Effect of change in land use on the hydrological response in the Puyango-Tumbes basin, Ecuador-Peru

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Abstract

Land use change is one of the main driving factors of hydrological change in watersheds. Therefore, hydrological responses to land use changes require detailed assessments to ensure sustainable management of both water resources and natural ecosystems. The objective of this study was to simulate the impact of different land use change scenarios (LULC: 1985, 1995, 2005 and 2015) on the water balance, through the hydrological model Soil and Water Assessment Tool (SWAT), in the Puyango Tumbes river basin belonging to Ecuador and Peru during a period of 35 years (1981 - 2015). The LULC analysis shows that there was an increase in the percentage of watershed area covered by grasslands by 18 % while there was a decrease in savannahs by 38 %. In addition, the characteristics of the flow changed from 1985 to 2015 considering their corresponding LULC in the three hydrometric stations analyzed for the period 1981 - 2015. Thus, decreases in annual flows were estimated in that period for the Pindo station (Ecuador) in 4 m 3/s, the Puyango station (Ecuador) at 29 m^3/s and the El Tigre station (Peru) with 16.48 m3/s. The dynamics of the hydrological cycle throughout the basin presented (1981 - 2015) an increasing trend in evapotranspiration with 2.14 % and, on the contrary, a decrease in surface flow by 20.7 %, percolation by 29.29% and lateral flow by 0.93 %. The evidence of these changes and the evaluation of their effects are particularly relevant for the long-term sustainable management of water resources and especially as it is a binational basin.

Keywords: land use change; flow; hydrological cycle; SWAT model.

Introduction

Human population growth projected to be 9 billion by 2050; as well as agricultural development, deforestation and other human activities lead to spatial and temporal changes in land use, which can affect water flow pathways and water balance, changes that have become significant and are now considered to mark a new era of the Anthropocene. Land cover and land use (LULC) plays an important role in land-atmosphere interactions and biodiversity loss as it is a factor influencing sustainable development such as water provision and regulation, climate regulation and air quality. (Alvarez-Garreton et al., 2019; Dale et al., 2011; Welde & Gebremariam, 2017) (Lewis & Maslin, 2015; Smith & Zeder, 2013; Zalasiewicz et al., 2011) (Turner et al., 1995) (Aide, 2013; Foley et al., 2005; Sala et al., 2000)

Many regions of the world have experienced massive LULC change in recent decades. Although the net decline in natural forest area was slowing globally in the period from 2000 to 2010, deforestation remains one of the main processes of LULC change, with multiple implications for global environmental change. For example, extensive deforestation occurred in Latin America and the Caribbean during the first decade of the twenty-first century, but extensive areas of woody vegetation (>360 000 km2) were also recovered (Schirpke et al., 2012) (Meyfroidt & Lambin, 2012) (Lambin & Geist, 2008) throughout the region. Much of natural land in China, including wetlands and forests, has been converted to arable land and human settlements due to rapid urbanization over the past two decades. About 30% of total forest land is under pressure from the rapid LULC shift in northeast India, which is one of the recognized global biodiversity hotspots. Water flow and its regulation are key components in human well-being, where the latter determines the influence of natural systems on the control of hydrological flows. Water regulation capacity corresponds to the proportion of rainfall that can be stored in a watershed and subsequently contribute to the constant flow of surface water over time. (Aide, 2013) (Song & Ding, 2009; Yu et al., 2011) (Lele & Joshi, 2009) (De Groot et al., 2002; Haines-Young et al., 2012) (Haines-Young et al., 2012)

The Puyango Tumbes basin has been affected by serious problems, threats and environmental impacts such as: erosion and soil degradation generated by deforestation of natural flora (logging) and irrational exploitation of dry forest (burning of vegetation and excessive grazing for goat breeding). Behind these threats are the use of land for agricultural activities, including monocultures, short-cycle crops, or for crops unsuitable for the agrological capacity of the soil; inappropriate agricultural and irrigation techniques; poor management of agriculture and irrigation systems. Another problem is the contamination of surface and groundwater through direct discharge to water sources in the areas of Zaruma, Portovelo, Piñas, El Pache in Ecuador and in Peru to Villa Puerto Pizarro. The storm drainage of San José is used for the discharge of wastewater with gold mining pollution in the upper part of the basin by the mining districts of Zaruma-Portovelo (Ecuador) which affects the aquaculture activity that takes place in the lower basin (Peru).

Another relevant point is the decrease in water reserves due to the inefficient and illegal use of water for human consumption and agricultural activities. 90% of the groundwater withdrawn is for agriculture and 10% is for human consumption. (Nuñez & Zegarra, 2006) (Nuñez et al., 2006) (National Water Authority, 2012)

There are three main methods used to quantitatively analyze the impacts of LULC change on hydrology and water resources: 1) the experimental "paired catchment" method, 2) the time series analysis method, and 3) the hydrological model method. (Bosch & Hewlett, 1982) (Li et al., 2012) (Mwangi et al., 2016)

In the experimental method of "paired basins", two basins with similar areas, shapes, climate, vegetation and soil are selected and observed. In general, the first 3 to 5 years (preferably including a wet year, a normal year, and a dry year) are the control period without experimental measures. After that, the land use of one of the basins will be artificially changed, while the other conditions will remain the same. The other basin remains in the original state and is called the "reference basin". After a period of observation, runoff in the two experimental basins is compared and analyzed, and the impacts of LULC change on water quantity are quantitatively analyzed. (Li et al., 2012).

The second method, the time series analysis method, can be used to analyze the changing trend of hydrological and climate data, but due to the spatial heterogeneity of a basin and the mechanisms of LULC change it is not possible to determine climate change in the water cycle. (Li et al., 2012).

In the third method, hydrological models provide a framework for conceptualizing and studying the relationships between climate change, land-use change, and the water cycle. Among these models, distributed hydrological models have significant applications because they directly relate model parameters to land surface characteristics. Therefore, determining how to construct a distributed hydrological model to study the hydrological response to LULC changes is a question that needs to be investigated in depth. (Legesse et al., 2003) (Bronstert et al., 2002)

SWAT (Soil and Water Assessment Tool) is a semi-distributed, physically-based basin-scale hydrologic model developed by Arnold et al., (1998) at USDA-ARS. This model simulates long-term hydrological variables (e.g., flow) on a daily time scale. (Brown et al., 2015)

SWAT is considered one of the most appropriate models for assessing hydrological responses (loss of water, sediment and nutrients) to land-use change in watersheds with different land use and management conditions. In general, vegetation growth management is necessary in distributed hydrological models because evapotranspiration is an important component of the water cycle. (Arnold & Fohrer, 2005) (Abbaspour, 2015)

From a landscape ecology perspective, the spatial pattern of LULC change plays a major role in hydrological processes such as infiltration, groundwater recharge, baseflow, and surface runoff in the basin by altering surface roughness and leaf area index (LAI). This leads to alterations in surface energy balance and evapotranspiration (PET) and also accelerates sediment loading. Therefore, the process of flow regimes and surface runoff could be significantly affected by any modification of the territorial structure of a basin and even more so if the exchange of water resources is at the transboundary level since it depends on the long-term changing interactions between upstream and downstream countries, That is, the potential benefit to the upstream country under the cooperative strategy must exceed its benefits from water use under the non-cooperative strategy to obtain the full stable cooperation of the downstream countries. (Lin et al., 2007; Shi et al., 2013) (Pielke & Avissar, 1990) (Huber & Iroume, 2020; Putuhena & Cordery, 2000; Randhir & Tsvetkova, 2011; Yeh & Huang, 2009) (Bronstert et al., 2002) (Nodoushan et al., 2021)

The objective of this study is to analyze the impacts of LULC change in the Puyango Tumbes basin through hydrological modeling, in support of the development of urgent strategic plans in the management of land, biodiversity and water through the SWAT model, in order to support decision-making from a technical-scientific perspective. The specific objectives of this study were: (1) to evaluate the performance of the SWAT model to simulate the flow of the Puyango Tumbes River and (2) to evaluate the impact of LULC change on the components of the hydrological cycle considering different vegetation scenarios.

