of the generating process by infiltration excess overland flow. Therefore, we select the set of parameters with one of the lowest values of FEX (Figure 6), which have physical meaning consistent with the observed hydrological functioning of studied páramo ecosystem.

Table 5. Results of the validation process with the series of records for the year 2009 (10000 iterations).

Parameter	Unit	Parameter set				
		6	7	8	9	10
qs0	[m]	$2.52x10^{-5}$	$1.79x10^{-5}$	$3.97x10^{-5}$	$2.22x10^{-6}$	$7.95x10^{-6}$
LnTe	[m^2 h^{-1}]	1.889	1.821	1.948	1.808	1.926
m		$5.85x10^{-4}$	$6.52x10^{-4}$	$6.51x10^{-4}$	$6.15x10^{-4}$	$6.24x10^{-4}$
Sr0	[m]	$7.56x10^{-3}$	$8.30x10^{-3}$	$2.69x10^{-3}$	$1.69x10^{-2}$	$5.50x10^{-3}$
Srmax	[m]	0.197	0.153	0.122	0.137	0.120
td	[h m^{-1}]	0.239	2.765	0.541	2.269	2.170
vch	[m h^{-1}]	1000	1000	1000	1000	1000
vr	[m h^{-1}]	1705.6	1750.2	1787.4	1700.5	1768.0
K0	[m h^{-1}]	0.902	0.716	0.860	0.790	0.602
CD	[m]	4.667	3.697	3.780	2.971	2.635
dt	[h]	0.5	0.5	0.5	0.5	0.5
FEX	[m]	0.4298	0.3723	0.3725	0.4158	0.4223
E(θ)		0.7618	0.7604	0.7604	0.7603	0.7601

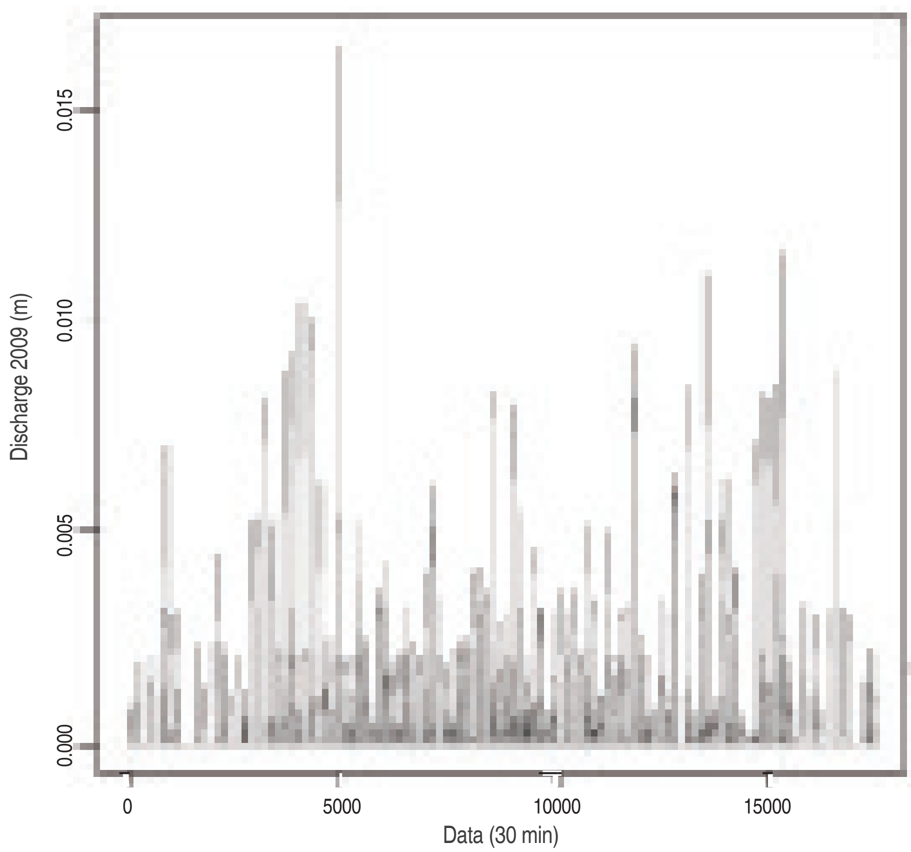


Figure 6. Observed (black) and simulated (gray) discharge from The Chucua basin during 2009.

