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Key Points:

- The Soil and Water Assessment Tool is used to simulate saturation excess surface runoff processes.
- A soil-based modeling approach can reasonably represent the hydrology of Neotropical Alpine grasslands or Andean Páramo.
- Despite satisfactory performance metrics, modeling the Páramo's runoff using the infiltration excess approach can generate unreliable outcomes.

Abstract

To support the hydrological assessment of Alpine ecosystems, we studied the suitability of the SWAT model to simulate neotropical alpine grasslands or so-called Andean Páramo. Given the paucity of observational data in páramo catchments, data-driven models are usually underutilized, and their outcomes are arguable. However, our research examined if SWAT can reasonably represent the hydrological response of grassland-dominated páramo catchments under data-abundance conditions. Therefore, we set up a soil-based SWAT model that emphasized the role of the soil in the hydrological response and the dominance of saturation excess surface runoff over infiltration excess. Specifically, we incorporated detailed characteristics of Andean soils by horizons, parameterized SWAT to replicate high infiltration rates and high lateral flow in the hillslopes, and restricted groundwater interactions to replicate local streamflow responses. Our soil-based modeling approach reasonably reproduced daily discharge during dry and wet periods throughout the year and the cumulative occurrence of high and low flows. The ratio of precipitation and simulated runoff and the partitioning of the total runoff into the lateral flow and surface runoff were physically meaningful. More significantly, SWAT was able to simulate saturation excess overland flow, which is dominant compared to infiltration excess, and it is a distinctive characteristic of páramo catchments. Based on the overall model performance, we conclude that SWAT can reasonably simulate the hydrological response of Andean páramo catchments, and therefore, its application can extend to similar tropical alpine catchments. Nevertheless, the model showed limitations for simulating low flows.

1 Introduction

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) SWAT has shown limitations when applied to tropical alpine catchments where highly conductive soils generate surface runoff as saturation excess overland flow (Moges et al., 2017). These limitations are particularly pronounced in high-elevation peat-dominated areas that remain saturated with water throughout the year, such as the marshy grasslands in Scotland, the Afroalpine wetlands of South-central Ethiopia, or the Andean Páramo in South America, among others. In Páramos, the soil infiltration rates usually exceed rainfall intensities (Buytaert et al., 2005) and, therefore, surface runoff by infiltration excess (which is SWAT's default assumption) is negligible (Buytaert et al., 2007; Crespo et al., 2011; Poyck et al., 2006). For example, in a model intercomparison study in a tropical alpine catchment in the tropical Andes, Plesca et al. (2012) stated that the main disadvantage of SWAT in comparison to other models was that it required a detailed description of soil's physical properties while soil data are relatively scarce in the tropical Andes and other mountainous regions. In another model comparison study in the Ethiopian Highlands of Africa, Moges et al. (2017) explained that, despite the inadequacy of SWAT to simulate saturation excess surface runoff, infiltration excess could generate satisfactory results at the monthly scale. Finally, two studies in a catchment with a predominance of saturation excess surface runoff in the state of New York (Hoang et al., 2017; Steenhuis et al., 2019) showed that SWAT failed to identify saturated areas that generate surface runoff. Despite the limitations, SWAT is still widely applied in Páramo catchments because the understanding of the Páramo's hydrology has substantially improved in the last decade and has improved the ability of hydrological models to reproduce streamflow better (Correa et al., 2020).

Efforts to improve SWAT applications in tropical alpine catchments have focused on calibrating vegetation-related model parameters and simulating surface runoff by saturation excess. However, few studies reported the significant role of the soil's physical properties and local soils' massive water storage capacity. For example, modified SWAT versions such as SWAT-T (Alemayehu et al., 2017) and SWAT-Tb (Valencia et al., 2021) satisfactorily reproduced streamflow and Leaf Area Index (LAI) variability of tropical Andean forests. In the Peruvian Andes, Fernandez-Palomino et al. (2021) improved the prediction capacity of SWAT by adjusting LAI-related parameters using remote sensing data and applying a multi-objective calibration scheme based on statistical performance metric and hydrological signatures (e.g., flow duration curves (FDC) and baseflow index (BFI)). These modifications have improved SWAT simulations in Andean basins, but their application in Páramos was limited because surface runoff was still modeled through infiltration excess.

Although SWAT versions such as SWAT-Hillslope (SWAT-HS) (Hoang et al., 2017) and SWAT-with-impermeable-layers (SWAT-wil) (Steenhuis et al., 2019) can reproduce surface runoff by saturation excess, these models are based on topographical characteristics. Thus, these models disregard the significant role of soil's physical properties in the local watershed hydrology. For example, SWAT-HS and SWAT-wil were tested in the Town Brook watershed, a mountainous catchment in the U.S. on moderate slopes with impermeable bedrock layers and shallow soils with infiltration rates that resemble the Páramo characteristics. These models divide the watershed into subbasins and classify them by wetness classes using a topographic wetness index. Then, saturation excess surface runoff is reproduced by restricting overland flow in wet areas, usually near the riparian zone. Both models (SWAT-HS and SWAT-wil) reasonably identified saturated areas and simulated the spatial distribution of the runoff components, such as surface runoff and lateral flow. However, to generate overland flow in saturated areas, these models assumed a reduced water storage capacity of riparian soils. This assumption is unsuitable for Páramo catchments, whose soils exhibit excellent water retention capacity (Buytaert et al., 2007). So far, SWAT applications in tropical Andean catchments have not modeled the Páramos' runoff as saturation excess or considered the variability of soil properties at several depths.

Therefore, we propose a soil-based SWAT simulation with an improved representation of saturation excess overland flow that can accurately simulate the rainfall-runoff responses of neotropical alpine catchments in Páramos. Our approach considers a detailed representation of soil physical properties at several depths and constraining soil-related model parameters based on field measurements. The model setup assumes an absence of groundwater return flow with an impermeable bedrock layer below the soil root zone and a controlled generation of overland surface runoff. Overland flow generation is reduced at steep slopes but increased at lower slopes. Finally, the modeling outcomes are evaluated based on statistical performance metrics, flow duration curves, and the distribution of the water balance components. The study also highlights how SWAT simulations that calculate surface runoff by infiltration excess may lead to inaccurate outcomes, despite satisfactory results (Kirchner, 2006). Given the versatility of the SWAT model for simulating processes in land surface and water at the catchment level and over long periods, our soil-based SWAT model can be suitable to explore short- and long-term impacts due to links among land-use change, changes in the soil physical properties, and streamflow generation of Andean Páramo catchments.

