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Hydrological bases for the natural resources conservation in the Lake Moa catchment, Bolivia

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Abstract: Water is life and knowing the availability of this resource and even more so in possible climate change scenarios, is essential to ensure sustainable development and especially the conservation of natural resources of vulnerable rural populations far from urban centers, such as the Tacana Native Indigenous region of northern La Paz, with emphasis on the sub-basins around the Botanical Garden implemented by DINA/UMSA in the basin of Lake Moa, the second largest lake in the department of La Paz, which tends to dry up in the dry season. For the evaluation of water resources, two meteorological stations were installed and gauging of the rivers of the sub-basins was carried out at monthly level from October 2018 to September 2019 and the SWAT (Soil & Water Assessment Tools) and WEAP (Water Evaluation & Planning) hydrological models were applied. Once the watershed models were built, most of them were preliminarily calibrated and validated, with the exception of only two watersheds, which obtained a Nash coefficient of less than 0.5. On this basis, we proceeded to simulate the availability of water in climate change scenarios, demonstrating a tendency to decrease flows and the sensitivity of this region to climate change, as well as the hydrological response of Lake Moa itself to this temporary supply. These studies should allow declaring these basins as protection areas, in order to stop and avoid forest exploitation and, on the contrary, to promote hydro-eco-productive and ecosystem protection activities, facilitating in the short term an Integrated Water Resources Management Strategy based on the results obtained in this research.
Key words: water resources; climate change; water resources management

1 Introduction

Water is life, and understanding the availability of this resource, especially in the context of possible climate change, is crucial for ensuring sustainable development, particularly in protecting the natural resources of vulnerable and remote rural populations. Therefore, it is a priority to evaluate water resources at the spatial and temporal level and to determine the water supply of the watersheds of the Indigenous Tacana region of northern La Paz, with emphasis on the sub-basins around the Botanical Garden implemented by the Division of Integral Development of the Amazonian North (JB/DINA/UMSA) and the basin of Lake Moa, the second largest lake in the department of La Paz. These studies should make it possible to declare the basins and sub-basins as protection areas, to stop and avoid logging and, on the contrary, to promote productive activities to protect the ecosystem in general. Water resource assessment is one of the fundamental foundations of integrated water resource management. As the next stage, it aims to cultivate a culture of resilience to climate change and develop projects related to water resource development. This is not only for scientific purposes, but also for the rational utilization of water resources, in order to meet the growing population in the region, especially in Tumupasa, in the future.

The evaluation of water availability is complemented by the objectives and goals that DINA has set for the region and will make it possible to know the water characteristics, including the Moa Lake basin, which tends to dry up during low water levels, so that these areas, so sensitive to human intervention and the effects of climate change, can be protected with greater emphasis and future uses can be planned to meet the growing demands and also diversify productive activities by promoting tourism in the surrounding area, such as the Botanical Garden, visits and boat rides on Lake Moa, sport fishing, local gastronomy, beekeeping, the implementation of the Integral Productive Center for Sustainable Agroforestry (CIPAS), gastronomic tourism and Community HydroEcoTourism, and other activities and/or productive enterprises that are carried out by the beneficiaries themselves and that are related to water resources. With all the available information, hydrological models based on the geographic information system (GIS) were adopted as a fundamental tool for the sustainable management of the basins, the generation of a database and for the simulation of the hydrological response of the basins and sub-basins considering climate change scenarios. The river basin or sub-basin, whether independent or interconnected with others, is the accepted territorial unit of study for integrated water resources management (Dourojeanni et al., 2002).

On the other hand, for more educational purposes and for interaction with beneficiaries, their broad participation, through their grassroots organizations, has been promoted to support field missions and information collection whose results are presented at their assemblies or meetings for full knowledge, not only of the results, but also of the processes to achieve them. In this phase, the involvement of the stakeholders and their authorities of the Tumupasa population in the protection and care of the installed meteorological equipment and in the collection of such information has been vital. However, many attempts to implement IWRM have often failed, due to the use of inadequate tools and methods and also due to the lack of motivation for stakeholder participation (Calizaya, 2009). In this sense, in the process of assessing the preliminary supply of water resources, in order to generate the basis for a rational use and adequate IWRM (GWP, 2006), which contribute to the development of the region and to the improvement of the quality of life of the inhabitants and populations of the Indigenous Council of the Tacana People (CIPTA), a series of field activities have been carried out jointly with the community members, as part of the training on the topic of water resources.

In this case, the purpose of the study is to use hydrological response models to determine the water supply situation at the watershed and sub watershed levels of the land in the Tacana community. These models can help simulate historical periods and climate change scenarios to strengthen decisions related to future water resource management and planning.

2 Material and method

2.1 Location of the research area

The research area is located in the second part of the Abel Itirald department in the city of San Buenaventola, La Paz province. Geographically, it is located between UTM coordinates 61000ME-845000ms and 66000ME-8410000ms. The research area has been divided into two regions, A and B (Figure 1). Zone A is located near the town of Tumupas in Tacana, which facilitates flow measurement in six sub basins. The B division of the Moa Lake Basin is divided into two parts: the upper part consists of 9 sub basins (the last ridge of the mountain range), and the lower part or plain is divided into 4 sub basins. Area A, covering an area of 60.87 square kilometers, includes the Colorado, Siruna, Eshagai, Ebutudu, Tumupasa, and Mamuk basins, which are characterized by mountainous terrain; The area of Zone B or Moa Lake Basin is 706.14 square kilometers, divided into two regions: one is the mountainous region, namely Sayuba, Camel, Chanare, Idiria, Moa Alto 1, 2, and 3 sub basins, and Lemon Alto, followed by the flat or plain region composed of Moa Low 1, 2, 3, and 4 sub basins and Lemon Low (Figure 1).

Figure 1. Geographical location of the research area, UTM-WGS1984 projection

2.2 Methodological

The population of the area, according to the surveys conducted, is 2,912 inhabitants, mostly of Tacana origin, distributed in 13 communities, the largest being Tumupasa with 1,827 inhabitants and the smallest being Nueva Jerusalén with 22 inhabitants. The inventoried water demand for human consumption does not exceed 1,500 L s^{-1} per day (Table 1).

Table 1. The population of the research area

Study area	Community	Population (inhabitants)	Consumption (L inhabitant-day-1)
Zone A Watersheds around the Botanic Garden	Río Colorado	27	59.00
	Tumupasa	1,827	148.07
	San Silvestre	127	106.30
Zone B Moa lake basin	La Esmeralda	242	103.21
	Santa Ana	198	100.00
	7 de Diciembre	120	106.30
	Everest	86	102.94
	25 de Mayo	82	107.79
	Esmeralda 1	71	59.00
	El Dorado	44	57.10
	Nueva Palestina	27	60.00
	Nueva Jerusalén	22	65.00
	Villa Aroma	39	59.00
	Total	2,912	

River gauging missions were carried out, as well as the installation and data collection of meteorological equipment, and the reconnaissance and travel of the sub-basins. Also, although very difficult to access by land, air and river to Lake Moa, to know and determine the area of maximum and minimum flooding of the water mirror, the collection of data from the Rurrenabaque station operated by AASANA Airport, and the collection and processing of existing information in the SISMET/SENAMHI (2019) were carried out.

