AQUA

Water Infrastructure, Ecosystems and Society

 AQUA — Water Infrastructure, Ecosystems and Society Vol 72 No 12, 2262 doi: 10.2166/aqua.2023.133

Performance indicators to characterize the water supply to meet the demands of the Lurin River Basin

Christiand Olortegui Artica [a], Javier Paredes Arquiola [b], Lia Ramos Fernández [a,*], Camila Leandra Cruz Grimaldo [c], Wilian Salazar Coronel [d] and Lisveth Flores del Pino [e]

[a] Department of Water Resources, Agraria La Molina National University, 15024 Lima, Perú
[b] Environmental Water Engineering Research Institute (IIAMA), Universitat Politècnica de València, 46022 Valencia, España
[c] Division of Agrarian Technological Development, National Institute for Agrarian Innovation (INIA), Av. La Molina, 1981 Lima, Perú
[d] Directorate of Supervision and Monitoring in Agricultural Experimental Stations, National Institute for Agrarian Innovation (INIA), Av. La Molina, 1981 Lima, Perú
[e] Center for Environmental Research in Chemistry, Toxicology and Biotechnology, Agraria La Molina National University, 15024 Lima, Perú
*Corresponding author. E-mail: liarf@lamolina.edu.pe

COA, 0000-0002-1066-1094; JPA, 0000-0003-3198-2169; LRF, 0000-0003-3946-7188; CLC, 0000-0002-0337-3799; WSC, 0000-0002-1574-2125; LF, 0000-0002-8478-680X

ABSTRACT

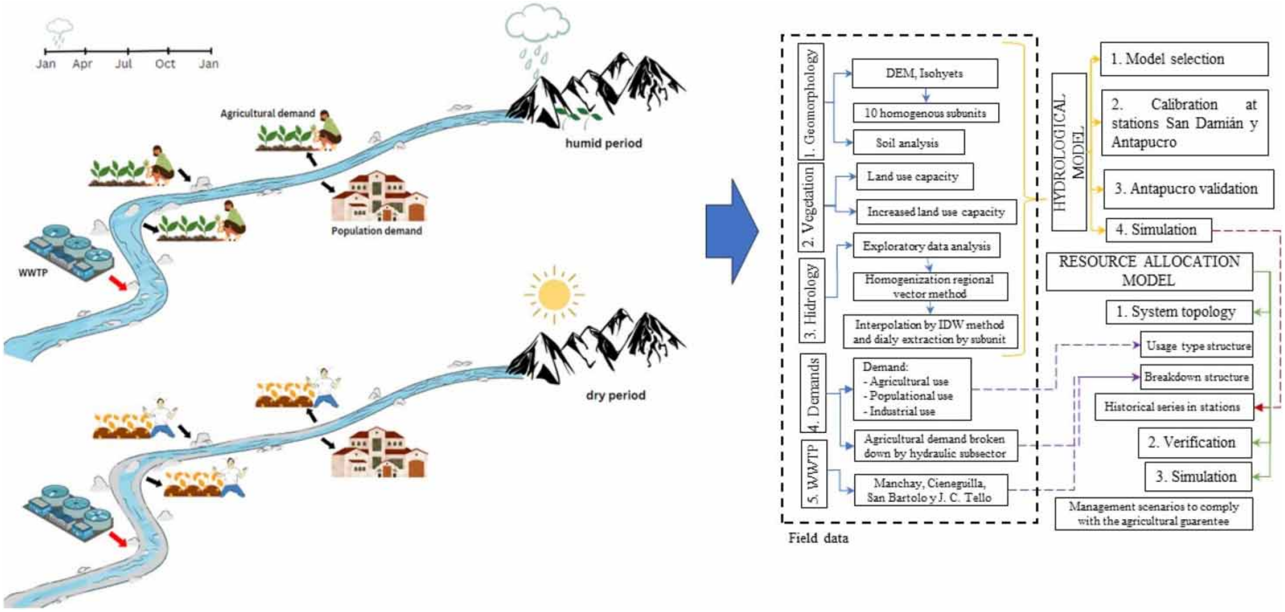
Water scarcity and the planning of socioeconomic activities are challenges in the management of water resources. Therefore, the objective of this study was to use reliability indicators (RI) to simulate management scenarios in the Lurin River Basin. First, flow rates for the period 1969–2019 were calculated using the EvalHid HBV hydrological model and SIMGES, both from the AQUATOOL decision support system, to simulate demands. The estimation of agricultural demand IRs was made under three conditions: that the deficits for one, two, and 10 years should not exceed 20–40, 40–60, and 80–100% of the annual demand. The goodness-of-fit indices obtained for flow calibration were 0.716, 0.89, and 0.901 for Nash index (NSE), Nash natural logarithm (Ln NSE), and Pearson's correlation coefficient (*R*), representing the values of satisfactory, very good, and good, respectively. Agricultural demands present annual deficits of 59–96, 92–138, and 333–688% for one, two, and 10 years, so a 50 m^3 reservoir is proposed to meet the IR. Thus, the information generated could be used to improve water resource management in the Lurin Basin.

Key words: AQUATOOL, Lurín, management model, reliability indicator, system

HIGHLIGHTS

- Improvements in the management of water resources are proposed to guarantee the supply of agricultural demands in terms of a reliability indicator (RI) according to legal guidelines in Peru and Spain.
- Implementation of a calibrated and validated watershed management model, using the AQUATOOL system, which provides useful information for decision-making on effective public investment in water resource management.

GRAPHICAL ABSTRACT



INTRODUCTION

Water availability is critical for food production, hydropower generation, and sustainable development (Anjum *et al.* 2019). Despite Peru being an emitter of only 0.2% of global greenhouse gases (Gütschow *et al.* 2019), it is a country highly exposed to the impacts of climate change (Tostes *et al.* 2019). Water governance seeks to regulate the availability of this resource among different stakeholders – fulfilling social, economic, ecological, and cultural aspects, among others. This process is called integrated management of water resources whose objective is to maximize profit by water allotment. For that, it is necessary to understand the relationship between the physical components of a basin, such as precipitation, temperature, flow, reservoir volume, pumping, the demand for water, and infrastructure management. There are several variables to consider in a system of hydric resources that can be included through indicators to facilitate decision-making by the managers in charge (Monzonis *et al.* 2015).

The results of water accounting, which are aimed at achieving a sustainable water balance between supply and demand as well as fair and transparent water governance, are one of the indicators related to water planning and management. One of them, the reliability indicator (RI), uses a binary criterion to ascertain whether the requirements are met for reliable supply to meet agricultural demands. In this way, water use levels in the basin are assessed to suggest management and governance improvements in emergency situations (Palop *et al.* 2020).

The Lurin River Basin in Peru, which originates in the Andes Mountains, is rainy mainly in January and February with semi-frigid and humid temperatures in the upper part of the basin; in the middle part, the temperature varies from temperate to semi-cold with a semi-dry climate and no rain in most months; and in the lower part, with a semi-warm and desert climate with scarce rainfall (Meléndez-Saldaña *et al.* 2021). This water scarcity causes unproductive development of agriculture and livestock, the main economic activities in the basin (Chapple & Montero 2016).

However, it possesses the last large expanse of green areas in the city of Lima, which plays a fundamental role in the food supply of the urban population (Arias *et al.* 2022). However, inadequate urban and industrial wastewater management, agricultural drainage, inefficient solid waste management (Momblanch *et al.* 2015), an accelerated process of unplanned urbanization, strong pressure for land at risk of becoming a new industrial park, overexploitation of groundwater, and inefficient use of this resource have become threats to the water and environmental conditions necessary for agricultural development that can lead to severe agro-economic impacts (Osorio-Díaz *et al.* 2022). However, it preserves areas destined for agriculture with the potential for tourism and archeological resources but with high poverty rates.

Given the scarcity of hydrometric information in the Lurín River, Meléndez-Saldaña *et al.* (2021) calibrated and validated the Tetis distributed hydrological model, and Osorio-Díaz *et al.* (2022) projected flows until the end of the 21st century with six global climate models, obtaining maximum reductions of 65 and 57% in dry and wet periods, respectively. In addition, water quality evaluation studies were carried out with contaminant transport models such as Aquatool Gescal (Arias *et al.* 2022) and the two-dimensional river modelling simulation tool, IBER model (Mori-Sánchez *et al.* 2023), obtaining high levels of contamination in the last 5 km of the river, before discharge to the Pacific Ocean.