2 Data and Methods

2.1 Study Area

The Zhurucay Ecohydrological Observatory (ZEO) is an intensively monitored experimental site established in 2010 by the University of Cuenca in the Tropical Andes in southern Ecuador (Figure 1). The drainage area comprises 7.53km^2 of nested catchments in which altitude spans between 3400 and 3900 m.a.s.l (Mosquera et al., 2015). Its geomorphology consists of U-shaped glacial valleys with slopes ranging between 0% and 20%, although slopes up to 40% can be found (Mosquera et al., 2016b). The geology is dominated by the Quimsacocha (basalts, feldspars, and andesitic pyroclasts) and the Turi formations (tuffaceous andesitic breccias, conglomerates, and stratified fluvial sands), and Quaternary deposits in a smaller proportion (Pratt et al., 1997)

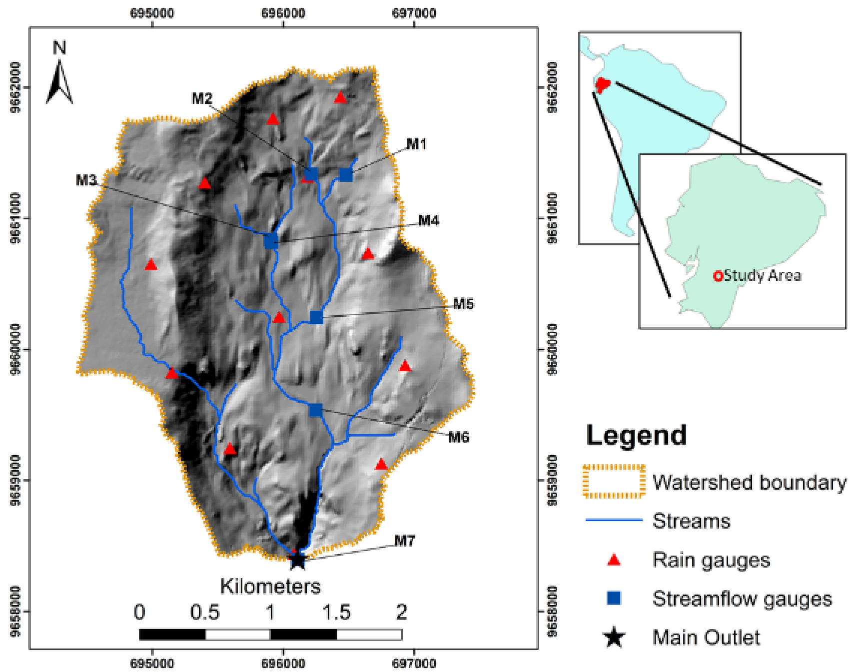

Figure 1. Location of the study area and monitoring network of rain gauges and streamflow weirs (M) within the Zhurucay Ecohydrological Observatory in Ecuador.

The Pacific regime mainly influences climate from the west and air masses originating from the Amazon Basin in the east (Vuille et al., 2000). The mean air temperature is 6 C at 3780 m.a.s.l. (Cordova et al., 2015) and generally constant throughout the year (Crespo et al., 2011). The annual precipitation is 1345 mm (Mosquera et al., 2016a), but fog and drizzle interception account for an additional 15% (Padrón et al., 2015). Rainfall intensities are low and rarely exceed 5 mm h-1 (Padrón et al., 2015). The annual average discharge is 864 mm y-1 representing about 60% of the total rainfall (Mosquera et al., 2015). Reported runoff coefficients values of 0.68 (Mosquera et al., 2015) and 0.8 (Correa et al., 2016) suggest the catchment is highly responsive to rainfall events. Annual reference evapotranspiration is 732 mm (Cordova et al., 2015), representing about 40% of the annual precipitation volume (Mosquera et al., 2015).

The main soils in the Zhurucay River catchment are Histosol and Andosol (IUSS-WorkingGroup, 2015) (approximately 24% and 76% of the catchment area, respectively), although there are small areas of Cambisol and Leptosol soils (Correa et al., 2016). Histosols are found at the bottom of the valleys and the foot of the hillslopes (Buytaert et al., 2006). However, small isolated patches of Histosol can also be found on the hilltops, which are hydrologically disconnected from the slopes (Mosquera et al., 2016a). Histosols usually consist of a highly organic H horizon, ranging from 24 to 70 cm depth, and a mineral C horizon with an average depth of 30 cm; however, they may be several meters deep in wetland areas (Buytaert and Beven, 2011).

In most páramos, Andosols are located at the hillslopes and are shallower than Histosols, and their depth varies according to the physiographic position (Aucapiña and Marín, 2014). For example, Andosols located in the middle slopes exhibit an organic Ah horizon and a C horizon. They are more profound than other soils found in the upper slopes and hilltops, where Andosols exhibit an Ah horizon only (Aucapiña and Marín, 2014). Due to their high organic carbon content, low bulk density, and high saturated hydraulic conductivity, both soils present a high infiltration rate and a water storage capacity of up to 90% of their volume (Buytaert et al., 2004; Iñiguez et al., 2015).

Vegetation coverage mainly comprises tussock grasses and cushion plants and is highly correlated with the main soil types (Ramsay and Oxley, 1997; Sklenář and Jørgensen, 1999). Cushions plants dominate the bottom of the valley, and its surface extent matches closely with Histosols (Mosquera et al., 2015), while Andosols extension is occupied mainly by tussock grasses and small patches of riparian forest species and introduced pine trees (Correa et al., 2017b).

2.2 Available Data

Zhurucay arguably counts with the densest hydro-meteorological monitoring network in the Andean páramos. Over the years, Zhurucay has been equipped with: Two automatic meteorological stations that record temperature, relative humidity, precipitation, atmospheric pressure, wind speed and direction, solar radiation, and long and short wave net radiation; a network of 5 permanent rain gauges, which, during experimental periods, has been extended to twelve gauges; a water quality monitoring system based on isotopic tracers; 38 sensors for monitoring soil moisture dynamics in a hillslope; two sets of energy balance sensors; a LICOR Eddy Covariance station; and nine weirs for discharge measurements spatially distributed in the upper, middle, and lower watershed. Additional information about Zhurucay is available at https://www.ucuenca.edu.ec/idrhica/index.php/en/laboratories-and-observatories/zhurucay-ecohydrological-observatory/.

We used weather data (e.g., air temperature, relative humidity, solar radiation, and wind speed) from two locations, precipitation volume from 12 gauges, and discharge rate from 7 weirs (Figure 1). Observed streamflow at the main outlet was used to calibrate and evaluate the model. Model performance metrics were also calculated at internal weirs. Hydro-meteorological data were available at the 5-minute temporal resolution but were aggregated into daily timesteps. Data for this study covered the period 8/2010 to 2/2016. However, the period used for the simulation was 1/1/2011 to 12/31/2015.

2.3 The SWAT Model

SWAT is a semi-distributed physically-based model developed to predict the impact of management practices in watersheds and large river basins over long periods (Neitsch et al., 2011). For modeling purposes, SWAT divides the watershed into spatially related subbasins subdivided into hydrological response units (HRU), portions of the subbasin with a unique combination of land use and management and soil attributes (Neitsch et al., 2002).

