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Hydrological Scenario of the Quilca-Vitor-Chili River Basin: Current and Future Estimates

Escenario hidrológico de la cuenca del río Quilca-Vítor-Chili: estimaciones actuales y futuras

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ABSTRACT: The objective of the study was to estimate current and future hydrological scenarios in the Quilca-Vitor-Chili basin for both population and agricultural water demands. The methodological process involved collecting climatic and hydrological data from SENAMHI, as well as high-resolution Digital Elevation Model (DEM) data from NASA. The data were processed using the SWAT model for hydrological estimation. The model's performance was evaluated using the coefficient of determination (R^2), the Nash-Sutcliffe Efficiency index (NSE), and the Percent Bias (PBIAS). The hydrological scenario showed average annual streamflows of 11.54 m³/s for the year 2024, with a slight increase to 14.87 m³/s projected for 2040, based on a SWAT model validation with $R^2 = 0.75$, NSE = 0.72, and PBIAS = -18.4%. The analysis identified that both current and future hydrological scenarios exhibit water stress levels exceeding 80%, highlighting the urgent need to implement integrated water resources management strategies.
Keywords: water balance, climate change, water demand, sustainable water management, swat model, future projections.

RESUMEN: El estudio tuvo como objetivo estimar los escenarios hidrológicos actuales y futuros en la cuenca Quilca - Vitor - Chili para la demanda poblacional y agrícola. En el proceso metodológico se recopiló información climática e hidrológica de SENAMHI, así como datos del Modelo Digital del Terreno de alta resolución de la NASA. Los datos fueron procesados utilizando el modelo SWAT para la estimación hídrica. La eficiencia del modelo se midió mediante el coeficiente de determinación (R^2), el índice de Nash-Sutcliffe (NSE) y el sesgo porcentual (PBIAS). El escenario hidrológico mostró caudales promedio anuales de 11,54 m³/s para el año 2024 y un ligero incremento de 14.87 m³/s para el año 2040 para una predicción de validación en el modelo SWAT de $R^2 = 0,75$, NSE = 0.72 y PBIAS = -18,4%. Se identifica que para los escenarios hidrológicos actuales y futuros existe estrés hídrico superior al 80% para lo cual es inminente implementar estrategias de gestión integrada de los recursos hídricos. En conclusión, el modelo SWAT logró simular con precisión el balance hídrico de la cuenca en contextos presentes y futuros, validando su eficacia como herramienta de análisis.
Palabras clave: balance hídrico, cambio climático, demanda hídrica, gestión sostenible del agua, Modelo SWAT, proyecciones futuras..

INTRODUCTION

The basins on Peru's southern slope face significant challenges due to the lack of hydrological monitoring and the limited availability of runoff flow data (Autor & Quijano, 2018), which, as they note, hinders immediate decision-making for water planning and management. This situation exacerbates water insecurity, since the lack of up-to-date data hinders and limits the ability to anticipate extreme events, such as floods and droughts. Furthermore, climate change highlights water variability in river basins. (Drenkhan & Castro-Salvador, 2023). According to Carpio Fernández et al. (2022), the basins of the southern slope are composed of eight distinct morphostructural domains. Likewise, the region exhibits climatic diversity, influenced both by altitude and by the cold Humboldt Current. In particular, the demand for water suitable for human consumption in the analyzed watershed is considered very high. According to the Water Resources Management Plan (PGRH) (ANA, 2023). The region's population stands at 1,273,976 inhabitants, with an intercensal growth rate of 1.9%. On the other hand, there is a high demand for agricultural products, as well as a need for greater volumes of water for crops.

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Therefore, it is essential to understand the dynamics of the water balance in a basin, leveraging its unique characteristics, such as the climate diversity influenced by altitude, the irregular terrain, and the water sources. Water quality significantly impacts human consumption, as evidenced by the inherent characteristics of the water in the Quilca-Vítor-Chili River basin (Carpio Fernández et al., 2022). However, research on this basin is limited and focuses primarily on hydrogeological aspects and water quality.

Currently, studies stand out that analyze environmental and hydrological conditions as stipulated by Ramos & Delgado (2022), covering water quality, vegetation, and the Human Development Index. For their research, they conducted a Watershed Sustainability Assessment, which revealed a greater water demand to meet human needs, domestic use, and productive activities.

It is important to note that there are various methodologies for evaluating the water balance over a specific period, employing modeling tools such as the Soil and Water Assessment Tool (SWAT). This model allows for the long-term evaluation of a watershed's dynamics and examines how climate variability affects and influences land cover, providing us with a comprehensive view of the hydrological processes involved (Guug et al., 2020).