Several studies have used the AQUATOOL platform with the Evalid and SIMGES modules to assemble hydrological simulation and water resource management models to obtain management rules to reduce the number of deficit demands (Lerma *et al.* 2015; Rangel *et al.* 2023). In addition, the use of evolutionary algorithms such as shuffled complex evolution SCE-UA (shuffled complex evolution method developed at The University of Arizona) and Scatter Search allows for optimizing these operating rules (Lerma *et al.* 2015).

In Peru, RIs are adopted in the main management entities, such as the Water Resources National Policy and Strategy (WRNPS) and the National Water Resources Plan (NWRP), both approved by the Ministry of Agriculture and Irrigation (Supreme Decree N° 006-2015-MINAGRI 2015; Supreme Decree N° 013-2015-MINAGRI 2015). According to Peruvian law, the restrictions must be set by the basin's administrative authorities and justified by the region's agro-climatic and hydrological characteristics of the exploitation system (Supreme Decree N° 013-2015-MINAGRI 2015). Therefore, it is established as an RI if the deficit in one year exceeds 20% of the annual demand, if in two consecutive years exceeds 40%, and if in 10 consecutive years exceeds 80% of the annual demand for agriculture. In Spain, the Hydrological Planning Instruction (HPI08) establishes an RI if the deficit in one year exceeds 50% of the annual demand, if in two consecutive years exceeds 75% and if the deficit for agricultural demands in 10 consecutive years exceeds 100% (Decret ARM/2656/2008 2008).

The Basin of Lurín River in Peru is characterized by an arid climate with very variable rainfall and inadequate management of water sources. This causes unproductive developments of agriculture and livestock, the main economic activities in the basin (Chapple & Montero 2016).

Based on Spanish and Peruvian legal requirements, improvements in the management of water resources were suggested in an IR for the Lurin Basin. For this, the AQUATOOL decision support system's EvalHid Hydrologiska Byrns Vattenbalansavdelning (HBV) precipitation-runoff hydrological model and the SIMGES water resource allocation model were simulated. There were representations of hydraulics, hydrology, and the level of agricultural water resource exploitation. The IR identified whether the 12 agricultural demands of the hydraulic subsectors (HSs) of the Lurin Basin were met or not, and it allowed for the recommendation of alternative regulatory measures that support integrated management of water resources to enhance water governance in the Lurin Basin.

The study has provided a tool to jointly model the hydrology and management of water resources in the Lurin Basin (arid in the lower and middle parts) with the simulation of different management scenarios to improve water supply and propose new policies and management strategies with participatory social awareness to value water and achieve a culture of peace around water.

MATERIALS AND METHODS

Study zone

The study area was conducted in the Basin of the Lurin River, with a drained area of 1,645.7 km^2, a perimeter of 242.76 km, a main channel of 110.4 km, and an average slope of 4.76%. With a compactness coefficient and a shape factor of 1.69 and 0.13, respectively, an average altitude of 2,496 msnm, a drainage density and frequency of rivers of 0.51 km/km^2 and 0.18 river/km^2, respectively, these physical characteristics indicate an elongated basin with less exposure to peak flows. The Lurín watershed is located at the coordinates 76°17′11″, 76°56′33″ West longitude and 11°50′31″, 12°16′34″ South latitude. Geopolitically, it is situated in the provinces of Lima and Huarochirí in the Lima region.

The Lurin River, which originates in the Andean Mountain range, is in the central coast of Peru, where an arid climate with low rainfall and inadequate management of water sources generate inefficient agriculture and livestock, the main economic activities in the area (Chapple & Montero 2016).

Climatic and hydrometric information

Daily climatic and hydrometric records were collected from the National Service of Meteorology and Hydrology of Peru (SENAMHI) and the National Water Authority (ANA) from nine, four, and three stations of precipitation (*P*), temperature

Table 1 | Climatic and hydrometric stations in the study area

Stations	Province	District	Elevation m.a.s.l.	Coordinates UTM East	Coordinates UTM North	Information *P* (mm)	Information *T* (°C)	Flow ($m^3 s^{-1}$)
Chalilla	Huarochirí	San Damián	4,050	354,801	8,680,469	0–255.6		
San Damián	Huarochirí	San Damián	3,248	349,407	8,671,225	0–581.2		
Matucana	Huarochirí	Matucana	2,479	349,887	8,690,876	0–192.9	5.2–26.8	
Huarochirí	Huarochirí	Huarochirí	3,154	365,700	8,657,790	0–156.0	−2.27 to 22.6	
San José de Parac	Huarochirí	San Mateo	3,866	362,933	8,595,196	0–301.9		
San Lázaro de Escomarca	Huarochirí	Langa	3,600	353,128	8,652,808	0–122.2		
Antioquia	Huarochirí	Antioquia	1,839	336,745	8,663,784	0–117.3	7.5–32	
Santiago de Tuna	Huarochirí	Santiago de Tuna	2,921	334,869	8,674,835	0–198.1		
Von Humboldt	Lima	La Molina	238	287,753	8,663,475	0–4.2	6–32.8	
Antapucro	Huarochirí	Antioquia	1,041	323,172	8,669,452			0.02–65
Manchay	Lima	Cieneguilla	229	298,703	8,654,331			0.05–100
San Damián	Huarochirí	San Damián	2,842	347,563	8,671,185			0.05–26

UTM = Universal Transverse Mercator.

(*T*), and flow (*Q*), respectively, for the period 1969–2019 (Table 1). Additionally, *P* and *T* information was obtained from the SENAMHI-PISCO database (Peruvian interpolated data of the SENAMHI's climatological and hydrological observations) with a spatial resolution of 0.05° (~5 km), daily records for the period 1981–2019, available at the link http://www.peruclima.pe/.

A process of systematization and completion of data was carried out in the missing periods, selecting the stations with the longest period of continuous information and grouping the data with the *K*-means clustering methodology (Murphy 2018). Groups of stations with less variance between the average precipitation and their location were obtained. Finally, the homogenization and correction of inconsistent data were performed by the regional vector method (Meléndez-Saldaña *et al.* 2021).

Potential evapotranspiration (ETP) was estimated from *T* using the Hargreaves method, previously adjusted with the Penman–Monteith method:

$$\mathrm{ET}_0 = C * Ra * (T_m + 17.8) * (T_D)^{0.5} \quad (1)$$

where $C = 0.00202$ was for the humid zone and 0.00242 for the dry zone. *Ra* is the extraterrestrial radiation in mm d^{-1}, T_m is the average daily temperature in °C, and T_D is the difference between daily maximum and the minimum temperature in °C (Meléndez-Saldaña *et al.* 2021).

Information about water demands

Four types of water use were distinguished: agricultural, populational, industrial, and recreational. Agricultural use is the one with the highest demands, which corresponds to the HSs to the local water authority of Chillón-Rímac-Lurín, with an annual consumption of 111.6 hm^3 (ANA 2019). Twelve HSs, Caña Hueca, Cieneguilla, Condorhuaca-Molino, Jatosisa Sotelo, Lurín, Mejorada, Pan de Azúcar, San Fernando, Cieneguilla, Tambo Inga, Nueva Toledo, and Venturosa (Figure 1(a)), are tributaries and collect water from the Lurin River.

