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Water estimation model for the agricultural and population sectors of the Tablachaca watershed in Peru

Modelo de estimación hídrica para el sector agrícola y poblacional de la cuenca Tablachaca en Perú

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ABSTRACT: Climate change and human-induced modifications to water resources negatively affect the natural flow regimes of the river. Therefore, understanding hydrological alterations is crucial for water estimation in watersheds. This study analyzed water estimation in the Tablachaca River watershed for the agricultural and population sectors. The water estimation model was developed in Soil and Water Assessment Tool (SWAT), in which the sensitivity analysis was applied to the model, as well as the degree of precision through the Nash-Sutcliffe efficiency coefficient (NSE), percentage bias (PBIAS) and the coefficient of determination (R^2). The main results were the water availability of the basin was 40.67 m^3/s and 23.29 m^3/s for agricultural use and human consumption with a probability of 75 % and 95 %, respectively. Model calibration reached an NSE of 0.79; PBIAS of -5.69 % and R^2 of 0.80 and a validation with NSE of 0.75; PBIAS of -19.22 % and R^2 of 0.82, which in effect made it possible to obtain a water estimation model with effective performance.
Keywords: Water Accessibility, Hydrographic Basin, Water Availability, Water Resources, Hydrological Modelling.

RESUMEN: El cambio climático y las modificaciones inducida por el hombre en los recursos hídricos afectan de forma negativa la disponibilidad de los volúmenes de agua para el sector agrícola y poblacional. Por tanto, comprender las alteraciones hidrológicas es crucial para la estimación hídrica en las cuencas hidrográficas. En este estudio se analizó la estimación hídrica en la cuenca del río Tablachaca para el sector agrícola y poblacional. El modelo de estimación hídrica se desarrolló en Soil and Water Assessment Tool (SWAT) donde se aplicó el análisis de sensibilidad al modelo, así como el grado de precisión mediante el coeficiente de eficiencia de Nash-Sutcliffe (NSE), sesgo porcentual (PBIAS) y el coeficiente de determinación (R^2). Los principales resultados alcanzados fueron la disponibilidad hídrica de la cuenca de 40.67 m^3/s y 23.29 m^3/s para el uso agrícola y consumo humano con una probabilidad del 75% y 95% respectivamente. La calibración del modelo alcanzó un NSE de 0.79; PBIAS de -5.69% y R^2 de 0.80 y una validación con NSE de 0.75; PBIAS de -19.22% y R^2 de 0.82, en efecto permitió obtener un modelo de estimación hídrica con un rendimiento eficaz.
Palabras clave: accesibilidad al agua, cuenca hidrográfica, disponibilidad hídrica, recursos hídricos, modelación hidrológica.

INTRODUCTION

Efficient water resource management is a fundamental aspect for the sustainable development of watersheds (Rosen *et al*., 2023). Studies by Cai *et al*. (2023) show that issues such as urbanization threaten human survival and socio-economic development. Additionally, the combination of meteorological phenomena and socioeconomics has become a complex issue for resource management. Therefore, the optimal evaluation of hydrological processes is necessary to quantify and improve the distribution of water to different sectors of society, while contributing to the sustainable management of water resources.

The Tablachaca River basin in northern Peru faces serious challenges in establishing efficient water resource use. The main causes include its geographic location in the Andes of Peru, which leads to analyses of spatial-temporal variability due to the mountainous region, climate, precipitation variability, and various water uses, such as drinking water supply, hydroelectricity, mining, and agriculture. Secondly, the high specific solid flows resulting from water erosion affect soil fertility, water availability for crops, and consequently the loss of useful water storage volume in reservoirs, as well as the sustainable production of electricity (Velásquez-Castro *et al*., 2019).

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Thirdly, the scarce information on complete and updated hydrological data. Historically, flow data were limited until 1997, leaving a knowledge gap about the fluvial dynamics in subsequent decades.

The semi-distributed hydrological estimation model called Soil and Water Assessment Tool (SWAT) is one of the most used by water resource professionals. Due to its interdisciplinary nature, the SWAT model is recognized as a robust tool that contributes to water management, particularly in simulating agricultural management (Chen *et al*., 2024).

Rosen *et al*. (2023) observed prolonged droughts lasting 3 years in 11 sub-basins due to the lack of northeast monsoons. Shin *et al*. (2021) accurately estimated long-term monthly flows using SWAT, reflecting the internal hydrological processes of the basin. A similar result was achieved by Pandi *et al*. (2023) in India, enabling sustainable water management based on basin, rainfall, and soil condition data. Jiang *et al*. (2024) emphasize that in mountainous areas, high rainfall accuracy is essential to improve SWAT model evaluation, as they obtained underestimated results in monthly runoff with a percentage bias ranging from 5% to 19%.