Materials and methods

Area of study

The Puyango – Tumbes River basin has an area of 4 800 km2, of which 60% belongs to the provinces of El Oro and Loja, corresponding to the southeast of Ecuador and 40% is located in the Department of Tumbes located in northern Peru. The Puyango-Tumbes River is born at 3,500 meters above sea level, in the area of Portovelo where it is called the Pindo River (in the Chilla and Cerro Negro mountain ranges of Ecuador), which later becomes Puyango and finally the Tumbes River in Peruvian territory. The total length of the Pindo-Puyango-Tumbes River is 230 km. In the upper region, the main tributaries are the Ambocas, Luis, Amarillo and Calera rivers (See Figure 1). The average monthly flow in the Puyango River on the Ecuadorian side in the upper part of the basin is 13.34 m^3/s; in the middle basin it is 85.01 m^3/s, while on the Peruvian side in the Tumbes River the average monthly flow is 110.31 m^3/s. The basin comprises a coastal plain and a mountainous region, with an altitudinal range of 0 to 3 500 m.a.s.l. The hills/mountains range from 50 m.a.s.l. to about 3,000 m.a.s.l. where they form the Tahuín, Celica and Chilla mountain ranges, characterized in parts by steep slopes in the mountain areas.

The climate of the basin is subtropical, with an average annual rainfall of 1 200 mm with marked variations from 100 mm to 2 700 mm and significant dry and wet periods. The average annual temperature in the plains is 24.5 °C and 22 °C in the mountainous area.

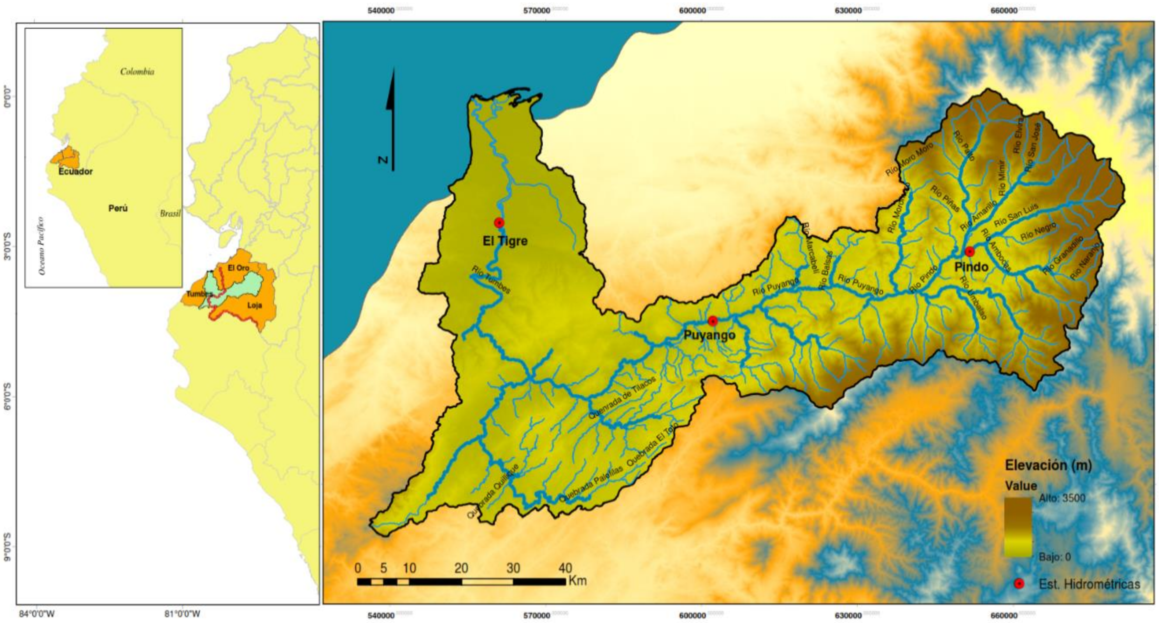


Figure 1: Geographic location map of the Puyango – Tumbes Basin.

In the basin there are different types of vegetation such as broadleaf and deciduous evergreen forests; perennial scrub, woody savannah and likewise the existence of pastures and farmland the same that come to be part within the nine life zones that the basin has as premontane semi-arid desert, tropical scrub scrub, premontane desert scrub, tropical thorny scrub, premontane thorny scrub, very dry tropical forest, dry tropical, dry premontane and humid subtropical. (United Nations Development Programme, 2015)

About 70% have soil suitability for protection and/or restoration; Almost two thirds of the basin is made up of fragile lands, whose natural conditions are not suitable for agro-productive establishment and their use implies severe risks of erosion and soil degradation. (MAP & GIS, 2018)

SWAT Model Description

In this study, hydrological modeling was performed with SWAT on a daily and semi-distributed time scale based on the sub-basin scheme derived from the digital elevation model (DEM). The configuration of the sub-basin through the TauDEM tool preserved the channels and natural flow routes. First, the watercourses were defined, choosing the minimum surface threshold automatically established by SWAT as a criterion to create them and obtain a rigorous representation of the channels (See Figure 2 a). (Abbaspour, 2015)

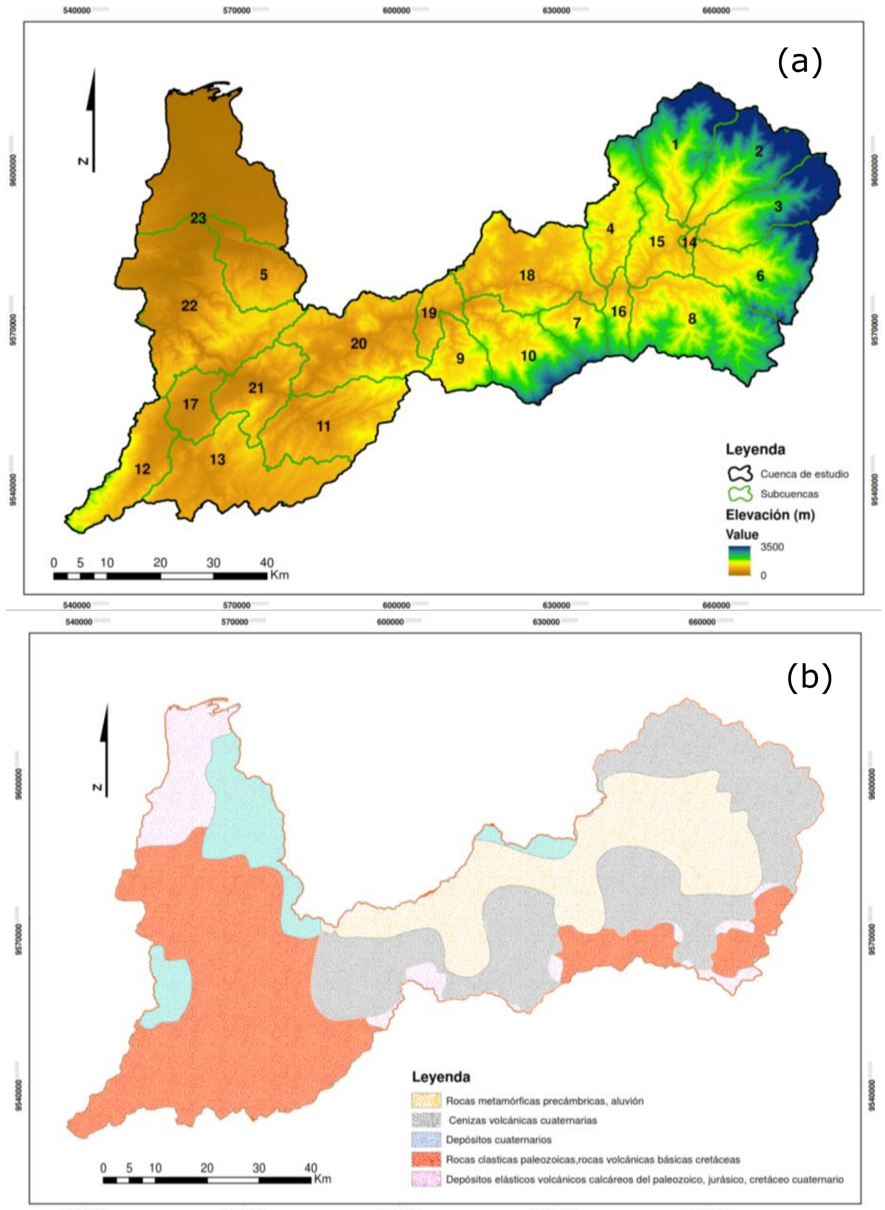
The Hydrological Response Units (HRU) were obtained considering the type of soil, land use and landscape slope. This discretization method accurately reflects the spatial variability relative to the process of transformation of rainfall into runoff, as well as the routing of water in each HRU, improving the accuracy of the simulation. (Moriasi et al., 2007; Zhang, 2014)

SWAT modeling also considers daily climate information, specifically precipitation, maximum and minimum temperatures for the determination of the main processes related to the hydrological cycle. (Abbaspour, 2015)

Input data

Topographic, soil, meteorological and flow data

Based on the DEM, the slope was divided by the SWAT model into three categories (See Figure 2a, Table 1). The Harmonized World Soil Database v 1.2 (HWSD) global soil map (See Figure 2b, Table 1); the maximum and minimum temperature were obtained from the grilled product PISCO v2.0 (See Figure 2 c, Figure 3, Table 1).



