04-033

STUDY OF FUTURE SCENARIOS IN A DRINKING WATER SOURCE, MILLUNI CASE – BOLIVIA

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Water is a necessary resource for life on earth, therefore, water sources for consumption must be prioritized in their care and preservation. This research takes as a study area the lagoons of the upper part of the Milluni micro-watershed, which supply two important cities in Bolivia, La Paz and El Alto. Various studies have exposed the problem of heavy metal contamination in Milluni due to mining activity in the area. However, corrective actions have not yet been taken to reduce the risk to public health and ecosystems. This study aims to identify possible future temperature and precipitation scenarios for Milluni and to observe the repercussion of the impact of the change on the area's water resources. The main result of this research is to generate specific information on the study area, which facilitates decision-making to address Milluni's water problems.

Keywords: water quality; heavy metals; safe water; future scenarios

ESTUDIO DE ESCENARIOS FUTUROS EN UNA FUENTE DE AGUA POTABLE, CASO MILLUNI – BOLIVIA

El agua es un recurso necesario para la vida en la tierra, por lo tanto, las fuentes de agua para consumo deben ser priorizadas en su cuidado y preservación. Esta investigación toma como área de estudio las lagunas de la parte alta de la microcuenca Milluni, que abastecen a dos importantes ciudades de Bolivia, La Paz y El Alto. Diversos estudios han expuesto el problema de la contaminación por metales pesados en Milluni debido a la actividad minera en la zona. Sin embargo, aún no se han tomado acciones correctivas para reducir el riesgo para la salud pública y los ecosistemas. Este estudio tiene como objetivo identificar posibles escenarios futuros de temperatura y precipitación para Milluni, y observar la repercusión del impacto del cambio en los recursos hídricos del área. El principal resultado de esta investigación es generar información específica sobre el área de estudio, que facilite la toma de decisiones para abordar la problemática hídrica de Milluni.

Palabras clave: calidad del agua; metales pesados; agua segura; escenarios futuros

Agradecimientos: Los autores agradecen al Proyecto CReA y el VLIR-UOS por el financiamiento para la difusión de este estudio.

1. Introduction

Water is essential for life and development on Earth; its quality deterioration has become an increasingly important problem (Tkaczyk, Mitrowska, and Posyniak, 2020). Drinking water is indisputably linked to public health, and this in turn to sustainable development (Pereira and Marques, 2021). Currently, considerable amounts of time, effort, and money are invested in controlling, protecting, managing, and restoring surface water resources, recognizing the importance of water for the economic development and social well-being of nations (Rivas and Maldonado, 2011; Ha et al., 2016; Slaughter et al., 2017). This is why caring for natural water sources available for supply has become a priority considering that water is only a finite resource. The above is presented as priorities in Goal 6, "Clean Water and Sanitation", within the Sustainable Development Goals (SDG) that frame the 2030 agenda (United Nations, 2015).

Climate change is expected to cause significant modifications in the hydrological cycle, which may particularly impact the systems most vulnerable to anthropogenic pressures and deteriorate the quality of water resources (Barbieri et al., 2021). To protect water resources, water management decisions must consider the complex socioeconomic conditions further challenged by climate change (Bates et al., 2008). Scenarios are a helpful forecasting tool for coherently, consistently, and reasonably exploring future implications. Future scenarios are designed to understand, analyze, and communicate information about the future, often to clarify current action in light of possible and plausible futures (Durance and Godet, 2010). Scenarios can serve as decision tools and are increasingly used by government organizations for strategic planning, enabling policymakers to explore and understand the uncertainties in their environment, frame internal strategic conversations, and take action to seize strategic opportunities (Chermack, 2011).

Scenarios have been applied in the field of water management to develop insights into future uncertainties and assess the robustness of different management actions in a variety of futures (Lienert, Monstadt, and Truffer, 2006; Haasnoot, and Middelkoop, 2012; Rasi Nezami et al. al., 2013; Dong et al., 2013). Using scenarios allows the identification and visualization of underlying drivers of change, which influence the development of broader policies, strategies, programs, and actions (Alcamo, 2008). By creating multiple future scenarios, decision-makers can implement actions that aim to mitigate the occurrence of unintended consequences and ensure that there are more resilient responses to future uncertainties (Maack, 2001; Wright et al., 2008). In addition, scenarios provide decision-makers and practitioners with a decision-making empowerment tool to develop a shared understanding of future risks and opportunities and a commitment to take action (Hulme and Dessai, 2008). Therefore, scenarios are useful to help decision-makers to develop a better long-term strategy, policy, and delivery mechanism (Henriques et al, 2015).