SWAT was designed to represent the components of the water balance and its primary function is to predict how different soil conservation techniques influence runoff and soil erosion. Runoff in the SWAT model is calculated independently for each hydrologic unit and then combined to obtain the total basin runoff, thereby improving accuracy and providing a more detailed description of the water balance (Douglas-Mankin, 2010).

Given the above, this model can offer various solutions. In particular, the analyzed basin faces water scarcity, primarily attributed to a high evaporation rate, which poses a serious availability problem for the population and activities dependent on this water resource (Nevermann, 2024). These circumstances are referred to as water stress; Ghajarnia (2025) highlights a high demand for water resources relative to water availability during a given period. Motschmann et al. (2022) provide a global overview of countries facing high levels of water stress, ranking Peru 66th. In the Latin American context, Peru ranks fourth, with a medium-to-high risk of being affected by this phenomenon. Consequently, the central purpose of this research is to estimate the current and future water availability in the Quilca-Vítor-Chili River basin, taking into account the demands of the population and agricultural sectors.

MATERIALS AND METHODS

The Quilca-Vítor-Chili River basin is located in southwestern Peru, encompassing the Arequipa region as well as small portions of Puno and Moquegua.

Data collection and analysis

Current hydrometeorological data records on water supply covering the period from 1981 to 2016 were obtained. However, the hydrological database was extended to 2023 using the HEC-4 model. The NASA DEM file located at 16°47′10″ South latitude and 72°26′35″ West longitude was used, known for its high accuracy in hydrological studies (SRTM, 2025). This model was developed thru the comprehensive reprocessing of the Shuttle Radar Topography Mission (SRTM). (Tran *et al.,* 2022).

It provides global elevation data with a 1-arc-second spacing and a root mean square error of 5.30 ± 6.05 m in the vertical direction.

SWAT modeling

The SWAT model, based on physiographic data, was applied to simulate various hydrological scenarios and analyze the water balance variables. This tool enables both spatial and temporal evaluation of hydrological processes. The SWAT model parameterization process is shown in Figure 1, which details the input and output data involved in the simulation.

Calibration and validation of the SWAT

Model SWAT-CUP, a software package specialized in calibrating hydrological models such as SWAT, was used in this study, as shown in Figure 1.

According to Abbaspour (2013), this calibrator includes five algorithms: Sequential Uncertainty Fitting (SUFI-2), Particle Swarm Optimization (PSO), Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol), and Bayesian Inference Methods (MCMC).

The SUFI-2 algorithm was applied for model calibration due to its ability to effectively manage the uncertainty associated with a wide range of factors, from input variables to observed data. (Weber & Ocampo,2019).

As defined for conducting the calibration process for runoff and groundwater flow generation, there are several parameters that exhibit some degree of sensitivity, such as baseflow and bank recession constants, hydraulic conductivities, and curve numbers, among others. To evaluate the predictive performance of the SWAT model, three statistical indicators widely used in hydrology were employed: the coefficient of determination (R^2), the Nash-Sutcliffe efficiency (NSE), and the percent bias (PBIAS). (Panda et al., 2021 & Krause, 2005).

SWAT model performance indicators such as R2, NSE, and PBIAS range from less than 0.7 to greater than 0.85, from less than 0.5 to greater than 0.75 and less than 1, and from greater than ±25 to less than ±10, respectively (Moriasi, 2007). The performance rating based on the results can be unsatisfactory, satisfactory, good, or very good.

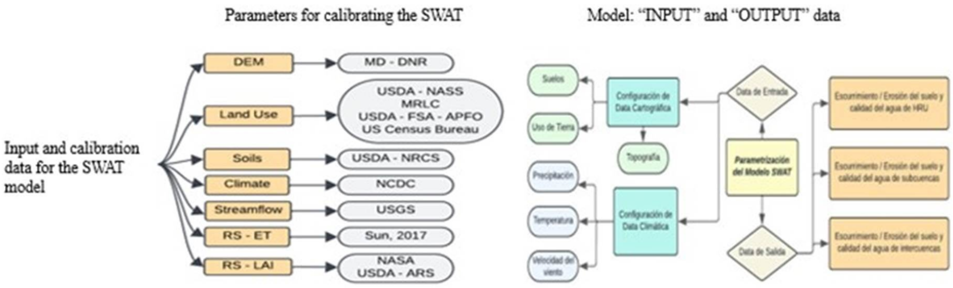

Figure 1. Parameters for calibrating the SWAT model: "INPUT" and "OUTPUT" data

RESULTS AND DISCUSSION

The geomorphological parameters of the Quilca-Vítor-Chili River basin include a total area of 13,430.04 km², a catchment area of 7,498.3 km², and a humid area of 2,504.9 km². The drainage system characteristics showed a sixth-order stream, resulting in a drainage density of 0.458 km/km² and a mean overland flow length of 548.25 m. Meanwhile, the relief characteristics range from elevations of 416 m above sea level to 6,252 m above sea level, with a basin slope of 16.85% and a maximum flow slope of 1.47%. All of this indicates that it is a basin with a high capacity to generate runoff, a moderate risk of erosion and flooding, and potential for mixedmanagement.

