An analysis of unmet water demand under climate change scenarios in the Gualí River Basin, Colombia, through the implementation of Hydro-BID and WEAP hydrological modeling tools

Darwin Mena, Abel Solera, Lina Restrepo, Melissa Pimiento, Miguel Cañón and Freddy Duarte

ABSTRACT

Climate change can affect hydrological services in Andean basins, so a possible reduction in water supply can lead to not meeting the needs of different users, which has become a real challenge for decision-makers with regards to water management. This paper presents the results obtained from hydrological modeling exercises in the Gualí River Basin (Colombia) by combining the Hydro-BID modeling tool, which consists of an analytical hydrology database for Latin America and the Caribbean that provides a great advantage for countries with limited information and the Water Evaluation and Planning System (WEAP) modeling tool, in order to determine the potential impacts of climate change on unsatisfied demand for water in the basin. The results show a possible decrease in flow compared to current conditions; between 5.8% and 9.56% for CPR 2.6, and between 2.18% and 6.86% for CPR 8.5. The approach presented is useful to ensure that timely decisions are made to meet the demands of users under the conditions of climate change.

Key words | climate change, downscaling, Hydro-BID, WEAP

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INTRODUCTION

Integrated water resources management (IWRM) is a worldwide concept that seeks to advance proper water planning and management to ensure its sustainability and conservation, while promoting the generation and access to information in order to solve water-related problems, provide assistance and implement tools and resources that facilitate decision-making. To this end, one of the fundamental principles is reducing risk associated with the current and future supply and availability of water. Water storage plays a key role in the development of economic and cultural activities of communities, not just for human consumption but also to develop irrigation operations and industrial processes. For this reason, meeting the water demand from the available supply in basins is a fundamental part of IWRM (Global Change Centre Catholic University of Chile & Stockholm Environment Institute 2009; Ministry of Housing & Territorial Development 2010).

Worldwide consumption of water has increased eightfold since the 19th century and has doubled in the last 15 years. Moreover, demand from the agricultural, domestic, and industrial sectors has increased by 7, 20, and 12 times, respectively. Urban water consumption has increased 20 times in the last 100 years. Consequently, in 2050, approximately 55% of the world population will face a water crisis (Song *et al.* 2004). In the specific case of Colombia, despite being considered one of the countries with the largest natural

water supplies in the world, with an approximate water yield of 56 L/s*km^2, which greatly surpasses the average world yield of 10 L/s*km^2, on the water scarcity index nearly 4% of the population suffers from a high scarcity, 7% medium-high, and 30% medium. It is estimated that in 2025, the population affected by water shortages could reach 39%, which is why actions aimed at conserving this resource must be prioritized (Domínguez *et al.* 2008).

Different studies that use population behavior projections to determine the effects of climate change on water demand for specific areas have been conducted all over the world (Jensen *et al.* 2015; López-García *et al.* 2016). This study was carried out using official information provided by the Colombian National Administrative Department of Statistics (DANE), and took into account the country's main economic sectors (domestic, industrial, and agricultural). As a result, the findings obtained from this process can be used as inputs for decision-making by the regulatory bodies of each sector.

This research project integrates the WEAP and Hydro-BID modeling tools in order to evaluate the impact of climate change on the hydrological regime and its repercussions on the unmet water demand of the Gualí River Basin in Colombia, given that it has been demonstrated that climate and hydrological cycles are closely related. In this manner, an increase or decrease of variables such as precipitation and temperature have repercussions on the water supply, as established by the Third National Communication on Climate Change, which states that the hydrological regime may be affected by climate fluctuations reducing or increasing runoff rates and altering the temporal availability of the resource (IDEAM UNDP MADS Chancellery & Science & Technology Observatory 2016).

Modeling the water resource is a key tool in planning, forecasting, and evaluating variables, policies, and strategies, among many other factors. However, one of the main problems in Latin American and Caribbean countries is the scarcity of information that provides sufficient and quality data to use in hydrological models. Even though WEAP has a hydrological modeling module and has already been widely used to evaluate the climate's effect on water resources and optimize demand points in states such as California, Massachusetts, Georgia, as well as in African and Asian countries (Strzepek *et al.* 2007), the advantage of integrating Hydro-BID is that it uses an analytical hydrology database that reduces difficulties related to information scarcity in developing countries.

Hydro-BID software has been implemented to simulate hydrology and water resources management in the Latin American and the Caribbean (LAC) region, under climate change scenarios in countries such as Argentina, Peru, and Ecuador with pilot models in Colombia (Fekadu *et al.* 2014). Consequently, for the purposes of this study, Hydro-BID will be implemented to generate a time series of flows for the current climate and future climate projections and WEAP will be used to simulate water availability and unmet demand.

METHODS

Case study

The Gualí River Basin (Figure 1) is located in the northern region of the department of Tolima, Colombia, with the coordinates of 5°12′0″ N and 4°43′60″ W, lying in the Cordillera Central mountain range. The study area is shared with Los Nevados National Park (PNNN), covering an area of 82,147.8 hectares, with an approximate population of 83,500 inhabitants. Its elevation rises to approximately 4,850 meters above sea level and it flows down into the Magdalena River Basin, in the municipality of Honda, approximately 600 meters above sea level (Cortolima 2014).

The basin is primarily characterized by a tropical climate with a bimodal rainfall pattern due to the Inter tropical Confluence Zone, with a maximum annual precipitation of 3,105.12 mm. The average temperature is 18.7 °C, with a maximum of 20.3 °C and a minimum of 17.7 °C, varying throughout the basin due to changes in its elevation, with its relative humidity reaching a maximum of 90%, highlighting that this parameter behaves inversely to temperature. Likewise, the water supply measured in the basin is approximately 42.8 m^3/s, with an average water yield of 67.75 L/s*km^2 (Cortolima 2014).