Al (r): land suitable for clean cultivation, high agrological quality; Ar2s(r)-X: land suitable for clean cultivation, medium agrological quality; X: protective ground; X-P3c: protection land, suitable for pasture, low agrological quality; X-P2e-A2sc: protected soil suitable for pasture, medium agrological quality, risk of erosion, suitable for clean cultivation; X-P2e: protective

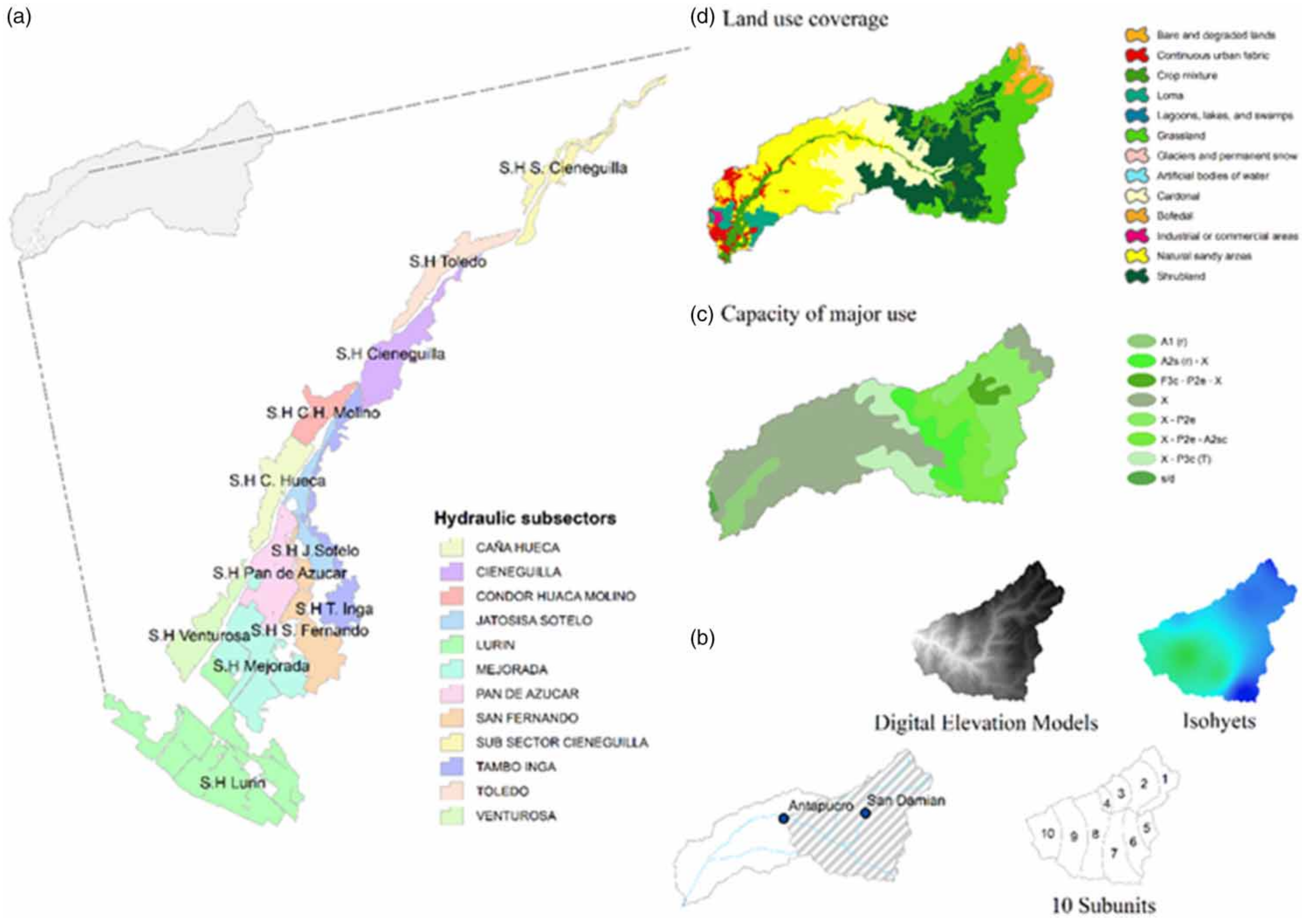


Figure 1 | Spatial distribution of the 12 HSs (a), land use coverage map (b), major land use map (c), and 10 homogeneous bands for hydrological modeling (d).

land, suitable for pasture, medium agrological quality, with risk of erosion; F3c-P2e-X: land suitable for forestry production; s/d: land suitable for pasture.

Four wastewater treatment plants (WWTPs) situated in Julio C. Tello, San Bartolo, Manchay, and Cieneguilla discharged their waters into the Lurín River.

Spatial information

Information was obtained from the digital elevation model (DEM) of the Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR)-DEM platform, free access information, and with good spatial resolution, 12.5 × 12.5 cm (ALOS PALSAR 2019); the map of 13 land use covers was obtained by supervised classification of images from the Sentinel-2A satellite, predominantly natural sandy areas (23.19%), grasslands (20.72%), shrubland (17.16%), and cardonal (8.10%), with the presence of hills in the lower part of the basin in winter season (Figure 1(b)). The major use capacity map of the ANA platform was obtained, highlighting the use capacity for protected lands (X) with an extension of 7,373 km^2 (Figure 1(c)).

To get a better characterization of the precipitation in the basin, 10 subunits were obtained in the Antapucro sub-basin from altitude curves and precipitation isohyets (Figure 1(d)). The information of P, T, and ETP was calculated as an average value for each subunit.

Simulation of hydrological series (EvalHid)

The historical series of P, T, and ETP for all seasons are the homogenized outcomes of the climatic characterization. Using a programming algorithm to automate the process, these data were interpolated throughout the basin using the inverse weighted distance method, creating raster images of daily precipitation from which values of the centroids of the 10 subunits previously defined with the altimetric data and the isohyet map were obtained.

The characterization of soil was done during a visit to the district of San Damián, the place of origin of the San Damián River, where the hydrometric station of the same name was located.

EvalHid includes a series of aggregated and semi-distributed models. To parameterize these models, a series of P, T minimum, and ETP were entered to define the parameters and state variables for each delimited subunit. It is noteworthy that subunits that share the same exit point have the same parameters. Initially, simulation tests were carried out on six conceptual models contained in EvalHid to select the hydrological model and the snow melting model that were more suitable for the system under study.

At the San Damián station, the analysis of the precipitation and flow regime was carried out to define if the regime is snowy or seasonal. To compare both variables, the precipitation was multiplied by the contributing surface, and the result was compared with the monthly volumes of the San Damián station.

Calibration was carried out daily at the hydrometric stations of San Damián and Antapucro using both manual and automatic adjustments. The automatic calibration maximizes an objective function f_n (θ), whose interpretation was accomplished with hypercube Latin and Rosenbrock (HCLR) and SCE-UA algorithms (García *et al.* 2019).

The models with the best fit to the indicators were selected: Nash indices (NSE), Nash natural logarithm (Ln NSE), Pearson's correlation coefficient (R), and mean symmetry coefficient.

The exploratory analysis and the correction of inconsistent data were performed by selecting the stations with the longest period of continuous information and grouping the data with the K-means clustering methodology (Murphy 2018). Groups of stations with less variation between the mean and their location were obtained, based on which the homogenization and correction of inconsistent data were performed by the regional vector method (Meléndez-Saldaña *et al.* 2021).

A hydrological simulation was used to acquire continuous monthly information in the period 1969–2019, and the water resource produced by the basin was quantified (Paredes *et al.* 2014). Finally, the series of flows obtained were entered into the management system developed, downstream of the Antapucro hydrometric station.

Hydric resource management simulation (SIMGES)

The topology of the system was designed through a network that has input elements (contribution from the Antapucro sub-basin and Tinajas stream) and output elements (by agricultural catchments of 12 HSs and population demands according to districts). In addition, return elements for the discharge of four WWTPs are the aquifer storage tank or unicellular model, aquifer recharge, and pumping extractions (Figure 2).

Information about the water flow in the Antapucro sub-basin came from a simulation with a selected hydrological model from EvalHid. Then, the information about the demands for agricultural and populational use and the losses and returns in the pipelines at each demand was incorporated into the system. For demands in agriculture, a gravity irrigation efficiency of 0.4 was assigned (MIDAGRI 2015), which meant that 60% returns to the aquifer by deep percolation. The demand for population use revealed an estimated consumption coefficient of 80% and the rest returned to the river through WWTPs (ANA 2019).

The aquifer is hydraulically connected to the river with a discharge coefficient alpha, whose size was estimated for the characterization of the aquifer (Andreu & Álvarez 1993) with a value of −0.00015, considering percolation due to irrigation efficiency and that of the riverbed.

The order of priority in which the system supplies to demands was the following: (i) the provision for population use and (ii) the agricultural requirements of the 12 HSs. The validation of the management model was carried out at the hydrometric station in Manchay, where the allocation of water resources for the period from 1972 to 1984 was simulated.

The current hydrological conditions present a challenge due to the presence of two months of rain per year that originate masses of water in the river that are lost to the Pacific Ocean (Meléndez-Saldaña *et al.* 2021), intense rainfall events in short periods, and prolonged droughts (Osorio Díaz *et al.* 2022). Faced with this critical scenario, it is necessary to have storage systems and measures to save water: increase irrigation efficiency with pressurized systems and change to a crop pattern with lower water consumption, among others. The first scenario reflects the system's current state of operation, in which there is no infrastructure for regulation and no hierarchy among the HSs.

Three RIs were used to simulate management scenarios for the proposed scenario, which improved the water supply to the 12 HSs.

