Using the SWAT Model to Simulate the Hydrological Response to LULC in a Binational Basin between Ecuador and Peru

Robinson Fabricio Pena Murillo
Universidad Nacional Agraria La Molina, Av. La Molina s/n, Lima 12, Peru | Centro Experimental de Riego, Escuela Superior Politecnica de Chimborazo, Ecuador | Universidad Tecnica de Ambato, Tungurahua, Ecuador
20200867@lamolina.edu.pe (corresponding author)

Waldo Lavado Casimiro
Servicio Meteorologico e Hidrologico del Peru SENAMHI, Lima, Peru | Universidad Nacional Agraria La Molina, Av. La Molina s/n, Lima 12, Peru
wlavado@senamhi.gob.pe

Yenica Cirila Pachac Huerta
Facultad de Ciencias Agrarias, Universidad Santiago Antunez de Mayolo, Av. Centenario N° 200, Huaraz, Peru | Research Center for Environmental Earth Science and Technology, Universidad Santiago Antunez de Mayolo, Av. Centenario N° 200, Huaraz, Peru | Universidad Nacional Agraria La Molina, Av. La Molina s/n, Lima 12, Peru
ypachach@unasam.edu.pe

Melania Zapana Quispe
Universidad Nacional Agraria La Molina, Av. La Molina s/n, Lima 12, Peru | Facultad de Ingenieria Agricola, Universidad Nacional del Altiplano, Puno, Peru
mzapana@unap.edu.pe

Deysi Guevara-Freire
Facultad de Ciencias Agropecuarias, Universidad Tecnica de Ambato, Tungurahua, Ecuador
da.guevara@uta.edu.ec

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ABSTRACT

Land use change has played a crucial role in altering the hydrological behavior, making detailed assessments essential to ensure sustainable water resource management and the conservation of natural ecosystems. This study focuses on simulating the impact of different Land Use and Land Cover (LULC) scenarios for the years 1985, 1995, 2005, and 2015 on the water balance in the Puyango-Tumbes River basin, which spans across Ecuador and Peru, during the period 1981-2015. The results indicated an 18.3% increase in the grassland areas and a significant 38.2% reduction in the savanna zones, contributing to an annual 2.1% increase in the Evapotranspiration (PET) rates. These land use changes led to a 29.2% decrease in the Percolation (PERC), a 20.7% decrease in the Surface Runoff (SURQ), a 33% reduction in the Groundwater Flow (GW_Q), and a 26.6% decrease in the Annual Water Yield (WYLD), as well as a slight reduction of 0.9% in the Lateral flow (LAT_Q). These findings highlight the importance of considering land use changes to ascertain the sustainable management of natural resources, particularly in a transboundary basin.

Keywords-LULC; SWAT; streamflow; hydrological cycle; basin

I. INTRODUCTION

In the recent decades, numerous regions of the world have undergone massive changes in LULC [1, 2]. Although the net decrease rate of the natural forest area worldwide slowed down between 2000 and 2010 [3], deforestation remains one of the main processes of LULC change, with multiple implications for global environmental change [4, 5]. The Puyango-Tumbes River faces serious environmental difficulties and threats, including soil erosion and environmental degradation, due to the deforestation and excessive exploitation of the dry forest, involving logging and overgrazing by goats. These problems are related to LULC, which also applies for agricultural activities, such as monocultures, short-cycle crops, inadequate agricultural and irrigation practices, and poor management of agriculture and irrigation systems [6]. The spatial arrangement of LULC change plays a crucial part in the hydrological processes of the basin, which could significantly affect flow regimes and surface runoff [7], especially concerning transboundary water resource exchanges, as they depend on long-term changing interactions between countries located upstream and downstream [8, 9]. SWAT is recognized as one of the most suitable models for examining hydrological responses, such as water loss, sediment, and nutrient loss, to changes in LULC in watersheds [10]. The objective of the current study is firstly to evaluate the performance of the SWAT model in simulating the flow of the Puyango-Tumbes River and secondly, to analyze the impact of the LULC change on the components of the hydrological cycle.