With respect to the climate change analysis, there is no specific climate variation data for the basin, but there are for the region of Tolima. The Third National Communication on Climate Change (IDEAM, UNDP, MADS, DNP & Foreign Ministry 2015) states that by the end of the century (2081–2100), the temperature may rise by up to 2.3 °C on top of the reference value (1986–2005), while precipitation
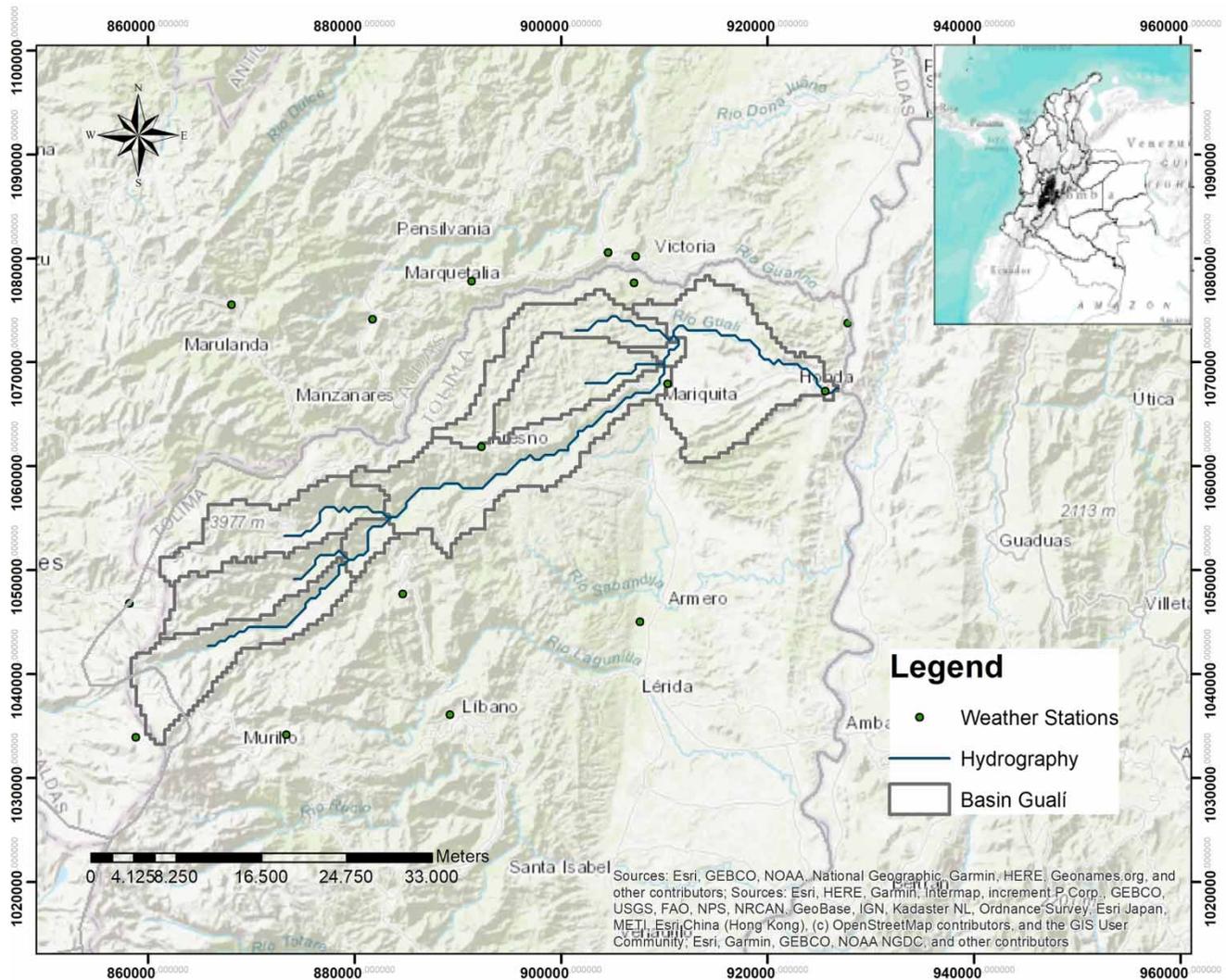
Figure 1 | Location of the Gualí River Basin (*source*: authors).

could increase by up to 17%. The expected impacts will be seen in the livestock sector due to high temperatures and in the agricultural sector due to precipitation increases (IDEAM UNDP MADS Chancellery & Science & Technology Observatory 2016).

Hydro-BID modeling tool

Hydro-BID is an integrated and quantitative system to simulate hydrology and water resource management in the LAC region under climate change scenarios. Moreover, it facilitates the evaluation of water quantity and quality, infrastructure needs, adaptation strategies, and project design to address these changes. This software is centered on an analytical hydrographic dataset (AHD), which analyzes information on basin topology, currents, land use, soil types, precipitation, temperature, and observed current flows for its calibration. The rainfall–runoff model implemented is distributed and named the generalized watershed loading function (GWLF) (Haith *et al.* 1992; RTI international 2017), which calculates the runoff volume for each basin and performs simulations to the scale of each sub-basin (Fekadu *et al.* 2014).

'*The model computes runoff and base flows by catchment: runoff is generated in the form of excess infiltration and*

base flow is a gradual release from the saturated layer. After accounting for runoff from precipitation events, any water in excess of a calculated evaporation volume is infiltrated to the unsaturated layer. Over time, the infiltrated water percolates from the unsaturated layer downward to replenish the saturated storage. Water within the saturated layer enters the stream channel as base flow where it combines with runoff from the catchment and any inflows from the upstream catchments to provide the stream flow volume' (Fekadu *et al.* 2014).

The Hydro-BID hydrological model requires input data such as precipitation, temperature, and river flow series, expressed in centimeters (cm), degrees Celsius (°C), and cubed meters per second (m^3/s), respectively. Specifically, these data were entered on a daily basis given that Hydro-BID manages the step related to time (Nalesso 2015). These data were provided by the Institute of Hydrology, Meteorology and Environmental Studies (also known by its acronym in Spanish, IDEAM).

Moreover, the model implements data on soil use and vegetation cover that were obtained from the AHD, from which data on drainage, hydrography, the delimitation of the study area, as well as information on the basin's geometry such as its area, main channel length, and other data were obtained. The model has a resolution of approximately 11 km for the length of the river segments, and 92 square kilometers for the areas under analysis (Fekadu *et al.* 2017).

Sixteen precipitation stations, five temperature and four flow stations were selected with a 23-year historical record (01/01/1989–1/30/2013) with a daily temporality, with which a homogeneity analysis was performed by using the double-mass curve methodology, which found that the correlation factor, R^2, varied by 0.9931 and 0.9995. To account for this, no adjustment factor was applied and the estimation of missing data was performed using the arithmetic mean method.

Calibration and validation of the Hydro-BID model

The model was calibrated by sub-basins, in order to identify optimal parameter values, by which the simulated data are correctly adjusted to the observed series. This process was performed manually by trial and error, from the upstream

to the downstream basin, relating the parameters obtained for the basin immediately preceding it, to the mouth of the main riverbed. To carry out this process, the period between 01/01/1993 and 02/28/2005 was selected, since the data in this time interval were more complete for the three climatological variables, which reduced error throughout the calibration process.

Figure 2 shows the relationship between the flow stations and the Gualí Sub-basins, which were used to perform the calibrations of the four sections. The first calibration was with Sub-basin COMID 301270200, followed by the sub-basins immediately upstream that correspond to the area marked with the number 1 on the map, which were calibrated with Station 23017040. A second calibration was performed on Sub-basin COMID 301235900, corresponding to the area marked with the number 2 on the map, with Station 23017060; the third with COMID 301224300, corresponding to the area marked with the number 3 on the map, with Station 23017080; and the final calibration was of COMID 301237900 with Station 23017030, identified with the number 4 on the map.

The parameters used in the calibration are the curve number, which is used to characterize the type of soil of the basin and its hydrology, which ranges between 0 and 1; and the available water capacity (AWC) that represents the quantity of water that can be stored in the soil to be used by plants, affecting the infiltration towards groundwater. Moreover, the recession coefficient (R) is used, which calculates how groundwater found close to the surface contributes to river flows or surface streams after a rainfall event. This is followed by losses from the system, or seepage, which represents the exchange between subsurface water with deeper bodies of water, in which the quantity of water attributed to this parameter is considered an output of the model. There are also the grow season and dormant season ET evapotranspiration factors, which are used for when there are, or are not, crops in the basin. These last two parameters are given a value of 1 when they are not taken into account, which was the case in this study, as a result of the diversity of crops that vary in type and seasonality in this zone (Fekadu *et al.* 2014; RTI International 2017).

