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Optimization of Water Resources to Counteract the Effects of Water Deficit Using the WEAP Model

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Abstract – The water deficit generates a great impact in regions where demand for this resource is of vital importance for socio-economic development. The high concentration of urban centres, the poor management of the resource, the various climatic changes, are some of the factors that cause its limitation. This research aims to analyze the best alternative to optimize the resource and meet the demands in areas where its availability and supply are scarce. A hydrological simulation model of the Coata River Basin (CRB) was carried out using the Water Assessment and Planning System (WEAP). Data such as precipitation, temperature, relative humidity, wind speed, and flow were extracted from the historical records of 10 rainfall stations for a period of 50 years (1971-2022). Three scenarios were established in the CRB, the construction of a dam (S1), the implementation of a diversion (S2) and the implementation of a sprinkler irrigation system (S3). The results revealed that S1 has a supply of 1103.1 MMC and a demand of 1308.4 MMC, leaving an unsatisfied demand of 205.3 MMC. The S2 has a supply of 1103.1 MMC and a demand of 1285.6 MMC, leaving an unsatisfied demand of 182.5 MMC. Finally, the S3 presents a supply of 1103.1 MMC and a demand of 912.3 MMC, with the demand for water being fully covered. The implementation of a sprinkler irrigation system proved effective in improving the volume of water required in the CRB.

***Keywords*:** Water deficit, water demand, WEAP model, water balance, water resources management.

1. Introduction

Water is one of the most indispensable natural resources used by man. Improve quality of life, economic development, and ecological stability [1]. The high concentration of urban centres, anthropogenic activities, climate change, groundwater depletion and increased energy demand generate an increase in the demand for the resource in areas where availability and supply are scarce [2]. If we add to this reality factors that affect water supply, such as hydrometeorological phenomena (droughts, floods, frosts) or natural phenomena (El Niño/La Niña phenomenon), they gradually exacerbate the imbalance between the supply and demand of the resource, resulting in a chronic seasonal water deficit [3].

Peru is considered the eighth country with the highest water availability, covering approximately 2% of the world's fresh water and 1.89% of the planet's total surface water. However, Peruvian territory is highly vulnerable to the harmful effects of climate change and one of the most affected countries due to the impact of hydrometeorological phenomena [4]. These climatic events greatly influence regional rainfall and stream flow in the region. It is essential to quantify the water balance and spatio-temporal variations of the basin for optimal allocation and effective management of water resources [5].

Hydrologic models focus on understanding how water flows within a watershed in response to hydrologic events, while water resource planning models focus primarily on water allocation management [5]. The Water Assessment and Planning System (WEAP) is a hydrological model developed by the Stockholm Environment Institute. It is a data processing tool that allows water management entities to evaluate different management scenarios in a given area [6]. The built-in algorithms use climate time series data, simulate rainfall and runoff from watersheds and sub-basins [7]. Currently, there are different hydrological simulation methods in the WEAP model, such as the soil moisture method, the simplified coefficient, and plant growth methods. The performance of the WEAP model is evaluated based on statistical justification, such as the Nash-Sutcliffe Efficiency Coefficient (NSE) [8]. Numerous academics and administrators around the world have used the WEAP program, and developed it in order to understand the water-energy-food-environment nexus for climate change adaptation [6].

Yang et al. [9] mention that the scarcity and quality of water in Beijing, China is due to the water deficit of the Bejing basin as a result of poor management of the resource and overexploitation of it. Orkodjo et al. [10] developed a set of hydrological models with which water demand for irrigation and energy are assessed in conjunction with hydrological changes and water planning using the WEAP model. The projected results revealed options for adaptation to climate change, the future availability of water for irrigation, and hydropower generation in the Omo-Gibe basin. Mirzaei, A. & Zibaei [11] proposed an economic-hydrological-behavioral model in the Harilud basin, Kerman province. They analysed the potential effects of climate change and adaptation strategies on agriculture. They formulated a model using the WEAP based on hydrological, agronomic and socio-economic agents. The model revealed that strategies to restore vegetation cover require the management of a cropping pattern, which will increase hydrological and economic yields.