This study will develop possible future temperature and precipitation scenarios for the Milluni area, a source of water supply in Bolivia. Some studies on Milluni expose its vulnerability to contamination, especially by heavy metals (Salvarredy-Aranguren et al., 2008; Miranda et al., 2010; Alvizuri et al., 2019). There are also primary studies on future conditions at the Milluni Dam (Medina, 2021). However, information on future conditions at Milluni is still limited. This work aims to develop and interpret future climate scenarios in Milluni and their relationship with water availability. The result of this study will be the basis for capturing and prioritizing attention in the study area and thus managing to direct actions for preserving a natural water source.

2. Goal

Develop and interpret future climate scenarios in Milluni, a source of drinking water in Bolivia, to show their effect on the water availability for the population.

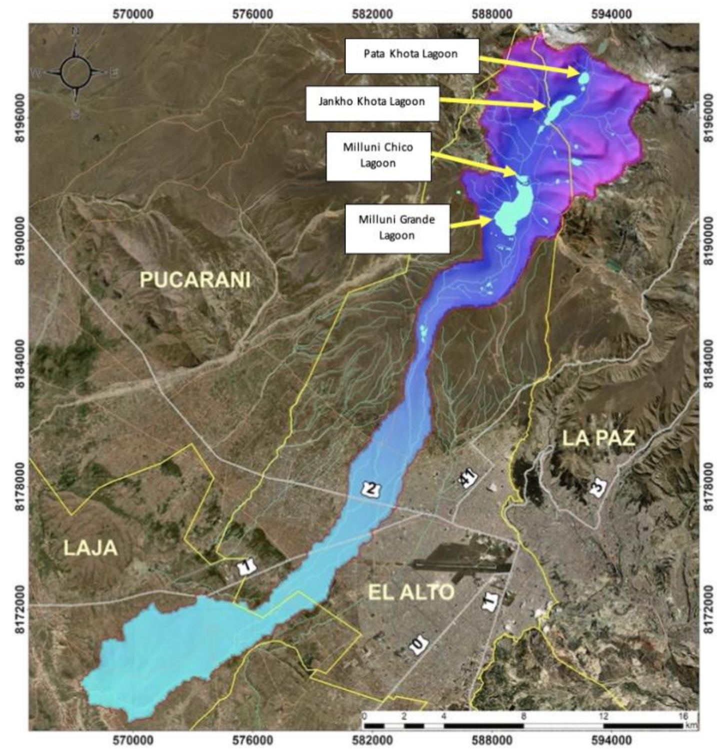
3. Material and Methods

This section has two parts, the first describes the study area, and the second exposes the research methodology.

3.1. Milluni micro-basin

Milluni is located in the Murillo province of the department of La Paz (16°08' to 16°10' south latitude and from 68°17' to 68°21' west longitude), approximately 25 km north of the urban area of the city of El Alto and about 30 km from the city of La Paz (Miranda, Arancibia, and Quispe 2010). It is located at 4,500 - 4,700 meters above sea level, has an extension of around 40 km^2, and is part of the Altiplano basin system (Iltis, 1988). This micro-basin presents extreme climatic conditions, such as high solar radiation and low temperatures, typical of the altiplano zone (Ahlfeld, Schneider-Scherbina, and Bolivia 1964). Figure 1 shows the existence of natural water sources in the upper part of the Milluni Micro-basin; these water resources supply approximately 500,000 inhabitants of two important cities in Bolivia, La Paz and El Alto.

Figure 1. Milluni micro-basin and its main lagoons



Source: redraw of Alvizuri et al., 2022.

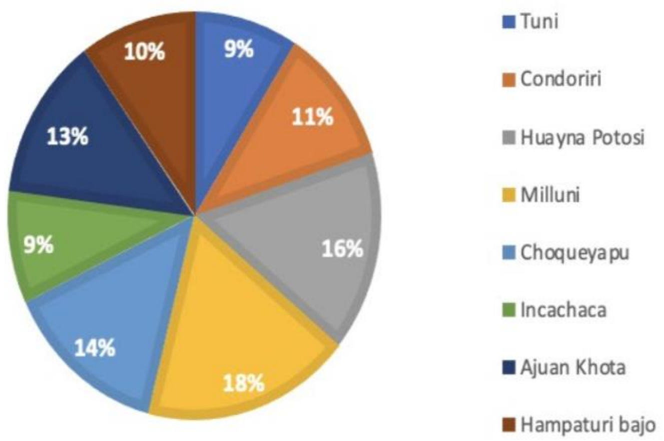
Figure 1 shows the 4 lagoons in the upper Milluni basin (Iltis, 1988). Below are their details:

- Pata Khota lagoon is a natural lagoon with an irregular shape that receives water from the snowmelt of the snowy Huayna Potosí. It is located at the beginning of the lagoon system at 4665 meters above sea level and does not present any apparent contamination.