The model efficiency (0.7579) was slightly higher than that obtained during the calibration process, however discharge results shows a slightly underestimation of the peaks and overestimation of minimum values.

The efficiencies found are close to the values obtained for a proven model in a páramo basin in Ecuador [E(θ)= 0.67] (Buytaert and Beven, 2011). However, it is possible that shorter periods of time could help ensure better simulations and adjustments, because to the extent that more data is added to model variability increases. Moreover, it is widely known that TOPMODEL has some problems to accurately represent low flows during droughts (Dietterick *et al.,* 1999; Güntner *et al.,* 1999; Gallart *et al.,* 2007; Buytaert and Beven, 2011). For periods where precipitation exceeds evapotranspiration (as most of the time in this study), the wide range of parameters provide acceptable simulations for basin discharge, although base flow is less accurately simulated, as it happen in other sites (Gallart *et al.,* 2007).

Finally we identified the dominant hydrological processes for the studied páramo ecosystem (Table 6), based on the selected set of parameters, during the calibration and validation phases (set 3). These results showed that in general terms, the dominant process that control the hydrological processes of the studied páramo is mainly controlled is the subsurface flow discharge (q_s). This process is 1.7 times greater than the surface discharge process excess saturation (q_o) which generates only 933 mm of water on average for 2008 and 2009, thus, this process can also be considered important for these ecosystems, which is control the saturated contributing areas.

Table 6. Key processes during calibration and validation of TOPMODEL for The Chucua basin.

Phase	E(θ)	Q_{obs} (m)	Q_{sim} (m)	q_o (m)	q_s (m)	FEX (m)
Calibration	0.7557	2.30	2.50	0.84	1.66	0.23
Validation	0.7579	2.32	2.62	1.02	1.60	0.40

Q_{obs}: observed discharge; Q_{sim}: simulated discharge

Comparisons with previous findings in similar páramo ecosystems (Buytaert and Beven, 2011), show that there is a tendency in the order of parameter sets, for the sensitivity analysis, but also a similarity on the parameters that control the hydrological functioning of the páramo ecosystems. This implies that undisturbed páramos, similar to that studied here, may have identical behavior of water flows, when investigated with TOPMODEL.

CONCLUSIONS

TOPMODEL applied to the páramo ecosystem in The Chucua basin, adequately represents the relationship between rainfall and discharge, since the parameter sets obtained had a physical explanation and generated high efficiency predicting flows with high efficiency coefficients Nash - Sutcliffe (greater than 0.75). In addition, the values of model parameters remain relatively stable over time, and indicate that subsurface discharge is the dominant process in studied basin. This result provides comparative advantages for the simulation of hydrological processes in tropical montane ecosystems, specifically in those sites where with difficulties to measure hydrological variables.

Although TOPMODEL showed to be a reliable tool to simulate several flows by component, certain shortcomings persist. These modelling challenges associated with complexity related to the spatial variation of hydrological processes and the structure of the model, can be effectively addressed in future research of hydrology of páramos ecosystems, with more accurate predictions.

ACKNOWLEDGMENTS

The authors are grateful to Department of Science, Technology and Innovation -COLCIENCIAS for its Young Researchers and Innovators Program, years 2008-2009 and 2009-2010 and also the International Potato Center -CIP / Consortium for Sustainable Development of the Andean Ecoregion –CONDESAN, for providing financial support for this work.

REFERENCES

Albek M, Ogutveren UB and Albek E. 2004. Hydrological modeling of Seydi Suyu watershed (Turkey) with HSPF. Journal of Hydrology 285: 260–271. doi:10.1016/j.jhydrol.2003.09.002.

Almeida S, Bulygina N, McIntyre N, Wagener T and Buytaert W. 2013. Improving parameter priors for data-scarce estimation problems. Water Resources Research 49(9): 6090–6095. doi: 10.1002/wrcr.20437.