To evaluate the calibration, Hydro-BID integrates a series of metrics which include: the overall error volume,
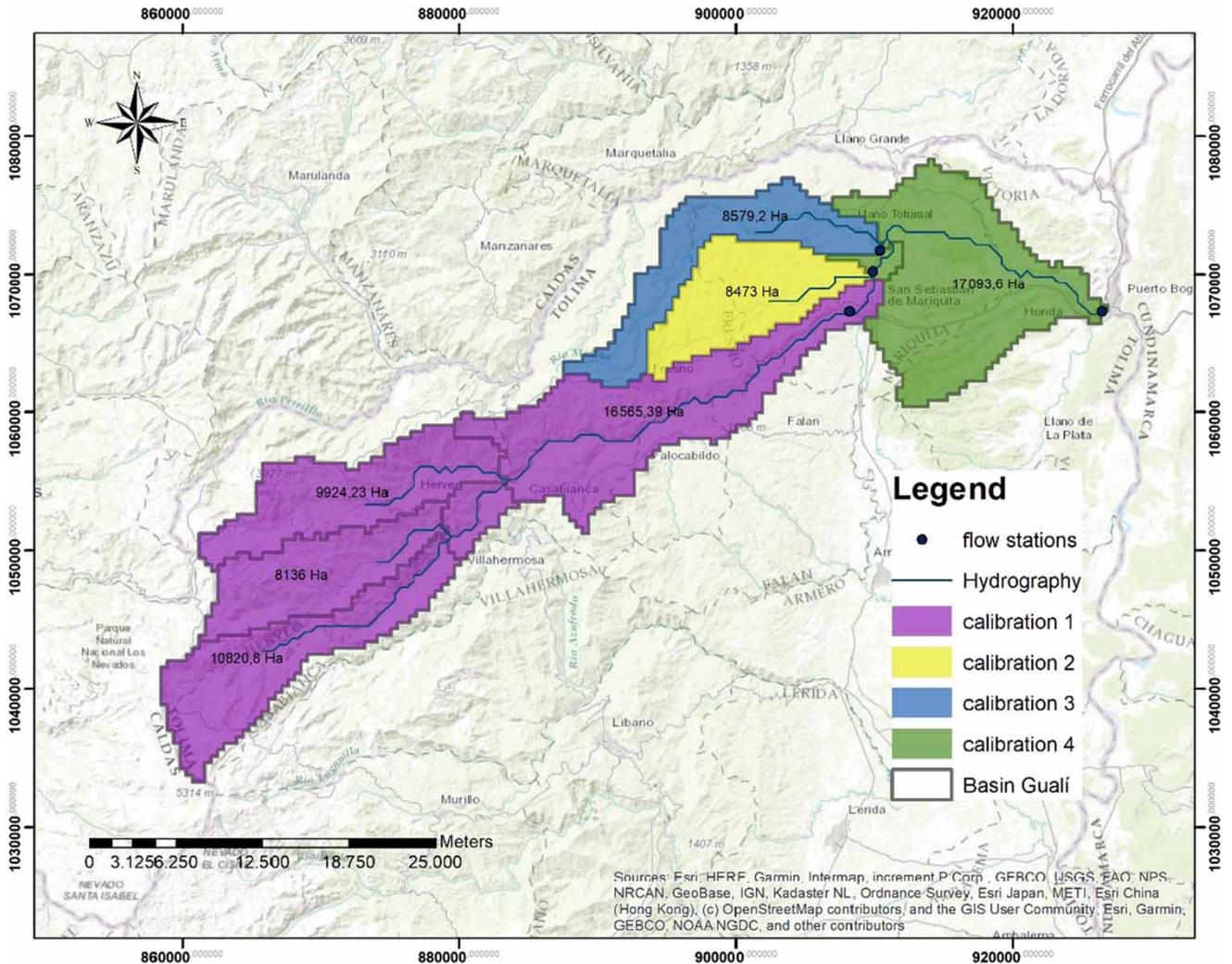
Figure 2 | Calibration by sub-basin (*source*: authors).

for which the closer the result is to zero, the better the model's performance; correlation metrics (R); the modified correlation; and the Nash-Sutcliffe efficiency, which range between 0 and 1, in which the closer the result is to 1, the greater the reliability of the simulation (Dawson *et al.* 2007).

General circulation model (GCM) and downscaling

In performing an analysis of the impacts of climate change on basins, having seasonal and spatial information at a smaller scale than those given by general circulation models (GCM) is indispensable. To this end, carrying out a downscaling process on general series is necessary, based on the assumption that large-scale climate conditions have a strong influence on climate at a local level (Maraun *et al.* 2010). In this study, a statistical downscaling method based on the chaos theory was employed, also referred to as downscaling. This method was chosen because existing scale reduction techniques, even though they have presented successful outcomes, are based on the assumption that climate systems are linear, while other studies have demonstrated their non-linear and chaotic behavior (Mihailović *et al.* 2017).

Two climate change scenarios, RCP 2.6 and RCP 8.5 which represent opposite projections, were selected. RCP 2.6 establishes a strict mitigation scenario where population

growth decreases, the use of energy and fossil fuels is limited, and a strict climate change policy is created. This is designed so that, under these conditions, there is a greater probability of maintaining global warming at less than 2 °C above pre-industrial temperatures. On the other hand, RCP 8.5 poses a scenario with exponential population and energy consumption growth, with minimal mitigation policies, while also projecting very high greenhouse gas emissions (IDEAM UNDP MADS Chancellery & Science & Technology Observatory 2016).

A GCM was preselected to obtain the climate variable projections. A search was conducted for studies that previously evaluated GCMs in Colombia, and one was found from the United States Agency for International Development (USAID), titled 'Methodology for including climate variability and climate change scenarios in the WEAP model of the Magdalena macro basin and simulation results,' in which the performance of the models for different sections of the Magdalena River Basin was evaluated (Angarita 2014).

Due to the fact that the Gualí River Basin is located within the project study area, the three most suitable GCMs were preselected by taking into account the relative bias for the Magdalena-Cauca Basin. The models that have the least amount of bias for this zone were MPI-ESM-MR, CCSM4, and NORESM1-M. Subsequently, the square root metric of the mean square error (RMSE) between the historical GCM, and precipitation and temperature station records for each of the models was calculated. Based on these results, the MPI-ESM-MR model was selected, which generated an RSME of 5.44 for precipitation and 6.91 for temperature.

The downscaling method implemented considers deterministic chaos concepts and the non-linear dynamic in climatological series. This method takes into consideration two main components: the evaluation of the presence of chaos, and the synchronization of global data series with data from weather stations, which for input data, requires precipitation and temperature series from weather stations, and a catalog that has the stations' coordinates and the GCM historical model, in addition to selected RCP data. For outputs, it generates reduced series and an error that evaluates the performance of the model; RMSE in this case, for its validation (Duarte 2017).