- Jankho Khota lagoon is the second natural lagoon in the lagoon system, it has an irregular shape. This lagoon receives the waters of the Pata Khota lagoon. It is located at 4560 meters above sea level and does not present any apparent contamination in its waters.
- Milluni Chico lagoon located at an altitude of 4550 meters above sea level, is an artificial lagoon, with an irregular shape. Its tributaries are natural springs and acid mine drainage. It was built to capture the water coming from the mines to prevent it from entering the Milluni Grande lagoon.
- Milluni Grande lagoon receives effluents mainly from natural springs and from the Milluni Chico lagoon (with acid mine drainage). It also receives water from the Jankho Khota lagoon through a "bypass system", which consists of a pump that draws water from the Jankho Khota lagoon, this is conducted through an open cement channel, to the Milluni Grande dam. It is the last lagoon in the system and is located at 4530 meters above sea level.

The Milluni lagoons contribute to the storage dam located at Milluni Grande lagoon. The dam has a capacity of 10,000,000 m^3 and an area of 2,450,000 m^2 (Raffailac, 2002). Figure 2 shows the water contribution by basin for the department of La Paz, where the Milluni micro-basin is the one with the highest contribution to the water supply. For this reason, the quality of water in this area is a matter of great importance.

Figure 2. Contribution to supply by storage dam



Source: EPSAS, 2013.

Large-scale mining was carried out at Milluni from 1940 to 1990, mainly extracting Sn, Zn, and Pb. A maximum production of 110,000 T/a of crude minerals was extracted between 1970 and 1980 (Ríos, 1985). Contamination by acid mine drainage spread dangerously on the slopes of the Milluni Chico lagoon (4.6 km) (Miranda et al., 2010). Although mining in the area stopped some 20 years ago, the impact of mining waste on water quality continues to be a serious national environmental problem (Ríos, 1985; Salvarredy-Aranguren et al., 2008). In recent decades, small-scale mining has emerged that operates without any regulation. For the most part, this activity is intermittent and illegal, so there is very little information on its impact on water quality (Alvizuri et al., 2019). Contemplating the above, it is exposed that Milluni has a high vulnerability to its surface water bodies being contaminated by heavy metals due to past and current mining, this being an imminent risk to public health.

The increasing demand for potable water for the cities of La Paz and El Alto, and the low volume of water from glaciers due to climate change, have led to Milluni's polluted waters being used for water supply. Although Milluni waters receive treatment, it does not mean that their quality is safe for supply (Alvizuri et al., 2019). Few recent investigations study possible future scenarios and their impact on the quality and quantity of water resources in this area. For this reason, it is necessary to predict the main future climatic conditions (temperature and precipitation), and their affection for the water resources in Milluni to take action and thus avoid the loss of a natural water source.

3.2. Methodology

The methodology of this work is summarized in 4 stages: 1) Selection of Representative Concentration Pathways for the prediction of future data, 2) Election of software and model for data processing, 3) Determination of points to generate data for future scenarios, and 4) Construction of maps of future scenarios.

3.2.1. Selection of Representative Concentration Pathways for the prediction of future data

For this point, the Representative Concentration Pathways (RCP) were taken, representing possible scenarios according to the route of current and possible greenhouse gas concentrations to be established in the future. The representative concentration pathways selected were RCP 2.6, RCP 4.5, and RCP 6.0. The 3-greenhouse gas concentration pathway scenarios adopted and approved by the 5th IPCC report (2014) are described below.

- RCP 2.6: Optimistic scenario of deficient levels of concentration of greenhouse gases, whose “peak emissions” are constant after 2100 and then decrease. This means that negative emissions will occur after the year 2070.
- RCP 4.5: Scenario where RCP emissions peak around 2040 and then decline. A temperature increase of +1.6 °C to 2.3 °C is estimated
- RCP 6.0: Scenario where the RCP of emissions peaks around 2080 and then declines.

3.2.2. Election of software and model for data processing

Once the global climate change projections were selected, the MarkSim DSSAT software was chosen. This weather generator weather simulator uses 720 weather classes scattered around the world to calculate the coefficients of a rain generator based on them (Jones, and Thornton, 2013). This platform is the web version for IPCC data analysis (Institute, 2023) since it is software that adjusts the data from more than 9200 stations, using data from around the world. The precision with which this software generates the data allows a “stochastic downscaling” for the clustering of meteorological data for the site of interest. MarkSim DSSAT employs 17 predictive climate models with different latitude and longitude resolutions from different institutions and with cumulus mass flow parameterization scheme references, atmospheric physical parameter dynamics, global climate-earth system models, geoscientific model development, mean states, climate variability and sensitivity, aerosol-climate interactions, cloud-climate, among others.