2.3 Installation of meteorological station

In November 2018, Davis Hobo Vantage Pro2 meteorological stations were installed in San Buenaventura and Tumupasa, located at the coordinates and elevations shown in Table 2.

Table 2. The location coordinates of Davis Hobo Vantage Pro2 meteorological station

Station	Elevation	East	North	South latitude	West longitude
San Buenaventura	211	657480	8403680	14° 25′ 44″	67° 32' 20"
Tumupasa	473	619868	8435601	14° 08' 33"	67° 53' 21"

Tumupasa station is 262 meters higher than San Buena Ventura station.

2.4 Capacity campaign

Since there were no flow records for the rivers of interest, they were gauged with a windlass and with the support of trained technical personnel from DINA and Tumupasa residents. The gauging was carried out only on a monthly basis and the control points were established at the intersection of the rivers with the road that connects the towns of San Buenaventura and Ixiamas, which practically separates the mountainous zone from the plains.

Figure 2. Gauging in the Moa (left), Chanare (center) and Came (right) rivers

2.5 Bathymetry and overflight of Moa lake

Moa Lake is very shallow, with a height of less than 1.8 meters and an area of 16.5 square kilometers. It was formed thousands of years ago and is the result of the winding Beni River. In May 2019, aerial surveys were conducted on the lake using airplanes (Figure 3) to evaluate its configuration under maximum flood conditions. According to residents in the area, in some years, the lake was connected to the Beni River. In many difficult situations, preliminary water depth measurements of the lake were conducted in collaboration with the National Meteorological and Hydrological Service (SENAMHI), determining the accessible depth and establishing an elevation curve (m.s.n.m.) relative to the volume (m^3).

Figure 3. Aerial view of the main body of Moa Lake

2.6 Description of hydrological models for determining water supply

Water resource assessment is conducted at the watershed or sub watershed level. In order to generate these watershed hydrological response models, the WEAP and SWAT models were used, each with its own potential, which makes it possible to compare the results of the two models. Once established, they can be used for future water resource development planning and deepen the analysis of different impacts on water resources. Due to the lack of historical information, these models cannot be calibrated.

The WEAP Model -- Water Evaluation and Planning System (SEI-USA) contains a hydrology component calibrated to the Soil Moisture Model (SMM). The SMM is a one-dimensional model, and consists of the notion of water transfer between two buckets (Figure 4), which represent the dynamics between evapotranspiration, surface runoff, subsurface runoff, percolation, for an element of analysis or watershed (Yates et al., 2005).

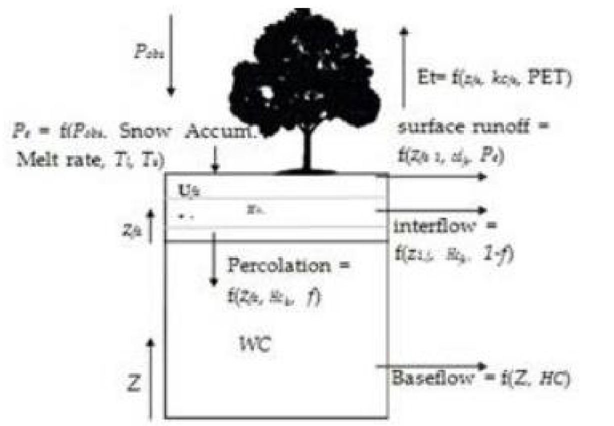

Figure 4. Conceptual schematic of the soil moisture model (SMM) (Yates et al., 2005)

According to the model established by WEAP, in the second stage, a comprehensive water resources management strategy that is urgently needed by beneficiaries can be formulated, which also confirms the high sensitivity of the region to human intervention.

Another model is SWAT (Soil and Water Assessment Tool), which is a watershed scale model used to simulate the quality and quantity of surface water and groundwater, and predict the impact of land use, land management practices, and climate change on the environment. SWAT (Arnold et al., 2012) is widely used to evaluate the prevention and control of soil erosion, non-point source pollution control, and regional management in watersheds.

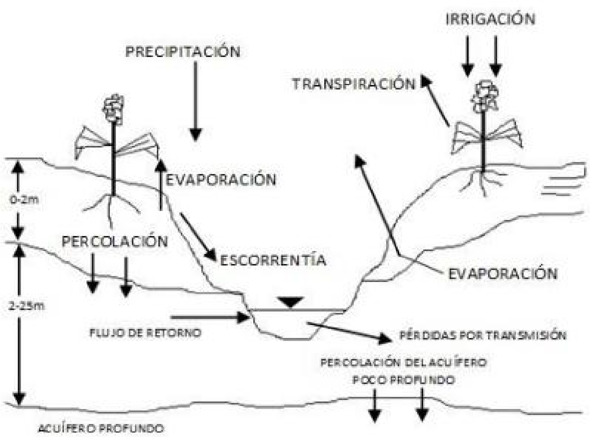

Figure 5. Hydrological cycle representation in SWAT (Basic Concepts and Quick User Guide Version SWAT2005, Uribe, 2010)

The hydrological cycle is simulated by SWAT based on Equation 1 of the water balance:

$Sw_t = Sw_0 + \sum (R_{day} + Q_{surf} + E_a + W_{seep} + Q_{gw})$ [Equation 1]

Where: S_{wt} =final soil moisture content (mm); S_{w0} = initial soil water content on day i (mm); t = time (days); R_{day} = amount of precipitation on day i (mm); Q_{surf} = amount of surface runoff on day i (mm); E_a= amount of evapotranspiration on day i (mm); W_{seep} = amount of water percolating in the soil profile on day i (mm); Q_{gw}= amount of return flow on day i (mm).

SWAT has a proprietary weather engine which can fill the data gap. This climate engine is generated by means of empirical equations. It also works with the database of soil types and cover, which are modified according to FAO (2009) information and the existing cover type. The land cover and soil type information helps to elaborate the hydrological response units determining the runoff of the basin.

3 Results and discussion

3.1 Information generated by Tumupasa and San Buena ventura meteorological stations

Tables 3 and 4 show the precipitation and temperature data from two new meteorological stations during the hydrological year from October 2018 to September 2019. In the recorded data, the total rainfall at Tumupas station (2,330.9 millimeters) is slightly higher than that at San Buenaventula station (2,293.6 millimeters). On a monthly basis, the maximum rainfall at Tumupasa station occurs in December, at 328.5 millimeters, while the maximum rainfall at San Buenaventula station occurs in November, at 410.8 millimeters. Regarding the average temperature during the recorded period, it can be seen that the average temperature at Tumupasa station is 24.3 degrees Celsius, slightly higher than the average temperature of 23.9 degrees Celsius in San Buenaventula. The straight-line distance between stations is 49.5 kilometers.