Beven KJ and Kirkby MJ. 1979. A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin-des Sciences Hydrologiques 24(1): 43 - 69. doi: 10.1080/02626667909491834.

Beven KJ, Kirkby MJ, Schofield N and Tagg AF. 1984. Testing a physically-based flood forecasting model (TOPMODEL) for three U.K. catchments. Journal of Hydrology 69(1-4): 119-143.

Beven KJ and Binley A. 1992. The future of distributed models: model calibration and uncertainty prediction. Hydrological Processes 6: 279–298. doi: 10.1002/hyp.3360060305.

Beven K. 1997. TOPMODEL: A critique. Hydrological Processes 11(9): 1069-1085.

Beven K and Freer J. 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. Journal of Hydrology 249(1-4): 11-29. doi:10.1016/S0022-1694(01)00421-8.

Beven KJ. 2001. Rainfall-runoff modelling: the primer. 2nd edition. Wiley-Blackwell, 360p.

Blasone RS, Madsen H and Rosbjerg D. 2008. Uncertainty assessment of integrated distributed hydrological models using GLUE with Markov chain Monte Carlo sampling. Journal of Hydrology 353(1-2): 18-32. doi:10.1016/j.jhydrol.2007.12.026.

Buytaert W, Celleri R, De Bièvre B, Deckers J and Wyseure G. 2003. Modelización del comportamiento hidrológico de microcuencas de páramo en el sur del Ecuador usando TOPMODEL. http://páramo.cc.ic.ac.uk/pubs/ES/topmodel.pdf.

Buytaert W, Célleri V, De Bièvre B, Cisneros F, Wyseure G, Deckers J and Hofstede R. 2006a. Human impact on the hydrology of the Andean páramos. Earth-Science Reviews 79(1-2): 53-72. doi:10.1016/j.earscirev.2006.06.002.

Buytaert W, Célleri R, Willems P, De Bièvre B, Wyseure G. 2006b. Spatial and temporal rainfall variability in mountainous areas: a case study from the south Ecuadorian Andes. Journal of Hydrology 329: 413–421. doi: 10.1016/j.jhydrol.2006.02.031

Buytaert W, Reusser D, Krause S and Renaud J.P. 2008. Why can't we do better than TOPMODEL?. Hydrological Processes 22: 4175-4179. doi: 10.1002/hyp.7125.

Buytaert W, Célleri R and Timbe L. 2009. Predicting climate change impacts on water resources in the tropical Andes: the effects of GCM uncertainty. Geophysical Research Letters 36(L07406). http://páramo.cc.ic.ac.uk/pubs/2009_GRL.pdf.

Buytaert W and Beven K. 2011. Models as multiple working hypotheses: hydrological simulation of tropical alpine wetlands. Hydrological Processes 25(11): 1784-1799. doi: 10.1002/hyp.7936.

Buytaert W, Cuesta F and Tobón C. 2011. Potential impacts of climate change on the environmental services of humid tropical alpine regions. Global Ecology and Biogeography 20(1): 19-33. doi: 10.1111/j.1466-8238.2010.00585.

Buytaert W and De Bièvre B. 2012. Water for cities: The impact of climate change and demographic growth in the tropical Andes. Water Resources Research 48(8): 1-13. doi: 10.1029/2011WR011755.

Buytaert W and Breuer L. 2013. Water resources in South America: sources and supply, pollutants and perspectives. pp. 106-113. In: Proceedings of the IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 359, 2013).

Campling P, Gobin A, Beven K and Reyen J. 2002. Rainfall-runoff modelling of a humid tropical catchment: the TOPMODEL approach. Hydrological Processes 16: 231-253. doi: 10.1002/hyp.341.

Croke BFW, Merritt WS and Jakeman AJ. 2004. A dynamic model for predicting hydrologic response to land cover changes in gauged and ungauged catchments. Journal of Hydrology 291(1-2): 115-131. doi:10.1016/j.jhydrol.2003.12.012.