WEAP water allocation module

As a water assessment and planning system, WEAP is a robust computational tool that evaluates and carries out IWRM. Its ultimate aim is to represent current and future water conditions in a determined study area, in order to calculate water supply and demand. This model was developed by the Stockholm Environment Institute, with support from the Engineering Hydrologic Center of the US Army. It can be applied both in agricultural and drinking water storage systems (Global Change Centre Catholic University of Chile & Stockholm Environment Institute 2009).

This program implements a continuous rain–runoff hydrological model that employs a simple algorithm, configured based upon a study area composed of a set of contiguous sub-basins that cover the entire study area and integrate the different coverages and land uses within them. Furthermore, this model has two water receptors or buckets that distribute superficial runoff, infiltration, evaporation, baseflows, and percolation based on a set of climate data that integrates precipitation, temperature, relative humidity, and wind speed variables (Global Change Centre Catholic University of Chile & Stockholm Environment Institute 2009).

The WEAP modeling tool consists of several modules, including the hydrological module that contains a rain–runoff model which provides five different methods for calibration. Another module, which was used in this work, is the water allocation. The latter is a support system for decision-making to facilitate the management of water resources, which is based on optimizing the satisfaction of the demands of different users.

In this investigation, the first module mentioned (hydrological) was not used, because the objective was to test the versatility of being able to integrate the Hydro-BID hydrological model and the WEAP water allocation module, which was verified in the results.

The water allocation module or demand analysis establishes a multisectoral analysis that includes municipal, industrial, agricultural, and ecological flow demands. It also has a demand injection methodology, through which it is possible to evaluate future consumption scenarios. It also allows the allocation of water resources in the different sectors according to the assigned supply priorities, obtaining

as a result the unsatisfied flow rate or the percentage of unsecured demand.

The main advantage of this software is that it creates analysis scenarios based on border conditions such as political and technological constraints, priorities, and costs, in addition to other factors that condition supply and demand in an area. These scenarios are integrated into the model through key assumptions that enable variables to be created that can be independent from one scenario to another, which benefits the model perfection process (USAID 2016). Moreover, WEAP also provides other advantages associated with its versatility to integrate different water resource management components for decision-making, such as a sectoral analysis of water demand, monitoring, and quality, in addition to being able to set water distribution and consumption priorities, as well as ecosystem requirements and cost–benefit projections for future scenarios (Sithiengtham 2019).

This water modeling tool has also been successfully used in other case studies around the world, which assessed the impacts of climate change on supply availability, variations in the water demand for different economic sectors, as well as figures on unmet water demand and their correlation with population dynamics (Berredjem & Hani 2017; Khalil *et al.* 2018; Javadinejad *et al.* 2019).

Although the analysis of the quality and availability of water are of importance to carry out a correct management of the water resource, for the purpose of this research the evaluation of the availability of the resource was taken as a priority, so the quality module of water available within WEAP was not addressed. It should be clarified that not implementing this component does not affect the results on availability and unmet demand for water or for the development of the proposed scenarios. It is recommended to apply it in future research to deepen and/or complement studies carried out in the area.

Integration of WEAP and Hydro-BID models

The integration of WEAP and Hydro-BID was a three-step process. In the first, current demand was calculated and a projection was made for future demand. The second entailed the topology design in WEAP, and in the final step, flows produced by Hydro-BID were integrated.

To calculate the current demand of the basin, it was necessary to refer to records from the Regional Autonomous Corporation, Cortolima, in order to obtain the values corresponding to the concessions assigned within the study area that are classified as domestic, agriculture, or industrial. Based on these data and complemented with information found in the River Basin Management Plan (also known by its acronym in Spanish, POMCA) of the Gualí River, the demand points along the study area were classified, depending on the current from which the catchment is performed; thus obtaining the classifications of domestic aqueduct, agricultural, and industrial demand points for the Medina, Sucio, Gualí, Cajones, and Aguacatal rivers, the main tributaries of the basin.

Furthermore, it was necessary to know the extent of the population that is supplied by each aqueduct, both at the municipal and village levels, in order to calculate the rate of water use corresponding to the domestic demand points. This was calculated from the sum of the populations that are linked to each aqueduct, resulting in water consumption per year in units of m^3/inhabitant/year. With respect to calculating the water use rate for the agricultural classification, it was necessary to obtain the number of hectares of crops present in each sub-basin to thus be able to calculate the annual water consumption in units of m^3/hectare/year. Lastly, to classify the industrial demand, calculations were made with the registered flow in the concessions mentioned above in units of m^3/s.

Figure 3 shows the scheme implemented in the WEAP tool, in which the different currents in the basin were included, the demand points according to the classification mentioned above, which are presented in Table 1. The flow stations located in the area, which are attributed to historical data in m^3/s recorded between 1989 and 2012 and finally sewage collection and discharge, taking into account a value of 85% return. Additionally, the acronym Arg represents the agricultural demand points, Ac represents the aqueducts of the municipalities, Ind represents the industrial demand points, and finally, Rio refers to the main currents of the basin.

It was also necessary to include the loss percentage that occurred along the water pipelines to the demand points. These data were obtained from Cortolima and the aqueducts in the area for the domestic points, as well as from a bibliographic review carried out specifically for Title A of RAS
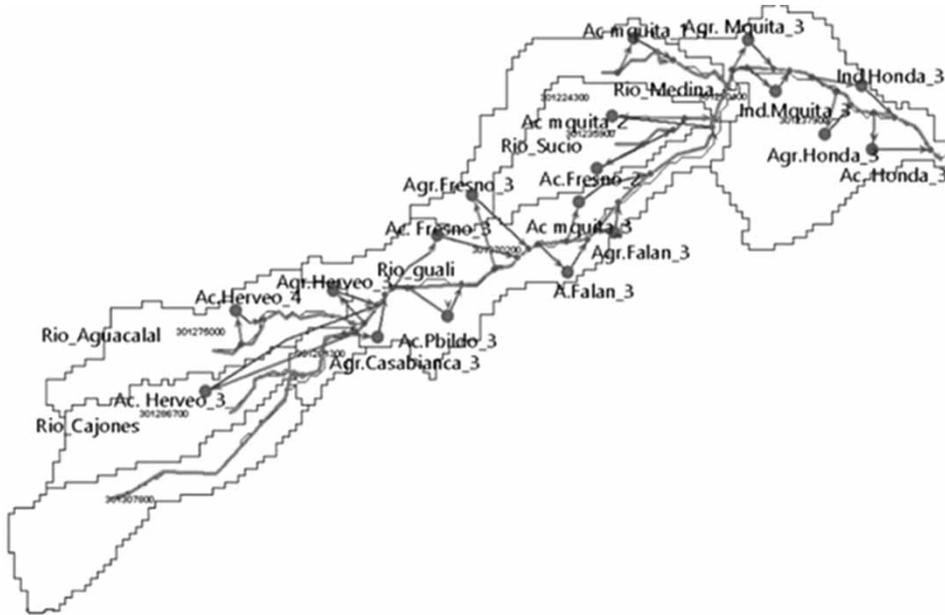
Figure 3 | Demand scheme of the Gualí River Basin (*source*: authors).