Table 3. Precipitation and temperature data collected from station Tumupasa

Year	2018			2019								
Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep
Precipitation(mm)	178.5	291.4	328.5	313.0	324.3	178.4	231.6	183.2	84.1	109.8	13.2	94.9
Minimum temperature (°C)	18.8	17.3	19.7	21.3	20.1	20.4	16.8	14.1	13.8	12.5	12.7	19.6
Maximum temperature (°C)	32.7	31.1	33.6	31.5	32.7	31.3	31.8	31.6	31.0	31.4	34.9	37.4
Average temperature (°C)	24.7	23.6	24.6	24.1	24.6	24.7	24.7	23.2	23.2	22.7	24.3	26.8

Table 4. Precipitation and temperature data collected from San Buena Ventura station

Year	2018			2019								
Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep
Precipitation(mm)	141.2	410.8	239.7	471.6	267.3	261.5	219.4	110.9	81.4	74.8	0.3	11.1
Minimum temperature (°C)	17.9	17.6	17.7	17.0	18.2	21.9	19.0	17.6	15.1	14.6	12.1	19.7
Maximum temperaturea (°C)	32.5	31.3	30.0	29.0	26.0	25.3	27.0	32.2	31.8	32.4	35.8	38.3
Average temperature (°C)	25.1	23.5	23.2	22.7	23.8	23.9	23.1	24.1	24.0	23.0	24.3	26.9

3.2 Database of gauged flow rates

The gauging campaign began in September 2018 in 10 rivers of interest, of which there were six around the town of Tumupasa and the Botanical Garden in zone A (Figure 6) and the other four rivers in the upper part (end of the highlands) of the Lake Moa basin, Moa Alto, Chanare, Came and Sayuba (Figure 7).

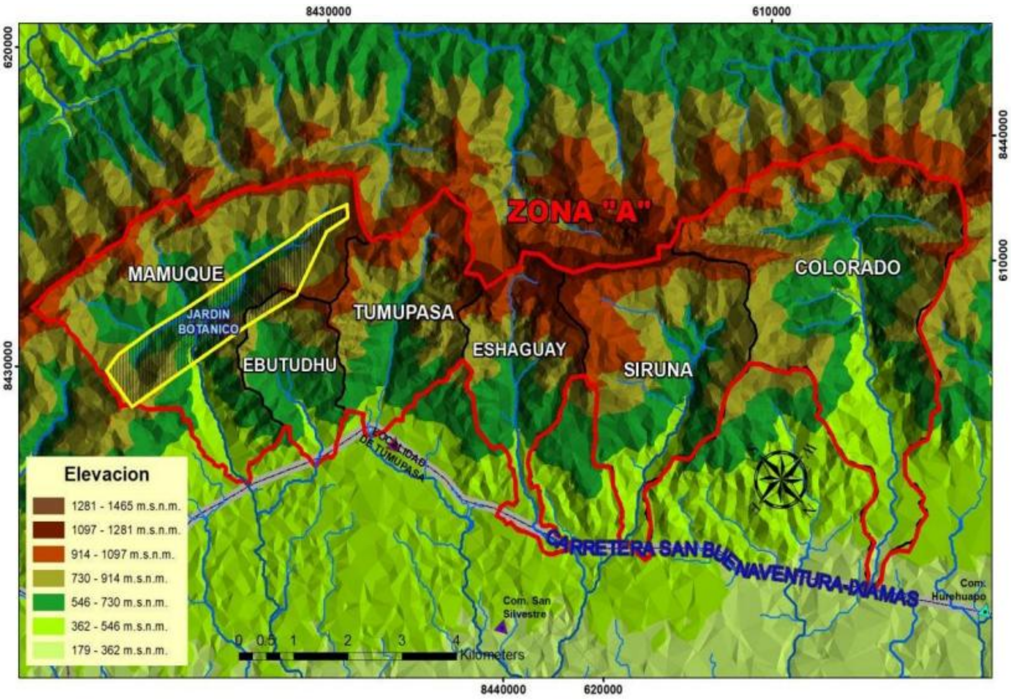

Figure 6. Geographical location of the six sub-basins of zone A and the Botanical Garden

The surface runoff of the watershed reaches its peak in March and its lowest value in November, while some watersheds in Zone A (Table 5) and Zone B (Table 6) completely dry up.

In existing databases, temporal variations in runoff can be observed, depending on its own input region or watershed, with significant changes between them.

Table 5. Actual flow rates of six sub basins in Zone A

Sub basin	Area (km^2)	Caudales aforados ($m^3 s^{-1}$)											
		Sep 2018	Oct 2018	Nov 2018	Dec 2018	Jan 2019	Feb 2019	Mar 2019	Apr 2019	May 2019	Jun 2019	Jul 2019	Agu 2019
Mamuque	15.13	0.03	0.08	0.03	0.00	0.42	0.97	1.17	0.66	0.42	0.53	0.13	0.07
Ebutudhu	3.93	0.08	0.03	0.05	0.11	0.20	0.40	0.39	0.39	0.29	0.24	0.16	0.21
Tumupasa	7.23	0.03	0.07	0.02	0.17	0.18	0.44	0.51	0.41	0.31	0.19	0.12	0.09
Eshaguay	6.14	0.00	0.04	0.00	0.11	0.11	0.43	0.44	0.31	0.18	0.05	0.00	0.00
Siruna	10.37	0.06	0.02	0.09	0.15	0.68	0.52	0.71	0.52	0.32	0.20	0.13	0.08
Colorado	18.07	0.03	0.06	0.03	0.16	0.24	0.58	0.84	0.58	0.31	0.10	0.09	0.05

From Table 5, it can be observed that, although the gauging was carried out on the same day, the hydrological response in the case of the Mamuque river basin is higher than that of the Colorado river because it has a smaller surface area. In this regard, it is worth mentioning that the Colorado river basin has been more intervened by man in the highlands, which could be the reason for this difference. In most of the basins of the highlands, springs and subsurface flows have been observed in the lower parts. The Botanical Garden is practically 95% distributed in the Mamuque river basin. Although the basin is well preserved, the gauging in December was null with a subsurface flow difficult to quantify.

Figure 7. Details of the Moa Lake Basin and Upper and Lower Parts (Zone B)

According to the gauging carried out (Table 6), there is a similarity in the contributions according to the area of the sub-basins, similar to the flows of zone A. Similarly, in the Chanare and Came sub-basins it has been observed that there are subsurface flows in the direction of Lake Moa, i.e., although the bed is dry, there is a subway contribution that descends towards the lake and emerges downstream due to the characteristics of the gravelly-sandy terrain in the transition zone of the highlands and the plain.