SWAT has two simulation phases: a land phase that determines the amount of loadings (e.g., water, sediment, nutrient, and pesticide) discharged to the main channel of each subbasin; and a routing phase that simulates the movement of loadings through the channel network towards the main outlet. SWAT hydrologic cycle representation is based on the water balance equation:

$\mathrm{SW}_t = \mathrm{SW}_0 + \sum_{i=1}^{t} \left(R_{\mathrm{day}} - Q_{\mathrm{surf}} - E_a - w_{\mathrm{seep}} - Q_{\mathrm{gw}} \right)$ (1)

Where SWt is the final soil water content, SW0 is the initial soil water content on day i, Rday is the amount of precipitation on day i, Qsurf is the amount of surface runoff on day i, Ea is the amount of precipitation on day i, wseep is the amount of water entering in the vadose zone on day i, and Qgw is the amount of return flow on day i.

2.4 Model setup

The ArcSWAT 2012 interface was used to set up and parameterize a SWAT model. We used a 3-m resolution digital elevation model (DEM) to delineate the watershed area, internal sub-catchments, and stream network and calculate morphometric basin parameters. We applied a threshold drainage area of 20ha that generated 28 subbasins and 251 hydrological response units (HRUs). Slopes, expressed as percentage, were classified in five slope categories: 0-5, 5-10, 10-20, 20-40, and >40 (Figure 1c). The Curve Number (C.N.) method was selected to simulate surface runoff. We allowed the SWAT model to automatically adjust the C.N. number based on the slope gradient. Potential evapotranspiration (PET) was estimated using the Penman-Monteith method. The simulation period was set from 1/1/2011 to 12/31/2015 and divided into three years for model warm-up (2011-2013), one year for calibration (2014), and one for validation (2015).

The Department of Water Resources and Environmental Sciences (iDRHICA) of the University of Cuenca provided land coverage and soil data. Land coverage in the ZEO catchment consists of tussock grasses (78%), cushion plants (17%), small patches of pine forest (4%), and Polylepys forest (1%). However, land use distribution was reclassified for hydrological modeling purposes to match SWAT's land use classification.

Based on a previous application of SWAT in Andean watersheds (Quintero et al., 2013; Uribe et al., 2013), the land uses at ZEO were reclassified as follows: Winter pasture (WPAS) for representing tussock grasses, bluegrass (BLUG) for representing cushion plants, pine forest (PINE) for representing pine plantations, and deciduous forest (FRSD) for representing the Polylepis forest. For the features WPAS and BLUG, we modified the leaf area index (LAI) according to Krajenbrink (2007). The growing season for these features was set from January/1 to December/31 to represent the local perennial vegetation system better.

The soil map was reclassified into two classes: Andosol and Histosol. Areas with Leptosols and Cambisols were assigned with more dominant soil—Andosol because of their small extension. The soil physical properties for each soil type were compiled in a table and linked to the SWAT model database to assimilate the soil data into the SWAT model. Soil parameters were derived from three sources: Field measurements at 62 points across the catchment—provided by iDRHICA— and previous studies by Quichimbo et al. (2012) and Aucapiña and Marín (2014) in the same catchment. The soil sequence for each soil type was defined as follows: Horizons Ah, A, and C for Andosols, and horizons H, A, and C for Histosols. A list of averaged soil-related SWAT parameters classified by soil horizon, soil type and land coverage are presented in Table 1.

Average values for each parameter were used to create two soil classes in the SWAT soil database, while maximum and minimum values were used as a reference threshold during the calibration process. The soil parameters required by SWAT are Maximum rooting depth (Sol_ZMX), Soil layer thickness (Sol_Z), Moist bulk density (Sol_BD), Available water capacity of the soil layer (AWC), saturated hydraulic conductivity (KSat), organic carbon content (CBN), Clay content (Clay), Silt content (Silt), Sand content (Sand), Rock fragment content (Rock), Moist soil albedo (ALB) and USLE equation soil erodibility (K) factor (USLE-K).

Table 1. Soil-related input parameter used by SWAT model. Parameters are classified by soil type, soil horizon, and vegetation coverage.

Soil Type	Andosol	Andosol	Andosol	Histosol	Histosol	
Land Cover	Tussock Grass	Polylepis Forest	Pine Forest	Cushion Plants	Polylepis Forest	
Soil Horizon	Ah	A	C	Ah	A	C
Parameter						
Sol_ZMX (mm)	120	120	120	120	120	12
Sol_Z (mm)	460	760	1060	380	710	10
Sol_BD($g\ cm^{-3}$)	0.40	0.43	0.85	0.43	0.50	0.4
AWC($mm^3\ mm^{-3}$)	0.34	0.34	0.31	0.39	0.39	0.4
Ksat ($mm\ h^{-1}$)	13.00	15.30	11.00	17.50	19.50	7.8
CBN (%)	18.58	17.06	5.12	19.40	16.96	11
Clay (%)	16	25	34	16	28	21
Silt (%)	15	37	24	16	30	21
Sand (%)	69	38	42	68	42	58
Rock (%)	0.00	0.00	0.00	0.00	0.00	0.0
ALB	0.10	0.10	0.20	0.10	0.10	0.2

Soil Type	Andosol	Andosol	Andosol	Histosol	Histosol	
USLE-K	0.16	0.16	0.16	0.16	0.16	0.1

2.5 Model Calibration

Two rainfall-runoff simulation approaches were evaluated during the calibration process: a SWAT with infiltration excess runoff and a SWAT with saturation excess runoff that emulates a saturation excess surface runoff signal. SWAT has been applied with the infiltration excess runoff calculation in several Andean catchments (Espinosa and Rivera, 2016; Hasan and Wyseure, 2018; Plesca et al., 2012; Quintero et al., 2009), and all of them have reported satisfactory results. Modified SWAT versions that simulate saturation excess surface runoff, such as SWAT-HS and SWAT-wil, have not been tested in the Andes. However, the application of these models in catchments with steep slopes and impermeable bedrock layer (Hoang et al., 2017; Steenhuis et al., 2019), which resembles the Andean paramos' configuration, demonstrate that an improved representation of the saturation excess overland flow may be suitable to simulate ZEO.

Both approaches had the same setup and initial set of parameters but only differed in defining the average slope length parameter (SLSBSSN), which controls the distance sheet flow is the dominant runoff process. The initial set of parameters aimed to represent two assumptions related to the natural characteristics of ZEO: the absence of groundwater contribution and the virtual nonexistence of overland surface runoff generation. To represent the first assumption in the model setup, we set the depth-to-the-impermeable layer parameter (DEP_IMP) equal to the depth of the deepest soil horizon for each soil type to prevent deep percolation and groundwater recharge. This impermeable layer restricted the conversion of infiltrated rainfall into aquifer recharge or groundwater return flow (GWQ) and kept the soil water (S.W.) high, and allowed increased lateral flow (LATQ).