Figure 2 | Topology of water resource allocations by the irrigation commission.

Reliability indicators

The system was evaluated on a monthly basis over a period of 20 years, in which RIs were estimated with monthly and annual averages of the following indicators: a (i) monthly reliability, which refers to the percentage of months of the 240 possible (in the period of 1999–2019) where agricultural requirements have been taken care at 100%; (ii) the volumetric reliability, which is the percentage of the required volume that needs to be accomplished; and (iii) the reliability of supply, defined as the percentage of years, out of a total of 20, in which the system does not fail.

The agricultural demand determined with RIs must meet three conditions: the deficit of water supply in one year does not exceed 20–40% of the annual demand; for two years, it should not exceed between 40 and 60% of the annual demand, and for 10 consecutive years, between 80 and 100% of the annual demand. In case these requirements are not fulfilled, then it is considered a failure in the demand (Andreu *et al.* 2013; Supreme Decret N° 013-2015-MINAGRI 2015), which can be represented in the following equation:

$$\text{FA: failure if } \rightarrow \sum_{t=1}^{t=n} \text{Deficit} > m\% \text{ Annual Demand} \tag{2}$$

where if $n = 1$, $m = <20\text{–}40>$, if $n = 2$, $m = <40\text{–}60>$, and if $n = 10$, $m = <60\text{–}80>$.

Subject to the restrictions of mass conservation (the law of continuity) and to the physical limits of transport in the river sections with and without connection to the aquifer, and catchments in the demands.

RIs of agricultural demand comply with the guidelines of the NWRP for Peru with the limitations established by the Water Resources Management Plans in the Basins (WRMPB). Likewise, compliance with the deficit was assessed according to the guidelines found in the HPI08 established in Spain's management plan for basins.

Finally, management scenarios were simulated using a regulation of the reservoir that supplies to the hydric system to improve supply of water to the 12 HSs. The regulated management scenario included an operation rule through an iterative process until the lowest of the deficit in agricultural demands was achieved.

The procedure followed in this study can be seen in a sequential way in Figure 3.

RESULTS AND DISCUSSION

Simulation of hydrological series (EvalHid)

Figure 4(a) shows an evident monthly dependency between precipitation converted into water flow and the measurements of the flow. In addition, low variability found in the minimum temperature did not favor snow melting; hence, it was not considered in the hydrological modeling.

In the calibration of the precipitation-runoff models in the EvalHid module, two automatic calibration algorithms were used: (i) SCE-UA and (ii) HCLR, both with maximum run times of 30 and 10 s, respectively. As a result, the best fit of the NSE, NSE-Ln, r, and mean square error (MSE) indices (Figure 4(b)) was obtained with the HBV model using both algorithms.

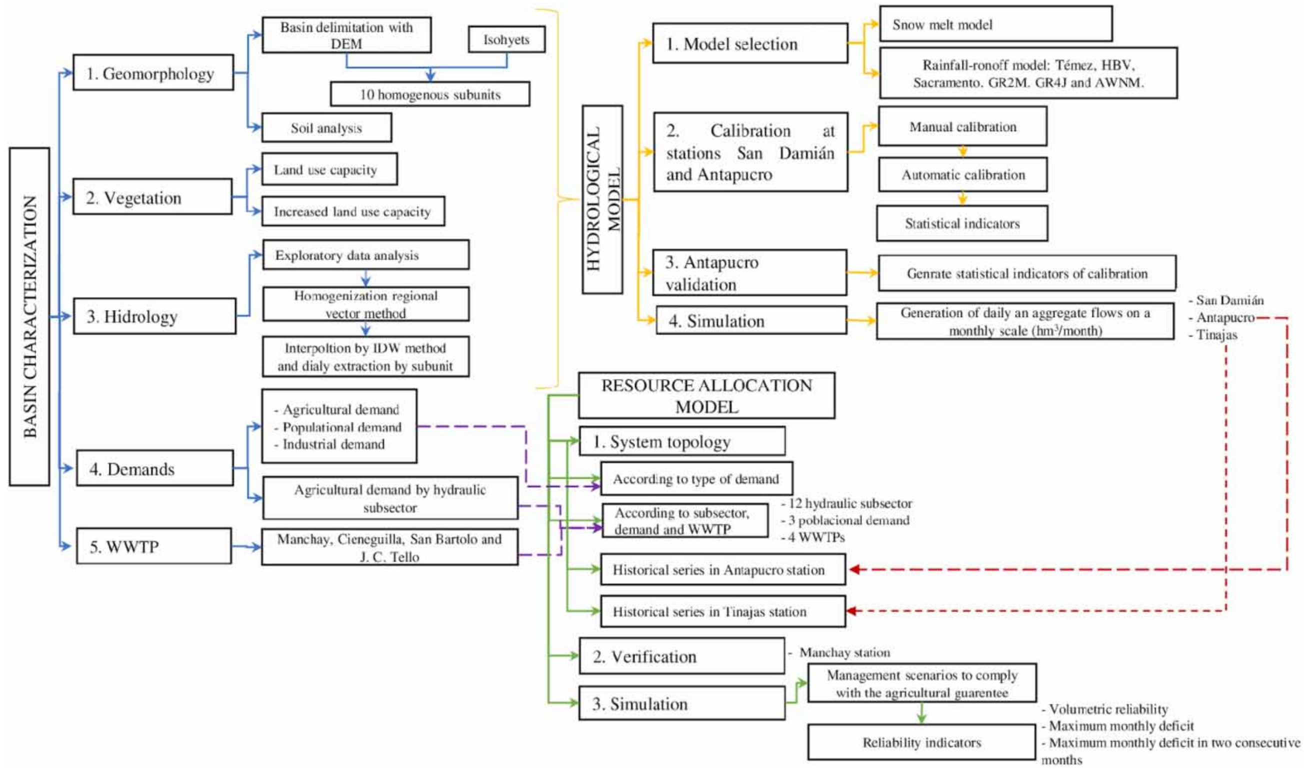


Figure 3 | A sequential diagram of the methodology in the study.