Table 6. Measured flows of the mountainous part of the Lake Moa basin

Sub-basin	Area (km^2)	Flow rate (m^3 s^{-1})											
		Sep 2018	Oct 2018	Nov 2018	Dec 2018	Jan 2019	Feb 2019	Mar 2019	Apr 2019	May 2019	Jun 2019	Jul 2019	Agu 2019
Moa Alto 1	15.55	0.07	0.08	0.01	0.21	0.52	0.96	1.26	0.62	0.53	0.60	0.29	0.10
Chanare	20.15	0.00	0.08	0.00	0.25	0.93	1.48	1.07	0.54	0.40	0.80	0.16	0.20
Came	4.33	0.00	0.00	0.00	0.01	0.13	0.23	0.17	0.05	0.05	0.07	0.01	0.00
Sayuba	13.51	0.07	0.06	0.06	0.30	0.81	1.43	0.90	0.82	0.59	0.79	0.33	0.27

3.3 Hydrologic modeling - simulated flow rates

The hydrological models were calibrated with the gauged flows for each sub-basin, performing up to 10 iterations in order to obtain a model that adjusts to the observed flows. For calibration and validation, statistical coefficients such as the Nash and Sutcliffe Efficiency Coefficient (Equation 2), the BIAS relative bias (Equation 3) and Pearson's correlation coefficient (Equation 4) were used.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Q_i^{SIM} - Q_i^{OBS})^2}{\sum_{i=1}^{n}(Q_i^{SIM} - \overline{Q_i^{OBS}})^2}\right] \qquad (2)$$

$$BIAS = \frac{\sum_{i=1}^{n}(Q_i^{SIM} - Q_i^{OBS})}{\sum_{i=1}^{n} Q_i^{OBS}} x100 \qquad (3)$$

$$R = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_i^{SIM} - \overline{Q_i^{SIM}}\right) * \left(Q_i^{OBS} - \overline{Q_i^{OBS}}\right)}{\frac{1}{(n-1)}\sqrt{\sum_{i=1}^{n}\left(Q_i^{SIM} - \overline{Q_i^{SIM}}\right)^2} * \sqrt{\sum_{i=1}^{n}\left(Q_i^{OBS} - \overline{Q_i^{OBS}}\right)^2}}} \qquad (4)$$

Where: Q_i = flow rate; *SIM* and *OBS* = simulated and observed values respectively and the upper bar indicates the mean value in the study period; *NSE* = Nash coefficient; *BIAS* = relative bias; *R* = correlation coefficient, "*i*" and "n" are the amount of flow data.

Table 7 shows the acceptance ranges for each statistical coefficient NSE (Nash Coefficient from 0 to 1), BIAS (Bias Relative in percentage) and R^2 (Correlation Coefficient from 0 to 1).

Table 7. Acceptance ranges of the statistical coefficients

Criterion	Value	Classification
NSE	0.75<NSE≤1.00	Very good
	0.65<NSE≤0.75	Good
	0.50<NSE≤0.65	Satisfactory
	NSE≤0.5	Unsatisfactory
BIAS	BIAS<±10	Very good
	±10≤BIAS≤±15	Good
	±15<BIAS≤±25	Satisfactory
	BIAS>±25	Unsatisfactory
R^2	0.75<R^2≤1.00	Very good
	0.65<R^2≤0.75	Good
	0.50<R^2≤0.65	Satisfactory
	R^2≤0.5	Unsatisfactory

Table 8 shows the statistical coefficients obtained from the iterations performed in each sub-basin. It can be observed that there are sub-basins where the SWAT (Soil and Water Assessment Tools) and WEAP (Water Evaluation and Planning) models fit very well, although there are also basins in which the models do not fit or have Nash coefficients at the validation limit. The Ebutudhu basin does not have an acceptable Nash coefficient, with a value of 0.35 in the SWAT model and 0.48 in the WEAP model. In the case of the Colorado river basin, the WEAP model has a Nash limit value of 0.52 while in the SWAT model it reaches a value of 0.69, validating the modeling. In the Moa Bajo 4 sub-basin, the SWAT model reaches a low Nash value of 0.43, while in WEAP it has a Nash of 0.77, which validates the modeling. The low values of the Nash coefficient in the Ebutudhu and Moa Bajo 4 basins are due to certain measurement failures. In the case of the Ebutudhu basin, it is due to the fact that the gauged flows were not representative of the basins and may have been taken just after an unexpected event.

Regarding the correlation coefficient R^2, it can be noted that all the sub-basins are in the acceptance range, and that the lowest R^2 value is 0.74 which corresponds to the Came river sub-basin in the WEAP modeling. Regarding the BIAS bias, all the basins are in the adequate range with the exception of the Ebutudhu, Eshaguay and Moa Bajo 4 basins, which present BIAS values of 23% (SWAT), 21% (WEAP) and 23% (SWAT) respectively, being at the limit of the acceptance of the BIAS coefficient.

Table 8. Statistical coefficients of the study watershed

Sub basin	Model	NSE	R^2	BIAS (%)	NSE	R^2	BIAS
Iridia	WEAP	0.69	0.83	0	Good	Very good	Very good
	SWAT	0.64	0.84	- 12	Satisfactory	Very good	Good
Moa Alto 1	WEAP	0.73	0.89	- 12	Good	Very good	Good
	SWAT	0.61	0.80	- 8	Satisfactory	Very good	Very good
Chanare	WEAP	0.75	0.87	3	Good	Very good	Very good
	SWAT	0.63	0.81	- 6	Satisfactory	Very good	Very good
Came	WEAP	0.50	0.74	11	Satisfactory	Good	Good
	SWAT	0.73	0.86	4	Good	Very good	Very good
Sayuba	WEAP	0.73	0.91	- 16	Good	Very good	Satisfactory
	SWAT	0.71	0.85	- 4	Good	Very good	Very good

Mamuque	WEAP	0.81	0.91	0	Very good	Very good	Very good
	SWAT	0.74	0.87	-2	Good	Very good	Very good
Ebutudhu	WEAP	0.48	0.83	- 11	Unsatisfactory	Very good	Good
	SWAT	0.35	0.88	- 23	Unsatisfactory	Very good	Satisfactory
Tumupasa	WEAP	0.74	0.89	- 13	Good	Very good	Good
	SWAT	0.86	0.93	1	Very good	Very good	Very good
Eshaguay	WEAP	0.75	0.92	21	Good	Very good	Satisfactory
	SWAT	0.75	0.89	10	Good	Very good	Very good
Siruna	WEAP	0.63	0.92	0	Good	Very good	Very good
	SWAT	0.64	0.84	- 12	Good	Very good	Good
Colorado	WEAP	0.52	0.94	15	Satisfactory	Very good	Satisfactory
	SWAT	0.69	0.83	5	Good	Very good	Very good
Moa Alto 2	WEAP	0.72	0.89	- 13	Good	Very good	Good
	SWAT	0.69	0.83	0	Good	Very good	Very good
Moa Alto 3	WEAP	0.72	0.89	- 13	Good	Very good	Good
	SWAT	0.73	0.86	- 1	Good	Very good	Very good
Limon Alto	WEAP	0.72	0.89	- 13	Good	Very good	Good
	SWAT	0.73	0.86	- 3	Good	Very good	Very good
Moa Bajo 1	WEAP	0.75	0.89	- 10	Good	Very good	Very good
	SWAT	0.66	0.84	- 2	Good	Very good	Very good
Moa Bajo 2	WEAP	0.75	0.89	- 11	Good	Very good	Good
	SWAT	0.65	0.82	- 1	Good	Very good	Very good
Moa Bajo 3	WEAP	0.76	0.89	- 10	Very good	Very good	Good
	SWAT	0.58	0.77	1	Satisfactory	Good	Very good
Limon Bajo	WEAP	0.75	0.89	- 10	Good	Very good	Good
	SWAT	0.71	0.85	- 3	Good	Very good	Very good
Moa Bajo 4	WEAP	0.77	0.89	- 8	Very good	Very good	Very good
	SWAT	0.43	0.80	23	Unsatisfactory	Very good	Satisfactory

In a comparison of the results obtained from the application of the models for study zones A (Figure 8 and Table 9) and B lake basin (Figure 9 and Table 10), it can be observed that the SWAT values are higher than the WEAP results, due to the fact that the missing data in the SWAT modeling were replaced by its climatic engine, which are empirical values, as compared to WEAP, which fills in the missing data with the cycle function. Nevertheless, the behavior and sequence are similar in both models, as a result of the response to precipitation.