Reduced SURQ resulted in increased LATQ and S.W. The saturated hydraulic conductivity (Ksat) and the soil available water content (AWC) parameters were set to their maximum feasible values presented in Table 1. High Ksat values increased the soil infiltration rate and favored lateral flow, while higher AWC increased soil water retention. Finally, low SLSUBBSN values reduced SURQ generation from HRUs with steep slopes. On the other hand, high SLSUBBSN favored SURQ at lower slopes near the riparian areas to generate overland surface runoff. For the default SWAT simulation, the SLSUBBSN definition criteria were disregarded, and the parameter value was defined through the automatic calibration process.

2.5.1 Automatic Calibration

The calibration software package for the SWAT model (SWAT-CUP) (Abbaspour, 2011) was used for automatic calibration. Within SWAT-CUP, we selected the Sequential uncertainty fitting (SUFI-2) algorithm (Abbaspour et al., 2004) for model calibration and used NSE as an objective function. SWAT-CUP was set on 500 iteration batches to find a set of parameters that optimizes the model performance. Several batches were required until optimizing the model. Table 2 presents the calibrated parameters with their minimum, maximum, and best-fitted values. The analyses of model uncertainties and parameter sensitivity were also performed using SWAT-CUP.

Table 2. SWAT Best-Fitted Parameters Values and Sensitivity Ranking

Parameter	Description	Fitted Value	Minimum V
V___SLSOIL.hru	Slope length for lateral subsurface flow (m)	1.41	0.00
V___SLSUBBSN.hru	Average slope length (m)		
Slope class	*(0-5)*	97.02	80.00
	(5-10)	57.66	50.00
	(10-20)	28.98	10.00
	(20-40)	3.81	0.00
	(> 40)	2.29	0.00
R___CN2.mgt	SCS runnoff curve number		
Land Use	*WPAS*	0.19	-0.25
	BLUG	-0.06	-0.25
	PINE	0.06	-0.25
	FRSD	-0.08	-0.25
V___SOL__BD.sol	Moist bulk density (Mg/m3 or g/cm3)		
Soil type (Horizon)	*Andosol(Ah)*	0.50	0.40
	Andosol(A)	0.47	0.43
	Andosol(C)	0.87	0.40
Parameter	Description	Fitted Value	Minimum V
	Histosol(H)	0.12	0.11
	Histosol(A)	0.24	0.15
	Histosol(C)	0.23	0.17
Parameter	Description	Fitted Value	Minimum V
V___SOL__AWC.sol	Available water capacity of the soil (mm H2O/mm soil)		
Soil type (Horizon)	*Andosol(Ah)*	0.29	0.24
	Andosol(A)	0.28	0.24
	Andosol(C)	0.29	0.23
	Histosol(H)	0.39	0.39
	Histosol(A)	0.59	0.39
	Histosol(C)	0.50	0.41
V___SOL__K.sol	Saturated hydraulic conductivity (mm/hr)		
Soil type (Horizon)	*Andosol(Ah)*	13.89	13.00
	Andosol(A)	36.49	15.00

Parameter	Description	Fitted Value	Minimum V
	Andosol(C)	29.61	8.00
	Histosol(H)	12.98	4.90
	Histosol(A)	10.12	5.00
	Histosol(C)	6.08	2.10
V__SOL_CBN.sol	Organic carbon content (%soil weigth)		
Soil type (Horizon)	*Andosol(Ah)*	18.99	18.00
	Andosol(A)	17.59	17.00
	Andosol(C)	9.53	1.00
	Histosol(H)	19.32	19.00
	Histosol(A)	22.27	18.00
	Histosol(C)	30.58	12.00

2.6 Uncertainty and Parameter Sensitivity Analysis

Uncertainties from all sources (e.g., input data, model parameters, conceptual model) in SWAT-CUP are expressed as the 95% probability distributions calculated at the 2.75% and 97.5% levels of the cumulative distribution of an output variable by using Latin hypercube sampling. This threshold is referred to as the 95% prediction uncertainty, or 95PPU, which defines a threshold of possible good solutions generated by specific parameter ranges. The goodness of fit is determined by two indices: The P-factor and the R-factor. The P- and R-factors both range between 0 and 1. The P factor represents the percentage of observations bracketed by the 95PPU (1 indicates 100% bracketing), and the R-factor denotes the width of 95PPU, respectively.

A global parameter sensitivity analysis was performed using SWAT-CUP. Parameter sensitivity is expressed in terms of the t-stat and p-value. Sensitive parameters are the ones having larger values of t-stat and lower p-values.

2.7 Model Evaluation

Model calibration based solely on observed discharge records may not guarantee the global optimization of the model parameters or the reliability of modeling outputs (Larabi et al., 2018; Triana et al., 2019). In this study, we evaluated hydrological signatures such as flow duration curves (FDC), the evaluation of the water balance and runoff components regarding paramo's hydrological behavior, and estimated statistical performance metrics to improve calibration accuracy.

2.7.1 Statistical Performance Metrics

The statistical metrics used to evaluate the model performance during the calibration and validation processes included the Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970), the RMSE-observations standard deviation ratio (RSR) (Moriasi et al., 2007), and the Percent Bias (PBIAS) (Gupta et al., 1999).

2.7.2 Flow Duration Curves (FDCs)

FDCs were used to compare the flow characteristics observed at ZEO with the flow characteristics generated by the two SWAT models because Crespo et al. (2011) found that, despite differences in climate and altitude, FDCs from high-elevation tropical catchments show the same particular shape, (except for highly intervened catchments) with moderate slope and predominance of low flows. Flow rates were expressed on a unit area basis (specific yield), and flow regimes were defined based on a previous study by Mosquera et al. (2015) in the same catchment. Flow regime classification was defined as follows: high flow regime corresponds to non-exceedance runoff values between Qmax and Q90; moderate flow regime corresponds to values between Q90 and Q35, and low flow regime corresponds to values below Q35.

2.7.3 Water Balance Distribution

In the ZEO catchment, there exists little groundwater flow coming in or out of the catchment(Correa et al., 2017a), and therefore, precipitation (P) was assumed as the only water input. Water outputs were restricted to evapotranspiration (E.T.) and water yield (WYLD). Water yield comprises overland surface runoff (SURQ), and subsurface or lateral flow throw the soils (LATQ). The simulated average volume of each water balance component was compared to values reported from ZEO and other Andean páramo catchments.