II. MATERIALS AND METHODS

The Puyango–Tumbes River basin spans an area of 4,800 km^2, with an average flow rate of 13.4 m^3s^{-1} in the upper basin, 82.8 m^3/s in the middle basin, and 103.5 m^3s^{-1} in the lower basin. Approximately 70% of the area has soil capacity for protection and/or restoration. However, nearly two-thirds of the basin consists of fragile lands, whose natural conditions are not suitable for agriculture, posing significant risks of erosion and soil degradation associated with their use [11].

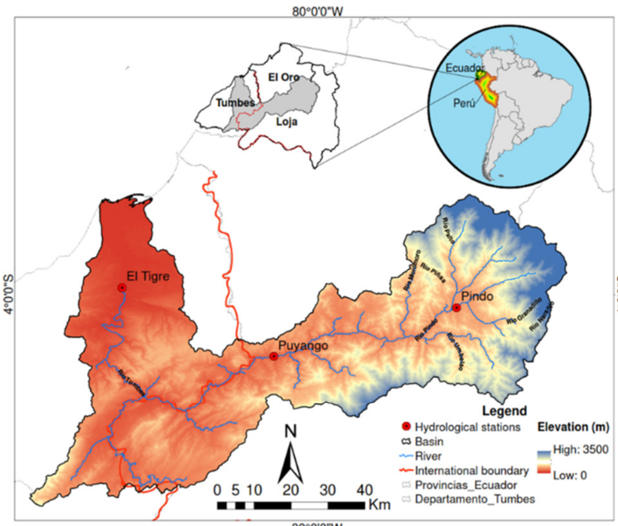

Fig. 1. Cartographic representation of the Puyango-Tumbes Basin.

A daily time scale and a sub-basin scheme generated from the Digital Elevation Model (DEM) were employed. In Figure 2a, watercourses were identified using the minimum surface threshold automatically set by SWAT as a criterion for delineation, which allowed for a representation of the watercourses [12]. Hydrologic Response Units (HRUs) were defined considering factors, such as soil type land use, terrain slope, and water routing [13, 14]. As evidenced in Figure 2b, the soil type utilized the Harmonized World Soil Database v1.2. Figures 2c and 3 demonstrate that extreme temperatures were obtained from the PISCO v2.0 product. In Figure 2c, it can be noted that the precipitation data were collected from the RAIN4PE product [15]. Figures 2 and 3 display the flow data from the "Pindo," "Puyango," and "El Tigre" hydrometric stations, which were obtained from INAMHI and ANA.