Table 1 | Demand points of the Gualí River Basin (*source:* authors)

Municipality	Type of use	Current	Concession (L/s)
Fresno	Agriculture	Gualí	14.47
		Aguacatal	25
	Domestic	Sucio	2.7
		Gualí	190.29
Falán	Agriculture	Gualí	0.35
	Domestic	Gualí	0.625
Honda	Industrial	Gualí	7.95
	Domestic	Gualí	0.846
	Agriculture	Gualí	0.115
Herveo	Agriculture	Gualí	3.96
	Domestic	Gualí	244.57
	Domestic	Aguacatal	40
Casabianca	Agriculture	Gualí	0.55
Mariquita	Domestic	Gualí	67.79
		Medina	21.32
		Sucio	183.31
	Agriculture	Gualí	203.24
		Medina	50.7
		Sucio	2,006
	Industrial	Gualí	8.45
Palocabildo	Domestic	Gualí	19.92
Total concession			3,092.15

2000 (Technical Regulation of the Drinking Water and Basic Sanitation Sector) and other similar case studies, such as one carried out in the Rio Grande Basin in Argentina (Wyatt *et al.* 2016). Based on this analysis, the initial losses were set at 35% for domestic demand points, 30% for industrial demand points, and 55% for agricultural points.

To determine the future demand, a forecasting exercise was performed for the consumption mentioned, which was based on historical gross domestic product (GDP) records obtained from data recorded by the National Administrative Department of Statistics (DANE) and the Bank of the Republic from 2000 to 2016, corresponding to each of the three sectors (agriculture, industry, and services). Based on these data, average variations of 2.34%, 2.88%, and 2.37% were found, respectively. These values were then applied to the model for the scenarios of the time period between 2012 and 2100, producing annual time series of consumption and population projections. It was necessary to recalculate the water use rate for each demand point. The last input data that were included in this model were the flow series obtained from the Hydro-BID model for the current scenario, and for RCP 2.6 and RCP 8.5 scenarios for each sub-basin in the study area.

Once the analysis and projection of water demand in the basin was completed, the monthly flows obtained from Hydro-BID were used as input data in the WEAP software

to analyze unmet demand in each of the climate change scenarios (Figure 4), over an analysis period of 2012–2100, on a monthly basis. Lastly, adaptation measures were proposed to reduce the unmet demand found in each sub-basin and for each scenario analyzed.

In the modeling carried out in the WEAP software, it was not necessary to perform any calibration process given that the program only used the analysis module and demand projections. In this sense, the flows obtained from the Hydro-BID program were integrated into the WEAP topology as the base flows for each sub-basin and as the primary information to obtain the results in each of the proposed scenarios.

Indicator approach for unmet demand and potential reduction measures

The indicator used to estimate the potential effect of climate change on water supply and its repercussions on demand is the unmet demand, which represents the total water deficit in m^3/s. In order to decrease the identified levels of unmet demand, three management scenarios were considered that consist of decreasing the level of loss throughout the distribution system, from the catchment points to the demand points. Measure A corresponds to a 30% loss in the distribution system for the domestic point, 45% for the agricultural point, and 20% for the industrial point. Similarly, Measure B represents system losses of 20%, 35%, and 10%, while Measure C establishes system losses of 10%, 20%, and 5%, respectively.

The proposed measures for the reduction of losses in distribution systems are posed hypothetically, taking into account the technical and economic capacity presented in the aqueducts and distribution systems of the country, and taking into account that the points of demand are part of municipalities in rural areas of Colombia (Monsalve Monroy & Uribe Gomez 2011).

RESULTS AND DISCUSSION

General circulation model (GCM) and downscaling

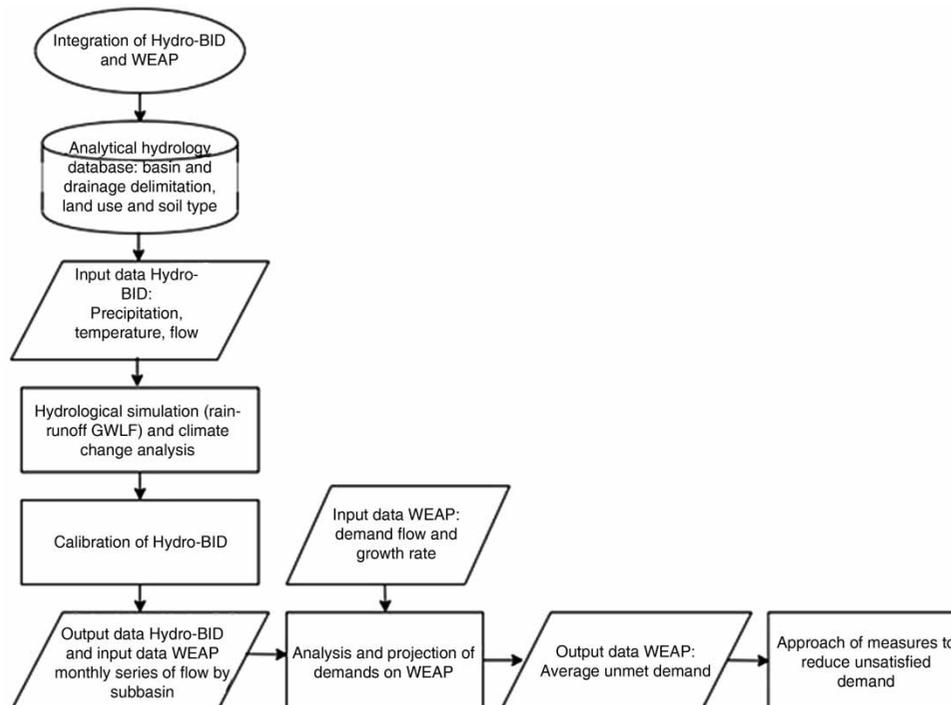The performance of the downscaling exercise was evaluated with the RSME metric to estimate the correlation between

**Figure 4** | WEAP and Hydro-BID integration flowchart (*source*: authors).

GCM data before and after the downscaling process, with respect to historical series from the climatological stations.

Table 2 │ Comparison of RSME before and after downscaling (*source*: authors)

RMSE

GMC and historical				GCM after downscaling and historical			
Precipitation		Temperature		Precipitation		Temperature	
RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
7.79	7.97	8.36	8.69	1.526	1.525	3.0	2.94

As shown in Table 2, the correlation between the data is closer to the optimal value, which is zero for a fully adjusted model, after carrying out the downscaling process, verifying that the downscaling technique minimizes error levels that are generated by applying GCM (Fekadu *et al.* 2014).