For future data analysis, the CSIRO-Mk3.6.0 model from the Commonwealth Scientific and Industrial Research Organization and Queensland Center of Excellence for Climate Change was chosen. The CSIRO-Mk3.6.0 model is an update of the CSIRO-Mk3.5 GCM (Gordon et al., 2010). Rotstayn et al. (2010) give details of the model. The atmospheric component has a horizontal resolution of approximately 1.9°x1.9°, and each atmospheric grid point is coupled to two oceanic grid points. This improved north-south resolution in the oceanic component is expected to increase the ocean's ability to simulate important seasonal tropical and extratropical interactions. The most significant improvement of the CSIRO-Mk3.6.0 model over its predecessor is the inclusion of an interactive aerosol scheme which also required an update to the radiation scheme used in the model (Collier et al, 2011).

3.2.3. Determination of points to generate data for future scenarios

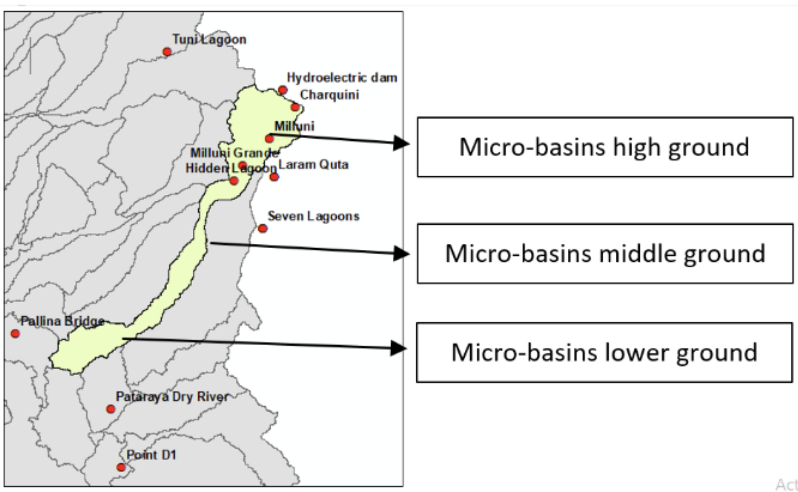
The distribution of points for the interpolation and construction of precipitation and temperature isolines was developed by selecting geographic points of bodies of water within the micro-basin and close to it, then to perform interpolation by the Kriging Spatial Analyst method (Solow, 1986) and later with the contour tool (Pucha-Cofrep et al, 2017) the isohyets with 10 mm difference and isotherms with 1 degree of thermal difference were developed for the area of the Milluni micro-basin. Below, Table 1 and Figure 3 detail the coordinates and the respective location of the selected reference points.

Tabla 1: Puntos seleccionados para interpolación

Point	Description	Latitude	Length	Height
1	Tuni Lagoon	-16.243477	-68.244384	4468
2	Hydroelectric dam	-16.283304	-68.123218	4805
3	Charquini	-16.302185	-68.109903	5095
4	Milluni	-16.334427	-68.136773	4832
5	Laram Quta	-16.37546	-68.132152	4631
6	Seven Lagoons	-16.428835	-68.144593	4273
7	Point D1	-16.680095	-68.292133	3862
8	Hidden Lagoon	-16.379414	-68.174678	4579
9	Milluni Grande	-16.618806	-68.165469	4553
10	Pataraya Dry River	-16.618806	-68.30362	3867
11	Pallina Bridge	-16.539369	-68.403833	3856

Source: Own elaboration, 2023.

Figure 3. Distribution of reference points and grounds of the micro-basin



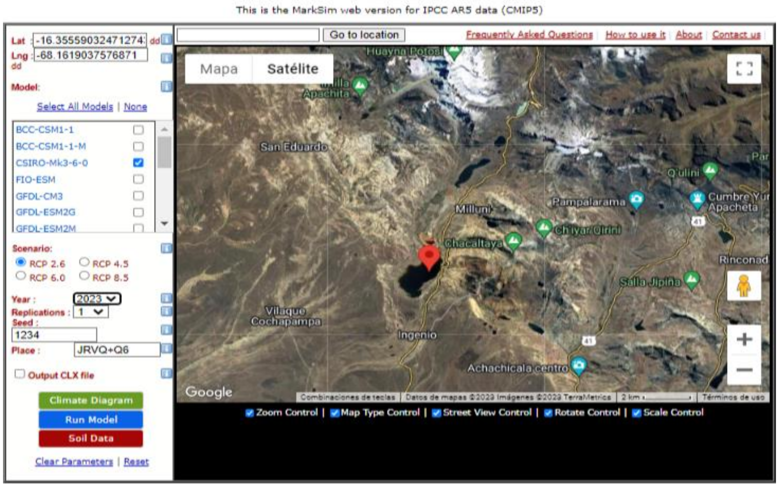
Source: Own elaboration, 2023.