MATERIALS AND METHODS

The research was conducted in the Tablachaca River watershed, located on the western slope of the Andes in Peru. The watershed includes two secondary rivers, the Angasmarca and Huaychaca rivers, which drain their tributaries into the main Tablachaca River.

Spatial, climatic, and hydrometric data were used for accurate modeling in the SWAT program. For spatial data, land use analysis was performed using the Ecosystems Map of Peru provided by the Ministry of the Environment, obtained from https://sinia.minam.gob.pe/mapas/mapa-nacional-ecosistemas-peru. Equivalencies were established between the ecosystem types and general land uses that could be interpreted by SWAT.

Soil type information was obtained from the World Digital Soil Map (DSMW) available at https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/cc45a270-88fd-11da-a88f-000d939bc5d8, which follows the FAO (Food and Agriculture Organization of the United Nations) nomenclature. Subsequently, terrain slopes were processed in the ESRI format for manipulation, and their respective ranges were generated using ArcGIS Pro 2.0.

Regarding climatic data, five rainfall stations were considered: Cabana, Cachicadán, Huacamarcanga, Mollepata, and Quiruvilca, located between 2,726 and 4,123 meters above sea level. The data were obtained from the National Water Authority platform (https://snirh.ana.gob.pe/onrh/) and the National Meteorology and Hydrology Service of Peru (https://www.senamhi.gob.pe/servicios/?p=estaciones). The data collected covered the years 1972 to 2023, but data completion analysis was necessary using HEC 4 (Bhaskar & Whitlatch, 1980) and rainfall consistency analysis through TREND (Chiew & Siriwardena, 2005). Finally, for hydrometric data, the Chuquicara station was considered, with available historical data spanning 24 years from 1972 to 1997.

SWAT Hydrological Model

Water estimation for human and agricultural consumption was analyzed using the SWAT model based on the SCS-CN method to predict runoff from rainfall and soil saturation levels. In this regard, a 95th percentile was chosen as the standard for human consumption water, ensuring that only 5% of the data exceed the guaranteed minimum flow. For irrigation purposes, a 75th percentile was used, considering that crops tolerate a certain level of water stress due to limited water availability for irrigation.

Model Calibration and Validation

In modeling, uncertainties arise from four main sources: input data errors, inaccuracies in observed data, parameter variability, and structural uncertainty. Calibration required a clear objective function, such as the Nash-Sutcliffe efficiency in SWAT, to evaluate the model's adequacy. Validation compared simulations with observations, using statistical criteria to verify the accuracy of SWAT-CUP, which facilitated both processes.

Model Performance Indices

Three indices were proposed for evaluating the performance of predictive models: the Nash-Sutcliffe coefficient (NSE), the Percent Bias (PBIAS), and the Coefficient of Determination (R^2). In this regard, the accuracy of the model's predictions was evaluated in comparison with the mean of the observed data.

RESULTS AND DISCUSSION

Using Geographic Information Systems with ArcGIS Pro, the watershed presented a total area of 3,198.90 km², with a perimeter of 410.46 km. The altitude variation within the watershed is considerable, with a maximum elevation of 5,050 m.a.s.l. and a minimum of 505 m.a.s.l., indicating a notable topographic variation and potentially diverse hydrological and geotechnical conditions across the basin.

Five rainfall stations were identified within the watershed, which recorded precipitation data from 1972 to 2023. Table 1 shows the analyzed meteorological stations and their respective precipitation intervals. The Huacamarcanga station recorded the highest precipitation, while Mollepata had the lowest with values of 93.40 mm and 41.10 mm, respectively.

The three main rivers of the Tablachaca basin were also analyzed. The Angasmarca River, with a length of 18.82 km and a drainage area of 354.52 km², contributes 11.08% of the total flow in the basin. The Huaychaca River, extending 26.32 km in length and draining an area of 731.92 km², contributes 22.88% of the basin's flow. Finally, the Tablachaca River represents 66.04% of the total water contribution in the basin, with a length of 103.6 km and a drainage area of 2,112.46 km².