Figure 5 illustrates that there were differences between the average precipitation and temperature values between the stations in comparison with the historical data. Likewise, there is no constant upward or downward trend as some stations had higher magnitudes for RCP 2.6 in comparison to RCP 8.5, with the opposite true at other stations.
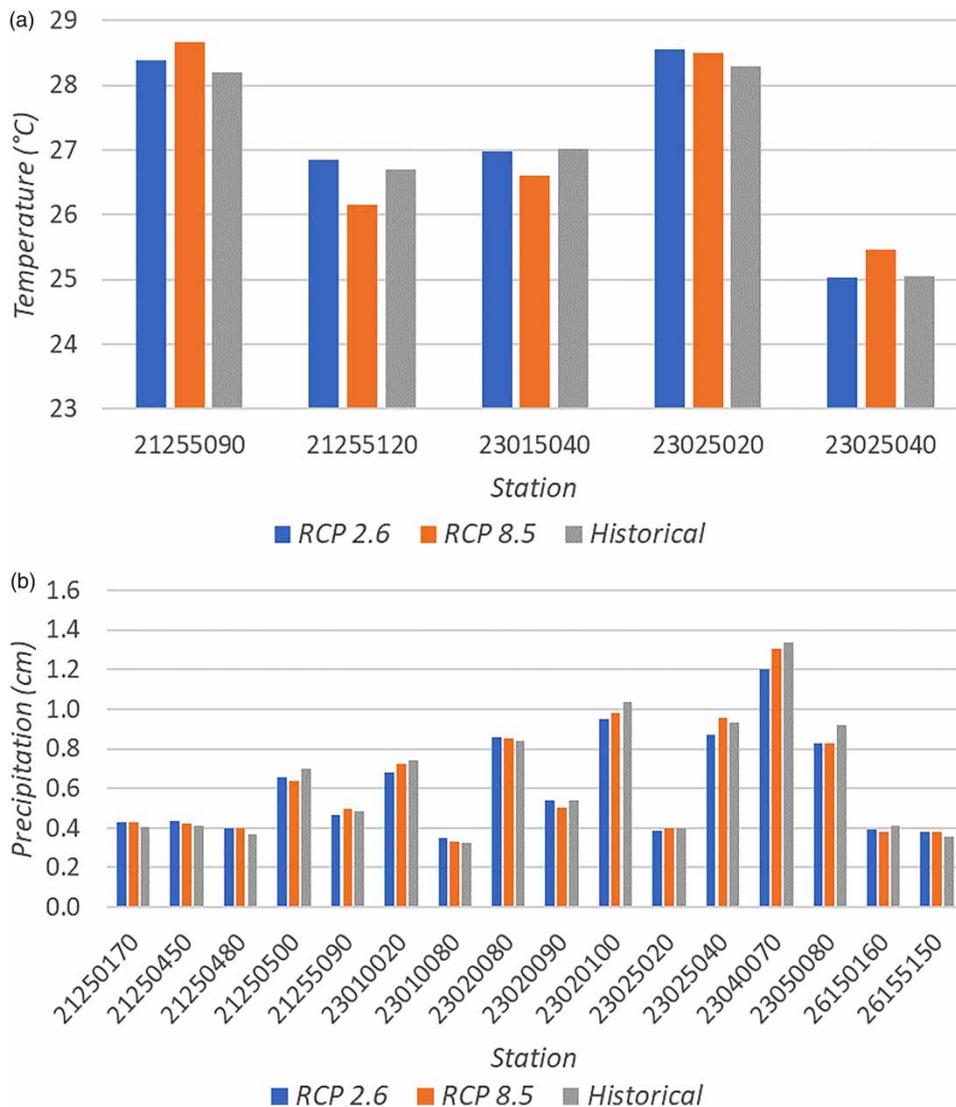
Figure 5 │ Comparison of (a) temperature and (b) precipitation averages at each station (*source*: authors).

Figure 5 shows that there is no general tendency of constant increase or decrease since in some stations RCP 2.6 has greater magnitudes compared to RCP 8.5 and in other stations there is an opposite behavior. This can be attributed to various factors such as the marked difference in altitude in the basin, the topography among others.

A percentage increase or decrease in precipitation and temperature was calculated in each season in two periods, before the middle of the century (half of century (HOC)) and at the end of the century (end of century (EOC)). It was obtained that on average for the RCP 2.6 scenario in the first half of the century, an increase of 2.01% and 0.06% is expected for precipitation and temperature variables; and for the second half of the century, a possible increase of 0.95% and 0.1%, respectively, will be generated compared to the current conditions. Likewise, the RCP 8.5 scenario showed an average decrease of 0.68% for precipitation in the first half of the century, and in the second half an increase of 1.1% was obtained for the same variable; in addition, for the temperature, an increase of 0.06% and a decrease of 0.08% are expected in the first and second half of the century, respectively.

Calibration and validation of the Hydro-BID model

As a result of the calibration, the final parameter values were obtained for the output sub-basin, specifically 1.75 for the curve number, 0.6 for the water content in the soil, 0.02 for the recession coefficient, 0.00005 for the seepage, and 1 for the grow season and dormant season ET factor parameters. As a result of applying the parameters obtained, monthly performance metrics were calculated as follows: 4.51 for the general error volume, 0.65 for the R correlation, 0.45 for the modified correlation, and 0.42 for the Nash–Sutcliffe efficiency.

From these results it is evident that the calibration process was satisfactory, comparing the performance metrics before and after said process, as evidenced in Table 3, where the calibration process is carried out, and various metrics approximate the optimal ranges.

While the value of the Nash–Sutcliffe index performance metric is not ideal, it is acceptable. This behavior is the result of the study area being considered a pulse basin, where there are sudden increases in runoff volumes

Table 3 │ Comparison of performance metrics before and after calibration process (*source*: authors)

Metric	Before calibration	After calibration	Optimal value
Overall volume error	−17.73	4.51	0
Correlation (R)	0.60	0.65	1
Modified correlation	0.33	0.45	1
Nash–Sutcliffe	0.31	0.42	Good 0.4–0.6
			Very good 0.61–0.8
			Excellent > 0.81

caused by thawing from the Nevado del Ruiz volcano (upstream). As this behavior was not considered in the calibration process, the adjustment of the results in the upper part of the basin only represents the atmospheric component, not additional inputs. In considering that the calibration was performed sequentially, this behavior caused the overall results from the same process to be acceptable, despite having sufficient data to correctly develop the model.

Furthermore, it should be noted that Hydro-BID is a planning software that is designed to represent average, not maximum, conditions. As such, the model does not represent flow peaks. This is in addition to the fact that it is a pulse basin, which implies a greater effect on calibration performance. Lastly, Figures 6 and 7 display the duration curves obtained after calibration and validation, clearly showing that flow volumes are preserved, validating the model for the purposes of this study.