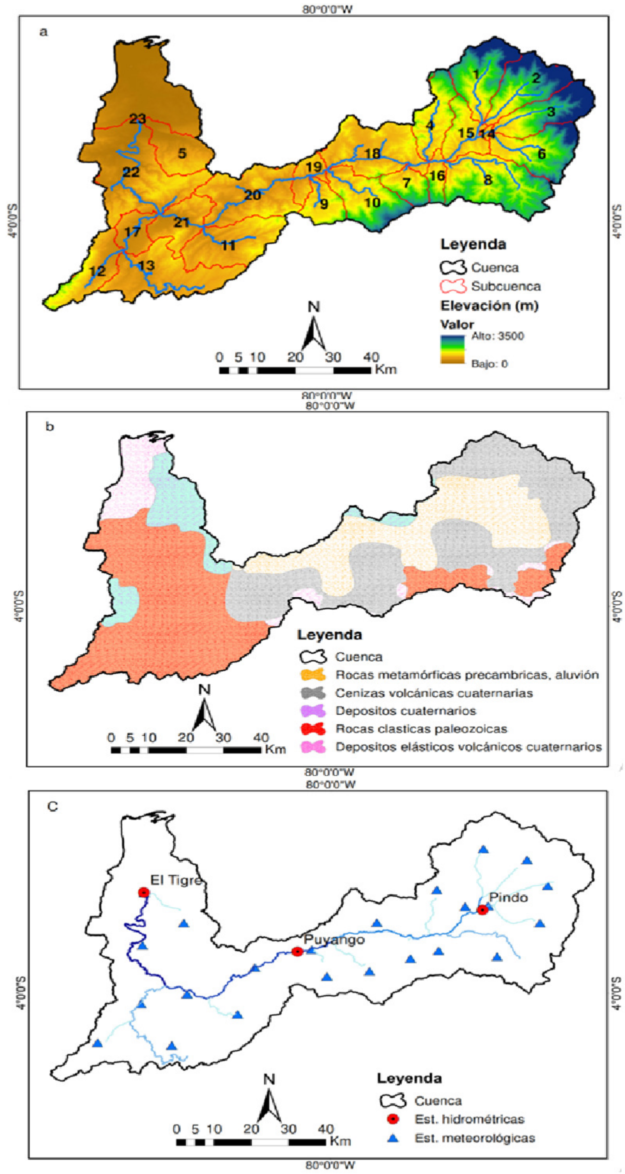

Fig. 2. Depiction of (a) elevation map (b) soil map (c) hydrometeorological stations.

The analysis and quantification of LULC changes were conducted using MODIS images for four scenarios, 1985, 1995, 2005, and 2015. LULC categories were determined through supervised classification following the maximum likelihood statistical method. These categories included:

1. Evergreen forests with a canopy height greater than 2 m.
2. Grasslands.
3. Savannas with a tree cover from 10% to 30% and a canopy height greater than 2 m.
4. Permanent wetlands, which are areas permanently flooded with a water cover from 30% to 60% and a vegetation cover of 10%.
5. Cropable lands, where at least 60% of the area is used for crops.
6. Urban and built-up areas covering at least 30% of the impervious surface.
7. Permanent bare lands.
8. Water bodies.

TABLE I. PARAMETERS USED FOR THE SENSITIVITY ANALYSIS OF THE SWAT CUP MODEL

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

The model was calibrated and validated using the daily streamflow for the period from 1988 to 2015 for the calibration and evaluation process, including the four initial years for the model warming up. Table I depicts the sixteen hydrological parameters selected for analysis [16, 18]. 500 simulations were conducted with reduced parameter ranges in the previous rounds of calibration [12]. To evaluate the uncertainty level in the calibration and validation of the model, the p-factor and r-factor were considered [12]. The hydrometric datasets were divided into three subsets, the first (i) was from 1988 to 1999, the second (ii) was from 1996 to 2008, and the third (iii) was from 2005 to 2015, to account for different changes in LULC [13, 19, 20]. The first scenario, associated with 1995, was used for model calibration, utilizing the data collected between 1988 and 1999. The hydrometric database for the period 1996-2008 was assigned to the second scenario, corresponding to 2005. The third scenario, linked to 2015, encompasses data collected between 2005 and 2015. The second and the third scenarios were employed as model validation periods. During model validation the parameters estimated in the calibration of 1995 were used, considering different sets of the observed values to demonstrate that the model maintains a satisfactory level of accuracy [21]. Furthermore, to validate the periods containing flow data deploying stable parameters, the 1985 scenario was utilized, as it can be seen in Figure 3.