Forty-nine hydrometeorological stations were identified in the basin, installed between 1922 and 2002. Of these, 17 stations are still in operation, recording meteorological variables to this day. Temperatures in the region are highly variable, with recorded lows of -7.4°C and highs of 27.5°C, and an average annual rainfall of 274 mm. Regarding evaporation values, they tend to decrease with increasing elevation above sea level, resulting in fluctuations across the basin from 1366 mm/year to 3055 mm/year. Figure 2 shows the curve number values, which range from 60 to 95. Low curve number values indicate favorable soil conditions for rainfall infiltration and low runoff. In this regard, 68% of the watershed has a curve number of 78, which indicates moderate infiltration typically associated with soil groups B or C.

The soil types in the basin are shown in Figure 2. Four soil types were identified in the basin: Dystric Leptosol-Umbric Andosol (LPd-ANu-R), Dystric Leptosol-Lithic Outcrop (LPq-R), Haplic Solonchak-Eutric Leptosol (SCh-LPe), and Dystric Leptosol-Vitric Andosols (LPd-ANz), representing 7.07%, 14.39%, 24.47%, and 54.07% of the total basin area, respectively.

In terms of their implications for water management, the largest soil area is LPd-ANz, which exhibits low water retention in Leptosol sectors, high retention in the vitric Andosols, and can affect infiltration, runoff, and groundwater recharge.

Regarding land cover, it is shown in Figure 2. The soil type with agricultural crops was found to be the most prevalent, at 21.75%, followed by soil with sparse vegetation at 54.28%.

This last aspect means, hydrologically, that Sparse vegetation cover reduces rainwater infiltration, increasing direct runoff and the likelihood of flash floods. Likewise, water retention in the soil is reduced, so part of the "sponge" effect provided by dense ground cover is lost. In other instances, land cover was classified into water bodies, dryland, urban areas, and grasslands, which accounted for 1.07%, 1.33%, 7.71%, and 13.86%, respectively.

Sensitivity analysis

When conducting a sensitivity analysis of the SWAT model, the runoff curve number (CN2) was identified as an important sensitive parameter-an indicator used to calculate the soil's absorption capacity based on the SCS method. This has a significant impact on flow simulation. Additionally, GW DELAY and ALPHA_BF also exhibited a noticeable deficiency, as did the average slope (HRU_SLP) and saturated hydraulic conductivity (SOL_K). Nevertheless, all of this facilitated the calibration phase of the hydrological model.

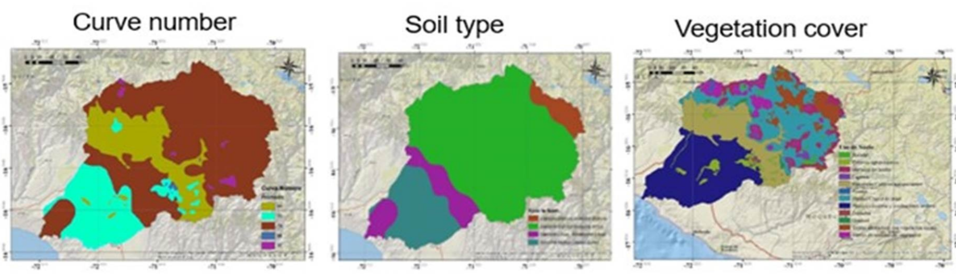

Figure 2. Curve number and soil type

Calibration and validation parameters

To improve the simulation quality, the SWAT hydrological model was calibrated using the SWAT-CUP algorithm. Previously, the model's most sensitive parameters were identified and adjusted to evaluate the uncertainty of the results using the SUFI-2 method. The simulation was run for a 16-year period, from 2024 to 2040. The calibration and validation results, evaluated using hydrographs, showed a good model fit, with NSE values of 0.77 and 0.72, respectively.