In this research, the main objective was to evaluate alternatives for sustainable water resource management in the face of the effects of agricultural water deficit in the Coata River basin. To this end, hydrological simulations were developed using the Water Assessment and Planning System (WEAP) through the soil moisture method. This system is designed to examine management alternatives based on the principle of water balance by providing a set of procedures that allow solutions to be found using a scenario-based approach.

2. Materials and methods

2.1. Description of the study area

The Coata River basin is located in the southeast of Peru, in the Puno region between the geographical coordinates 69° 55' 12" - 71° 12' 00" West Longitude and 15° 06' 36" - 15° 55' 12" South Latitude. It has a total area of 4908.44 km2 with a perimeter of 188.57 km and an altitudinal variation of 3800 to 5300 m.a.s.l. as shown in Figure 1. The seasonal characteristics of the climate in the basin are manifested in the variation of rainfall, directly influenced by altitude and proximity to Lake Titicaca. Crops are not only affected by low annual rainfall, but also by their irregular distribution throughout the year. Rainfall is very seasonal, with wet seasons from November to March with rainfall between 80 and 150 mm and dry seasons from June to August with rainfall between 3 and 15 mm, with a total annual rainfall of 300 mm to 800 mm, where the highest values are recorded around Lake Titicaca and in the upper part of the basin. As for the temperature, it ranges from -1 °C to 16 °C [12].

The hydrographic system of the Coata River basin has two main drainage axes, the Cabanillas and Lampa rivers, characterized by endorheic basins that flow into Lake Titicaca. The hydrographic characteristics of both basins are similar. In the upper part of the basins, grassland areas, extreme climatic conditions and naturally stored surface water reserves are observed. In the middle part, there are lands with low slopes and better climatic conditions that favor crop diversification and improve irrigation techniques.

Figure 1 shows that the upper part of the basin has extreme climatic conditions, limiting all human activity and generating scarce vegetation cover.

2.2. Data collection

For the simulation of the total future water demand with the WEAP model, cartographic information processed by a Geographic Information System (GIS) is used. For the delimitation of the basin, the limits of the sub-basins, river networks and slope, the Digital Elevation Model (DEM) S16W071 corresponding to zone 19 and with a spatial resolution of 30 meters was used. DEM detailing important topographical, geomorphological, and physiographic information of the watershed to integrate into the WEAP system. This model is a simple input layer that was extracted from the Ministry of the Environment and accessed through the GEO GPS PERU platform (www.geogpsperu.com). Hydrological data were extracted from 3 hydrometric stations as detailed in Table 1. The Unocolla Bridge Station, located on the Coata River, records the average daily and maximum monthly average flows of the river; while the Verde River Station, located in the Cabanillas River basin on the Verde River, records natural runoff flows. Rainfall data such as precipitation, temperature, relative humidity, wind speed come from the historical records of 10 meteorological stations located within the Coata basin, as detailed in Table 2. Hydrometeorological data corresponding to the historical record from 1971 to 2022, collected from the Servicio Nacional de Meteorología e Hidrología (SENAMHI). Water availability data were taken from the Cabanillas and Lampa river basins, and water demand data were extracted from the Autoridad Nacional del Agua (ANA) and the Regional Government of Puno. Agricultural data from the Ministry of Agrarian Development and Irrigation (MIDAGRI), Ministry of the Environment (MINAM) and population statistics from the National Institute of Statistics and Informatics (INEI).