2.7.4 Total Runoff Components

The model evaluation process used the simulated fractions of SURQ and LATQ with respect to the total runoff. Given that overland surface runoff at ZEO is minuscule, we considered SWAT performance satisfactory if the simulated fraction of SURQ was considerably lesser than LATQ. The soils' infiltration rate at ZEO largely exceeds the average rainfall intensities; thus, Hortonian flow is negligible, and surface runoff occurs as saturation overland flow only after extreme rainfall events (Correa et al., 2017a; Crespo et al., 2012b). Lazo et al. (2019) report that maximum, mean, and minimum rainfall intensities from 42 storm events recorded at ZEO ranged between 0.6 to 22.3, 0.1 to 5.4, and 0 to 1.1 $\mathrm{mm\,h^{-1}}$, respectively. These rainfall intensities are much smaller than the hydraulic conductivity of local soils, ranging between 5 to 41 mm $h^{-1,}$ as shown in Table 1.

3 Results

3.1 Streamflow Simulation

The SWAT model with either saturation excess or infiltration excess runoff approach reasonably reproduced daily discharge at the watershed outlet. SWAT with saturation excess runoff generated low and high flows that consistently matched observations throughout the calibration and validation periods (Figures 2b). SWAT with infiltration excess runoff accurately simulated daily discharge during rainy periods but consistently overestimated flow during dry periods (Figure 2b). However, considerable differences were found between the SWAT model with saturation excess and the SWAT model with infiltration excess after further analysis of the modeling outcomes.

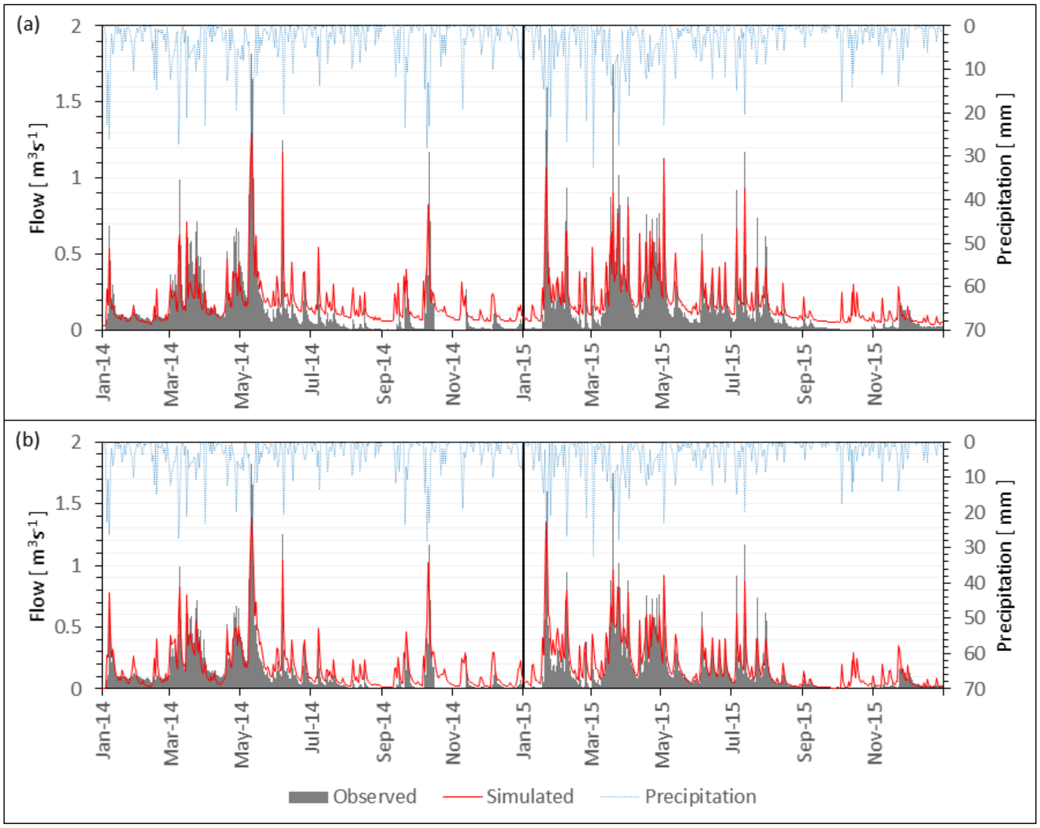

Figure 2. Daily precipitation (blue) and observed (gray) and simulated (red) discharge at the main outlet of Zhurucay Ecohydrological Observatory for two modeling approaches: a) SWAT with infiltration excess runoff and b) SWAT with saturation excess runoff.

3.2 Model Performance

Overall, the performance of both models was satisfactory (i.e., with either runoff estimation approach) (Table 3). SWAT with saturation excess runoff generated NSE = 0.86, RSR = 0.38, and PBIAS = -11.2 during calibration, and NSE = 0.84, RSR = 0.40, and PBIAS = -7.58 during validation. SWAT with infiltration excess runoff generated NSE = 0.80, RSR = 0.45, and PBIAS = -6.26, and NSE = 0.75, RSR = 0.50, and PBIAS = -13.58 for calibration and validation, respectively. Sucozhañay and Célleri (2018) reported similar performance (NSE ranging from 0.8 to 0.83) when they tested the Hydrologiska Byråns Vattenbalansavdelning (HBV-light) model at the same catchment. Buytaert and Beven (2011) also reported similar results (NSE 0.72 to 0.87) after testing the TOP model in a 2.53 km^2 páramo-covered catchment at a similar altitude. Both SWAT modeling approaches' performance metrics were satisfactory and similar to previous studies in páramo catchments. However, further analysis of flow duration curves (FDCs) (Figure 3) showed considerable differences in the streamflow simulation of each SWAT model.

Table 2. Statistical model performance of SWAT with saturation excess and SWAT with infiltration excess during the calibration and validation periods.

	SWAT with saturation excess		SWAT with infiltration excess			
	NSE	RSR	PBIAS	NSE	RSR	PBIA
Calibration	0.86	0.38	-11.2	0.80	0.45	-6.26
Validation	0.84	0.40	-7.58	0.75	0.50	-13.58

3.3 Flow Duration Curves

The FDC (Figure 3b) from the SWAT with saturation excess runoff resembled typical flow duration curves of small tropical Andean catchments with a predominance of natural grasslands, which are usually dominated by low flows and present a moderate slope that denotes good regulation capacity. Examples of FDCs from small Páramo catchments across Ecuador can be found in Crespo et al. (2011). The frequency of flow rates generated by the SWAT model with saturation excess indicated the runoff was generated mainly by flows lower than 60 l s^{-1} km^{-2} or 0.45 m^3 s^{-1}. This flow rate was exceeded only 10% of the time, which agreed with the results from Mosquera et al. (2015) in the same catchment. SWAT with saturation excess runoff reasonably simulated the streamflow characteristics for high, moderate, and low flow regimes at ZEO. However, the model showed limitations for simulating very low flow rates below 1 l s^{-1} km^{-2} or 0.0075 m^3 s^{-1}.