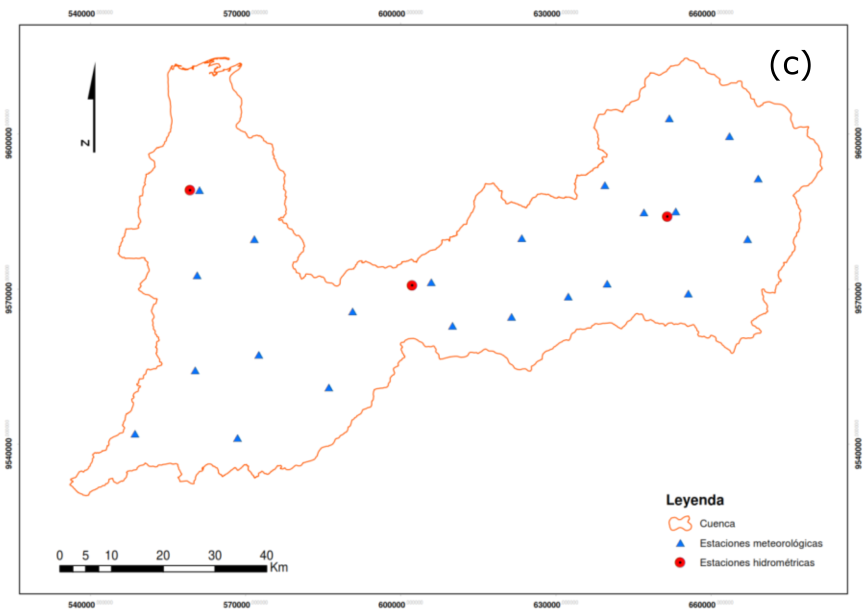


Figure 1: (a) Elevation map (b) Ground map (c) Weather and hydrometric stations.

Board 1: Input variables for SWAT modeling

Data	Input data	Description	Fountain
Hydrometeorological	Extreme temperatures	Daily maximum and minimum temperatures. Period 1988 – 2015.	PISCO (SENAMHI) Available in (http://iridl.ldeo.columbia.edu/SOURCES/.SENAMHI/.HSR/.PISCO/index.html?Set-Language=es)
	Precipitation	Daily precipitation. Period 1988 – 2015.	Rain for Peru and Ecuador (RAIN4PE) Available in https://dataservices.gfz-potsdam.de/pik/showshort.php?id=6f766e20-2d94-11eb-9603-497c92695674
	Caudal	Daily flow. Period 1992 – 2015.	INAMHI Available in (http://www.inamhi.gob.ec) ANA Available in (https://snirh.ana.gob.pe/visorsnirh/)
Spatial data	.DEM	Digital elevation model (Rs: 300 m).	NASA Shuttle Radar Topographic Mission (SRTM) obtained from the Spaces Consortium Information Website

			(CGIAR_CSI) Available at (http: //srtm.csi.cgiar.org)
	Soil type	HWSD (Rs: 1 km)	HWSD Available in (https://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/)
	Land use	Land use map 1985, 1995, 2005, 2015 (Rs: 500m)	MODIS Available in (https://ladsweb.modaps.eosdis.nasa.gov)

Precipitation records were obtained from the gridded product RAIN4PE (Rain for Peru and Ecuador) which is a daily gridded precipitation dataset obtained by merging precipitation data from multiple sources (satellite-based Climate Hazard Group Infrared Precipitation, CHIRP, ERA5 reanalysis, and ground-based precipitation with terrain elevation using the random forest regression method and supplemented with data from flow to correct for underestimation of precipitation over moors and mountain basins (See Figure 2c, Table 1). (Funk et al., 2015) (Martínez-Retureta et al., 2020) (Fernandez-Palomino et al., 2021)
The hydrometric stations "Pindo AJ. Amarillo", "Puyango en Campamento Militar (Puente Carretera)" and "El Tigre" were used as flow monitoring points, which we will call "Pindo", "Puyango" and "El Tigre" throughout the document (See Figure 2 c, Figure 3, Table 1).

Land use

The analysis and quantification of land use changes from the processing of satellite images was carried out. The analysis and quantification of changes in land use was obtained from the MODIS (Moderate Resolution Imaging Spectroradiometer) images, for which the images were selected from four years: 1985, 1995, 2005, 2015 (See Table 1).

To quantify and map the changes of each category of LULC, the year 1985 was analyzed through QSWAT and compared with the subsequent years of analysis until 2015.

The LULC categories were derived from a supervised classification using the maximum likelihood statistical method. This classification included the following categories: (1) evergreen forests with canopy > 2 m, (2) grasslands, (3) savannas covered with trees 10 – 30 % with canopy > 2 m, (4) permanent wetlands: permanently flooded land with 30 - 60 % water cover and 10 % vegetation cover, (5) Cropland at least 60 % of the area is cropland,

(6) Urban and built-up soils: at least 30 % impermeable surface including building materials, asphalt and vehicles, (7) permanent bare land, (8) bodies of water.

To analyze the data, we grouped some of the categories related (for example, with cover: broadleaf or deciduous plantations, tree thickets, bare agricultural land and soils).

The final maps were developed and incorporated into a geographic information system using ArcGIS 10.8. Table 1 summarizes the input information used for SWAT modeling.

SWAT sensitivity analysis, calibration and validation

The model was calibrated and validated on a daily scale using daily flows along the Puyango Tumbes River, at three hydrometric stations: "Pindo", "Puyango" and "El Tigre" (See Figure 1). A period of 28 years (1988 – 2015) was used for calibration and validation, including four years of model warm-up.

The calibration of the parameters was performed using the SWAT_CUP uncertainty procedures software. According to previous studies, 16 sensitive hydrological parameters were chosen for analysis (See Table 2). (Abbaspour, 2015) (Cibin & Sudheer, 2010; CIREN, 1999; Funk et al., 2015)

Board 2: Parameters used for sensitivity analysis of the SWAT CUP model.

Parameter	Description
CH_N1	Manning's "n" value for tax channels.
CNCOEF	Coefficient of the number of the ET curve of the plant.
ALPHA_BF	Base flow alpha factor (days)
GW_DELAY	Groundwater delay time
SURLAG	Runoff delay time
GWQMN	Threshold depth of water in the shallow aquifer required for the return flow to occur (mm)
SLSUBBSN	Average slope length (m)
SOL_AWC	Available water capacity of the soil layer
SOL_BD	Wet bulk density.
RCHRG_DP	Percolation fraction of deep aquifers
ESQUE	Soil evaporation compensation factor.
SOL_Z	Depth from soil surface to layer bottom
SOL_K	Saturated hydraulic conductivity.
GW_REVAP	Groundwater revap coefficient
CANMX	Maximum canopy storage
CN2	SCS runoff curve number f

An overall sensitivity analysis was performed to obtain relative and absolute sensitivity. The uncertainty sequential adjustment algorithm, version No 2 (Sufi-2) was implemented to identify the parameters of greater sensitivity, according to the response of the model. In Sufi-2, uncertainty in parameters, expressed as ranges (uniform distributions), accounts for all sources of uncertainty (such as uncertainty in rainfall variables), conceptual model, parameters, and measurement data. The propagation of the uncertainties in the parameters leads to the output variable of the model, are expressed as probability distributions of 95%, which corresponds to 95% prediction uncertainty (95 PPU). These 95PPUs are the results of models in a stochastic calibration approach. It is important to realize that we do not have a single signal representing the results of the model, but rather a set of good solutions expressed by the 95 PPU, generated by certain ranges of parameters. (Abbaspour, 2015) (Abbaspour, 2015)