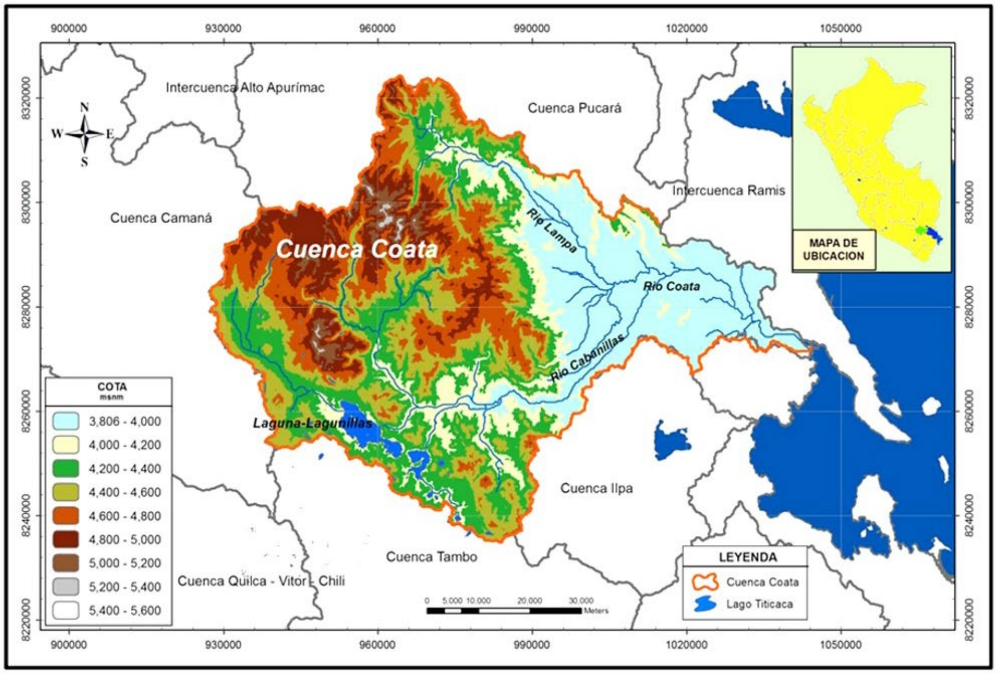


Fig. 1: Location and geographical demarcation of the Coata River basin.

Table 1: Hydrological stations used in the study.

Station	Latitude	Longitude	Altitude (m.a.s.l.)
Puente Unocolla	-15°27’03”	-70°11’29”	3838
Puente Río Cabanillas	-15°28’19”	-70°13’26”	3835
Río Verde	-15°41’03”	-70°36’00”	4036

Table 2: Weather stations used in the study.

Station	Latitude	Longitude	Altitude (m.a.s.l.)
Lampa	-15°21’48”	-70°21’53”	3892
Juliaca	-15°26’39”	-70°12’28”	4350
Jarpaña	-15°31’00”	-70°47’00”	4300
Cabanillas	-15°38’21”	-70°20’47”	3920
Lagunillas	-15°42’02”	-70°36’32”	3970
Santa Lucía	-15°42’00”	-70°36’00”	4050
Pampahuta	-15°29’01”	-70°40’33”	4400
Quillisani	-15°23’00”	-70°45’00”	4600
Paratia	-15°27’00”	-70°36’00”	4300
Colini	-15°39’01”	-70°53’01”	4380

2.3. Introduction to the WEAP Model

WEAP is a modeling platform that provides a comprehensive approach to water resource planning. The WEAP model is based on the balance between water supply and demand, replicating the behavior of the hydrological cycle. Unlike other water resource models, WEAP is a model forced by climate variables, studying the effect of climate on water resources and the optimal allocation between demand sites in a basin. Each procedure provides integrated assessment of climate, watershed conditions, available infrastructure, changes in water supply, demand projections, water quality, climate change, and anthropogenic effects. The WEAP model uses a standard linear scheduling model that allows you to maximize the percentage of supply demand centers' needs, with respect to supply and demand priority, mass balance, and other constraints [1].

3. Methodology

3.1. Hydrological Model

A hydrological model is based on the water balance that replicates the behavior of the hydrological cycle of a river basin [14]. The WEAP model provides five different methods that simulate catchment processes such as evotranspiration, runoff, infiltration, and irrigation demands. These methods include: the precipitation-runoff method, the simplified coefficients of irrigation demands method, the soil moisture method, the MABIA method, and the Plant Growth method [13]. In this study, the soil moisture method was chosen. This method, considered to be the most complex, divides the soil into two layers. In the toplayer, it simulates runoff, subsurface flow, evapotranspiration, and soil moisture. The second layer simulates percolation and baseflow that can be transported to an aquifer or river [13]. For a basin divided into subbasins, the water balance is calculated for each area, assuming that the climate is constant for each subbasin.