Simulated runoff from the SWAT with infiltration excess runoff (Figure 3a) was generated mainly by flows lower than 50 l s^{-1} km^{-2} or 0.38 m^3 s^{-1}. This flow rate was exceeded only 10% of the time, which is reasonable for páramo catchments. Simulated streamflow characteristics were similar for high flow regimes but differed particularly for moderate and low flow regimes. Moreover, SWAT with infiltration runoff excess was unable to simulate flow rates below 4 l s^{-1} km^{-2} or 0.03 m^3 s^{-1}. Differences between both models were clearly identifiable through the FDCs, in contrast to the analysis of hydrographs and statistical performance metrics, in which modeling outcomes were virtually identical.

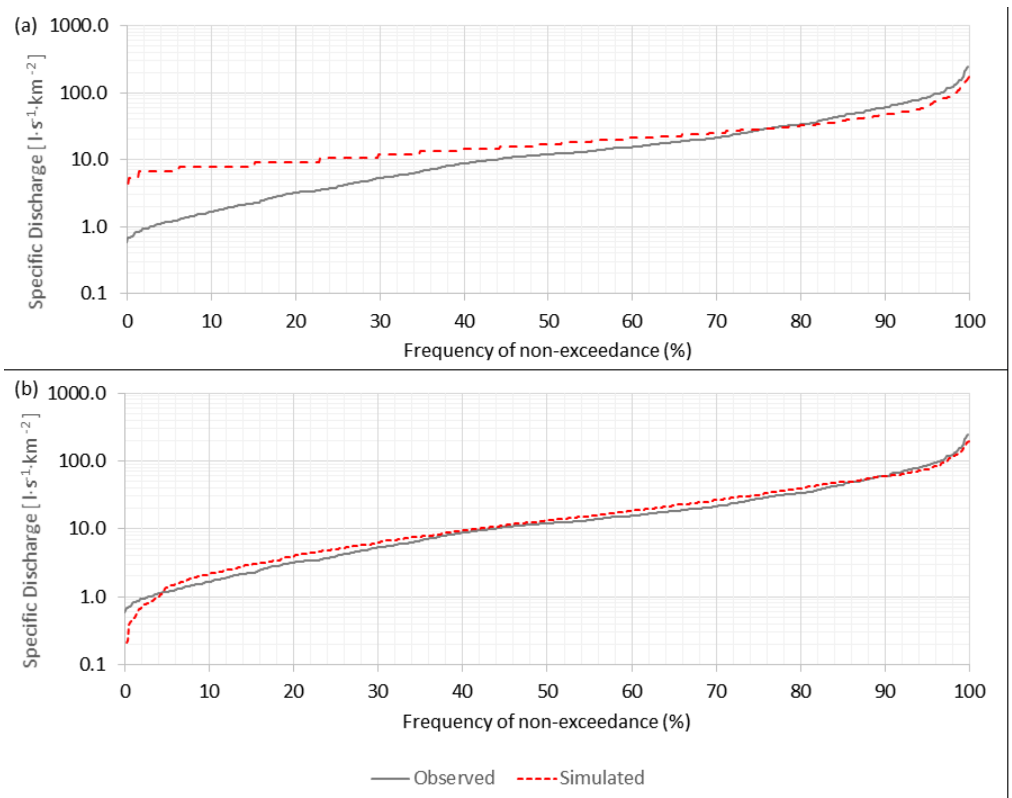

Figure 3. Observed (black) and simulated (red) flow duration curves for Zhurucay using two modeling approaches a) SWAT with infiltration excess runoff and b) SWAT with saturation excess runoff.

3.4 Water Balance and Runoff Components

The water balance distributions of both simulation approaches were similar and reasonable for natural Páramo catchments. The average annual precipitation (1206 mm) was partitioned to 446 mm (37%) evapotranspiration and 760 mm (63%) water yield in the SWAT with saturation excess runoff. The same model with the infiltration excess approach yielded similar partitioning of rainfall: 434 mm (36%) E.T. and 772 mm (64%) water yield (Table 3). The water yield to precipitation (runoff ratio) ratio for both approaches was virtually the same (0.64 and 0.63). These values agree with runoff ratios for tropical alpine regions, ranging from 0.54 in the Simien Mountains in the Ethiopian Highlands (Liu et al., 2008) up to 0.73 in the northern Andes of Ecuador and Colombia (Buytaert et al., 2007). Moreover, in a sub-catchment of Zhurucay, Crespo et al. (2011) reported a runoff ratio of 0.73, while Mosquera et al. (2015) reported 0.68 for the entire observatory. Even though the water balance components (P, E.T., and WYLD) from both simulations were similar, the evaluation of the total runoff components differed.

The Simulated total runoff from the SWAT with saturation excess runoff comprised 99.3% lateral flow and 0.7% surface runoff, while the SWAT with infiltration excess runoff comprised 91% lateral flow and 9% surface runoff. The former distribution of the runoff components resembled the Páramos' hydrologic behavior, in which overland surface runoff (Hortonian) is virtually nonexistent but occurs only a few times a year after extreme rainfall events as saturation excess surface runoff.

Table 4. Distribution of the water balance components and partition of the total runoff into surface runoff and lateral flow.

	SWAT with infiltration excess runoff mm (%)	**SWAT with saturation excess runoff mm (%)**
WATER INPUTS		
Precipitation	(100%)	(100%)
WATER OUTPUTS		
ET	(36%)	(37%)
Total Runoff	(64%)	(63%)
Runoff ratio		
Total Runoff components		
Surface Runoff	*70 (9%)*	*5 (0.7%)*
Lateral Flow	*704 (91%)*	*755 (99.3%)*
Ground Water Flow	*0*	*0*

Figure 4 shows the total simulated water yield (gray) and its components (lateral flow (blue) and surface runoff (red) for the period April to October 2015. The simulated water yield was mainly composed of lateral flow in both modeling approaches. However, the daily volume of surface runoff generated by the SWAT with saturation excess runoff (Figure 4b) was substantially lower than the SWAT with infiltration excess runoff (Figure 4a). Daily surface runoff generated by the SWAT with saturation excess was very low (minimum, average, and maximum were 0.01, 0.16, and 1.24 mm, respectively). Moreover, the contribution of surface runoff to the total runoff was almost negligible even during peak discharge, which is consistent with the notion that Hortonian flow is negligible in páramo catchments (Correa et al., 2019; Correa et al., 2017a).