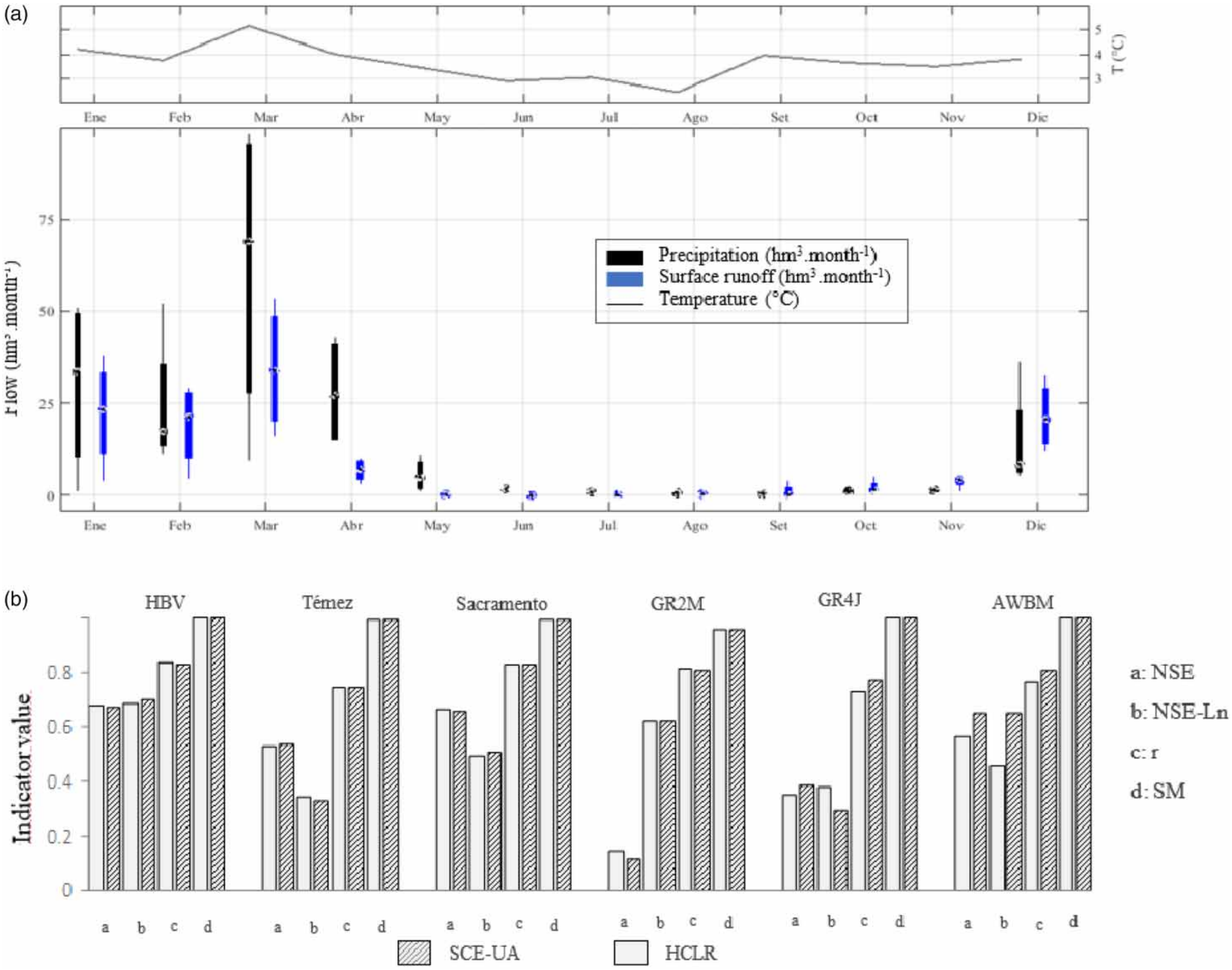


Figure 4 | Precipitation regime vs. flow regime and monthly variation of minimum temperature (a) and indicators of calibration efficiency at the San Damián hydrometric station (b).

Figure 5 shows the hydrographs of daily calibration and validation at the hydrometric station of Antapucro with their respective statistical indices (Table 2), which revealed ratings of satisfactory, very good, and good for the NSE, Ln NSE, and MSE indices, respectively, according to Moriasi *et al.* (2007). Similar results for the Lurin basin were obtained in the calibration and validation of the Tetis hydrologic model (Meléndez-Saldaña *et al.* 2021; Osorio-Díaz *et al.* 2022) with ratings from good to very good. In the calibration of pollutant transport models Gescal of Aquatool (Arias *et al.* 2022) and two-dimensional model Iber (Mori-Sánchez *et al.* 2023), they obtained ratings of satisfactory, very good, and, good.

A value of 0.791 was calculated for the Pearson's coefficient, and thus, the linear correlation was statistically significant, according to a Student's *t*-test (α-value of 5%), a value close to that obtained in the calibration of the pollutant transport model in the lower Lurin river, with the Aquatool Gescal model (Arias *et al.* 2022) and the two-dimensional Iber model (Mori-Sánchez *et al.* 2023).

Table 3 shows the calibration parameters with the HCLR algorithm in the HBV model. It has been verified that the parameters have a physical meaning that corresponds to the real conditions of the basin. For the infiltration coefficient (β), values of 0.5 and 1.0 were obtained for San Damián and Antapucro, respectively. This parameter has values between 1.0 and 3.0, but this range is not a calibration limit (Paredes *et al.* 2014). A high percentage of sand is seen because of the soil analysis's characterization, which denotes regions with rapid infiltration rates and supports the value obtained.

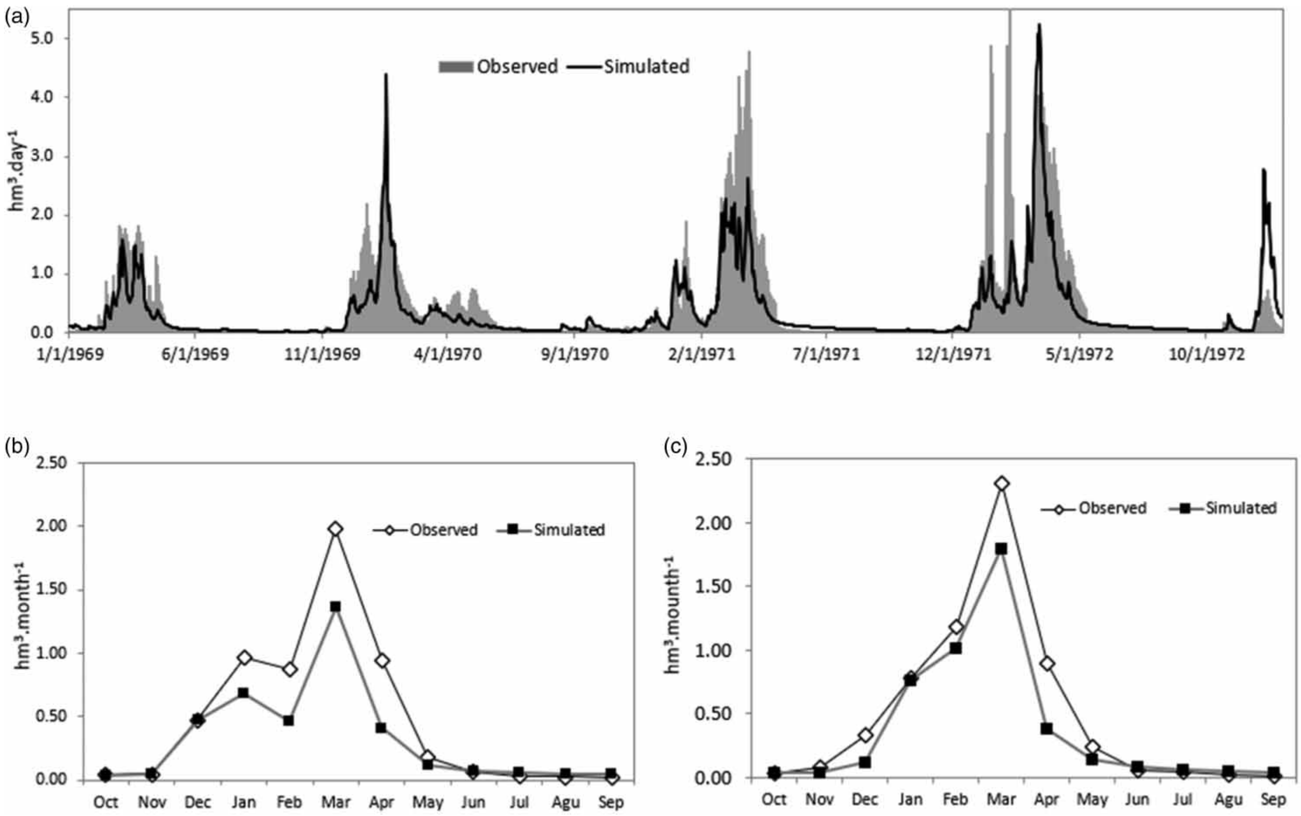


Figure 5 | Hydrographs of the daily calibration and validation at the Antapucro hydrometric station: observed and simulated daily calibrated volumes (a), calibrated average year (b), and validated average year (c).

Table 2 | Goodness-of-fit indices for calibrations and validations in the Lurin Basin

	Goodness-of-fit index			
Hydrometric stations	**NSE**	**Ln NSE**	**MSE**	***R***
Hydrologic model: HBV				
Calibration San Damián	0.564	0.730	0.141	0.936
Calibration Antapucro	0.716	0.899	0.785	0.901
Validation Antapucro	0.599	0.819	0.781	0.791
Management model: SIMGES				
Validation Manchay	0.719	0.819	0.806	0.879

In the case of the parameters for field capacity (FC) and permanent wilting point (PWP), values of 25.7–30.0 and 13.9–15.0 mm, respectively, were found. This reflects a storage capacity that relates to the texture of loam-clay-sandy and sandy-loam soils.

A period of 50 years (1969–2019) was simulated in the hydrometric station of Antapucro and evaluated for two periods: the first from 1969 to 1994 and the second from 1995 to 2019. In both periods, curves of seasonality were calculated for persistence at 70, 75, 80, 85, and 95%. The seasonality curve at 75% persistence was the level of reliability set to provide agricultural demands. It was observed that the month with the highest averaged volume was March with 17.68 hm^3 (1969–1994) and 32.4 hm^3 (1995–2019), while the lowest volume was found in September with 0.67 hm^3 (1969–1994) and 1.21 hm^3

Table 3 | Calibrated parameters of the HBV hydrological model

Parameter	Description	San Damián	Antapucro	Valid range
β	Infiltration coefficient	0.500	1	[0.001, 6]
FC	Field capacity (mm)	25.658	30	[25, 650]
PWP	Permanent wilting point (mm)	13.997	15	[10, FC]
L_{max}	Rapid discharge threshold (mm)	8.253	10	[0, 100]
$K0$	Fast discharge coefficient (upper tank)	0.237	0.200	[0.001, 1]
$K1$	Recession coefficient (upper tank)	0.132	0.100	[0.001, 1]
$K2$	Recession coefficient (lower tank)	0.009	0.008	[0.001, 1]

(1995–2019) (Figure 6(a) and 6(b)). When comparing the average flow of the first period (17.68 hm^3/month) with the last period (32.4 hm^3/month), there is an 83% increase. But comparing the months, monthly surpluses of 5.8, 12.6, and 21.7 hm^3 were observed in January, February, and March (1995–2019), respectively, and 1.5 and 7.9 hm^3 for February and March (1969–1994), respectively.