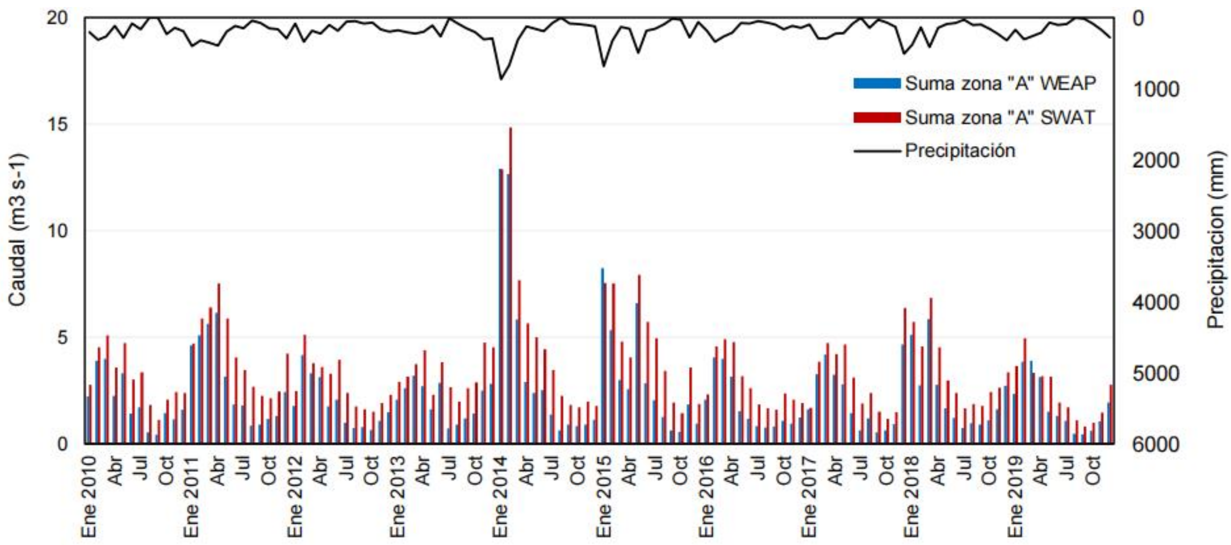

Figure 8. Results of SWAT and WEAP programs, total flow rates zone A (2010-2019)

Table 9. Simulated flows by basins in SWAT and WEAP (2010-2019), zone A, in $m^3 s^{-1}$

	Cuenca Mamuque		Cuenca Ebutudhu		Cuenca Tumupasa		Cuenca Eshahuay		Cuenca Siruna		Cuenca Colorado	
	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP
Jan	1.36	0.95	0.41	0.42	0.55	0.43	0.43	0.41	0.99	1.07	1.26	0.92
Feb	1.53	1.11	0.48	0.48	0.65	0.51	0.49	0.48	1.13	0.99	1.46	1.40
Mar	1.35	0.91	0.46	0.38	0.64	0.42	0.47	0.38	1.00	1.02	1.45	1.36
Apr	1.08	0.71	0.38	0.31	0.58	0.34	0.41	0.30	0.77	0.70	1.33	0.86
May	0.86	0.58	0.30	0.25	0.51	0.27	0.36	0.24	0.56	0.46	1.19	0.51
Jun	0.76	0.53	0.26	0.23	0.45	0.25	0.34	0.22	0.47	0.33	1.11	0.28
Jul	0.51	0.38	0.21	0.17	0.37	0.19	0.29	0.16	0.34	0.20	0.99	0.16
Agu	0.43	0.35	0.16	0.16	0.31	0.17	0.25	0.15	0.28	0.15	0.86	0.10
Sept	0.31	0.32	0.13	0.15	0.25	0.15	0.21	0.13	0.20	0.10	0.75	0.05
Oct	0.46	0.42	0.15	0.19	0.25	0.19	0.22	0.18	0.29	0.08	0.75	0.10
Nov	0.71	0.54	0.22	0.26	0.30	0.26	0.26	0.25	0.47	0.19	0.84	0.16
Dec	1.02	0.72	0.29	0.32	0.42	0.34	0.34	0.33	0.69	0.35	0.99	0.49

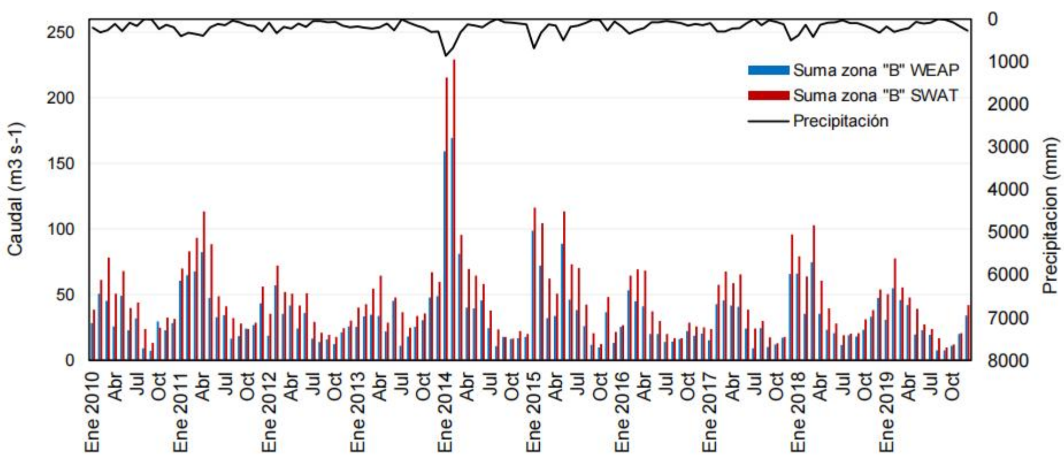

Figure 9. Flows simulated in SWAT and WEAP (2010-2019), zone B Lake Moa basin, in $m^3 s^{-1}$

Table 10. Simulated flow in the sub basin from 2010 to 2019, in the Moa mountainous area of Lake Kunka, measured in cubic meters S^{-1}