On the other hand, the SWAT with infiltration excess runoff consistently generated higher surface runoff than the other SWAT model. Besides, the contribution of surface runoff to the total runoff was also greater. During peak discharge (for example, May and July 2015 in Figure 4a), surface runoff and lateral flow contributed almost the same to the total runoff in the SWAT with infiltration excess. However, this behavior misrepresents the functioning of undisturbed Páramo catchments and therefore denotes a limitation of the SWAT with infiltration excess runoff to simulate neotropical alpine wetlands. Thus, the modeling outcomes from the SWAT with infiltration excess runoff were disregarded from further analysis.

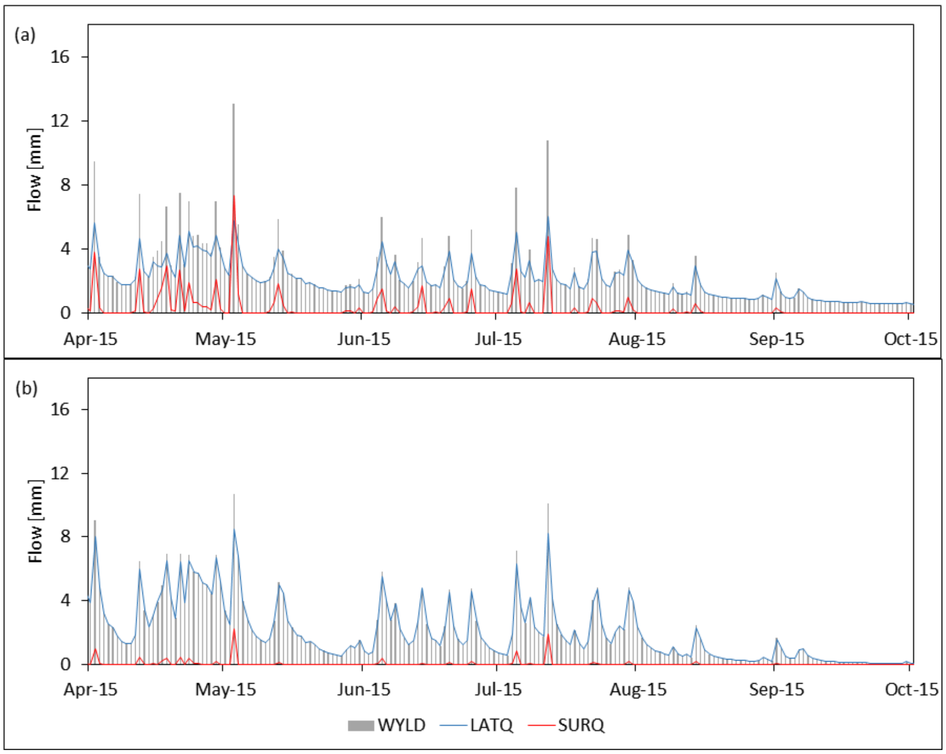

Figure 4. Partition of the simulated water yield (gray) into lateral flow (blue) and surface runoff (red) for two modeling approaches from April to October 2015: a) SWAT with infiltration excess runoff and b) SWAT with saturation excess runoff

3.5 Uncertainty Analysis

The uncertainty analysis from the SWAT with saturation excess runoff showed satisfactory results. The P- and R-factors values were 0.76 and 0.82, respectively, which indicates that the range of calibrated parameters generated a set of good solutions (the 95PPU) that bracketed 76% of the streamflow observations (Figure 5). P-factors greater than 0.7 and R-factors close to 1 indicate that the model uncertainty is insignificant (Abbaspour, 2013). However, in Figure 5, the 95PPU (green) brackets more observations (blue) in the first half of the year (2014) than in the second half. Moreover, the best simulation (red) underestimates low flows during the first half of the year while overestimating low flows during the second half. These results and the previous analysis of FDCs (Figure 4) exhibit that SWAT is somewhat limited in the simulation of low flows in high-elevation tropical grasslands despite the overall satisfactory model performance. This conclusion agrees with other studies conducted in Zhurucay and páramo catchments in general (Buytaert and Beven, 2011; Crespo et al., 2012a; Sucozhañay and Célleri, 2018).

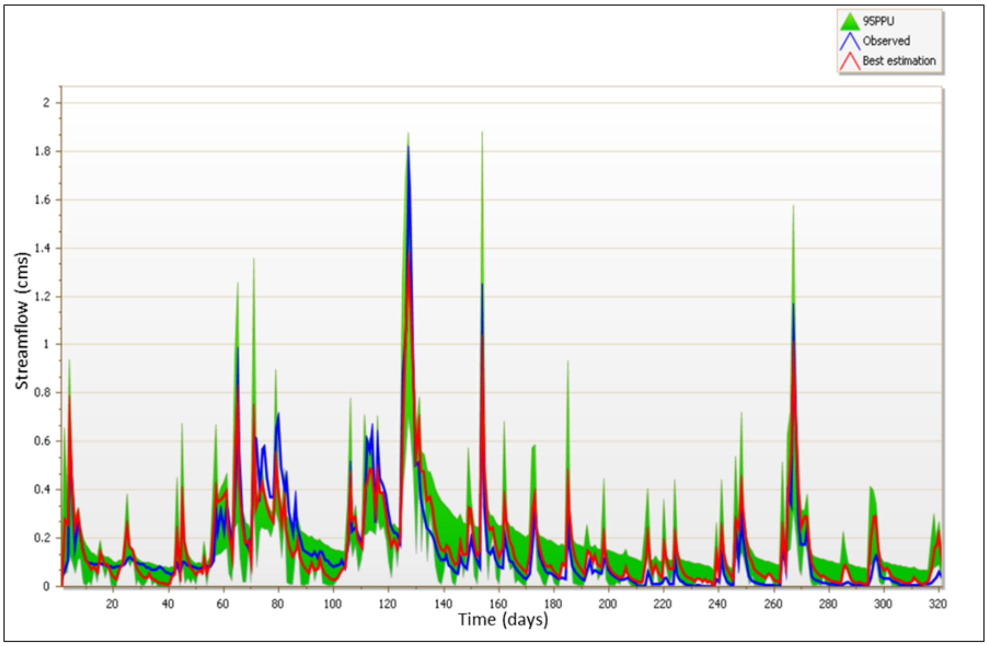

Figure 5. Observed (blue) and best simulated (red) daily flow series and the 95% prediction uncertainty envelope (95PPU) (green) at the main outlet of Zhurucay Ecohydrological Observatory from a SWAT simulation with saturation excess runoff.

4 Discussion

Our results show that a soil-based SWAT model with an improved simulation of saturation excess overland flow and a detailed representation of the soil physical properties is suitable for representing rainfall-runoff processes at the daily time scale in the neotropical alpine catchment. Controlling surface runoff generation according to the terrain slope was critical for SWAT to generate surface runoff as saturation excess overland flow. In addition, constraining the soil-related model parameters based on field measurements reduced model uncertainties. Hydrological signatures such as FDCs and the analysis of the water balance components were reliable criteria for model evaluation. Finally, our findings highlighted how SWAT applications, which by default assume surface runoff is driven by infiltration excess, may lead to inaccurate hydrological assessments in Páramo catchments.