The parameter ranges were determined according to the values obtained by calibration. Several iterations were performed, considering 500 simulations with reduced parameter ranges in previous calibration rounds. Time series plots and statistical methods were used to evaluate model performance in total flow simulations. (Abbaspour, 2015)

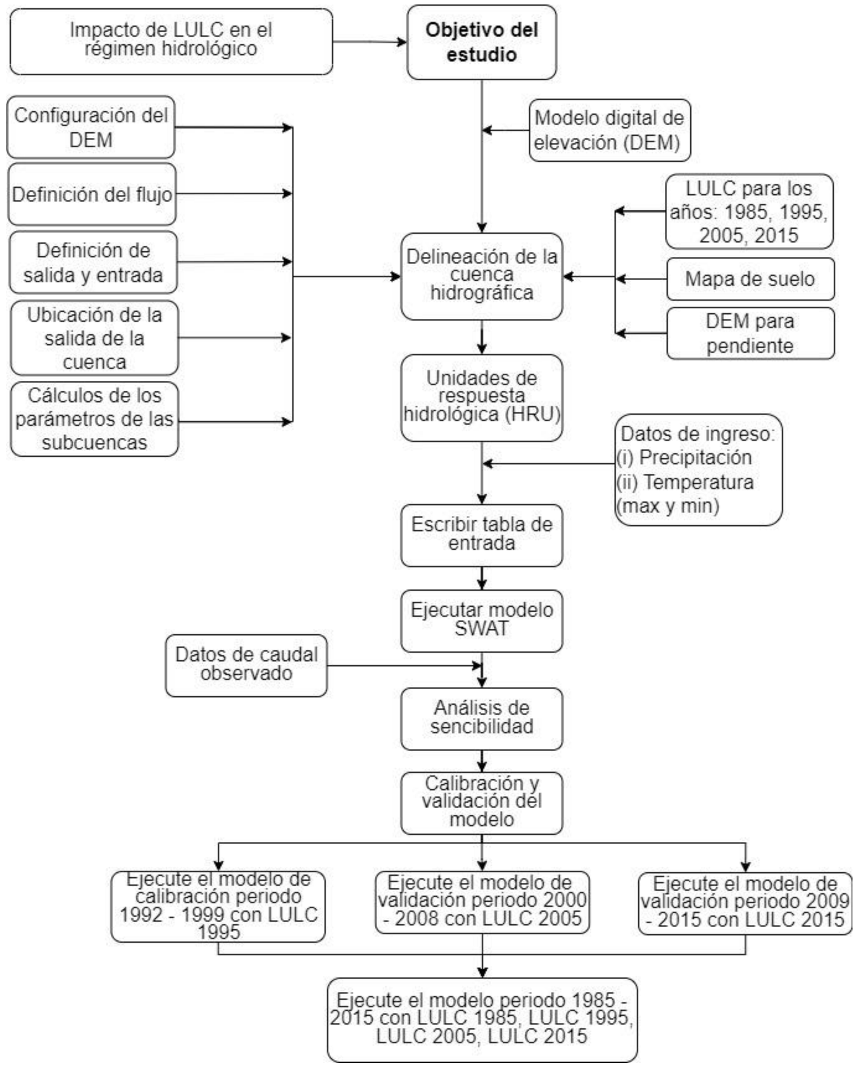


Figure 3: General conceptual methodology used to model hydrology in the Puyango Tumbes Basin.

To quantify the fit between the simulation result, expressed as a single signal, two statistics were applied: p-factor (is the percentage of observed data wrapped by our modeling result) and r-factor (is the percentage of observed data wrapped by our modeling result, i.e. the r-factor is the thickness of the envelope of 95 PPU.) To evaluate the degree of uncertainty in the calibration and validation of the model, a p-factor > 70%, r-factor <1 for the estimation of flows is considered desirable. (Abbaspour, 2015)

As recommended by different researchers, the hydrological and meteorological datasets were divided into three subdatabases: (i) 1988 – 1999, (ii) 1996 – 2008 and (iii) 2005 – 2015 (included in each subbase four years as a warming period), with different LULC changes. (Moriasi, et al., 2012; Martínez-Retureta et al., 2020; Thampi et al., 2010)

The calibration of the model was carried out in the period 1992 – 1999 and the LULC_1995 was used. The parameters estimated during the calibration were used for validation in two periods: i) 2000 – 2008 with the LULC_ 2005 and ii) 2009 – 2015 with the LULC_2015, this in order to demonstrate that the model has a satisfactory range of accuracy. Once calibration and validation of the model were acceptable, we proceeded to run the SWAT model for the period 1985 – 2015, considering the LULC_1985, LULC_1995, LULC_2005 and LUCL_2015 (Rykiel, 2006) (See Figure 3).

SWAT Model Performance Assessment

Model performance was evaluated using statistical tests such as Nash Sutcliffe Efficiency (NSE), percent bias (PBIAS), and coefficient of determination (R2) to examine the modeled process representation under real biophysical conditions. NSE is a standardized statistical method that determines the relative magnitude of the residual variance compared to the variance of the measured data (Equation 1). Theoretically, the NSE value ranges from -1 to 1; the NSE value 1 corresponds to a perfect match between observed and simulated PBIAS values (Equation 2) measures the estimation bias of the model. The value of PBIAS can be positive or negative indicating underestimation and overestimation, respectively; The zero value represents the best simulation performance of the model. R (Moriasi et al., 2007) (Moriasi et al., 2007) ^{2} (Equation 3) is used to measure the consistency of the model's simulated and observed data. The value of R2 varies between 0 and 1; The smallest error variance is indicated by higher values. (Moriasi et al., 2007)

$$\boldsymbol{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{obs}^{mean}\right)^2} \qquad (1)$$

$$\boldsymbol{PBIAS} = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)}{\sum_{i=1}^{n}\left(Y_i^{sim}\right)} * 100 \qquad (2)$$

$$\boldsymbol{bR^2} = \left(\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{obs}^{mean}\right)\left(Y_i^{sim} - Y_{sim}^{mean}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{obs}^{mean}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - Y_{obs}^{mean}\right)^2}}\right)^2 \qquad (3)$$

Where is the discharge of the flow, is the observation, while is the simulation. is the correlation coefficient, is the bias ratio (dimensionless) and is the ratio of variability (dimensionless).$Yobssimr\ \beta\gamma$

Evaluation of the effect of LULC change on hydrological response

For the evaluation of the LULC change on the hydrological response in the Puyango Tumbes basin, the SWAT model was executed for the four LULCs (LULC_1985, LULC_1995, LULC_2005 and LULC_2015) in the time period from 1981 to 2015 including the four years of model warming. Water discharge in the 23 sub-basins was calculated. The flow values measured at the Pindo, Puyango and El Tigre stations were used to compare the flow calculated by the model under the four LULCs.

For this evaluation, the parameters obtained during the calibration and validation steps of the model (LULC_1995) were used. In this way, the suitability of the calibrated and validated parameters in the different LULC scenarios was verified. The hydrological impacts of LULC change were determined in each LULC, but keeping all parameters constant during the study period.

The t-student distribution analysis was evaluated in order to determine significant differences between the simulated daily flow rates for each LULC. This was also applied to quantify the impact of land-use change scenarios on total flow during the aforementioned period for the Puyango Tumbes basin. In addition, the statistics (t-test) and trend analysis between the first and last LULC scenarios (LULC_1985 and LULC_2015) were estimated to evaluate the behavior of the components of the hydrological cycle such as evapotranspiration (PET), percolation (PERC), surface flow (SURQ),

lateral flow (LAT_Q), groundwater (GW_Q) and water yield (WYLD). This analysis was conducted on a monthly scale for the past 28 years.

Results

Land Use and Land Cover Change (LULC)

Native forests and scrub had the highest land use in the basin with an increase of 25% between 1985 and 2015. Grasslands progressively increased in land use with 18% between 1985 and 2015. There was a spatial distribution of increasing occupation from the lower areas during 1985 to the lands of the upper basin in 2015. This behavior is due to the trend of change of natural areas in livestock areas.