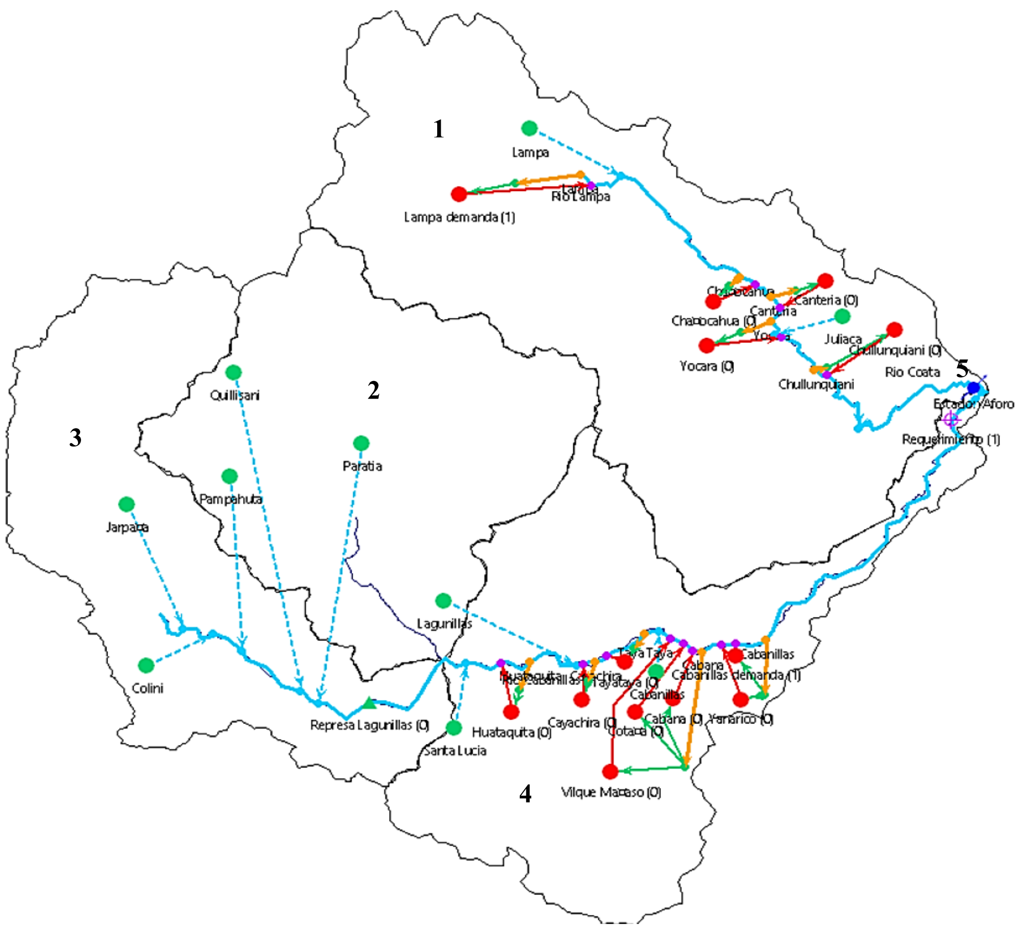


Fig. 2: WEAP hydrological diagram of the Coata River basin.

3.2. Hydrological diagram in WEAP

Once the necessary data for the hydrological model has been collected and analyzed, the WEAP model will be used to determine the water balance. The historical series used correspond to the period 1971-2022 (50 years). The WEAP model simulation method for this research is the Soil Moisture (precipitation-runoff) method. For this method, evotranspiration, surface runoff, soil cover and Key Assumptions parameters are taken into consideration. In addition, it focuses on population growth and rainfall deficiency as a result of climate change. For the analysis of water demand, information from the existing dam in the Basin, such as the Lagunillas reservoir, was used, as well as information on the potential evapotranspiration and effective precipitation of the Cabanillas and Lampa rivers. The information on the vegetation cover of the basin corresponds to 5 agricultural areas (Lampa, Cabana, Vilque-Mañazo, Cabanillas and Yocara), which represent the largest irrigated area [12]. The model includes the previous delimitation of the Coata River basin, the maps of the basin were obtained from the Digital Elevation Model (MED) S16W071 corresponding to zone 19 and with a spatial resolution of 30 meters. The sub-basins were divided and grouped around the main rivers of the basin, in order to simplify their hydrological modelling. The study area was subdivided into 5 sub-basins, for which a graphical interface based on a Geographic Information System (GIS) was used, such as the HEC-HMS software and the ARC-GIS software. These GIS programs provided us with the physiographic aspects of each of the sub-basins used in the hydrological model. Figure 2 shows the schematic of the model.