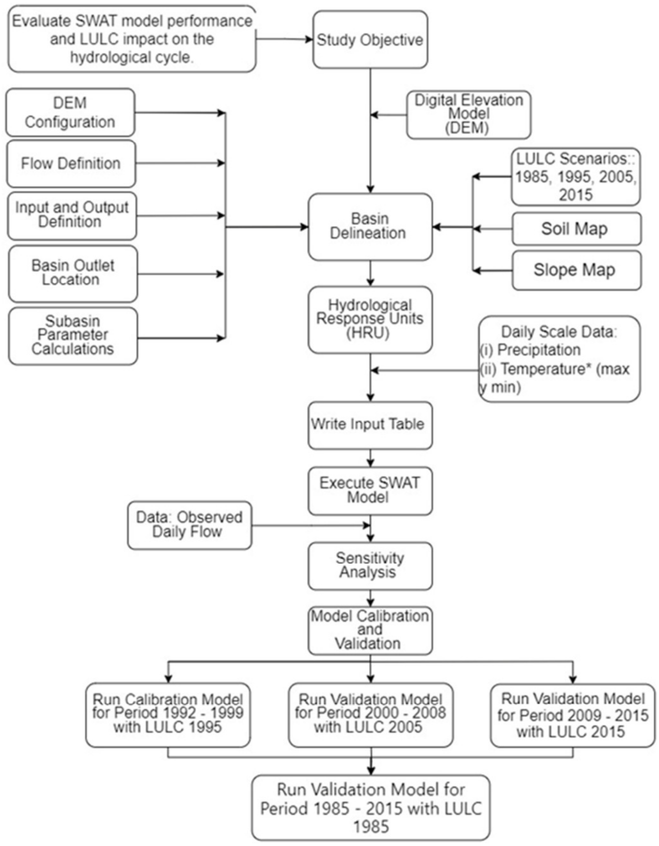

Fig. 3. Flowchart to evaluate the hydrology in the basin.

The streamflow in the 23 sub-basins was determined deploying the measured flow values at the hydrometric stations for the former to be compared with the runoff calculated by the model under the four LULC scenarios. The hydrological impacts were determined by altering the LULC while keeping all parameters constant during the study period.

III. RESULTS AND DISCUSSION

Between 1985 and 2015, native forests and shrublands (25%) constituted the primary LULC. During the same period, there was a progressive increase in the grassland occupation (18%) of the total area by 2015. This trend could be related to the destruction of the natural areas for livestock farming, as observed in Figure 4 and Table II. The analysis of the evolution of LULC between 1985 and 2015, presented Table III, revealed an increase in the extent of grasslands accompanied by a decrease in the use of savannas and native forests. Native forests, shrublands, and wetlands were the land covers that experienced the greatest changes in their percentages related to the total area in 1985. This phenomenon is primarily attributed to the reduction of the savanna areas (38%) between 1985 and 2015. Additionally, the forest plantations (25%) showed an upward trend relative to the 1985 scenario, as illustrated in Figure 4 and Table II.

TABLE II. PROPORTION OF THE AREA AFFECTED BY CHANGES IN LULC ALONG WITH THEIR RELATIVE VARIATIONS

	LULC (%)				Relative Changes (%)
	1985	**1995**	**2005**	**2015**	**1985-2015**
Bo	27.9	33.3	36.4	53.0	25.0
Pt	21.9	23.4	31.2	40.3	18.3
Sa	43.6	36.7	29.6	5.2	-38.4
H	0.6	0.8	0.7	0.3	-0.3
Ag	3.6	2.8	0.9	1.0	-2.6
Au	1.2	1.0	0.2	0.1	-1.2
Sn	0.6	1.0	0.0	0.0	-0.6
A	0.5	1.1	1.1	0.2	-0.3

*Forests: Bo; grasslands: Pt; savannah: Sa; wetlands: Hu; agriculture: Ag; urban areas: Au; non-vegetated: Sn; water: A.

TABLE III. ADJUSTED SENSITIVE PARAMETERS

Parameter	Calibrated values		
	Adjusted	**Minimum**	**Maximum**
ALPHA_BF	0.74	0	1
GW_DELAY	0.12	-0.25	0.25
GWQMN	41.61	30	450
SLSUBBSN	12.91	0	25
SOL_AWC	-0.02	-0.2	0.1
SURLAG	9.45	0.05	24