	Cuenca Iridia		Cuenca Moa Alta 1		Cuenca Chanare		Cuenca Came		Cuenca Sayuba		Cuenca Moa Alta 2		Cuenca Moa Alta 3		Cuenca Limon Alto	
	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP
Jan	1.30	0.90	1.08	0.92	1.74	1.24	0.35	0.15	1.28	1.10	2.19	1.75	1.85	1.95	2.67	2.02
Feb	1.49	1.06	1.27	1.09	2.04	1.46	0.39	0.20	1.50	1.24	2.66	2.07	1.95	2.31	2.97	2.40
Mar	1.32	0.88	1.27	0.91	1.85	1.21	0.37	0.18	1.43	1.00	2.72	1.72	1.31	1.92	2.74	1.99
Apr	1.10	0.69	1.18	0.71	1.51	0.94	0.32	0.15	1.18	0.77	2.53	1.35	0.87	1.49	2.18	1.56
May	0.89	0.57	1.07	0.59	1.18	0.76	0.28	0.13	0.95	0.63	2.20	1.10	0.68	1.22	1.79	1.28
Jun	0.72	0.53	0.99	0.54	0.95	0.70	0.26	0.12	0.84	0.58	1.88	1.01	0.62	1.12	1.63	1.18
Jul	0.51	0.39	0.85	0.40	0.70	0.51	0.22	0.09	0.65	0.42	1.54	0.74	0.37	0.81	1.29	0.86
Agu	0.41	0.35	0.73	0.36	0.57	0.46	0.19	0.08	0.51	0.39	1.28	0.67	0.38	0.73	1.20	0.78
Sept	0.29	0.32	0.61	0.33	0.37	0.42	0.16	0.07	0.41	0.37	0.99	0.61	0.31	0.66	1.04	0.71
Oct	0.40	0.41	0.58	0.41	0.48	0.54	0.17	0.07	0.48	0.50	0.91	0.75	0.57	0.82	1.21	0.88
Nov	0.64	0.52	0.66	0.53	0.80	0.70	0.21	0.09	0.67	0.66	1.14	0.97	0.94	1.06	1.56	1.12
Dec	0.94	0.69	0.84	0.70	1.22	0.94	0.27	0.12	0.92	0.85	1.58	1.28	1.40	1.42	2.06	1.48

Table 11. Simulated flows by sub-basin 2010-2019, Lake Moa basin, lower part or plain, in $m^3 s^{-1}$

	Cuenca Moa Baja 1		Cuenca Moa Baja 2		Cuenca Moa Baja 3		Cuenca Limon Bajo		Cuenca Moa Baja 4	
	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP	SWAT	WEAP
Jan	8.04	5.14	2.06	1.59	28.82	21.45	15.46	12.18	5.13	4.46
Feb	9.28	6.00	2.48	1.87	33.60	25.30	17.62	14.32	6.03	5.20
Mar	8.06	4.94	2.48	1.53	31.67	20.71	15.99	11.76	5.82	4.25
Apr	6.41	3.82	2.19	1.17	26.02	15.68	13.29	8.99	4.75	3.23
May	4.97	3.12	1.78	0.93	20.65	12.50	10.51	7.25	3.73	2.61
Jun	4.32	2.88	1.44	0.85	17.77	11.34	9.03	6.62	3.23	2.39
Jul	3.34	2.07	1.14	0.60	13.59	7.94	6.79	4.70	2.57	1.68
Agu	2.67	1.88	0.95	0.53	11.17	7.02	6.09	4.21	2.04	1.52
Sept	1.93	1.74	0.69	0.47	8.34	6.26	5.04	3.81	1.66	1.39
Oct	2.31	2.25	0.68	0.62	9.61	8.22	5.94	4.96	1.87	1.85
Nov	3.84	2.93	0.99	0.83	14.66	11.10	8.35	6.58	2.74	2.46
Dec	5.57	3.87	1.48	1.15	20.71	15.50	11.64	8.96	3.76	3.32

Based on the results obtained from the simulation and in comparison with the gauging carried out in the rivers of interest, it can be indicated that there is a certain correspondence not very far from reality, which means that in a preliminary way the models are reflecting the adequate hydrological response of the basins studied, but also confirms the need to continue monitoring the flow measurement without interruption, in order to better validate and calibrate the models used.

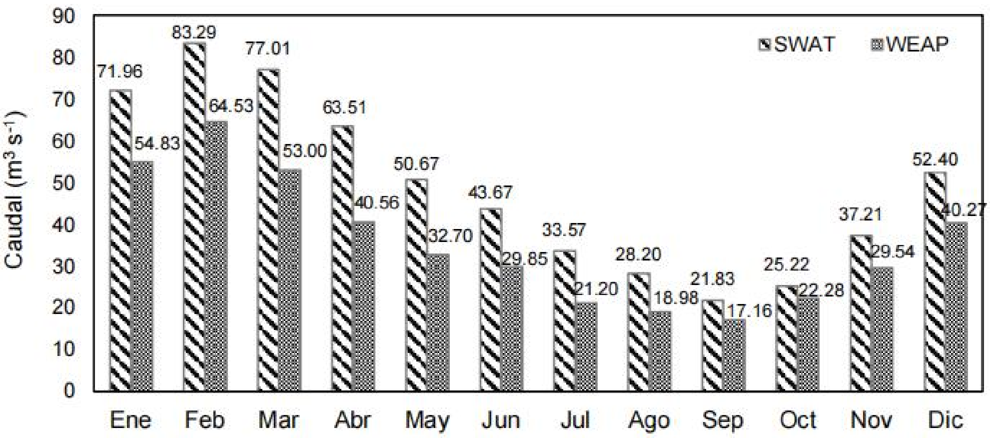

Figure 10. Simulated inflows to Lake Moa ($m^3 s^{-1}$)

According to the results obtained from the simulation of the Moa Lake basin (Figure 7), with data from one year of gauging, it only confirms the need for more hydrometric data to generate models that are more representative of the basins. The flow rates represented in Figure 10 show an overestimation throughout the year by the SWAT model, while the WEAP results are more conservative. However, according to the visual observations of the three most important inflows to Lake Moa, it has been hydraulically estimated that the inflow during the wet season is around 70 $m^3 s^{-1}$ approximately, which means that the SWAT model possibly simulates the wet season better, while the WEAP model simulates the low water season better, since it has been verified that the minimum inflow to Lake Moa during low water does not exceed 2. 0 $m^3 s^{-1}$ that were gauged in October 2019 in the Limón River, which is the only tributary during the dry season.

The dynamics of Lake Moa, whose dynamics have been preliminarily evaluated, require further investigation to clarify the temporal regulation compartment and its close relationship with the fluctuating levels of the Beni River. During the dry season, the lake drains into the Beni River, while during the wet season, the Beni River drains into the lake, to an unknown extent, according to the inhabitants of the Cachichira village, located on the banks of the Beni River. The lake bottom is at 171.83 m asl and the water level reaches 172.73 m asl normally during the dry season, while the water level in the Beni river is 170-258 m asl. During the rainy season, the lake's water level reaches approximately 173.59 m asl, while the Beni river's water level reaches 175.03 m asl (according to the inhabitants to be investigated), generating a difference in level of 1.44 m, which indicates that the Beni river is above the lake during the rainy season.

3.4 Depth measurement results - altitude curve - Moa Lake volume

A preliminary water depth map of the lake was drawn (Figure 11), and an elevation volume curve was plotted as shown in Table 12 and Figure 12.