3.2.4. Construction of maps of future scenarios

For the construction of the analysis maps of future climate scenarios, the MarkSim DSSAT platform was used, whose package generates daily meteorological data from the Latin American and African regions. Data of future total precipitation and average temperature were used for the 3 scenarios RCP 2.6, RCP 4.5, and RCP 6.0, with data from the years 2025, 2030, 2070, and 2095. 2025 was chosen because it was the closest to the present for exposing the nearest climatic changes. 2030 was used because it is a year that represents the objective of reducing emissions by 45% from the years 2010 to 2030, according to the global agenda. 2070 was taken because it means a period before 2100 as the top year in critical scenarios. Finally, the year 2095 was elected as it was the maximum year for calculating climate models.

The steps for downloading the MarkSim DSSAT data for each reference point were select the reference point, then choose the CSIRO-Mk3.6.0 climate model, and for the last step selection of the scenario and the year. Figure 4 is a screenshot of the MarkSim DSSAT program during the data download process.

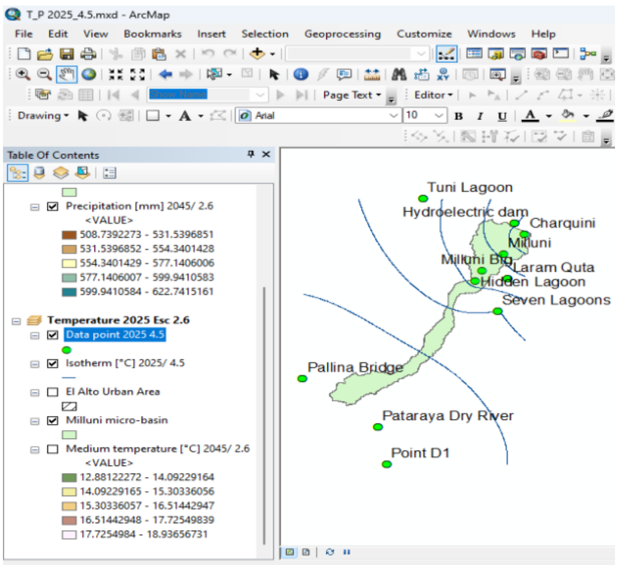
Figure 4. Weather file generation of software MarkSim DSSAT



Source: MarkSim DSSAT, 2023.

The generated data was entered into ArcGis, and interpolation and constructing isohyets and isotherms were performed. Figure 5 illustrates this process.