With respect to the sensitivity of the Hydro-BID calibration parameters, it was found that the most sensitive parameter is the curve number followed by the AWC, given that these coincide with the runoff quantity that is generated throughout the basin. This is mainly due to the curve number representing the waterproofing level that is present in the study area, due to natural or anthropogenic conditions, thus favoring, or not, infiltration processes from precipitation received on the soil. Furthermore, the AWC, by representing the soil's water content, determines the volume of water that is capable of being absorbed before the soil reaches its saturation point, in which from that
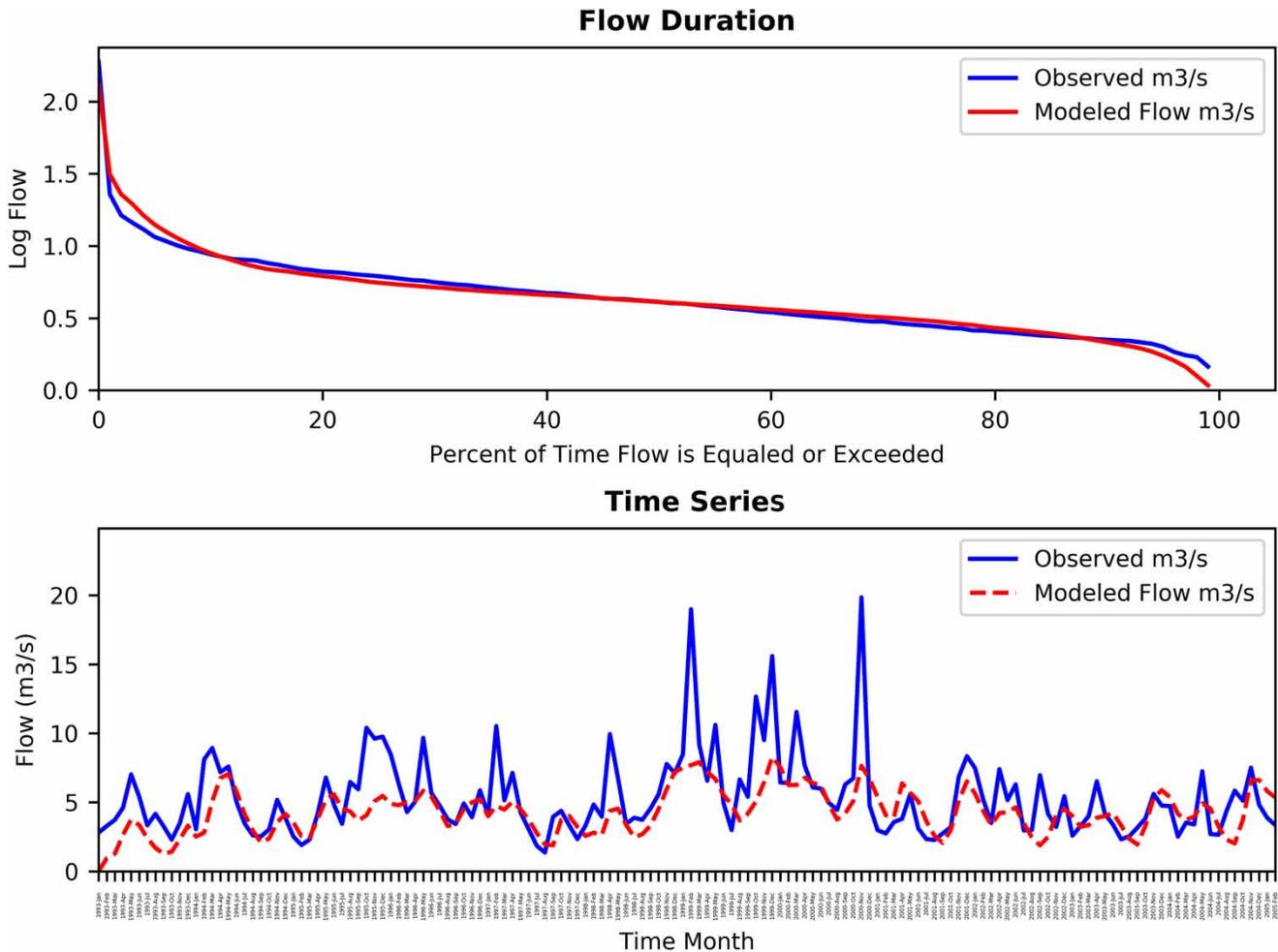
Figure 6 | Calibration duration curve and time series (observed vs simulated) (*source*: authors).

moment on, all water received in the area will be converted into flow.

The variations obtained in the modeling found that for the entire simulation period, there are possible flow reductions for the RCP 2.6 and RCP 8.5 scenarios when compared to historical records. These decreases were obtained by comparing the median of the projected changes in the flow rates for the two scenarios studied, with respect to current conditions for the three periods analyzed. In the period covering 2013–2040, it was found that probable flow decreases of 9.56% will occur for RCP 2.6 and 2.18% for RCP 8.5. Moreover, for the period covering 2041–2070, the decrease is 5.8% and 4.77%, respectively; and for the period between 2071 and 2100, estimated decreases of 6.39% and 6.86%, respectively, were found. Lastly, as a

result of the simulation exercise, it was determined that the average water supply between 2011 and 2100 is approximately 10.09 m^3/s for the RCP 2.6 scenario and 10.16 m^3/s for the RCP 8.5 scenario.

Likewise, the flow's behavior is directly proportional to that of precipitation, in which extreme rainfall events represent maximum flow peaks as a response throughout the Gualí River Basin.

Integrating the WEAP and Hydro-BID hydrological modeling tools

The integration of the results obtained by Hydro-BID with the WEAP software demonstrated in the first instance that for the reference period (1989–2012) there was no unmet