Da Silva RV and Kobiyama M. 2007a. Estudo Comparativo de Três Formulações do TOPMODEL na Bacia do Rio Pequeno, São José dos Pinhais, PR. Revista Brasileira de Recursos Hídricos, Porto Alegre 12(2): 93-105. https://www.abrh.org.br/SGCv3/index.php?PUB=1&ID=20&SUMARIO=287.

Da Silva RV and Kobiyama M. 2007b. TOPMODEL: Teoria integrada e revisão. Topmodel: integrated theory and review. R. RA´E GA. Curitiba, 14: 97-110. Editora UFPR.

De Bièvre B. 2009. Estado del conocimiento de la hidrología de ecosistemas andinos. In: Workshop on Integrated Space Technologies Applications for Sustainable Development in the Mountain Regions of Andean Countries. Lima, Peru, septiembre 14 a 18.

Departamento de Agricultura de los Estados Unidos USDA and Servicio de Conservación de Recursos Naturales NRCS. 2014. Claves para la taxonomía de suelos. Décima segunda edición. Montecillo, Texcoco, Estado de México. 410 p.

Dietterick BC, Lynch JA and Corbett ES. 1999. A calibration procedure using TOPMODEL to determine suitability for evaluating potential climate change effects on water yield. JAWRA Journal of the American Water Resources Association 35(2): 457-468.

Foster P. 2001. The potential negative impacts of global climate change on tropical montane cloud forests. Earth-Science Reviews 55(1-2): 73-106.

Franchini M, Wendling J, Obled C and Todini E. 1996. Physical interpretation and sensitivity analysis of the TOPMODEL. Journal of Hydrology, 175(1-4): 293-338. doi:10.1016/S0022-1694(96)80015-1.

Gallart F, Latron J, Llorens P and Beven K. 2007. Using internal catchment information to reduce the uncertainty of discharge and baseflow predictions. Advances in Water Resources 30(4): 808-823. doi:10.1016/j.advwatres.2006.06.005.

Güntner A, Uhlenbrook S, Seibert J and Leibundgut C. 1999. Multi-criterial validation of TOPMODEL in a mountainous catchment. Hydrological Processes 13(11): 1603-1620.

Instituto de Hidrología, Meteorología y Medio Ambiente -IDEAM. 2002. Páramos y Ecosistemas Alto Andinos de Colombia en Condición HotSpot y Global Climatic.

Monteith JL. 1965. Evaporation and environment. Symp. Soc. Exp. Biol, 19: 205-234 pp.

Nash JE and Sutcliffe JV. 1970. River flow forecasting through conceptual models part I. A discussion of principles. Journal of Hydrology 10(3): 282-290.

Pan F, Peters Lidard CD, Sale MJ and King AW. 2004. A comparison of geographical information systems–based algorithms for computing the TOPMODEL topographic index. Water Resources Research 40: 1-11. doi:10.1029/2004WR003069.

Sklenár P. 2000. Vegetation ecology and phytogeography of Ecuadorian superpáramos. PhD Thesis. Charles University. Praga.

Tobón C. 1999. Monitoring and modeling hydrological fluxes in support of nutrient cycling studies in Amazonian rain forest ecosystems. The Tropenbos Foundation - III. - (Tropenbos Series; 17). ISBN 90-5113-035-X. Wageningen, the Netherlands. 169p.

Tobón C. 2009. Los bosques andinos y el agua. Serie de investigación y sistematización #4. Programa Regional ECOBONA – INTERCOOPERATION, CONDESAN. Quito, mayo 2009. 127 p.

TOPMODEL. 2011. Implementation of the hydrological model TOPMODEL in R version 0.7.2-2 (septiembre 2011). Buytaert W. Imperial College London. Disponible en: http://cran.r-project.org/web/packages/topmodel/topmodel.pdf.

Viviroli D, Zappa M, Gurtz J and Weingartner R, 2009. An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools. Environmental Modelling & Software 24(10): 1209-1222. doi:10.1016/j.envsoft.2009.04.001.

Vuille M, Francou B, Wagnon P, Juen I, Kaser G, Mark BG and Bradley RS. 2008. Climate change and tropical Andean glaciers: Past, present and future. Earth-Science Reviews 89(3-4): 79-96. doi:10.1016/j.earscirev.2008.04.002.