3.3. WEAP Model Calibration and Validation

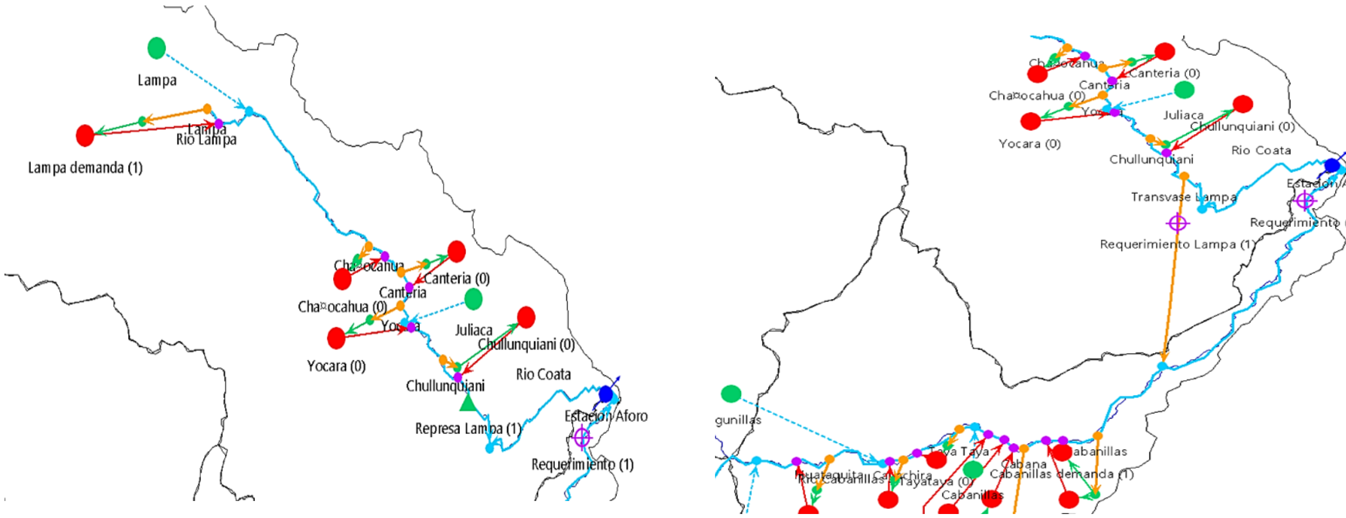
Calibration and validation of a model is necessary to minimize errors and ensure the reliability of the results [15]. In this research, the model was calibrated by comparing the simulated discharge data on a monthly scale with the data extracted from the selected hydrometric gauging stations. A period of 50 years (from the hydrological year 1971-2022) was used to calibrate and validate the model. The values of the uncalibrated parameters were selected based on the spatial and temporal conditions and the model defaults. During this process, the flow simulated by the model was compared with the flow observed at the selected hydrometric gauging stations. For the quantitative evaluation of the calibration and validation results of the model, the Nash-Sutcliffe Efficiency (NSE) correlation coefficient was used.

3.4. Scenario Development

Management strategies seek to increase water supply, irrigation efficiency, or reduce agricultural water demand [15]. In this research, 3 scenarios were developed based on management strategies, taking into account a base scenario (S0) which represents the current supply and demand of the basin. Scenario 1 (S1) proposes the hydrological simulation of the basin by implementing the construction of a storage dam with similar characteristics to the existing Lagunillas dam, located in the Cabanillas region. This dam will be able to meet the demands of the areas of Lampa, Chañocahua, Yocara, Canteria and Chullunquiani. Scenario 2 (S2) proposes the implementation of a water transfer between the Lampa River and the Cabanillas River, due to the fact that the latter has a higher demand and less water supply throughout the year. Scenario 3 (S3) proposes the implementation of a sprinkler irrigation system throughout the agricultural region of the Cabanillas region. It should be noted that the Lampa region has a sprinkler irrigation system, so only the irrigation efficiency value in the Cabanillas region will be modified.