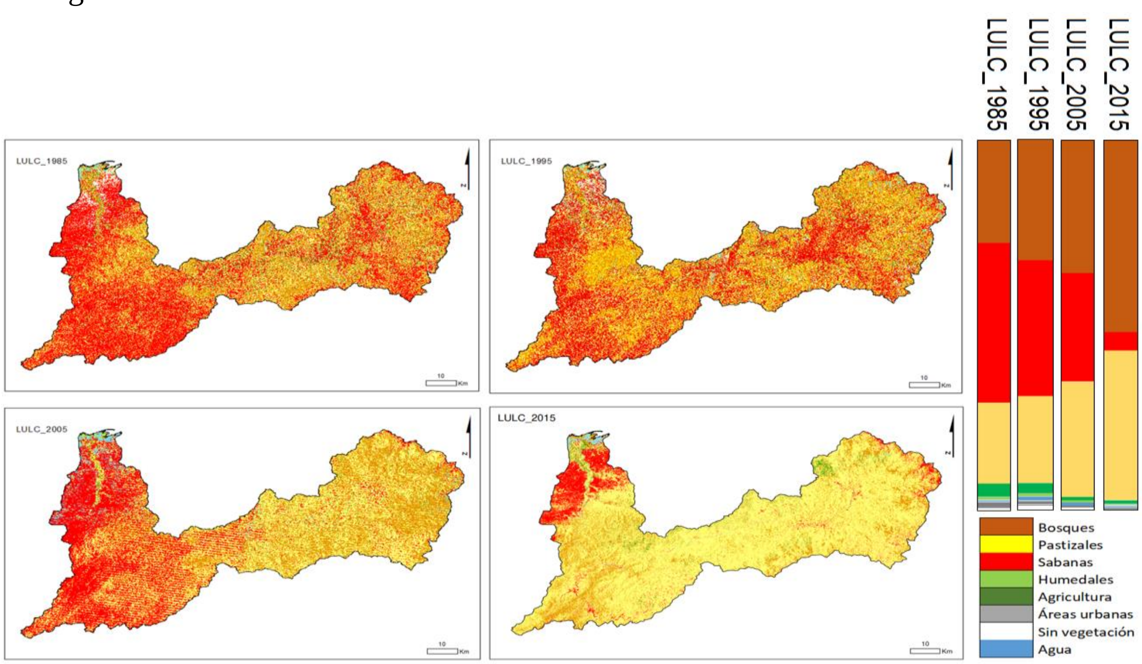


Figure 4: Spatial representation and percentage of the area of changes in land use for LULC_1985, LULC_1995, LULC_2005 and LULC_2015.

On the other hand, savannah areas had a decreasing behavior, showing a reduction of 38% from 1985 to 2015.

However, it can be seen that agriculture was dominant in the upper part and in the middle of the basin. Irregular behavior was observed in the different scenarios affecting wetlands and water bodies (See Figure 4, Table 3).

Board 3: Percentages of land use area for LULC_1985, LULC_1995, LULC_2005 and LULC_2015 scenarios and their relative changes.

	LULC (%)				**Relative changes (%)**			
	1985	**1995**	**2005**	**2015**	**1985 - 1995**	**1995 - 2005**	**2005-2015**	**1985-2015**
Bo	27.9	33.3	36.4	53.0	5.4	3.1	16.6	25.0
Pt	21.9	23.4	31.2	40.3	1.5	7.8	9.1	18.3
Sa	43.6	36.7	29.6	5.2	-6.8	-7.2	-24.4	-38.4
Hu	0.6	0.8	0.7	0.3	0.2	-0.1	-0.4	-0.3
Ag	3.6	2.8	0.9	1.0	-0.8	-1.9	0.2	-2.6
Au	1.2	1.0	0.2	0.1	-0.3	-0.8	-0.1	-1.2
Sn	0.6	1.0	0.0	0.0	0.4	-1.0	0.0	-0.6
To	0.5	1.1	1.1	0.2	0.6	0.1	-0.9	-0.3

*Forests: Bo; Grasslands: Pt; Savannah: Sa; Humidity: Hu; Agriculture: Ag; Urban areas: Au; Without vegetation: Sn; Water: A

LULC time series analysis between 1985 and 2015 indicates an expansion of grasslands with a reduction in the use of savannahs, agriculture and native forests (See Table 3).

Native forests, scrub and wetlands were the land covers with the greatest changes in their percentages with respect to the total area of 1985. This result is explained by the felling of savannah between 1985 and 2015, with a decrease of 38% with respect to the area occupied by this land use in 1985. Meanwhile, during the same period, forest plantations had a positive trend with an increase of 25% over the area of forest plantations during 1985 (See Figure 4, Table 3).

SWAT model sensitivity analysis

According to the sensitivity analysis using the LULC_1995 scenario, it was obtained that six parameters significantly affect the modeled surface flow of the Puyango Tumbes basin, such as the available water capacity of the soil layer (SOL_AWC), the average length of the slope (SLSUBBSN) and other parameters related to surface runoff (SURLAG) and groundwater (ALPHA_BF, GW_DELAYMM, GWQMN) (see Table 4). These parameters were calibrated to fit the actual water balance, according to information from the literature. (Le et al., 2012)

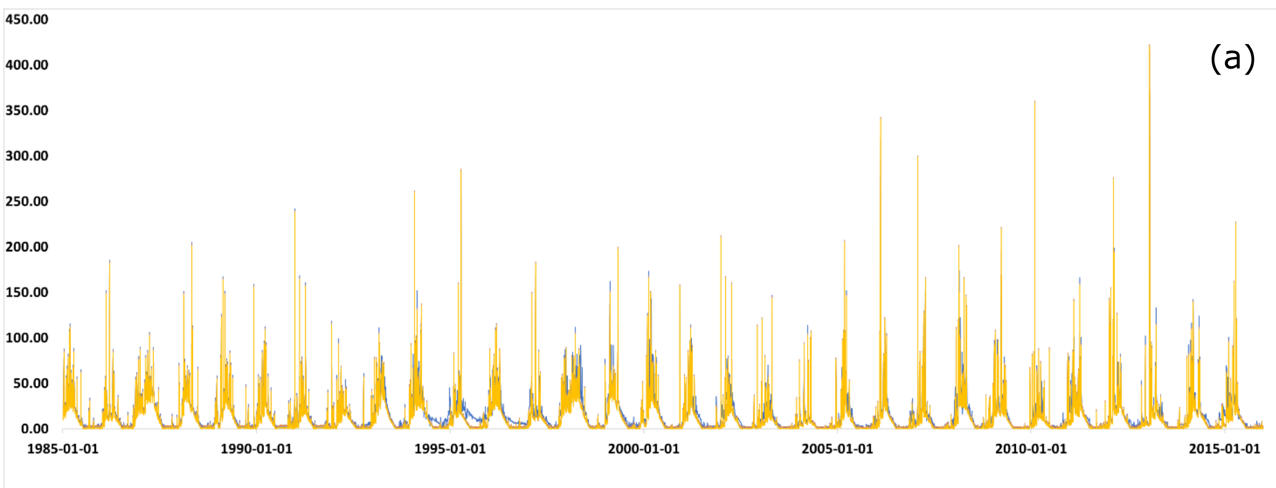
Board 4: Sensitive parameters in surface flow calculations, calibrated values.

		Calibrated values		
Parameter	**Description of parameters**	Adjusted	Minimum	Maximum

		value	value	value
ALPHA_BF	Base flow alpha factor (days)	0.74	0	1
GW_DELAY	Groundwater delay time	0.12	-0.25	0.25
GWQMN	Threshold depth of water in the shallow aquifer required for the return flow to occur (mm)	41.61	30	450
SLSUBBSN	Average slope length (m)	12.91	0	25
SOL_AWC	Available water capacity of the soil layer	-0.02	-0.2	0.1
SURLAG	Runoff delay time	9.45	0.05	24

When compared to the default values, the ALPHA_BF parameter was increased in the model to facilitate the flow of water from the aquifer to the river, increasing the base flow. The GWQMN and GW_DELAY parameters were also increased, increasing the surface flows and consequently decreasing the underground flow. The rest of the parameters related to the hydrological processes were calibrated in order to adjust the base and peak flows (See Table 4).