TABLE 1. Altitude and Precipitation Recorded at the Climate Stations

N°	Station	Altitude	Maximun	Minimun	Average
1	Cabana	3300	62.16	0.10	2.39
2	Cachicadan	2892	62.60	0.10	2.66
3	Huacamarcanga	4123	93.40	0.00	2.54
4	Mollepata	2726	41.10	0.10	1.61
5	Quiruvilca	3950	53.50	0.10	3.83

Sensitivity Analysis

The sensitivity analysis identified 16 parameters as most sensitive for optimization. Due to similarities in hydrological behavior, the CN2, SOL, and SFTMP parameters exhibited the highest relative sensitivity. This suggests that surface runoff, available water capacity in the soil, and temperatures are critical for flow generation in the river. Regarding the ESCO parameter, its value close to one indicates a high level of evaporation compensation in the soil due to the climatic and environmental conditions in the mountainous areas.

Calibration and Validation

The automatic calibration used objective functions defined by Das *et al.* (2024). During the calibration process, two-thirds of the observed flow data were used, and the remaining one-third was used for validation. Using performance indices, the model simulated rainfall from 1972 to 2023.

After calibrating the model for the period from 1973 to 1988, NSE values of 0.79 and PBIAS of -5.69% were obtained, indicating good model performance and good R^2 correlations with values exceeding 0.80. For the validation period from 1989 to 1996, an NSE of 0.75 and an R^2 of 0.82 were obtained, though the PBIAS showed a larger deviation with an error of -19.22%. However, these values remain within good performance ranges, with the calibration process proving to be more optimal than the validation. The results from the SWAT model's performance are shown in Table 2. During the calibration period, the simulated flow increased by 5.9% compared to the observed flow, while during validation, it increased by 23.8%. Therefore, there is a trend of greater uncertainty in the simulated flow for the validation period from 1989 to 1996.

In relation to the SWAT model calibration, Marahatta *et al.* (2021) achieved favorable results with NSE values of 0.78 and PBIAS of -1.46%, while their validation process yielded values of 0.81 and -17.1 for the NSE and PBIAS indices, respectively, which are similar to the values obtained in the current study. According to Colín-García *et al.* (2023); Xiang *et al.* (2022) NSE and PBIAS values may vary depending on watershed conditions, particularly soil type.

Figure 1 shows the calibrated and validated model, where the simulated flow curve closely matches the observed flow curve. With the exception of 1975, where there was an underestimation of simulated flow, and 1984, where there was an overprediction, the model's validation demonstrated a good fit between the simulated and observed flow curves for the period from 1989 to 1997.

TABLE 2. Performance Indices

Indicators	Calibration (1973-1988)		Validation (1989 - 1996)	
Observed Q	29.18	m^3/s	27.18	m^3/s
Simulated Q	30.93	m^3/s	33.65	m^3/s
NASH	0.79	-	0.75	-
PBIAS	-5.69	%	-19.22	%
R^2	0.80	-	0.82	-
Number of Months	192	Months	96	Months

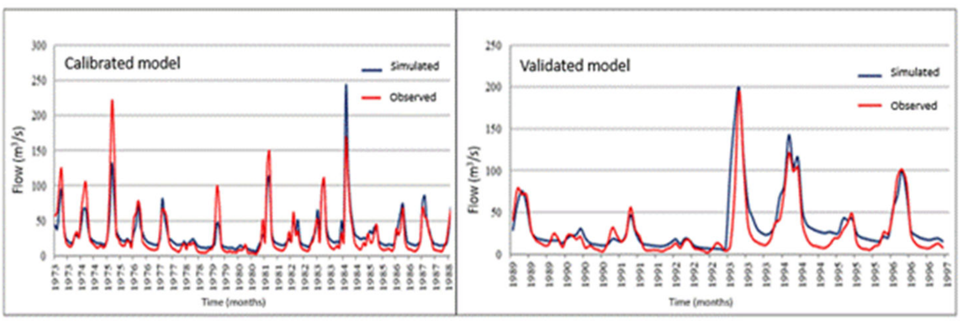

FIGURE 1. Calibrated and Validated Model

After validation, the SWAT model was extended to simulate flow data until 2023. The average monthly flows in each river analyzed allowed for differentiation between dry and wet periods. Regarding this, the water availability for human consumption and agricultural use was identified, as shown in Figure 2.

For the Angasmarca River, the average monthly flows ranged from 0.34 m^3/s to 12.39 m^3/s, with an annual average of 3.8 m^3/s.

The wet period was established between December and April, with March being the month of highest precipitation in the area. The dry period occurred between May and November. This variability in flows reflects water availability, with the river meeting the needs of human consumption and irrigation in dry and wet periods, satisfying 95% and 75% of demand probabilities, respectively. In comparison, the Huaychaca River showed a higher hydrological trend, with average monthly flows ranging from 1.87 m^3/s to 34.51 m^3/s. It also displayed a decreasing flow trend during the dry period from May to November, similar to the Angasmarca River's sub-basin. However, the Huaychaca River had a higher water reserve, meeting 95% and 75% of water demand for human consumption and agriculture, respectively. The minimum flows in August were 1.87 m^3/s, indicating reduced water availability for both agricultural and human consumption during critical months.