Figure 5. Construction of isohyets and isotherms in ArcGis



Source: ArcMap GIS 10.5, 2017

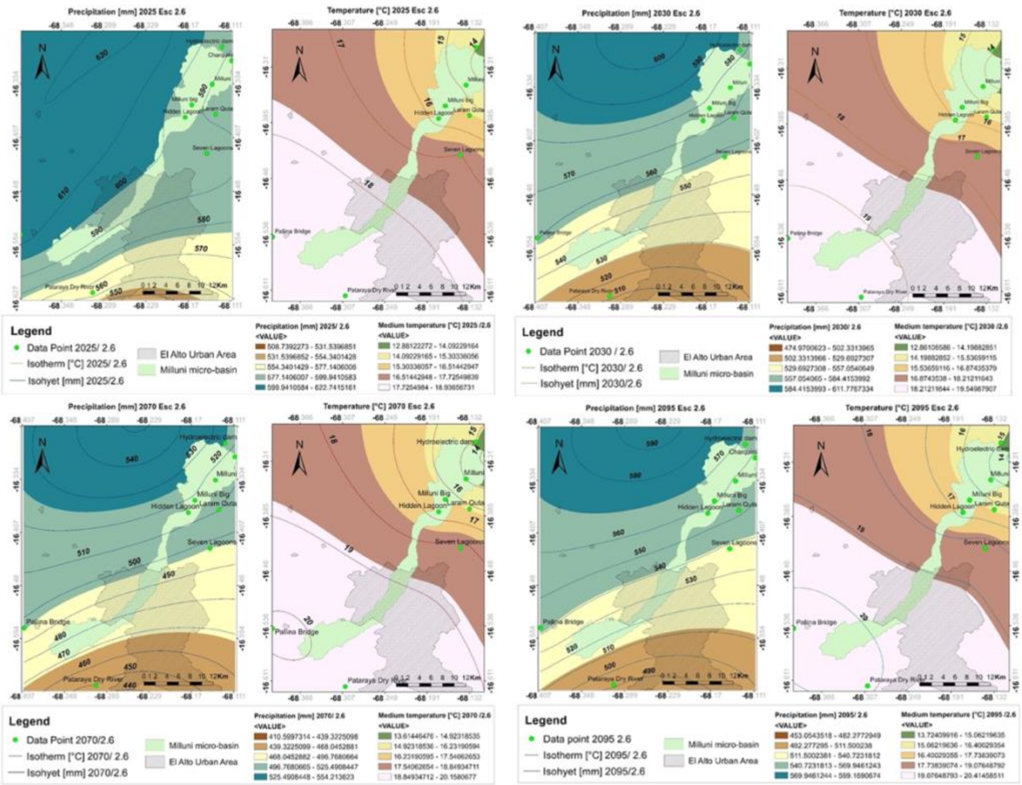
4. Results and discussions

For the evaluation of the possible climatic scenarios and the determination of the degree of environmental-hydric vulnerability of the Milluni micro-basin, the current precipitation and temperature conditions in the study area will be manifested, as a referential framework. The total annual precipitation currently recorded in the Millunies micro-basin area is 606 mm and the average temperature of 12 °C (SENAMHI, 2022; MarkSim DSSAT, 2023). The previous data allowed to see what would be the impact and possible effects on these parameters with the scenarios proposed for the throughout the micro-basin area, specifying high, medium to low grounds. The parts of the Micro-basin are presented in Figure 3.

4.1. Scenario RCP 2.6

Figure 6 presents the RCP 2.6 temperature and precipitation scenario for the Milluni Micro-basin for 2025, 2030, 2070, and 2095. Table 2 shows the temperature and precipitation averages for the three parts of the micro-basin in the 4 years studied.

Figure 6. Scenario RCP 2.6



Source: Own elaboration, 2023.

According to the data generated for the RCP 2.6 scenario, it is observed that the temperature will have a probable increase of 0.4 to 1.6 °C for the years projected until 2065, and for the years 2070 to 2095, the probable increase in temperature would be from 0.3 to 1.7 ºC According to the summary of the data in Table 2, it can be seen that there is a progressive increase in the mean temperature over time for the three parts of the basin. The upper part of the Micro-basin is the one with the lowest increase in temperature, however the increase, even if minimal, directly affects the change in the mountain ecosystem with a reduction in water availability due to the reduction of glaciers, as suggested by the study by Botero (2015). A decrease in precipitation is also observed for all the years analyzed under the RCP 2.6 scenario, which impacts the volume of water, according to the work of Medina (2021). considering a decrease in the volume of water in an area with a pollution problem could imply an increase in the concentration of pollutants in water bodies. The RCP 2.6 scenario is the most optimistic projection, but it still exposes a significant variation in temperature and precipitation that would affect Milluni's water resources.

Table 2. Average temperature and precipitation data - RCP 2.6 Scenario

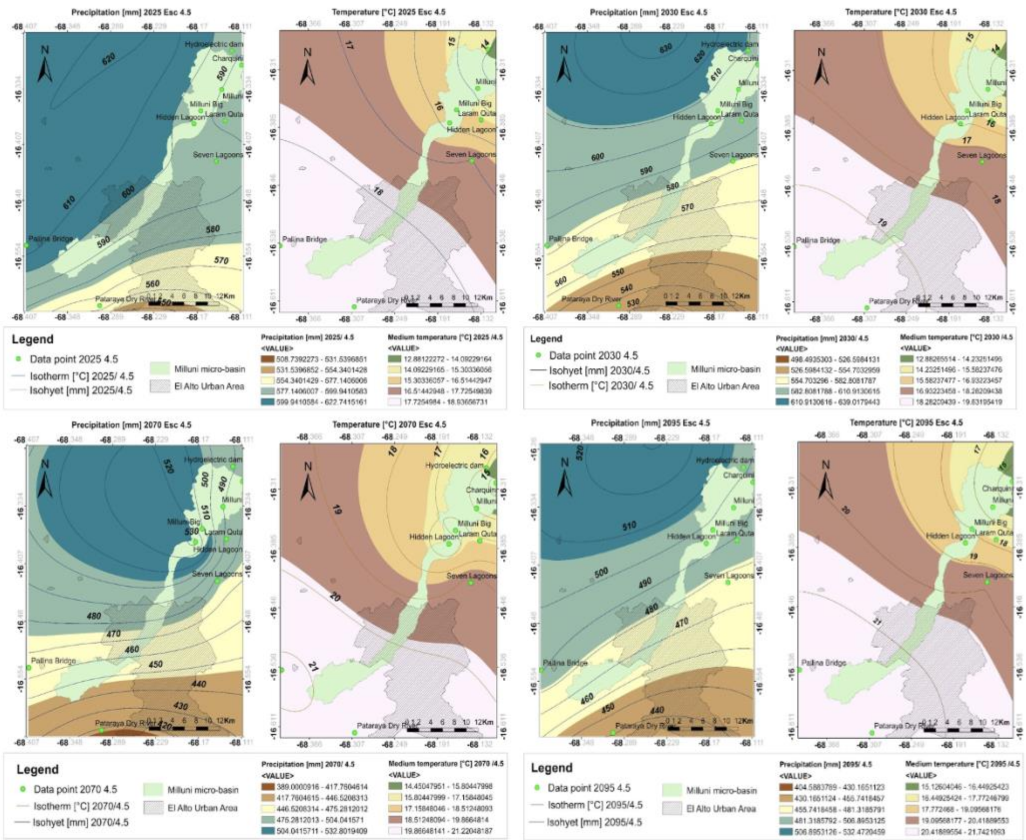
Year	Micro-basins high ground		Micro-basin middle ground		Micro basin lower ground	
	TP [mm]	MT[°C]	TP [mm]	MT[°C]	TP [mm]	MT[°C]
2025	590 - 600	14 - 15	600	17 - 18	590	18
2030	580 - 590	14 - 16	550 - 570	17 - 19	530 - 550	19
2070	510 - 530	14 - 17	490 - 510	17-19	470 - 490	19 - 20
2095	550 - 575	14 - 18	530 - 560	18 - 20	510 - 530	20