Fig.3 shows S1 and S2 respectively, where the collection points are represented by the green buttons, the demand points by the red buttons, the implementation of a dam by the green triangle and the implementation of a transfer by the longest orange arrow. In the case of demands, the deviation tool represented by the orange arrow was used, which is attached to the demand by the transmission link button represented by a green arrow; Finally, the return flow represented by the red arrow was drawn.

In the case of Scenario 3 (E3), an irrigation system will be implemented in the entire agricultural area of the Cabanillas region, where the decrease in unsatisfied demand will be evaluated based on each irrigation method used. This research will analyze the development of a sprinkler irrigation system, an existing, efficient and functioning irrigation method in the Lampa region. The irrigation efficiency value to be used in the Cabanillas region will be 0.80



(a)
1

(b)
1

Fig. 3: Hydrological model and simulation, **(a)** Scenario 1 (S1) and **(b)** Scenario 2 (S2).

4. Results and discussion

4.1. Model Calibration and Validation

Calibration and validation of a model are necessary to minimize errors and ensure the reliability of the results [5]. To calibrate and validate the results of this research (1971-2022), the Nash-Sutcliffe Efficiency Coefficient (NSE) was used, a value that resulted in 0.95. This NSE value is classified as "excellent". Therefore, it is shown that the model can similarize the hydrology of the study area accurately.

4.2. Scenario Assessment

Based on the WEAP hydrological simulation model of water management scenarios, Table 3 shows the results of the water balance and irrigation water deficit of each of the proposed scenarios. As shown in Table 3, the available supply of each sub-basin was evaluated and the surplus that exists in the rainy months (Jan-Mar) was calculated. The baseline or current scenario (S0) presents an available water supply of 330.8 MMC in the dry months (scarce precipitation). Scenario 1 (S1) presents 334.3 MMC, scenario 2 (S2) 340.2 MMC, and scenario 3 (S3) 447.7 MMC. Achieving a greater water supply in the proposal of Scenario 3.

According to Table 3, the implementation of water management scenarios has increased reliability and resilience and reduced the vulnerability of the resource in times of drought.

Table 3: Water balance of the hydrological simulation of scenarios.

Water balance	**S0**	**S1**	**S2**	**S3**
water supply (MMC)	1103.1	1103.1	1103.1	1103.1
Demand (MMC)	1353.0	1308.4	1285.6	912.4
Unmet Demand (MMC)	249.9	205.3	182.5	190.8
Demand Met (MMC)	772.3	768.9	763.0	655.5
Demand Met (%)	-	-	-	-
Deficit (MMC)	580.7	539.6	522.6	256.8
Surplus (MMC)	**330.8**	**334.3**	**340.2**	**447.7**

Table 3 also shows the calculation of the average monthly unmet demands by irrigation areas of each scenario. The Base Scenario presents an unsatisfied demand of 249.9 MMC per year, however; with the implementation of a water transfer from the Lampa River to the Cabanillas River, as detailed in Scenario 2, we obtain an unsatisfied demand of 182.5 MMC. In other words, a scenario where the impact of the water deficit is lower.

5. Conclusions

In this research, water resource management strategies were developed through scenario evaluation using the WEAP model. These scenarios simulated water supply and demand in the Coata River basin. The irrigation water deficit in times of drought was also analyzed. The WEAP software shows us the unmet demands in the monthly averages, compared to the unmet demand of the base scenario with 249 MMC and with scenario 2 with 182.5 MMC, showing a 73% improvement in unmet demand. The results showed that the implementation of an irrigation system as detailed in Scenario 3 (S3) yields a 35% optimal percentage of available water supply compared to the other two scenarios. The studies also showed that implementing a sprinkler irrigation system improves the annual volume required in the Coata River basin by 37%. Therefore, the implementation of a sprinkler irrigation system in the sub-basin of the Cabanillas River, the implementation of a water transfer from the Lampa River to the Cabanillas River or the construction of a dam in the Lampa region, as shown in the WEAP simulations give us efficient results in improving unsatisfied demand. in the required annual volume and in the available offer.

Based on the results, we recommend the complete collection of hydrometeorological data, such as precipitation, temperature, humidity, evotranspiration, and flows; as well as data on water demands in irrigated areas. The implementation of a sprinkler irrigation system provides us with an improvement in the management of water resources.

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