Finally, the Tablachaca River, as the main river of the basin, demonstrated significantly higher water availability compared to the Angasmarca and Huaychaca rivers. It has average monthly flows of 40.81 m^3/s. Similar to the other rivers, its wet period extends from December to April, and its dry period is from May to November. The highest flow recorded during the wettest month was 122.7 m^3/s, while the lowest during the driest month was 5.91 m^3/s. These values are considerably higher than those of the previously mentioned rivers. As a result, the evaluation determined that water resources available for agricultural and human consumption are much higher. During the wettest period, the flow allocated for agriculture reaches 60.59 m^3/s, while the supply for human consumption rises to 33.25 m^3/s. On the other hand, during the driest period, the flow available for irrigation decreases to 4.36 m^3/s, and for potable water, it drops to 2.41 m^3/s. In line with Chen *et al.* (2024) who performed two irrigation water simulation scenarios in SWAT, a 6.58% reduction in net water use for irrigation was observed.

The analysis of the scarcity index, based on water demand and supply, follows the classification from (IDEAM, 2004), which categorizes the index as low (<10%), moderate (10%-20%), medium (20%-40%), and high (>40%). Based on this classification, the scarcity index was determined monthly for the Angasmarca River sub-basin, with values ranging from 55% to 79%. The Huaychaca River sub-basin showed values from 57% to 79%, while the Tablachaca River basin had values ranging from 81% to 116%. Overall, the Tablachaca River basin reached a scarcity index higher than 100%, indicating that demand exceeded available supply. This suggests the need for authorities to implement new water resource management measures due to these limitations. However, Liao (2024) highlights the need to identify water scarcity indices from the perspective of human consumption and further examine the variables involved in agriculture.

CONCLUSIONS

- The SWAT hydrological model was successfully applied to the Tablachaca River basin, integrating spatial soil type distribution, climatic, and hydrometric data. The calibration demonstrated good model performance with an NSE of 0.79 and a PBIAS of -5.69%. Additionally, the validation confirmed the model's effectiveness, achieving an NSE of 0.75 and a PBIAS of -19.22%, with calibration being the more optimal phase.
- The temporal analysis revealed an increase in flow production from December to April, which corresponds to the wet period, followed by a significant decrease from May to November, representing the dry period.
- The total water availability in the basin allocated for agricultural use was 40.67 m^3/s, while for human consumption, 23.29 m^3/s was available, with 75% and 95% probability, respectively.
- The Tablachaca River exhibited the highest water availability within the studied basin. For agricultural use, a maximum flow of 60.59 m^3/s and a minimum of 4.36 m^3/s were observed. For human consumption, the maximum flow recorded was 33.25 m^3/s and the minimum was 2.41 m^3/s, respectively. However, the Angasmarca and Huaychaca Rivers showed limited availability, particularly during the dry period, with flows approaching zero.

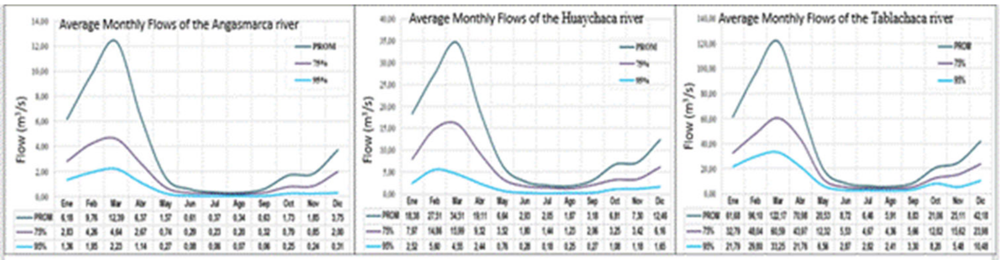

FIGURE 2. Average Monthly Flows of the Angasmarca, Huaychaca, and Tablachaca rivers.

- It is identified that the performance of the simulation model could be improved by using satellite precipitation data because the sensitivity and uncertainty of the parameters with respect to different precipitation inputs may reflect variations in performance when compared to a dataset from multiple sources.
- As fundamental elements for future research, it is recommended to harmoniously integrate numerical physical models with artificial intelligence science to estimate the water reserves of the basin more accurately. The need for hydraulic infrastructure such as reservoirs is also suggested to ensure water supply during periods of scarcity and to contribute to the regulation of the hydrological cycle.

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