TP: Total Precipitation, MT: Medium Temperature. Source: Own elaboration, 2023.

4.2. Scenario RCP 4.5

Scenario 4.5 for temperature and precipitation in the study micro-basin for the years 2025, 2030, 2070 and 2090 is presented in Figure 7. The temperature and precipitation averages for the three parts of the micro-basin in the 4 years studied are shown in Table 3.

Figure 7. Scenario RCP 4.5



Source: Own elaboration, 2023.

According to the data generated by the RCP 4.5 scenario, there will be a probable increase of 1.4 °C for the years 2040 to 2065 and for the years from 2070 to 2100, a probable increase in temperature of 1.8 °C. An increase in temperature has serious repercussions for the balance of ecosystems and the water balance of the area, by Botero (2015). It is also seen that rainfall from 2025 to 2095 decreases in the three parts of the micro-basin. In the upper part of the micro-basin where the supply sources are located, precipitation would decrease from 600 to 510 mm until 2095. The decrease in average precipitation affects the volume of water available for supply, in addition, it could generate an increase in the concentration of pollutants in the area, ratifying the results of Medina (2021).

Table 3 Average temperature and precipitation data - RCP 4.5 Scenario

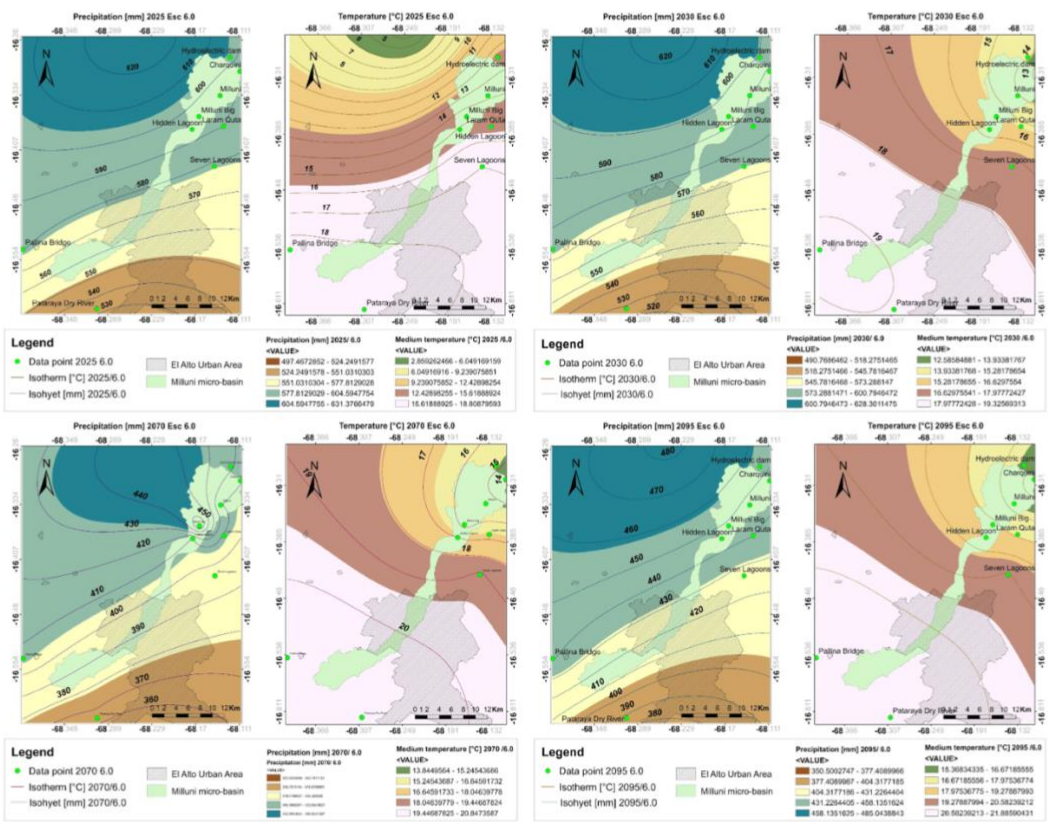
Year	Micro-basins high ground		Micro-basin middle ground		Micro basin lower ground	
	TP [mm]	MT[°C]	TP [mm]	MT[°C]	TP [mm]	MT[°C]
2025	590 - 600	14 - 16	600	17 - 18	590	18
2030	590 - 615	14 - 17	570 - 600	17 - 19	555 - 580	18 - 19
2070	480 - 530	15 - 18	460 - 510	17 -19	440 - 460	21
2095	490 - 510	15 - 19	470 - 490	20 - 21	460 - 480	21