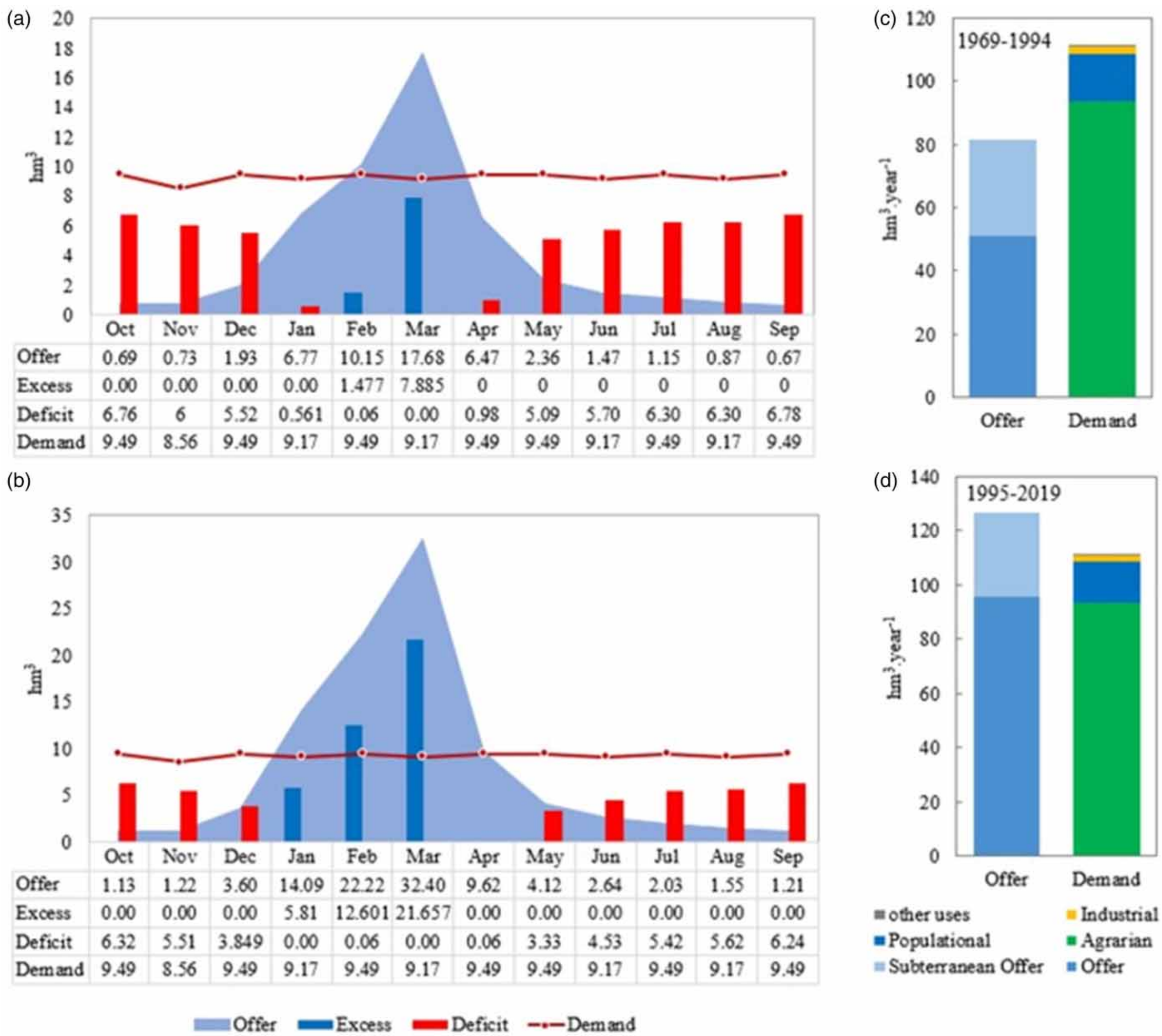


Figure 6 | Monthly water balance with flows at 75% persistence: 1969–1994 (a) and 1995–2019 (b). Annual water balance, analysis period: 1969–1994 (c) and 1995–2019 (d).

From the annual balance, it was detected that superficial availability was 51 and 96 hm^3 for the first and second periods, respectively (Figure 6(c) and 6(d)), which would reveal an upward tendency in flow for the last 25 years (1995–2019). The same was found in the Pampas region of Argentina, where increases in water flow and agricultural areas were observed in the last 50 years after using a distributed hydrological model (Ezequiel *et al.* 2018).

Hydric resource management simulation (SIMGES)

Contributions in Antapucro are the result of the hydrological model directly imported into the management system. From validations of the management model at the hydrometric station of Manchay, the ratings of good and very good were obtained for NSE indices, Ln NSE, and MSE based on Moriasi *et al.* (2007) (Table 2). In addition, a Student's *t*-test was performed for an R-value of 0.879 with α of 5%, which confirmed a significant linear correlation.

At the system, it was observed that percolation caused by losses in water used for irrigation and that produced in the riverbed, which annually reload the aquifer with an average volume of 52.76 hm^3 for a consumption coefficient of 0.4. This means that 60% of the provision returns to the aquifer of Lurin through deep percolation. However, out of the 40% efficiency of irrigation application, it is estimated that 10% returns as overflows. That would leave 30% as a coefficient of final consumption for agricultural demands.

Hence, greater irrigation efficiency in the system would reduce the recharge to the aquifer and the return of the flows like the springs; this is called the Jevon Paradox. For this reason, it is necessary to design policies and review the rights to use water to prevent improvements in irrigation efficiency from reducing recharge, as suggested by Monzonis *et al.* (2015).

For example, agricultural efficiency with pressurized irrigation systems has been improved, and crop records with greater water productivity, community and family reservoirs store water in rainy seasons to use in dry seasons and favor annual agriculture. On the other hand, it increases the recharge of the aquifer from the infiltration of treated wastewater and the management of an ecological flow (minimum flow) in the channel in times of drought.

Reliability indicators

In Table 4, the indicators of reliability based on the satisfaction of agrarian demands are shown for Peruvian and Spanish regulations. The status of these demands evaluated until 2019 and supported by the exploitation model of the basin of the Lurín River indicate that:

(i) The HSs show an annual deficit that varies from 23 to 61%, and the indicators of reliability reveal a non-satisfaction of the supply.
(ii) The one with the greatest deficit is the HS Tambo Inga, with 40% volumetric reliability. That is, in the 50 years evaluated, deficits were found in 40% of the months. On the other hand, the HSs with the lowest deficits were Jatosisa Sotelo and Cieneguilla subsectors, with values of 77 and 68% of volumetric reliability, respectively.
(iii) Agricultural demands present annual deficits of 59–96% in two years from 92 to 138%, and during 10 years between 333 and 688%.

The superficial provisions supply 56.7% of the total agricultural demand.

Management scenarios

The lower part of the Lurin Basin has a large extension of green areas of the city of Lima, which plays a fundamental role in the food supply of the urban population (Arias *et al.* 2022). Despite improvements in irrigation efficiency and water waste reduction, the agricultural demand is not being met (Melendez-Saldaña *et al.* 2021; Osorio-Díaz *et al.* 2022). Therefore, it is necessary to implement a reservoir to store water during this short period of intense rainfall. This reservoir will be located outside the riverbed to preserve the ecology of the area.

To deal with the lack of water resources, the regulation scenario was simulated with a reservoir capacity of 50 hm^3 and the monthly variable rate-operating rule. Therefore, a 10% restriction on water supply was established if the reservoir is full in April, 15% if it reaches a capacity of 40 hm^3 in May, and 20% for a capacity of 30 hm^3 in June; with this regulation, it is obtained that:

(i) The HSs meet the supply criteria of the agricultural demands, but this fails in Cieneguilla and Tambo Inga subsectors to a condition of deficit of 10 continuous years according to Peruvian and Spanish regulations.