Flow Duration
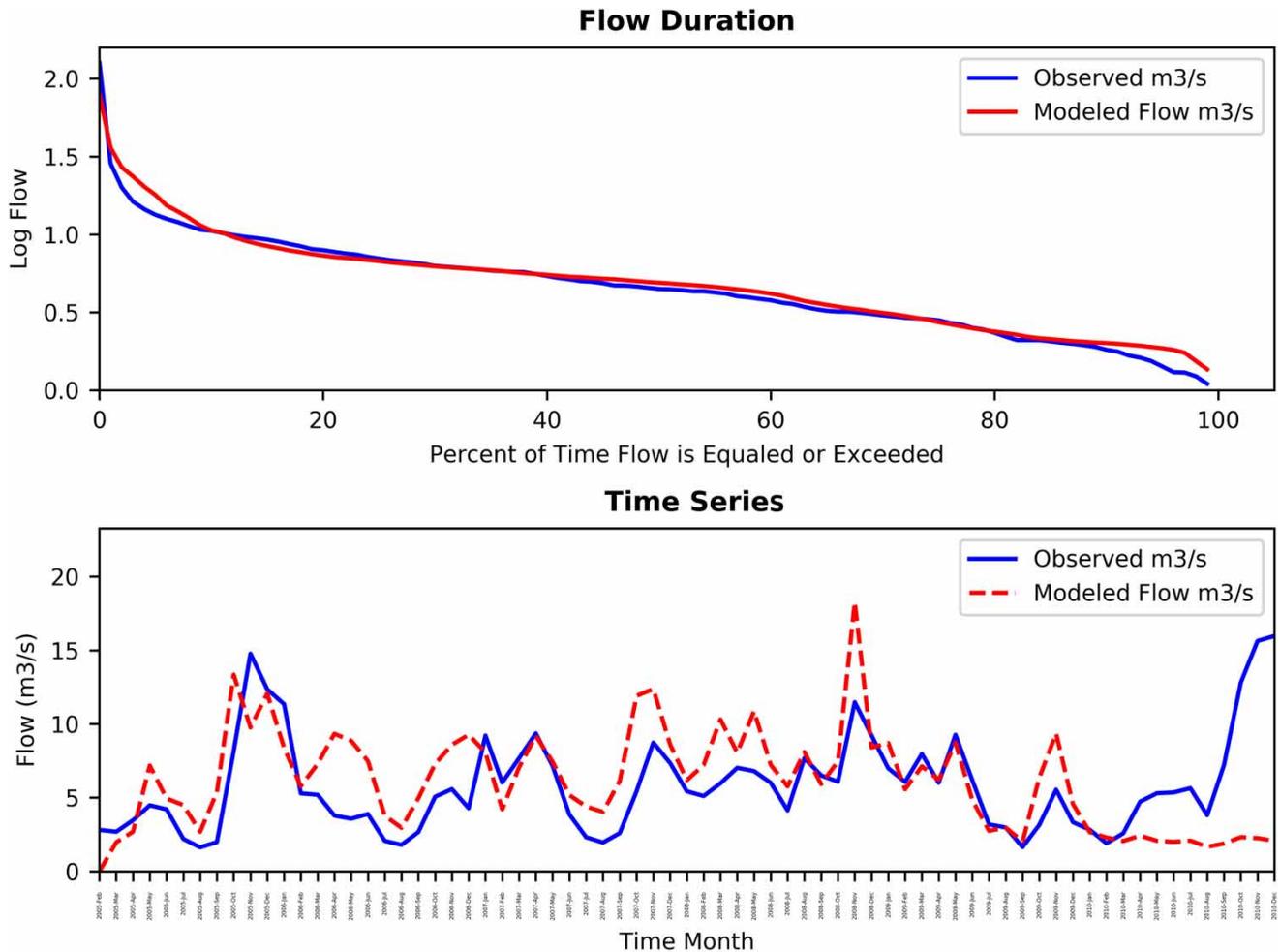
Time Series

Figure 7 │ Validation duration curve and time series (observed vs simulated) (*source*: authors).

demand, that is, the basin was capable of supplying the water requirement during that time period, which is consistent with the results from the analysis carried out by Cortolima in the POMCA for the Gualí River Basin. The average demand for this period was 3.36 m^3/s and the agricultural node of Mariquita located on the Gualí River had the highest average demand of 2.26 m^3/s.

For the RCP 2.6 and RCP 8.5 scenarios from 2012 to 2100, an average unmet demand of 0.041 m^3/s and 0.038 m^3/s were calculated, respectively. The most favorable unmet demand scenario is RCP 8.5. August is the most critical month as it has the highest unmet demand, while May and November have the lowest unmet demands. Furthermore, it was found that the demand points at greatest risk are the Mariquita and Fresno aqueducts, given that between

2071 and 2100, there is a projected average unmet demand of 0.00024 m^3/s for the climate conditions of RCP 2.6, and 0.00023 m^3/s under RCP 8.5 for the Fresno aqueduct; and 0.0410 m^3/s for RCP 2.6, and 0.0384 m^3/s for RCP 8.5 for the Mariquita aqueduct. Therefore, it is necessary that the environmental authorities of the basin prioritize these municipalities in order to prevent a possible emergency due to future water resource shortages.

With respect to modeling the measures proposed to reduce unmet demand, in focusing on reducing loss in the distribution system as the key component, it was found that the most favorable measure was Option C, given that it reduced unmet demand the most. It must be clarified that after reducing losses in the distribution system, there are still average unmet demands of 0.0055 m^3/s for the

RCP 2.6 scenario and 0.0037 m^3/s for the RCP 8.5 scenario, the results of which are shown in Table 4. Similarly, it is evident that the Mariquita and Fresno aqueducts are still the most affected and therefore present a greater risk of impacting the development of economic and cultural activities in the area. Lastly, an inversely proportional behavior was identified between the loss reduction percentage and the flow amount that is not completely supplied in the basin, in which the greater the reduction and improvement in the distribution system from the catchment point to the places of consumption, the lower the percentage of unmet demand.

Finally, it was found that by only reducing losses in the system as a measure, unmet demand can be reduced by up to 87.8% in the case of RCP 2.6 C, and up to 90.26% in the case of RCP 8.5 C. This is assuming that the concessions granted by the corporation will remain constant in the basin and that no additional catchment points will be created. Furthermore, carrying out field visits is considered pertinent in order to verify the information provided by Cortolima and identify possible catchment points not registered with the authority.

CONCLUSIONS

The downscaling process more accurately represents the real conditions of the study area, increasing the correlation between the observed data and the historical data from the GCM. This is reflected in the results from the RSME metric, which moved from an average of 7.79 cm before downscaling to 1.52 cm afterwards for RCP 2.6, and from 7.97 cm to 1.25 cm in RCP 8.5 for the precipitation variable.

Table 4 | Average unmet demand with the loss percentages modified (*source*: authors)

Period	Reduction measure	Average unmet demand (m³/s)
Current	None	0
RCP 2.6	None	0.041
	A	0.027
	B	0.011
	C	0.0055
RCP 8.5	None	0.038
	A	0.025
	B	0.0097
	C	0.0037

In the same manner, the temperature metric moved from 8.36 °C before downscaling to 3 °C in RCP 2.6, and from 8.69 °C to 2.94 °C in RCP 8.5.

In general, accurately depicting future climatic conditions implies a high level of complexity, especially for the precipitation variable, because when simulations are based on GCM, uncertainty increases in projecting flows obtained from the modeling process. Therefore, the results should be taken as a guide for potential changes that may occur in the basin from now until 2100, rather than a true fact.

In the Gualí River Basin, for the period covering 2011–2100, under the RCP 2.6 and RCP 8.5 scenarios, available flow decreases between 5.8% and 9.56% are expected for RCP 2.6, and 2.18% and 6.86% for RCP 8.5, in which 2013–2040 will be the period with the greatest reduction in flow.

With respect to the conditions of the reference period between 1989 and 2013, there was no unmet demand for any of the established demand points, which is consistent with the studies carried out by the POMCA for the Gualí River Basin. However, the scenarios simulated have a critical period between 2071 and 2100, in which there is unmet demand throughout the basin.

The simulation results demonstrate that there is unmet demand in the Fresno and Mariquita aqueduct nodes, with an average of 0.0413 m^3/s and 0.0386 m^3/s, respectively.

Implementing measures to reduce loss throughout the distribution system can decrease unmet demand by up to 87.8% and 90.26% for the RCP 2.6 and RCP 8.5 scenarios, respectively. However, it is not possible to cover the demand of every point in their totality by only applying this measure. Furthermore, of the proposed mitigation strategies, Option C is the most effective as it has the highest loss percentage reduction at every demand point.

To reduce losses, it is recommended that supply system operators optimize the use of micro-measurement, actively control system leaks, and overhaul and/or replace networks.

Of the climate change scenarios considered, RCP 8.5 has the highest flow when compared with RCP 2.6, resulting in a smaller unmet demand throughout the analysis period for the former.

Lastly, based on the Hydro-BID results, it was found that there will be a possible loss of available flow in the

Gualí River Basin. Conversely, it was found that demand will increase as a result of population growth and increases in agricultural and industrial activities, which will result in the demand in the basin not being 100% covered.

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