Table III outlines the six parameters that were identified and which have a significant impact on simulating the surface flow of the basin. The adjusted parameters ensured adequate correspondence with the actual water balance [22]. During the calibration at the Pindo station for the 1995 scenario, the model exhibited low uncertainty, with a p-factor of 0.36 and an r-factor of 0.23. For the validation periods under the 2005 and 2015 scenarios, a satisfactory level of uncertainty was achieved, with a p-factor of 0.64 (0.59) and an r-factor of 0.26 (0.23), respectively, as portrayed in Table IV. At the Puyango station, a p-factor of 0.60 and an r-factor of 0.33 were observed during calibration. For validation, p-factor values of 0.7 (0.65) and 0.31 (0.24) were, respectively, obtained as displayed in Table IV. Finally, at El Tigre, a p-factor of 0.63 and an r-factor of 0.23 were recorded during calibration, while for validation, p-factor values of 0.76 (0.68) and 0.27 (0.25) were, accordingly, obtained, as shown in Table IV. The model performance at the three hydrometric stations demonstrated a very good level of R^2 (0.75 – 0.89) for the different LULC scenarios during calibration. Table IV also indicates that very good levels of NSE (0.77 – 0.87) and low PBIAS were achieved, according to the classification made by authors in [13]. The model was validated to demonstrate the suitability of the calibrated values in the 1995, 2005, and 2015 scenarios, as depicted in Table IV. The agreement between the observed and validated flow in the three scenarios reached a good level for the Pindo station, with R^2 values of 0.78, 0.79, and 0.78, and NSE values of 0.69, 0.80, and 0.83, respectively. However, not very good classifications were observed for PBIAS, with values of -15.67%, -36.89%, and -19.33%, respectively.

TABLE IV. CORRELATION BETWEEN CALIBRATION AND VALIDATION PERIODS

			Pindo			**Puyango**			**El Tigre**		
SnC: 1992-1997 C: 1992-1997 V: 1998-1999			**SnC**	**C**	**V**	**SnC**	**C**	**V**	**SnC**	**C**	**V**
LULC 1995	P: 1992 - 1999	R^2	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: 2000-2006 C: 2000-2006 V: 2007-2008			**SnC**	**C**	**V**	**SnC**	**C**	**V**	**SnC**	**C**	**V**
LULC 2005	P: 2000 - 2008	R^2	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: 2009-2013 C: 2009-2013 V: 2014-2015			**SnC**	**C**	**V**	**SnC**	**C**	**V**	**SnC**	**C**	**V**
LULC 2015	P: 2009 - 2015	R^2	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
		PBIAS	-21.3	-17.6	-19.3	-25.6	-21.9	-18.2	-16.2	-13.4	-21.5

*Period: P; not calibrated: SnC; calibration: C; validation: V

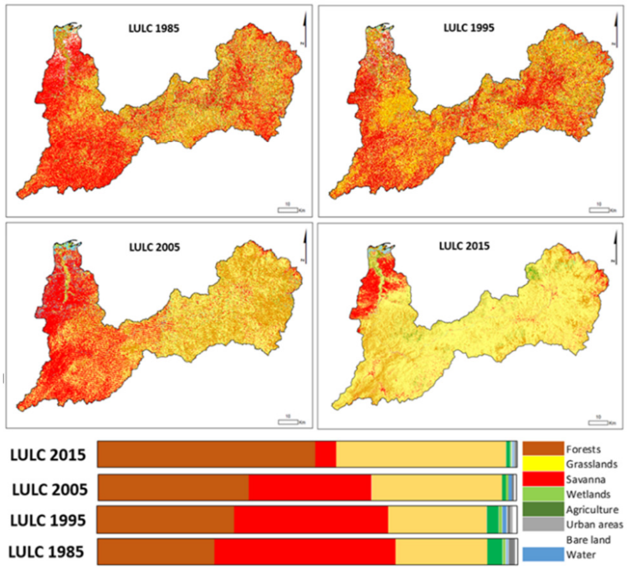

Fig. 4. Mapping of the territory affected by alterations in LULC.