Figure 3 shows the observed and simulated flow values. It is observed that there is adequate prediction of the basin's runoff flows, with an NSE of 0.77. The observed flow curves exhibit a slightly higher trend than the simulated ones, indicating that the SWAT model underestimates the input conditions. However, it was found that under current conditions there is an average annual flow supply of 11.54 m^3/s, but a water demand of 33.9 m^3/s for municipal water supply and 65.3 m^3/s for the agricultural sector. Therefore, a water deficit of 86.83% is demonstrated, and the urgent need to implement better water management strategies is also evident.

Model calibration

During the calibration process from 2024 to 2040, the R^2 value was 0.71, the PBIAS was −3.81%, and the NSE was 0.77. As indicated by Moriasi (2007), the performance rating is satisfactory, with a negative PBIAS indicating that the model is overestimated. It can also be seen that the simulated flow values fall within the observed flow range, which would indicate that the model for simulating streamflow was satisfactory.

Model validation

For the validation period from 2024 to 2040, the R^2 coefficient was 0.75, with a PBIAS of −18.4% and an NSE of 0.72. In accordance with Moriasi (2007), these values fall within the aceptable range. When comparing the results obtained with Juma (2022), it is observed that the NSE values of 0.77 and 0.72 for calibration and validation, respectively, are slightly lower. Juma (2022) reported an NSE of 0.89 in calibration and a PBIAS of 10.2%, suggesting model overestimation, a situation that is accentuated in validation with NSE = 0.74 and PBIAS = −12.6%. In contrast, the results achieved, although slightly lower than those reported, are considered satisfactory and within the acceptable range according to the established criteria.

CONCLUSIONS

- The analysis of the hydrological scenario in both the current and future situations reveals an evident presence of water stress in the basin, which is reflected in the insufficient flow available to meet the water demands of the population and the agricultural sector. The scarcity is projected to worsen in future scenarios due to climate variability, population growth, and the proliferation of agricultural activity, thereby compromising the sustainability of the resource.
- The continued water deficit may compromise the security of drinking water supplies, agricultural productivity, and the socioeconomic stability of the basin, especially in geographic areas with the highest population and agricultural concentration. Therefore, the results obtained highlight the need to implement integrated water resources management strategies that include water-use efficiency, prioritization of human use, irrigation modernization, and protection of water recharge areas.
- For future research, a more in-depth sensitivity analysis is recommended, as SWAT modeling is influenced by input data on hydrometeorological and soil characteristics, which affects accuracy. Overall, analyze variables and data using advanced technological techniques such as artificial intelligence.

REFERENCES

ABBASPOUR, K. C. (2013). SWAT-CUP 2013: SWAT Calibration and Uncertainty Programs-A User Manual. Swiss Federal Institute of Aquatic Science and Technology. https://www.scirp.org/reference/referencespapers?referenceid=3048706

ANA (2023) "Plan actualizado de gestión de recursos hídricos de la cuenca Quilca Chili, actualizado al 2023," Repositorio Institucional - ANA, Accessed: Junio. 08, 2025. Available: https://repositorio.ana.gob.pe/handle/20.500.12543/5656

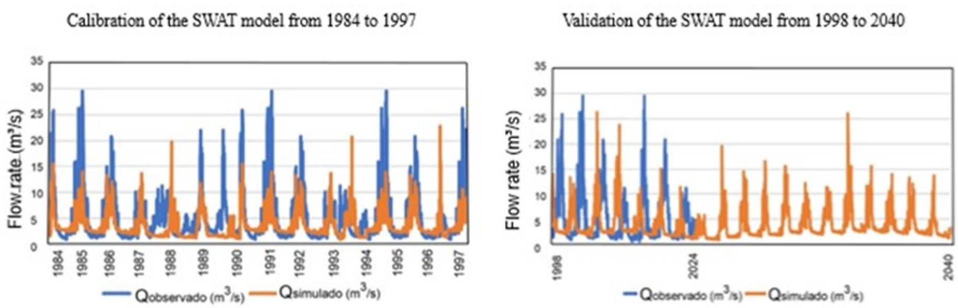

Figure 3. SWAT model calibration from 1984 to 1997 and SWAT model validation from 1998 to 2040

DOUGLAS-MANKIN, N. K. R., SRINIVASAN, N. R., & ARNOLD, N. J. G. (2010). Soil and Water Assessment Tool (SWAT) model: current developments and applications. Transactions of the ASABE, 53(5), 1423-1431. https://doi.org/10.13031/2013.34915