4.1 Streamflow Simulation

The similarity between observed and simulated hydrographs has been commonly used as a metric for evaluating the performance of hydrological models. However, this simple approach may lead to inadequate optimization of hydrological models when simulating tropical alpine catchments. This inadequacy is demonstrated by the results of the SWAT with infiltration excess runoff. The analysis of FDCs and the distribution of the runoff components (surface runoff and lateral flow) showed that SWAT with infiltration excess runoff misrepresented the generation of low flows, despite a satisfactory fitting of simulated and observed daily hydrographs. Improvement in the streamflow simulation was slightly visible by comparing simulated and observed hydrographs.

The differences between the hydrographs of our two modeling approaches, SWAT with infiltration excess and SWAT with saturation excess runoff, were minimal but more pronounced than in other studies. For example, in the studies conducted by Steenhuis et al. (2019) and (Hoang et al., 2017), the simulated hydrographs from SWAT 2012 (default) and SWAT-wil and SWAT-HS (models that simulate saturation excess runoff) were virtually identical. However, differences within these modeling approaches were only visible in the distribution of the runoff components. Similarly, the differences among several SWAT calibration approaches tested by Fernandez-Palomino et al. (2021) were invisible in the simulated hydrographs but identifiable through the evaluation of FDCs. Therefore, the similarity between observed and simulated hydrographs should be considered a reference when implementing a hydrological model but disregarded to validate the modeling outcomes.

4.2 Model Performance

Our findings reinforce the notion that the sole use of statistical metrics to quantify the similarity between observed and simulated discharge cannot guarantee the reliability of hydrological simulations in Páramo catchments. Interestingly, the performance of the SWAT model with infiltration excess runoff was comparable to other studies in Páramo micro catchments and larger Andean watersheds. The highest NSE value (0.8) with the infiltration excess approach found in the current study was comparable to the results of the saturation excess approach such as the TOP model (NSE=0.89) (Buytaert and Beven, 2011) and HBV-light (NSE=0.83) (Sucozhañay and Célleri, 2018). Studies that applied SWAT in large Andean watersheds, which reported NSE values ranging between 0.53 to 0.7 (Espinosa and Rivera, 2016; Hasan and Wyseure, 2018; Yacoub and Foguet, 2012), qualified the modeling outcomes as reliable based on recommended statistical performance measures (Moriasi et al., 2007). However, further analyses of FDCs showed that the infiltration excess method misrepresented the Páramo's hydrological behavior, suggesting that streamflow calibration is insufficient to replicate hydrological processes in Andean Páramo catchments, requiring additional graphical and statistical performance metrics, as recommended by Moriasi et al. (2007).

4.3 Flow Duration Curves

FDCs proved to be an effective measure to evaluate the suitability of the SWAT model for simulating Andean Páramo catchments. Limitations of the SWAT with infiltration excess approach for simulating low flows were evident in the analysis of FDCs. In the same way, FDCs showed that forcing surface runoff driven by saturation excess improved the overall streamflow simulation, especially for low flow regimes. The FDC from the SWAT with saturation excess runoff differed from the observed FDC at the lower end of the curve only. This behavior was similar to results from Hoang et al. (2017), who compared simulated FDCs from SWAT 2012 and a modified SWAT (SWAT-HS) that simulates saturation excess surface runoff. These studies suggest that the SWAT model may be limited in reproducing low flows in mountainous catchments where saturation excess surface runoff is dominant in relation to infiltration excess, though the performance issue is not limited to SWAT. Other studies that applied the TOP model (Buytaert and Beven, 2011) and HBV-light model (Sucozhañay and Célleri, 2018) in small Páramo catchments have reported the same issue, despite a satisfactory model performance. These findings imply that hydrological models can reasonably represent the total runoff of Páramo. Still, a proper representation of the low flow regime remains a challenge that requires further investigation.

4.4 Limitations

The application of our soil-based SWAT model is limited to daily streamflow dynamics, the distribution of the water balance components, and the partition of the total runoff into the surface and lateral flow. A soil-based SWAT model is limited for explaining the cause-effect relationships that control the generation of low flows in Andean Páramo catchments but may support hypotheses that contribute to understanding these cause-effect relationships. For example, in the SWAT model, rainfall water that flows out from each modeling unit (Hydrological Response Unit) is aggregated at the subbasin level, routed through a tributary, and finally routed from the head of the main channel to the main outlet. However, in the Páramos, rainfall water rapidly infiltrates through the soils located in the hillslopes (which remain unsaturated) and flows laterally towards the valley bottoms near riparian areas. In these areas, existing soil water in the saturated soil is pushed towards the streambanks by a piston flow mechanism. The soil-based approach of simulating excess saturation flow used in this study replicates these processes conceptually. Still, it is not a physically-based simulation of excess saturation flow.

5 Conclusion

The SWAT model exhibited reliable performance in simulating the catchment hydrology of neotropical alpine grasslands, or so-called Páramos. With saturation excess overland flow and detailed characteristics of the hydro-physical properties of Andean soils, SWAT reasonably simulated high and low flows and their cumulative occurrences. Although SWAT showed limitations for simulating extremely low flows (below $1\ l \cdot s^{-1} \cdot km^{-2}$), the soil-based modeling approach satisfactorily simulated streamflow, local water balances, and the distribution of total runoff between surface runoff and lateral flow. Our findings reinforce the notion that an evaluation of hydrological models, when applied in Andean catchments, must consider the analysis of hydrological signatures (such as FDCs) in addition to commonly used graphical and statistical performance metrics. Finally, this study showed that assuming infiltration excess runoff as the dominant runoff process in Andean Páramo catchments can generate inadequate hydrological modeling outcomes. Given the characteristics of SWAT and the reasonability of our findings, our soil-based SWAT model can be applied to other Páramo catchments to explore short- and long-term hydrological impacts due to land-use and climate change, which is currently a primary concern in the Andean region.

The representation of these highly complex grassland-dominated ecosystems in the high Andes, or so-called páramos, still constitutes a challenging hydrological modeling exercise that demands the availability of observational data with high spatio-temporal resolution and a clear understanding of the governing hydrological processes. Even though the availability of detailed soil data and the dense network of rain and streamflow gauges allowed us to represent the properties of the soil, capture the rainfall distribution across the catchment, and adequately set up and calibrate the model, it was the large body of literature generated through the observatory that allowed us to evaluate and interpret the modeling outcomes. Given the importance of tropical alpine catchments in providing freshwater and ecosystem services, our study highlights the necessity of replicating initiatives such as the Zhurucay Ecohydrological Observatory.

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