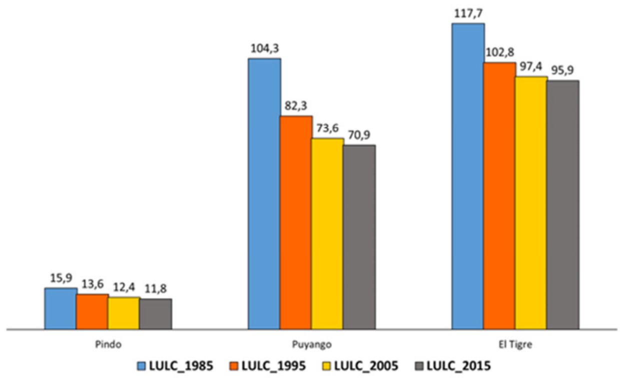

Fig. 5. Flow behavior in relation to the change in LULC.

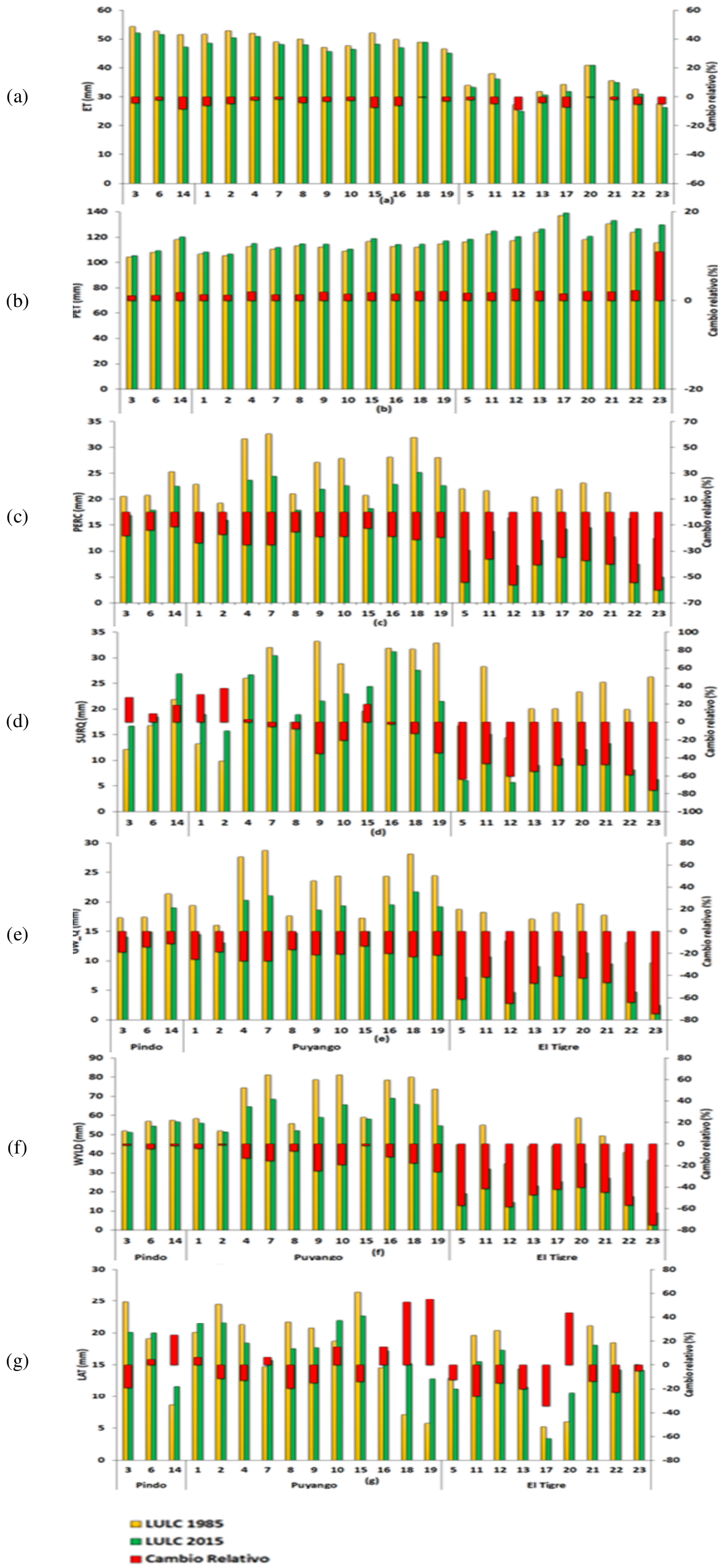

Fig. 6. Monthly average of hydrological cycle parameters: (a) ET, (b) potential PET, (c) PERC, (d) SURQ, (e) GW_Q, (f) WYLD, and (g) LAT_Q for the LULC_1985 and LULC_2015 scenarios.