Table 4 | Indicators of reliability of the supply, volumetric and monthly, to satisfy annual agricultural demand according to the HS: current scenario and scenario with reservoir regulation and operation rule

Name	Agrarian demand (hm^3 $year^{-1}$)	Demand deficit annual (%)	Reliability of supply (%) deficit of the annual demand: Current scenario 1 year	2 years	10 years	Proposed scenario 1 year	2 years	10 years	Volumetric reliability (%) Current scenario	Proposed scenario	Monthly reliability (%) Current scenario	Proposed scenario
Cieneguilla	5.44	31.48	38.4	76.5	383.1	**0.3**	**0.7**	**3.3**	62.0	99.7	33.3	91.7
Nueva Toledo	3.90	43.59	49.2	98.4	492.0	**7.8**	**15.7**	**78.4**	51.0	92.2	33.3	91.7
Cieneguilla	11.90	49.58	53.7	107.0	534.9	**22.8**	**43.8**	**211.6**	46.7	78.9	0.0	33.3
Condorhuaca-Molino	3.58	41.67	49.7	99.3	496.4	**0.0**	**0.0**	**0.0**	50.8	100.0	33.3	100.0
Tambo inga	5.10	60.78	63.5	126.9	634.7	**16.2**	**32.3**	**160.9**	36.5	83.9	25.0	58.8
Jatosica-Sotelo	3.90	23.08	31.1	61.8	307.8	**0.0**	**0.0**	**0.0**	69.6	100.0	33.3	100.0
Caña Hueca	4.78	35.42	47.0	93.9	469.2	**0.0**	**0.0**	**0.0**	53.4	100.0	33.3	100.0
San Fernando	9.53	47.37	57.6	115.2	575.6	**7.1**	**14.1**	**70.6**	42.7	92.9	33.3	58.3
Pan de Azúcar	6.21	43.55	52.6	105.2	525.6	**9.1**	**16.6**	**76.5**	47.7	92.4	8.3	49.6
Mejorada	11.40	39.47	47.4	94.8	473.7	**3.4**	**4.9**	**17.2**	52.8	98.6	25.0	91.3
Venturosa	5.90	45.76	55.7	111.4	556.5	**6.8**	**12.4**	**56.4**	44.6	94.4	16.7	41.3
Lurín	21.80	44.04	56.0	111.9	559.5	**6.4**	**10.4**	**42.7**	44.3	95.8	25.0	75.0

Note: In bold, values that do comply with the supply reliability for Peru-NWRP (20, 40, and 80% for one, two, and 10 years) and Spain-HPI (50, 75, and 100% for one, two, and 10 years).

(ii) The HSs have a volumetric reliability greater than 92% and a monthly reliability greater than 41%, except for the Cieneguilla and Tambo Inga subsectors, which have the lowest values of reliability.

(iii) The deficits of agricultural demands are reduced to the low values of 23, 44, and 212%, for one, two, and 10 years, respectively.

Figure 7 shows the results of the deficits for one, two, and 10 years for the current situation and for the proposed scenario, which are compared with the criteria of WRMPB and HPI08 to assess for compliance in agricultural demands. In the present situation, the values obtained through simulation are greater than those under the stipulated criteria. For example, for two years in the Tambo Inga commission, the value is greater than 100% when the established limit is 75%. The same occurs for 10 years with values greater than 600% of the deficit. Thus, it is essential to adopt measures to mitigate these deficits. The opposite occurs when a reservoir is implemented with an operation rule with deficits for one year are less than 23% in all irrigation commissions under the requirements of less than 40% (WRMPB) and 50% (HPI08). For the two years, the values are below 44% and are required to be less than 60% (WRMPB) and 75% (HPI08). In the 10 years, the value cannot exceed a deficit of 80% (WRMPB) and 100% (HPI08) with a maximum value of 78.4% observed in the HS of Nueva Toledo. In all cases, this was accomplished except for Cieneguilla and Tambo Inga.

The superficial provisions will supply 87.7% of the agricultural demands; hence, the effectiveness in the use of water for irrigation would be preserved, reducing pumping by farmers, which in most cases is illegal, so that the aquifer is protected.

A proposal of this type of model would provide knowledge and recognition of the value of water to help authorities be convinced that effective policies in management and socioeconomic measures must be developed and implemented (Alamanos *et al.* 2019). Therefore, it is necessary to update the rights of water use, mainly in the subsectors that demand more hydric resources, like Cieneguilla, Tambo Inga, and Pan de Azúcar.

CONCLUSIONS

The model for HBV precipitation-runoff was calibrated and validated, getting efficiency with qualification of satisfactory, very good, and good for NSE, Ln NSE, and MSE indices. The hydrological simulation of the supply and demand of the Lurin River Basin allowed establishing the demand RIs that represent the dissatisfaction of the supply in the agricultural demand.

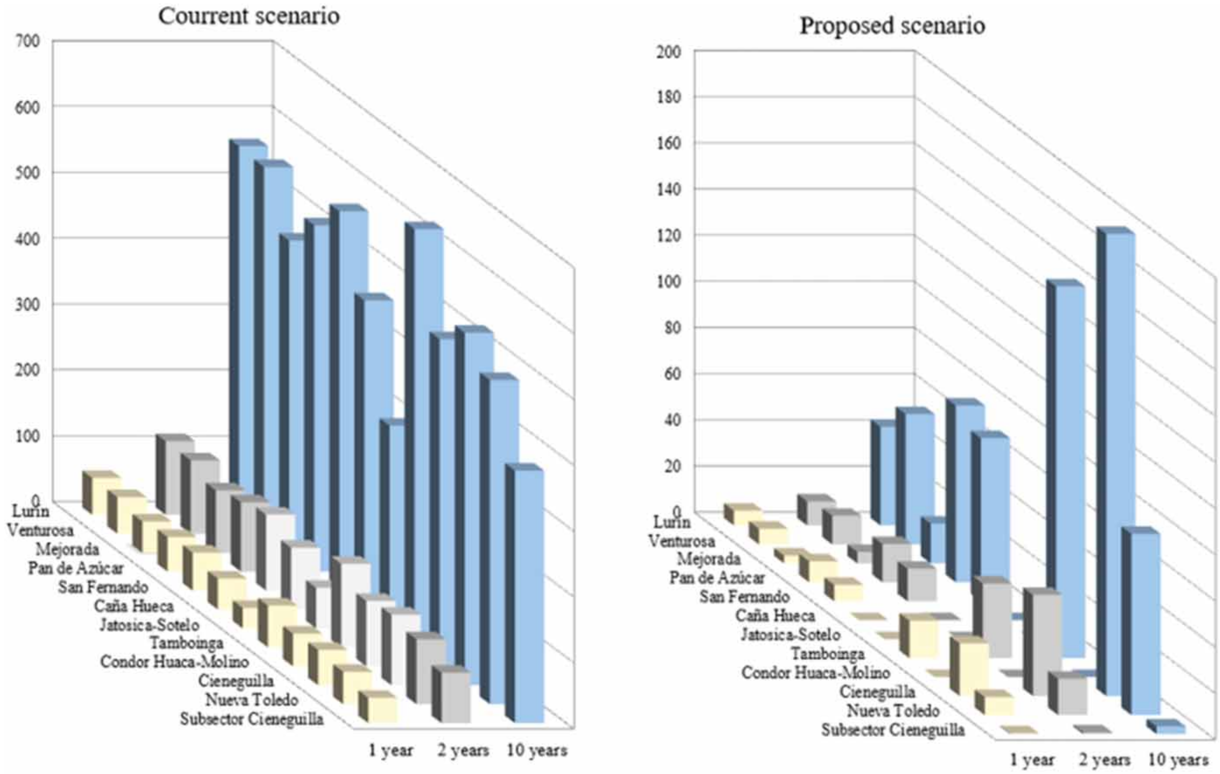


Figure 7 | Agricultural demand deficits for one, two, and 10 years based on the hydraulic sector: current scenario and scenario with reservoir regulation and operation rules.