SWAT model calibration and validation



(b)

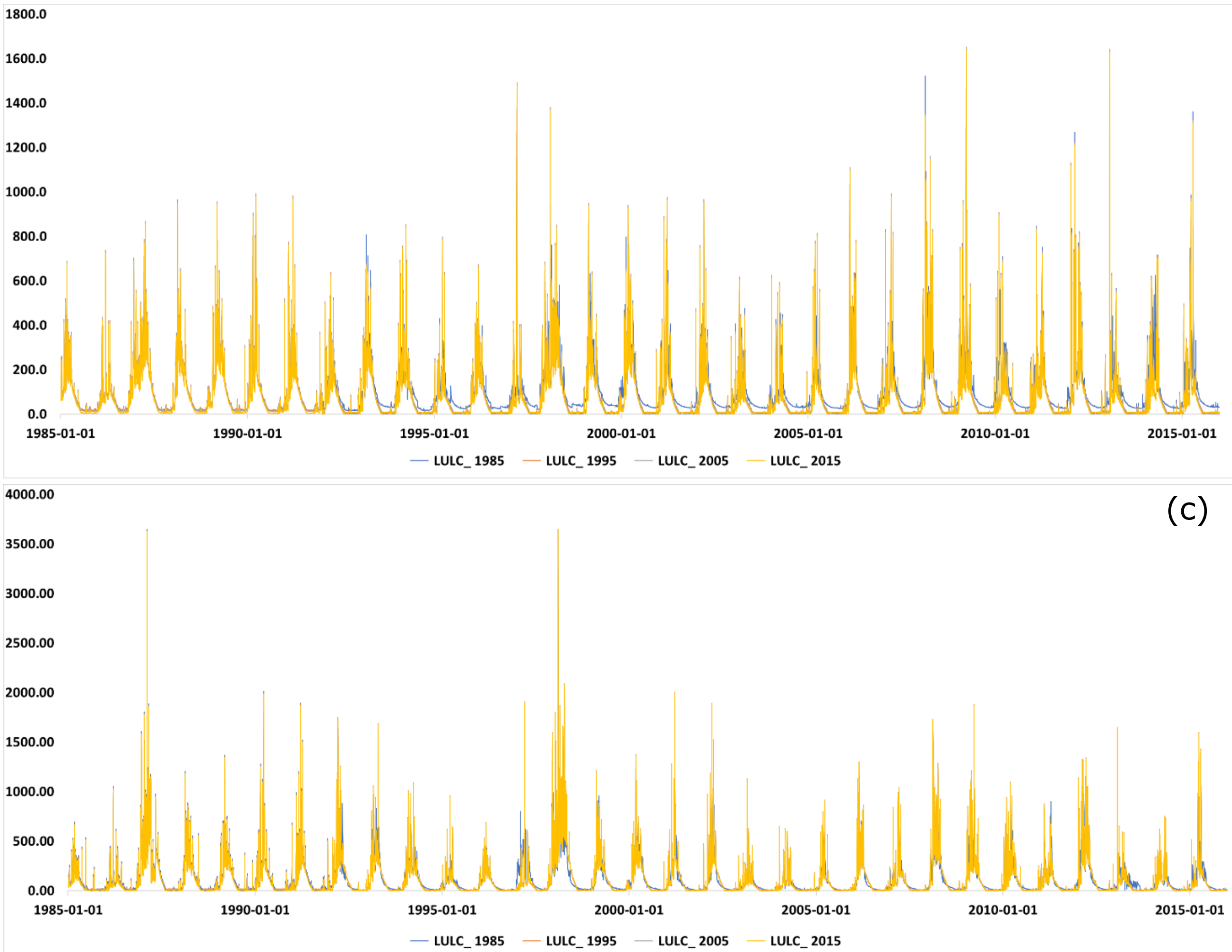


Figure 5. Validation of the daily flow for the time period 1985 -2015 for the Pindo (a), Puyango (b) and El Tigre (c) stations.

Acceptable estimates were obtained by uncertainty factors in the calibration and validation of the model according to the classification of . Abbaspour et al., (2007)
During the calibration period for the Pindo station in LULC_1995, the model showed a low uncertainty with a p factor of 0.36 and an r-factor of 0.23, while for the validation periods LULC_2005 and LULC_2015, a satisfactory level of uncertainty was obtained with a p-factor of 0.64 (0.59) and an r-factor of 0.26 (0.23), respectively.
Regarding the Puyango station for the LULC_1995 presented a p-factor 0.60 and an r-factor of 0.33, and for the validation LULC_2005, LULC_2015 p-factor of 0.7 (0.65) and an r-factor of 0.31 (0.24).
Finally, regarding the El Tigre station, the p-factor value was 0.63 and r-factor 0.23; For LULC_2005 validation, LULC_2015 p-factor of 0.76 (0.68) and an R-factor of 0.27 (0.25).
The statistical results to evaluate the performance of the model in the three hydrometric stations showed a very good level of coefficient of determination for the different LULC

(0.75 – 0.89) for calibration. However, a very good level was obtained in NSE (0.77 – 0.87) and low PBIAS according to the classification of Moriasi et al., (2007) (See Figure 5, Table 5).

The model was validated to demonstrate the adequacy of the calibrated values in the LULC_2005 and LULC_2015 scenarios (See Table 5).

The adjustment between the observed and validated flow of the three scenarios reached a good level for the Pindus station with an R2 of 0.78, 0.79 and 0.78, with NSE values of 0.69, 0.80, 0.83, respectively. A not very good classification was obtained for PBIAS, with values of -15.67%, -36.89 and -19.33 respectively.

The Puyango station an R2 of 0.78, 0.81 and 0.75, with NSE values of 0.69, 0.84, 0.80, respectively. A not very good classification was obtained for PBIAS, with values of -17.36%, -11.23% and -18.23% respectively.

The El Tigre station has an R2 of 0.79, 0.78 and 0.70, with NSE values of 0.69, 0.81, 0.80, respectively. A not very good classification was obtained for PBIAS, with values of -14.56%, -12.54% and -21.56% respectively.

Table 5. Correlation between calibration and validation periods for Pindo, Puyango and El Tigre station.

SnC: 1992-1997C: 1992-1997V: 1998-1999			**Pindus**			**Puyango**			**The Tiger**		
			SnC	**C**	**V**	**SnC**	**C**	**V**	**SnC**	**C**	**V**
LULC 1995	P: 1992-1999	R2	0.9	0.89	0.78	0.78	0.89	0.78	0.78	0.87	0.79
		NSE	0.38	0.77	0.69	0.68	0.77	0.69	0.46	0.82	0.69
		PBIAS	-22.3	-12.4	-15.6	-19.2	-14.5	-17.3	-16.4	-8.2	-14.5
SnC: 2000-2006C: 2000-2006V: 2007-2008			**SnC**	**C**	**V**	**SnC**	**C**	**V**	**SnC**	**C**	**V**
LULC 2005	P: 2000-2008	R2	0.8	0.85	0.79	0.73	0.85	0.81	0.76	0.84	0.78
		NSE	0.74	0.82	0.80	0.68	0.87	0.84	0.73	0.84	0.81
		PBIAS	-18.4	-25.6	-36.8	-13.2	-3.79	-11.2	-14.5	-5.8	-12.5
SnC: 2009-2013C: 2009-2013V: 2014-2015			**SnC**	**C**	**V**	**SnC**	**C**	**V**	**SnC**	**C**	**V**
LULC	Q: 2009-	R2	0.78	0.83	0.78	0.55	0.77	0.75	0.6	0.75	0.7
		NSE	0.73	0.86	0.83	0.76	0.84	0.8	0.78	0.8	0.8

2015	2015	PBIAS	-21.3	-17.6	-19.3	-25.6	-21.9	-18.2	-16.2	-13.4	-21.5

P: Period; SnC: uncalibrated; C, Calibration; V: Validation

Relationship between land use and flow in the Puyango Tumbes River basin

The SWAT model was executed for scenarios LULC_1985, LULC_1995, LULC_2005, and LULC_2015. In this way, the effect of LULC on the daily flow for the study period (1981–2015) in the three river stations "Pindo", "Puyango" and "El Tigre" was evaluated. The t-student test for paired samples showed significant differences between the flows obtained with all land use and cover scenarios with a confidence interval of 95 %.

Table 6. Behavior of the average annual flow of the period 1985 - 2015 according to the LULC in the Pindo, Puyango and El Tigre hydrometric stations.