Through the paired t-test, significant differences were found between the flows obtained in all LULC scenarios, with a 95% confidence interval. Figure 5 demonstrates that the greatest disparity in the daily flows was observed between the most contrasting scenarios (1985 and 2015). At Pindo, this was translated into an annual decrease of 4.1 m^3s^{-1}, while at Puyango and El Tigre, the reductions were 33.4 m^3s^{-1} and 21.8 m^3s^{-1}, respectively. The observed trend, indicating a gradual decrease in flow, could be attributed to the LULC change that occurred in the basin during the analyzed period, as evidenced in Figure 4 and Table III. A relative change trend in the SURQ was observed in the sub-basins located on the upper part of the basin. Figure 6d shows that the monthly fluctuations ranged from -76.12% in sub-basin 23 to 37.41% in sub-basin 2, with an overall monthly average of -20.72%. On the other hand, the LAT_Q recorded an average annual decrease of 0.93%, as it can be seen in Figures 5 and 6g. Additionally, a significantly decreasing trend in PERC values was observed in all sub-basins, with relative variations ranging from -60.11% in sub-basin 23 to -11.19% in sub-basin 14. This resulted in an average monthly relative decrease in PERC of -29.2%, as illustrated in Figure 6c. This reduction in PERC, which averaged 27.4 mm monthly, affected the water availability from the soil profile bottom to the shallow aquifer, leading to an average decrease of 6 mm in GW_Q availability. GW_Q values experienced a monthly average relative change showing monthly increases of up to 33%, as manifested in Figure 6e. The largest contribution to the WYLD came from the surface and groundwater flows. Despite the positive effect on basin WYLD, the decreasing trend of GW_Q outweighed the latter, resulting in a decrease in the average relative yield of 26.64%. Consequently, a decrease of 13.7 mm in the monthly average WYLD for the basin was recorded, as exhibited in Figure 6f.

The hydrological modeling approach employed in this study has proven to be effective in accurately representing the behavior of the total streamflow in the basin once calibrated for the different LULC scenarios. This reaffirms the suitability of the database used for integration into the SWAT model in basins situated in the border region between Ecuador and Peru. These findings underscore the importance of applying calibration and validation procedures in the present study, where error metrics for calibration and validation periods at hydrometric stations ranged between the "good" and "very good" categories, as defined by [13]. The inclusion of a calibration database and two extended validation periods contributed to a better simulation of the various components of the hydrological cycle on a daily scale for the three LULC scenarios. The analysis reveals that PET has experienced the most significant variations, directly impacting the streamflow production in the basin. According to authors in [23], PET is a key factor in understanding how LULC affects water production. In this basin, the annual increase of 30.08 mm in PET between the 1995 and 2015 scenarios could be attributed to the expansion of forest plantations and grasslands. In 1995, forest plantations covered 33.3% of the basin area, while by 2015, this figure nearly doubled, reaching 53%, similarly for grasslands, which increased from 23% to 40% of the basin area. This phenomenon has led to an increase in the leaf area, favoring rainfall interception, radiation, and the available area for evapotranspiration. These results complement the observations of authors in [24], who pointed out that SWAT calculates PET based on the canopy-intercepted water ET, maximum plant transpiration rate, and maximum soil ET rate. The increase in the forest plantations and grasslands has led to an annual increase in PET and SURQ rates of 2.14% and 33.32%, respectively. This has resulted in a decrease in PERC of 29.19%, in GW_Q of 33%, and in WYLD of 26.64%.