DRENKHAN, F., & CASTRO-SALVADOR, S. (2023). Una aproximación hacia la seguridad hídrica en los Andes tropicales: desafíos y perspectivas. Revista Kawsaypacha Sociedad Y Medio Ambiente, 12. https://doi.org/10.18800/kawsaypacha.202302.a006

AUTOR, G. AND QUIJANO, J. F. (2018) “Estudio hidrológico de las cuencas Camaná, Majes, Sihuas, Quilca - Vittor - Chili con información satelital,” Universidad Nacional Agraria La Molina. Accessed: Junio. 08, 2025. Available: https://hdl.handle.net/20.500.12996/3530

Ghajarnia, N., Bende-Michl, U., Sharples, W., Carrara, E., & Tijs, S. (2025). Evolving patterns of compound heat and water stress conditions: Implications for agriculture futures in Australia. Agricultural Water Management, 316, 109573. https://doi.org/10.1016/j.agwat.2025.109573

Guug, S. S., Abdul-Ganiyu, S., & Kasei, R. A. (2020). Application of SWAT hydrological model for assessing water availability at the Sherigu catchment of Ghana and Southern Burkina Faso. HydroResearch, 3, 124-133. https://doi.org/10.1016/j.hydres.2020.10.002

CARPIO, F. J., QUISPE, Y. B., PEÑA, L. F., AND SULCA, O. P. (2022) “Hidrogeología de la cuenca del río Quilca - Vitor - Chili (132)” Repositorio Institucional INGEMMET, Accessed: Junio. 08, 2025. Available: https://repositorio.ingemmet.gob.pe/handle/20.500.12544/3885

Juma, L. A., Nkongolo, N. V., Raude, J. M., & Kiai, C. (2022). Assessment of hydrological water balance in Lower Nzoia Sub-catchment using SWAT-model: towards improved water governace in Kenya. Heliyon, 8(7), e09799. https://doi.org/10.1016/j.heliyon.2022.e09799x

Krause, P., Boyle, D. P., & Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences, 5, 89-97. https://doi.org/10.5194/adgeo-5-89-2005

Moriasi, N. D. N., Arnold, N. J. G., Van Liew, N. M. W., Bingner, N. R. L., Harmel, N. R. D., & Veith, N. T. L. (2007). Model Evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50(3), 885-900. https://doi.org/10.13031/2013.23153

Motschmann, A., Teutsch, C., Huggel, C., Seidel, J., León, C. D., Muñoz, R., Sienel, J., Drenkhan, F., & Weimer-Jehle, W. (2022). Current and future water balance for coupled human-natural systems - Insights from a glacierized catchment in Peru. Journal of Hydrology Regional Studies, 41, 101063. https://doi.org/10.1016/j.ejrh.2022.101063

Nevermann, H., Aminzadeh, M., Madani, K., & Shokri, N. (2024). Quantifying water evaporation from large reservoirs: Implications for water management in water-stressed regions. Environmental Research, 262, 119860. https://doi.org/10.1016/j.envres.2024.119860

Panda, C., Das, D. M., Sahoo, B. C., Panigrahi, B., & Singh, K. K. (2021). Spatio-temporal modeling of surface runoff in ungauged sub-catchments of Subarnarekha river basin using SWAT. MAUSAM, 72(3), 597-606. https://doi.org/10.54302/mausam.v72i3.1309

Ramos, D. R. L., & Delgado, E. F. B. (2022). Evaluación de la sostenibilidad de cuencas hidrográficas. Estudio de caso: Cuenca del Chili, Arequipa-Perú. Revista Alfa, 6(18), 453-462. https://doi.org/10.33996/revistaalfa.v6i18.182

SRTM | Datos terrestres de la NASA.” Accessed: Jun. 08, 2025. Available: https://www.earthdata.nasa.gov/data/instruments/srtm

Tran, T., Nguyen, B. Q., Vo, N. D., Le, M., Nguyen, Q., Lakshmi, V., & Bolten, J. D. (2022). Quantification of global Digital Elevation Model (DEM) - A case study of the newly released NASADEM for a river basin in Central Vietnam. Journal of Hydrology Regional Studies, 45, 101282. https://doi.org/10.1016/j.ejrh.2022.101282

Visera SIG - Balance hídrico de SENAMHI. Accessed: Jun. 08, 2025. Available: https://idesep.senamhi.gob.pe/balance-hidrico/

Weber, J. F., & Ocampo, S. B. (2019). Calibración del modelo hidrológico SWAT para una cuenca de la región serrana de Córdoba (Argentina). AQUALAC, 11(1), 34-54. https://doi.org/10.29104/phi-aqualac/2019-v11-1-03