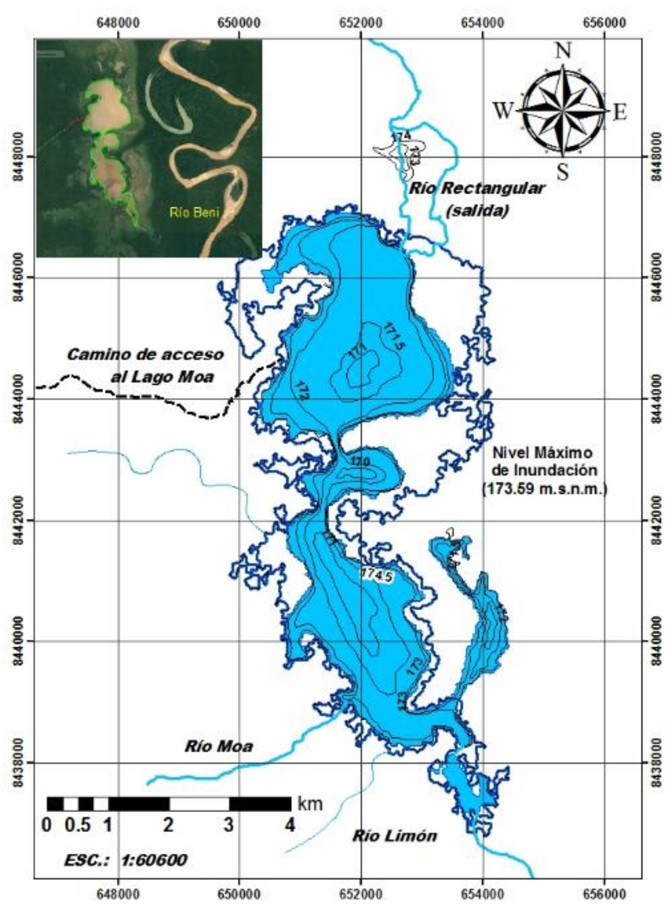

Figure 11. Depth of Moa lake water

Table 12 shows the measurement levels that were recorded at the inlets of Lake Moa, where the lowest, normal and flood water levels were recorded. H being the depth of water recorded in meters.

Date	H (m)	Cota (m s.n.m.)	Volume (hm^3)
Oct/2019	0.14	171.97	1.47
Sep/2018	0.90	172.73	12.09
Maximum flood level	1.76	173.59	29.57

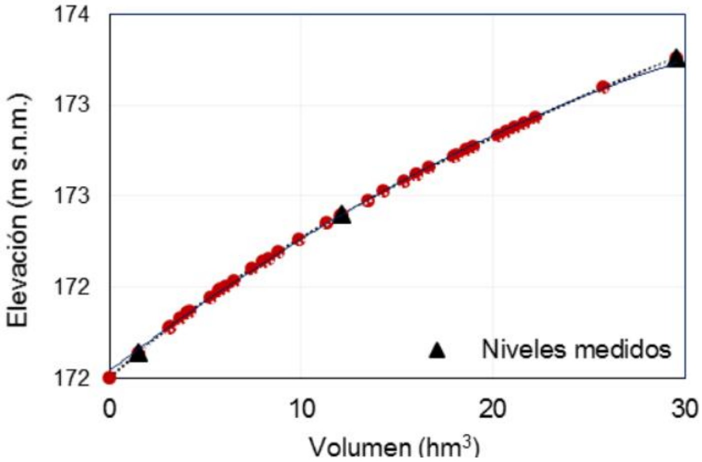

Figure 12. Elevation - Volume curve of Lake Moa, (hm^3).

In the rainy season it can exceed 1.5 m with an approximate mirror of 16 km^2, while in the dry season it can go down to 15.0 cm deep, forming only small lagoons in its central part with difficult access due to the swamp that is formed. Therefore, Moa Lake is completely sensitive to climatic variability and in periods of prolonged low water it can dry up, greatly affecting the fauna and any productive activity that is intended to develop, so it is of utmost urgency to propose alternative solutions to avoid this "environmental disaster".

3.5 Assessment in climate change scenarios

Most climate models for future projections in Bolivia do not agree in their results regarding rainfall estimates in terms of change in total sheets, intensity and geographic distribution, giving plausible situations of "dry" scenarios and "wet" scenarios, where uncertainties concern the total amount, cycles and intensity of rainfall (PMM, 2010). For the entire Bolivian territory on average, the wet scenarios predict an average increase in temperature of 1.5 °C and an average increase in annual precipitation of 22% until 2050, according to the World Bank (2010). The dry scenarios show an average temperature increase of 2.4 °C and an annual precipitation decrease of 19 % until 2050 (Climate Change Scenarios 2050 for Bolivia, World Bank, 2010).

Considering the climate scenarios proposed by the World Bank, we have obtained modeling results up to 2050, which are preliminary estimates that require further research to improve the resolution and reduce the uncertainty of the results.