The trend towards a decrease in the total streamflow due to increased forest cover has been reported in small and mesoscale watersheds by several studies [26-30]. Authors in [26] highlighted that watersheds mainly covered by native forests tend to have higher average annual runoff coefficients than those dominated by exotic plantations, and the reduction in the total streamflow is related to the expansion of the latter. Authors in [31] demonstrated that the annual runoff decreases with an increase in the forest plantation area although the magnitude of these changes depends on various factors, which aligns with the present study by showing a significant decrease in the streamflow among the three LULC scenarios. On the other hand, authors in [30] noted that the replacement of native forests with the fast-growing forest plantations has led to a decrease in the streamflow by 42.7% in mesoscale watersheds. The study reveals a LULC pattern dominated by forests, including evergreen conifers, deciduous and non-deciduous trees, and woody perennials in three different scenarios (1995, 2005, and 2015), representing 33%, 36.4%, and 53% of the total basin area, respectively. Additionally, there is a gradual increase in grasslands, reaching 23%, 31%, and 40%, respectively, which affects groundwater behavior and WYLD during the drier months. However, this impact is not as pronounced during the winter season, characterized by higher rainfall, when increased grasslands lead to higher rates of interception and evapotranspiration losses, thus reducing water storage in the soil.

The expansion of grasslands stands out as the primary driver of LULC changes in the study area, becoming the dominant land use in the basin. The results of this research could have significant importance in terms of governance and environmental planning between the two involved countries, Ecuador and Peru. According to authors in [32], planning in dynamic landscapes like these can be particularly challenging when landscape change processes are unregulated. This study arises from the growing concern about the impact of land use change on water resources and the need to sustainably manage transboundary basins, such as the Puyango-Tumbes River basin, which spans territories in Ecuador and Peru. Despite the existence of previous research on the effects of land use change in specific basins, there remains a knowledge gap regarding the precise quantification and simulation of LULC scenarios over extended historical periods and how these changes influence the water balance. The primary contribution of this research is the generation of robust quantitative evidence that demonstrates how modifications in the land cover have negatively impacted the water balance of the Puyango-Tumbes River basin. When comparing these results with those of other studies, this work stands out for its ability to provide a comprehensive and long-term analysis, utilizing advanced simulation tools that allow for more accurate predictions of the future impacts of land use change. The study's transboundary focus adds significant value, offering a replicable model for other international basins facing similar challenges. Furthermore, it highlights the need for effective international cooperation to sustainably manage water resources in areas where the impacts of land use change can have regional and global consequences.

IV. CONCLUSIONS

The application of the semi-distributed hydrological model in this study enabled a comprehensive analysis of the main components of the hydrological cycle at the sub-basin level, including Evapotranspiration (PET), Percolation (PERC), Surface Runoff (SURQ), Lateral Flow (LAT_Q), Groundwater Flow (GW_Q), and Annual Water Yield (WYLD). This detailed approach facilitated the understanding of how land use changes influence each of these processes, providing critical information for the formulation of water management, strategies that can mitigate negative effects and promote sustainability in the Puyango-Tumbes River basin. The analysis disclosed that between 1985 and 2015, the 18.3% increase in the grassland areas and the 38.2% reduction in the savanna zones led to a 2.1% increase in the PET rates. This change in the land cover has a notable impact on the hydrological cycle, resulting in a significant decrease in PERC (29.2%), SURQ (20.7%), GW_Q (33%), WYLD (26.6%), and LAT_Q (0.9%). These results underscore the importance of considering land use changes when evaluating the water balance and the sustainability of water resources in the basin. The observed changes in the total flow, with 95% reliability on a daily scale, are closely related to the increase in grassland areas and the 25% expansion of the forest zones. This expansion has contributed to the rise in PET rates. These findings stress the urgency for decision-makers to consider these variations to develop and implement effective sustainability and remediation strategies for water resource management and ecosystem preservation in the Puyango-Tumbes River basin.

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