LULC	Pindo (m3/s)	Puyango (m3/s)	El Tigre (m3/s)
1985	15.88	103.40	120.81
1995	13.53	83.03	109.89
2005	12.42	79.34	106.19
2015	11.54	74.26	104.33

The greatest difference in daily flows was obtained between the most extreme years (LULC_1985 and LULC_2015) (See Table 6), with respect to the Pindo station presented a decrease of 4.34 m3/s per year, the Puyango station 29.15 m3/s and the El Tigre station with 16.48 m3/s.

This change was characterized by the expansion of grasslands (18.32%) with a reduction in the use of savannas (38.37%), agriculture (2.56%) and evergreen coniferous forests (11.99%). During the study period, the Pindo, Puyando and El Tigre stations presented an average flow of 13.67, 81.91 and 103.70 m3/s respectively. The trend obtained, indicating a progressive reduction in flow, could be explained by the behavior of LULC that took place in the basin during the analysis period (See Figure 5, Table 6).

Impacts of LULC change on hydrological response

Table 7. Monthly relative change of ET, PET, PERC, SURQ, LAT_Q, DW_Q and WYLD, LULC_1985 versus LULC_2015 scenario.

Sub	ET	PET	PERC	SURQ	GW_Q	WYLD	LAT_Q
1	-6.04	1.30	-23.65	30.40	-25.34	-4.06	6.34
2	-4.65	1.26	-17.15	37.41	-18.53	-0.88	-11.63
3	-4.16	1.12	-18.00	27.34	-18.86	-1.12	-19.08
4	-2.20	1.97	-25.15	2.60	-26.67	-13.24	-13.23
5	-2.04	1.71	-53.98	-63.55	-61.14	-57.21	-12.67
6	-2.19	1.17	-13.95	9.08	-14.02	-4.58	4.49

7	-1.61	1.32	-25.07	-5.03	-26.77	-15.68	6.36
8	-3.90	1.31	-15.16	-7.71	-16.36	-6.63	-19.67
9	-3.01	1.92	-18.92	-35.10	-21.03	-24.95	-15.07
10	-2.42	1.45	-18.73	-20.32	-20.61	-19.18	14.72
11	-4.70	1.85	-36.07	-46.39	-41.33	-41.50	-26.57
12	-8.84	2.61	-55.96	-60.29	-65.03	-58.27	-15.31
13	-4.02	2.10	-40.69	-54.93	-46.89	-47.11	-20.24
14	-8.42	1.86	-11.19	18.48	-11.17	-1.34	25.04
15	-7.33	1.86	-12.28	19.61	-13.14	-1.59	-14.06
16	-5.89	1.45	-18.54	-2.14	-19.86	-11.95	14.84
17	-7.03	1.51	-34.78	-48.19	-40.39	-42.22	-34.46
18	-0.06	2.03	-21.05	-12.94	-22.98	-17.74	52.47
19	-2.98	2.03	-19.39	-34.52	-21.55	-25.99	54.96
20	-0.07	2.03	-37.25	-47.88	-42.16	-40.43	43.61
21	-1.81	1.94	-40.02	-47.36	-46.44	-44.81	-13.86
22	-5.18	2.29	-54.21	-58.95	-64.20	-56.81	-22.89
23	-4.91	11.03	-60.11	-76.12	-74.56	-75.34	-5.49

On a monthly scale, for the period between LULC_1985 and LU_2015, after the generation of the sub-basins (See Figure 2), a slightly increasing trend was observed in the sub-basins located in the upper part of the basin with the relative changes of SURQ. Monthly variations range from -76.12% in sub-basin 23 to 37.41% in sub-basin 2, with an average monthly average of -20.72% (See Table 7, Figure 6 d).

On the contrary, the LAT_Q registered a decreasing behavior for the sub-basins, with relative variations ranging from -34.46 % in sub-basin 17 to 54.96 % in sub-basin 19 with an average annual decrease of 0.93 % (Table 6, Figure 6 g).

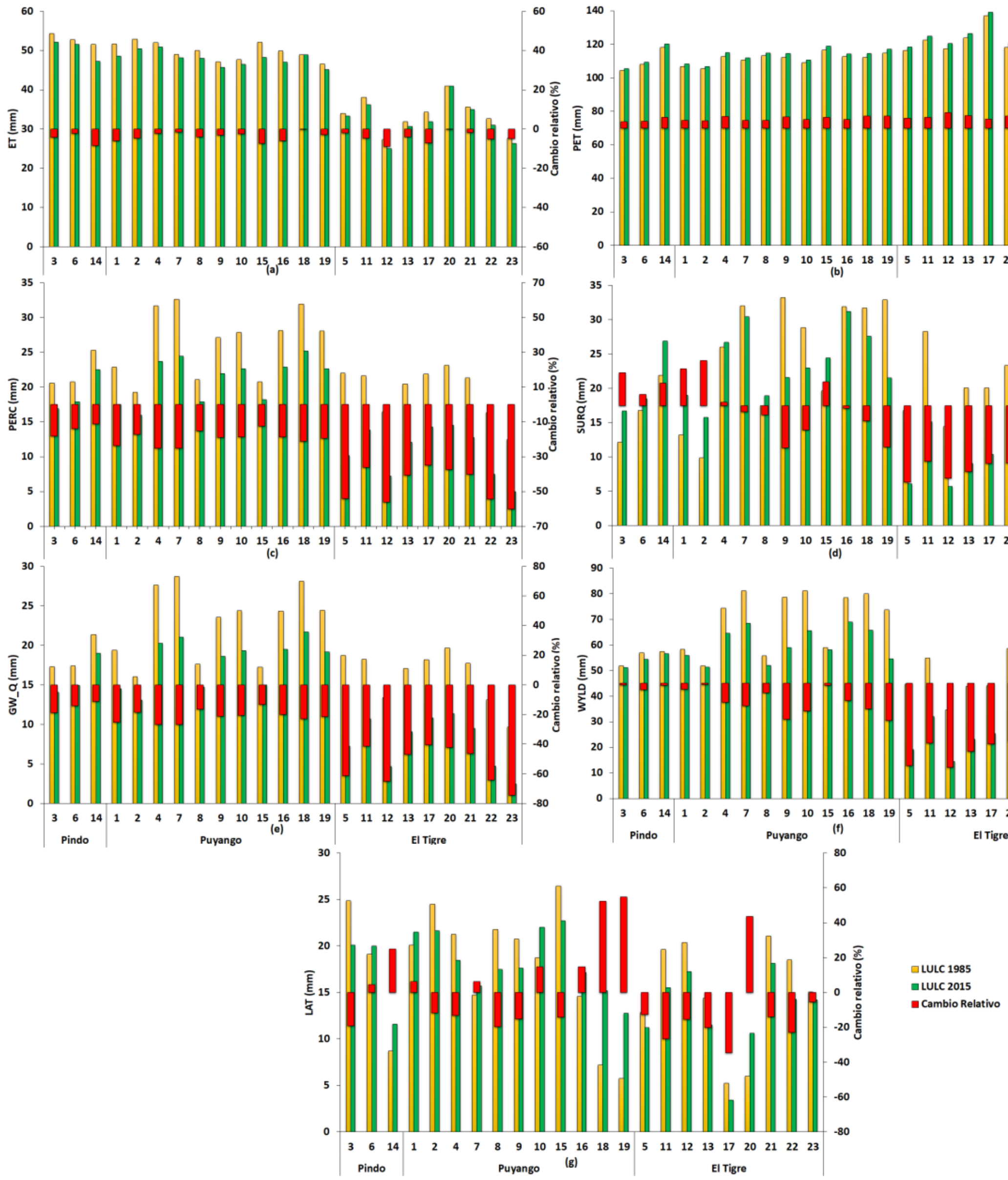


Figure 6. Monthly average of hydrological cycle parameters: evaporation (ET) (a), potential evapotranspiration (PET) (b), percolation (PERC) (c), surface flow (SURQ) (d), groundwater (GW_Q) (e), water yield (WYLD) (f) and lateral flow (LAT_Q) (g) for LULC_1985 and LULC_2015 scenarios.

In addition, the values obtained for the PERC had a significant decreasing trend for all sub-basins, with relative changes ranging from -60.11 (sub-basin 23) to -11.19 % (sub-basin 14), registering a relative monthly variation of -29.19 % (Table 6, Figure 6 c). Such a decrease in PERC of 27.37 mm (monthly average) caused the reduction in water availability from the bottom of the soil profile to the shallow aquifer, producing a negative impact on the availability of GW_Q whose average reduction registered 6.00 mm.