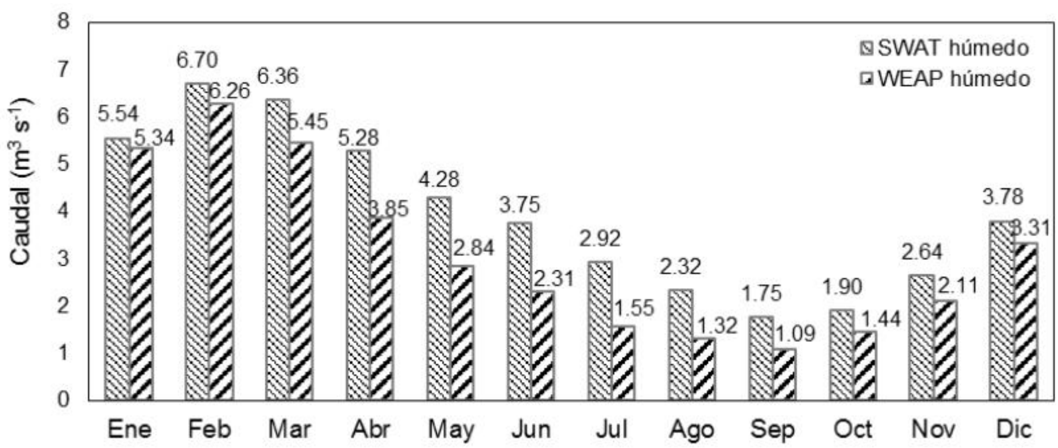

Figure 13. Comparison of wet scenarios of total flow for sub-basins in zone A

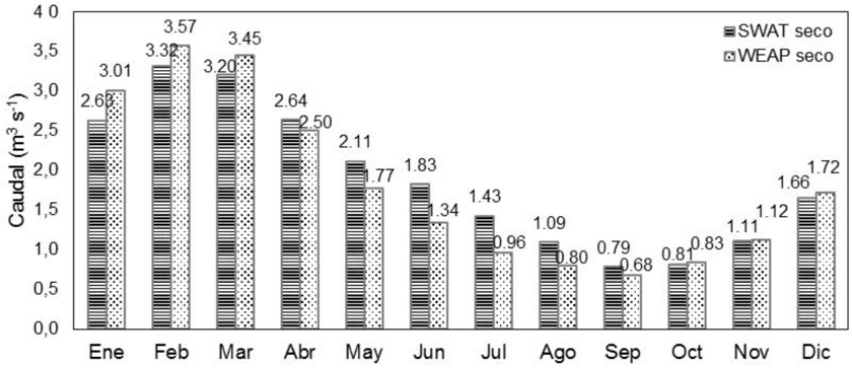

Figure 14. Comparison of dry scenarios of total flow for sub-basins in zone A

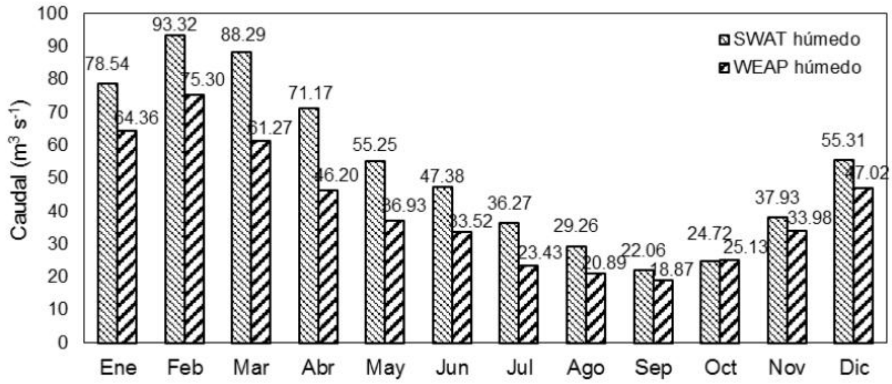

Figure 15. Comparison of wet scenarios of flow rates in the Lake Moa basin of zone B

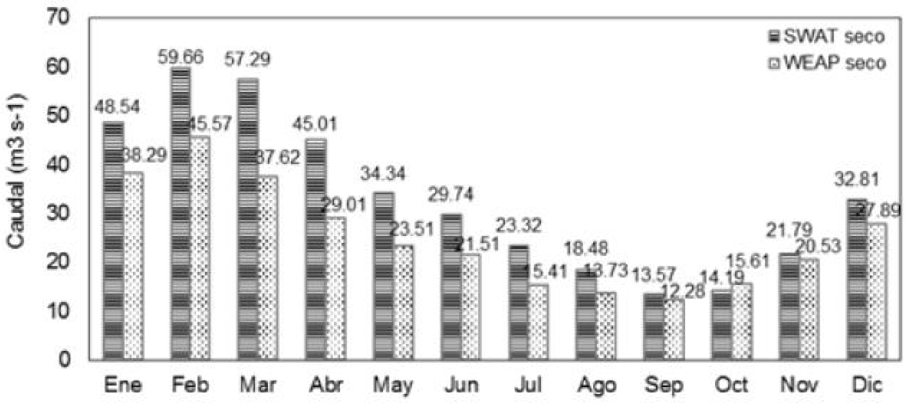

Figure 16. Comparison of dry scenarios of flow rates of the Lake Moa basin in zone B

Although the results are preliminary, it is evident that there is a significant decrease in the water supply of the six sub-basins studied in zone A, around the population of Tumupasa and the Botanical Garden, as well as in the basin of Lake Moa, which makes it a very sensitive and fragile system, whose substantial decrease could turn the lake into a swamp, forcing aquatic species to migrate and others to disappear.

4 Conclusion

Preliminary hydrological models have been generated and built for all 14 sub-basins (6 sub-basins of the highlands (zone A) and 8 sub-basins of the highlands and the 5 sub-basins of the plains that flow into Lake Moa (zone B), in the WEAP and SWAT hydrological models.

Preliminary simulations show that there are sufficient water resources to meet the human consumption demands of all the populations in the area, but also confirm that the influence of climate change tends to reduce the availability of water, which in turn depends largely on the vegetation cover, making the area very sensitive to human impact. In this sense, forest clearing and induced deforestation must be avoided. And as an example, we have the Colorado River sub-basin, which is more intervened by man in the mountainous area, and being larger, it has lower flows.

Lake Moa is very sensitive to the water supply of its 706.14 km^2 basin and even more to climate variability. In May and October 2019, the very abrupt change in levels was verified, confirming the analysis of the dry scenario in the climate change simulation, where Lake Moa would dry up in a very prolonged period of drought and therefore the outflow should be regulated to avoid this ecological disaster.

The estimated annual supply from the basin area to Lake Moa ranges between Qm=49.1 $m^3 s^{-1}$ from the SWAT model and Qm=35.4 $m^3 s^{-1}$ from the WEAP model. But in fact it has been proven that the flow entering October 2019 did not exceed the 2.0 $m^3 s^{-1}$ that were gauged in the Limón River, the only tributary during the dry season.

Coordination with local authorities (Sub Alcaldía, CIPTA, CIMTA) and community members who have plots around the lake is needed to guarantee controlled access to the lake at any time of the year and, therefore, instrumenting or equipping the lake with level sensors, an evaporimeter, and also a meteorological station in the body of the lake. This information will be very valuable to accurately determine the dynamics of the lake and its interaction with the Beni River and groundwater inputs.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Arnold, J; Moriasi, D; Gassman, P; Abbaspour, K; White, M; Srinivasan, R; Kannan, N. 2012. SWAT: Model use calibration and validation. Transactions of the ASABE, 55(4), 1491-1508.

[2] Banco Mundial. (2010). Economics of Adaptation to Climate Change, a Synthesis Report. Escenarios de Cambio Climático al 2050 para Bolivia, s.e.

[3] Calizaya Terceros, A. 2009. Water resources management efforts for best water allocation in the Lake Poopo basin, Bolivia. 112 p. ISSN:1101-9824, Suecia.

[4] Dourojeanni, A; Jouravlev, A; Chávez, G. 2002. Gestión del agua a nivel de cuencas: Teoría y Práctica, editorial CEPAL. Publicación de las Naciones Unidas LC/L.1777-P ISBN: 92-1-322070-7 ISSN versión impresa: 1680-9017 ISSN versión electrónica: 1680-9025 Copyright © Naciones Unidas, Santiago de Chile.

[5] Global Water Partnership (GWP), 2006. Reducción de la pobreza y gestión integrada de los recursos hídricos, ISBN: 1652-5396, Suecia. 125 p.

[6] Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO). (2009). Guía para la descripción de suelos. Traducido y adaptado al castellano por Ronald Vargas Rojas (Proyecto FAOSWALIM, Nairobi, Kenya-Universidad Mayor de San Simón, Bolivia). Cuarta edición. Roma, Italia.

[7] Proyecto Múltiple Misicuni (PMM). 2010. Estudios y Diseños Complementarios del PMM (Diseño para Construcción de la presa de 85 m). Estudio Hidrológico TAMS – INGETEC. 450 p.

[8] Servicio Nacional de Meteorología e Hidrología (SENAMHI/SISMET). 2019. Datos climáticos de la estación Rurrenabaque. Beni, Bolivia.

[9] Uribe, N. 2010. Conceptos básicos y guía rápida para el usuario Versión SWAT2005. Recuperado de https://swat.tamu.edu/media/46967/swat2005-tutorial-spanish.pdf.

[10] Yates, DD; Purkey, J; Sieber, A; Huber-Lee; Galbraith, H. 2005. WEAP-21 A Demand, Priority and Preference driven Water Planning Model, Water International, 30:4, 501-512.