TP: Total Precipitation, MT: Medium Temperature. Source: Own elaboration, 2023.

4.3. Scenario RCP 6.0

Figure 8 presents the RCP 6.0 scenario for temperature and precipitation in Milluni for the years 2025, 2030, 2070, and 2090.

Figure 8. Scenario RCP 6.0



Source: Own elaboration, 2023.

The temperature and precipitation averages for the three parts of the micro-basin in the 4 years studied are presented in Table 4.

Table 4. Average temperature and precipitation data – RCP 6.0 Scenario

Year	Micro-basins high ground		Micro-basin middle ground		Micro basin lower ground	
	TP [mm]	MT[°C]	TP [mm]	MT[°C]	TP [mm]	MT[°C]
2025	590 – 610	13 – 16	570 – 590	15 – 18	550 – 570	17 – 18
2030	580 – 605	14 – 17	560 – 590	17 -19	550 – 570	19
2070	410 – 450	14 – 18	390 – 420	18 – 20	380 – 400	20
2095	440 – 465	16 – 19	420 – 450	19 – 21	410 – 430	21

TP: Total Precipitation, MT: Medium Temperature. Source: Own elaboration, 2023.

For the RCP 6.0 scenario, the changes in the average temperatures of the study area are visualized with the maps in Figure 8, with an increase of 1.3°C up to 2.2°C. In addition, there could be changes in precipitation in the three areas of Milluni. Precipitation in the upper part of the micro-watershed ranges from 610 mm to 465 mm, which, as mentioned before, will have serious repercussions on the availability of water for supply and will also affect the balance of the ecosystems. This has already been proven in other studies such as Botero (2015) and Medina (2021).

Finally, it is necessary to mention that similar studies have been developed in other Latin American countries to incorporate future climate scenarios into planning for the management of watersheds and water resources (Angulo, 2006; Valverde 2013; Orozco, Ramírez, & Francés, 2018). Future scenarios can also be obtained through hydrological models and climate change scenarios, as in the case study by Escobar et al. (2013). Escobar et al. study was carried out with the WEAP tool for the basins that supply the cities of La Paz and El Alto in Bolivia, within which Milluni is located. The trend of the results of the previous study for Milluni is similar to that obtained in this study. However, the limitations of this research are related to the data provided by the MarkSim DSSAT meteorological file generator platform. Regarding their performance and reproducibility, these are based on the calibration of the climate model CSIRO-Mk3.6.0 used; if the model is adjusted in the MarkSim DSSAT platform, the results of the climatic scenarios obtained could change.

5. Conclusions

This study identified possible future scenarios according to the Representative Concentration Pathways (RCP) of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) of 2014. The information for the construction of maps of future scenarios was obtained through the model CSIRO-Mk3.6.0 of the free software MarkSim DSSAT, a weather file generator. The developed scenarios exposed the precipitation and temperature conditions in the Milluni area for the years 2025, 2030, 2070, and 2095; and the effect they will have on the area's water resources.

Based on the evaluation carried out in the possible future scenarios, it was identified that, either from the most optimistic level of projections, the increase in temperature is inevitable. Even if it is an increase of 0.4 °C, this causes changes in the ecosystem balance and the meteorological conditions, translating into a decrease in precipitation for the study area. Although the projections presented in this report are possible, it has been shown that the monitoring of the national climate observatory (SENAMHI) and the data obtained from the international future scenarios platform (MarkSim DSSAT) are consistent.

Of the three scenarios proposed, the results of the RCP 2.6 scenario are the closest in time and optimistic. However, the results will reflect that they would have impacted the different areas of the micro-basin, especially in the recharge zone (upper zone) from where the water comes to supply two important cities in Bolivia, La Paz and El Alto. Future studies could make the construction and evaluation of other scenarios, such as RCP 8.5, which was not used for this work. RCP 8.5 presents the most critical assumption where emissions increase due to overestimating coal production. A critical scenario could draw attention to once take action on the sight of a natural water source such as Milluni.

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