The values of GW_Q experienced relative monthly changes of -74.56 % (sub-basin 23) to -11.17 % (sub-basin 14), registering a monthly average relative change, with monthly increases of -33 % (See Table 6, Figure 6 e).

The largest contribution to WYLD was caused by surface and underground flows. The decreasing trend of GW_Q exceeded the positive effect on the WYLD of the basin, resulting in a decrease of 26.64 % in the relative average yield during the period studied, with monthly relative variations of -75.34 to -0.88 %. These results lead to a decrease of 13.74 mm in the monthly average WYLD for the Puyango Tumbes basin (See Table 6, Figure 6 f).

Discussion

Hydrologic modeling response

SWAT is one of the most widely used models when simulating the water balance within a basin. However, the software has some limitations mainly related to the large number of input parameters. (Thai et al., 2017; Tuppad et al., 2011)

Sometimes, various parameters must be obtained or estimated from global databases, equations, or other computer software. (Nyeko, 2014; Saxton & Rawls, 2006)

In this study, rainfall information from RAIN4PE and temperature from PISCO was used as a climate database for model input. This led to a satisfactory representation of the behavior of the total flow in the basin once the model was calibrated for the different land use scenarios. The results obtained validate the database used to be used within the SWAT model for the basins located in the border area of Ecuador and Peru.

However, the results did not adequately represent extreme rainfall values, overestimating precipitation in the study area. These results suggested the use of calibration and validation procedures in the present study. The results are consistent with whose findings show that the CHIRPS database overestimates precipitation in the south-central coast mountain range of Chile. However, it was also stated that, with good calibration, CHIRPS products can be used with satisfactory results, as verified in the present study. Zambrano et al., (2016)

SWAT has experimented with the continuous development of its geospatial structure to represent the physical features of the landscape as realistically as possible. Error metrics for calibration and validation periods at hydrometric stations range from "good" to "very good" according to . In relation to the performance rating of the model, the consideration of a calibration database and two long validation periods allowed a better simulation of the different components of the hydrological cycle on a daily scale for the three land use scenarios. (Bosch et al., 2010; Sun et al., 2015) Moriasi et al., (2007)

Hydrological response and LULC

The study shows that LULCs that occurred between 1985 and 2015 in the Puyango Tumbes River basin were characterized by a substantial increase in forest cover. Native forests and shrublands were slightly increased due to native species protection and conservation programs. But also the notable impact of the progressive increase of grass directly affects the behavior of the components of the hydrological cycle.

In the basin, PET presents the greatest variations, with impacts on the flow production of the basin. According to , PET is the key element in understanding the effect of land-use change on water production. In this basin, the increase of 30.08 mm per year of PET between LULC_1995 and LULC_2015 could be due to the increase in forest plantations and grasslands. During 1995, forest plantations occupied 33.3% of the basin area; while, in 2015, the percentage of these plantations almost doubled, occupying 53% and in the same way in the case of pastures step from 23% to 40% of the surface of the basin. (Moran-Tejeda et al., (2014)

This phenomenon caused an increase in leaf area, favoring the interception of rain, radiation and the area available for evapotranspiration. These results agree with and complement the statements, which show that the SWAT model calculates PET based on water evaporation intercepted by the canopy, maximum plant transpiration rate, and maximum soil evaporation rate. Neitsch et al., (2005)

The increase in forest plantations and grasslands has led to an annual increase in PET and SURQ rates of 2.14% and 33.32%, respectively. Subsequently, there is a decrease in PERC (29.19%), LAT_Q (45.95%), GW_Q (33%) and WYLD (26.64%).

The trend towards a decrease in total flows due to increased forest cover has been reported for small-scale watersheds and mesoscale watersheds. (Huber et al., 2008; Lara et al., 2009; Otero et al., 1994) (Iroumé & Palacios, 2013; Jones et al., 2017; Little et al., 2009)

Lara et al., (2009) He conducted a study in experimental basins where they determined higher average annual runoff coefficients in basins covered mainly by native forests compared to basins dominated by exotic plantations. It was also observed that a significant reduction in total flows was related to the increase in the area of exotic plantations.

Alvarez-Garreton et al., (2019) showed that annual runoff always decreases with increasing forest plantation area. However, the magnitude of the changes depends on several factors, including the initial percentage of land covered within the watershed, land use or replacement of the type of cover, the area and type of watersheds either dry or wet. The present study agrees with the results described by presenting a significant decrease in flows between the three land use scenarios studied.

On the other hand, he also noted that the replacement of native forests by fast-growing forest plantations has caused a decrease in flows by 42.7% in mesoscale basins. Little et al., (2009)

The present study presents a land use dominated by forests (evergreen conifers, deciduous and non-deciduous trees and woody perennials) in three different scenarios (LULC_1995, LULC_2005 and LU_2015), which represent 33.3%, 36.39%, 53% of the total area of the basin, respectively. In addition, the progressive increase is grasslands with 23.42%, 31.18% and 40.3%, creates an effect on groundwater and WYLD during the drier months. Not so for the winter season, characterized by greater rainfall, this and the increase in grasslands increased the rates of losses by interception and evapotranspiration, which causes less water storage in the soil.

The method used was a semi-distributed physically and spatially based hydrological model (SWAT). This method allows us to relate the climate of the study area (rainfall, temperatures) with its biophysical characteristics (topography, soil and land use), analyzing the different hydrological processes at any point.

This methodological approach substantially improves the calculation of water flows circulating within the basin. These values are validated with data observed at the flow stations available in the basin. Indeed, they recognize that it is possible to improve their analysis, particularly on issues related to water regulation, including more detailed data on complex variables such as PET and cropping coefficient. Benra et al., (2019)

In the study area of the present work, grassland expansion is the main driver of land use changes, becoming the dominant use of the basin. The results of this research could have a relevant contribution to environmental governance and planning between the two countries. According to , planning can be very difficult in these dynamic landscapes, especially when landscape change processes are not regulated. Jullian et al., (2018)

In the case of Ecuador and Peru, the policy instruments are indicative and not normative. Therefore, effective planning for plantation expansion to avoid negative impacts will likely require a combination, on the one hand, of market incentives (e.g., cattle ranching and legal mining) and the proper application of compensation for transforming land uses into monocultures.

Commitments associated with land-use conversion to rangelands need to be assessed. On the one hand, the social value of the ecosystem services provided by forests and other types of land cover that are being replaced must be considered. In addition, private landowners involved in the establishment of mining or grassland plantations should be monitored to avoid or reduce negative environmental impacts, this is essential for comprehensive landscape management. In addition, with the research provides scientific evidence to address future water availability issues as the growing demand for water resources faces future scenarios of rising temperature and decreasing rainfall. (Falvey & Garreaud, 2009)

Conclusions

The SWAT model is a powerful tool for predicting the impacts of land-use changes on the hydrological response of the Ecuador-Peru binational basins, even with limited data availability. This semi-distributed hydrological model allows to determine the behavior of the components of the hydrological cycle such as ET, PERC, SURQ, LAT_Q, GW_Q and WYLD.

The increase in grassland area by 18.32% and a significant reduction in savannas by 38.27%, between LULC_1985 and LULC_2015 scenarios, resulted in an annual increase in PET rates (2.14%), subsequently producing a decrease in PERC (29.19%), SURQ (20.72%), GW_Q (33.00%), WYLD (26.64%) and LAT_Q (0.93%).

The total flow of the Puyango Tumbes basin had significant changes for the period of 35 years (from 1981 to 2015) with a reliability of 95% on a daily scale, which have a direct relationship with the continuous increase in the area by grasslands with 18.32%, in addition to the role of forests in 25.01%, between the LULC_1985 and LULC_2015 scenarios, which influences the increase in PET rates.

The results of this study can be used in public policy discussions and decision-making involving changes in land cover, as they provide science-based tools quantifying the impacts caused on water resources during the last thirty years, mainly as a result of the replacement of native forests by forest plantations. It can also be an important basis for future research, including projections of land-use change combined with the effects of climate change.

Thanks

This study is supported by the Doctorate of Water Resources of the National Agrarian University La Molina Lima Peru.

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