In the management model, the current situation and the proposed construction of a reservoir of 50 $hm^3\ year^{-1}$ were evaluated. It was possible to get an increase of values greater than 92 and 41% of volumetric reliability and monthly reliability, respectively, with exceptions in the HSs of Cieneguilla and Tambo Inga. This regulation proposal with one reservoir, when an operation rule is applied, allows the reduction of the maximum deficits and the reliability of the supply for agricultural demands without increasing the volume at the aquifer. This information may be useful for decision makers in public policies of planning and water resource management.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Alamanos, A., Latinopoulos, D., Papaioannou, G. & Mylopoulos, N. 2019 Integrated hydro-economic modeling for sustainable water resources management in data-scarce areas: The case of lake Karla watershed in Greece. *Water Resour. Manage.* **33**, 2775–2790. https://doi.org/10.1007/s11269-019-02241-8.

ALOS PALSAR 2019 *ALOS Satellite Mapping Information*. Available from: https://search.asf.alaska.edu/#/ (accessed 1 September 2019).

Andreu, J. & Álvarez, J. A. 1993 *Concepts and Methods for Hydrological Planning (Spanish, the Title Is Translated Into English)*. Centro Internacional de Métodos Numéricos en Ingeniería, Barcelona.

Andreu, J., Solera, A., Capilla, J. & Ferrer, J. 2013 *SIMGES Model for the Simulation of Water Resources Management, Including Joint Use (Spanish, the Title Is Translated Into English)*. Universidad Politécnica de Valencia, Valencia. Available from: https://aquatool.webs.upv.es/files/manuales/aquatool/ManualSimGesEsp.pdf.

Anjum, M., Ding, Y. & Shangguan, D. 2019 Simulation of the projected climate change impacts on the river flow regimes under CMIP5 RCP scenarios in the westerlies dominated belt, northern Pakistan. *Atmos. Res.* **227**, 233–248. https://doi.org/10.1016/j.atmosres.2019.05.017.
Arias, E., Vela, R. & Ramos, L. 2022 *Development and Application of Water Quality Modeling with GESCAL-AQUATOOL in the Lurín River-Lima-Peru*. Tecnología y ciencias del agua. https://doi.org/10.24850/j-tyca-15-3-9.
Chapple, K. & Montero, S. 2016 From learning to fragile governance: Regional economic development in rural Peru. *J. Rural Stud.* **44**, 143–152. https://doi.org/10.1016/j.jrurstud.2016.01.009.
Decree ARM/2656/2008, of September 10, Which Approves the Hydrological Planning Instruction 2008 Boletín Oficial del Estado, 229, 38472–38582. Available from: https://www.boe.es/eli/es/o/2008/09/10/arm2656/con.
Ezequiel, G., Badano, N. G., Menéndez, A. N., Bert, F., García, G., Podestá, G., Rovere, S., Verdin, A., Rajagopalan, B. & Arona, P. 2018 Influencia de los cambios en uso de suelo y a precipitación sobre la dinámica hídrica de una cuenca de llanura extensa. Caso de estudio: Cuenca del Río Salado. *Ribagua* **5** (2), 92–106. https://doi.org/10.1080/2386 3781.2018.1495990.
García, L., Paredes, J., Solera, S. A., Belda, E., Andreu, J. & Sánchez, S. T. 2019 Optimization of the multi start strategy of a direct search algorithm for the calibration of rainfall runoff models for wáter resource assessment. *Water* **11** (9), 2073–4441. https://doi.org/10.3390/w11091876.
Gütschow, J., Jeffery, L., Gieseke, R. & Günther, A. 2019 *The PRIMAP-Hist National Historical Emissions Time Series (1850–2017), 2.1*. https://doi.org/10.5880/PIK.2019.018.
Lerma, N., Paredes, J., Andreu, J. & Solera, A. 2015 Comparativa de algoritmos para la optimización de un sistema de recursos hídricos. *Tecnología Y Ciencias del Agua* **6** (3), 79–92. Available from: http://www.scielo.org.mx/scielo.php?script = sci_arttext&pid = S2007-24222015000300006&lng = es&tlng = es (accessed 15 August 2023).
Meléndez-Saldaña, D., Ramos-Fernández, L., Velásquez-Bejarano, T. & Altamirano-Gutiérrez, L. 2021 Simulación con un modelo hidrológico distribuido de tipo conceptual a escala diaria en una cuenca semiárida del río Lurín, Perú. *Idesia* **39** (1), 17–26. http://dx.doi.org/10.4067/S0718-34292021000100017 .
Ministerio de Agricultura y Riego [MIDAGRI] 2015 *Manual de cálculo de eficiencias para sistemas de riego*. Direccion general de infraestructura agraria y riego – DGIAR, Lima, Peru. Available from: https://www.midagri.gob.pe/portal/download/pdf/manual-riego/manual_determinacion_eficiencia_riego.pdf.
Momblanch, A., Paredes, J., Andreu, J., Ramos, L., Baldeón, W. & García, J. 2015 *Análisis de medidas para la mejora de la calidad del agua en el tramo bajo del río Lurín (Perú)*. Available from: https://www.researchgate.net/publication/283624754_Analisis_de_medidas_para_la_mejora_de_la_calidad_del_agua_en_el_tramobajo_del_rio_Lurin_Peru.
Monzonis, M., Solera, A., Polo, F. J., Monreal, T. & Paredes, J. 2015 A review of water scarcity and drought indexes in water resources planning and management. *J. Hydrol.* **527**, 482–493. https://doi.org/10.1016/j.jhydrol.2015.05.003.
Mori-Sánchez, O., Ramos, L., Lluén, W., Pino, E. & Flores-del-Pino, L. 2023 Application of the Iber two-dimensional model to recover the water quality in the Lurín River. *Hydrology* **10** (4), 84. http://dx.doi.org/10.3390/hydrology10040084.
Moriasi, D. N., Arnod, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulation. *Trans. ASABE* **50** (3), 885–900. https://doi.org/10.13031/2013.23153 .
Murphy, K. P. 2018 *Machine Learning: A Probabilistic Perspective (Adaptive Computation and Machine Learning Series)*. The MIT Press, London. Available from: http://noiselab.ucsd.edu/ECE228/Murphy_Machine_Learning.pdf.
National Water Authority (ANA) 2019 *Initial Diagnosis for the Water Resources Management Plan for the Chillón, Rímac, Lurín and Chilca Basins (Spanish, the Title Is Translated Into English)*. Available from: https://repositorio.ana.gob.pe/bitstream/handle/20.500.12543/3901/ANA0002485_1.pdf.
Osorio-Díaz, K. J., Ramos-Fernández, L. & Velásquez-Bejarano, T. 2022 Projection of the impacts of climate change on the flow of the Lurín River Basin-Peru, under CMIP5-RCP scenarios. *Idesia (Arica)* **40** (1), 101–114. https://dx.doi.org/10.4067/S0718-34292022000100101 .
Palop, C., Paredes, J., Solera, A. & Álvarez, J. 2020 Comparing performance indicators to characterize the water supply to the demands of the Guadiana River Basin (Spain). *Hydrol. Sci. J.* **65** (7), 1060–1074. https://doi.org/10.1080/02626667.2020.1734812 .
Paredes, J., Solera, A., Martinez, F., Momblanch, A. & Andreu, J. 2014 Integrating water management, habitat modelling and water quality at the basin scale and environmental flow assessment: Case study of the Tormes River, Spain. *Hydrol. Sci. J.* **59** (3–4), 878–889. https://doi.org/10.1080/02626667.2013.821573 .
Rangel, R., Neira, X. & Dafonte, J. 2023 Estimación del balance hídrico y gestión usando modelos de simulación: Caso cuenca del río Cabe. *Tecnología Y Ciencias Del Agua* **14** (4), 01–39. https://doi.org/10.24850/j-tyca-14-04-01.
Supreme Decret N° 006-2015-MINAGRI 2015 *Water Resources National Policy and Strategy (Spanish, the Title Is Translated Into English)*. Available from: https://faolex.fao.org/docs/pdf/per147882.pdf.
Supreme Decret N° 013-2015-MINAGRI 2015 *National Water Resources Plan (Spanish, the Title Is Translated Into English)*. Available from: http://siar.minam.gob.pe/puno/sites/default/files/archivos/public/docs/1422.pdf.
Tostes, M., Villavicencio, A. & Motta, C. 2019 Vulnerability index elaboration for climate change adaptation in Peru. *Eur. J. Sustain. Develop.* **8** (5), 102–114. https://doi.org/10.14207/ejsd.2019.v8n5p102.

First received 2 June 2023; accepted in revised form 31 October 2023. Available online 17 November 2023