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Articles

Assessment of the hydrological response to precipitation and temperature changes in the Peruvian Altiplano

Evaluación de la respuesta hidrológica a cambios de precipitación y temperatura en el altiplano peruano

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Abstract

Mountain basins are considered the hydrologic systems most affected by climate change, estimating significant impacts on water resources and water demands. This study evaluates the hydrological response of a Peruvian Altiplano basin to changes in precipitation and temperature patterns. Knowing in advance the effect of climate change on water supply takes on relevant importance for decision-making in short, medium and long-term planning of water use and management of water resources. From the implementation of the Integrated Model of Climate Change and Water Resources (HydroBID), 30 climate scenarios were evaluated that considered changes in precipitation between -20 and +20 %, temperature between 0 and 6 °C, and combinations of these were formulated according to the projections for the study area available in the literature. The results showed that for every 10 % increase in precipitation there was an average increase of 23.4 % in flow; while for every 10 % decrease in precipitation, an average reduction in flow of 16 % was generated.

Likewise, it was evidenced that for every 1 °C increase in temperature, an average 5 % reduction in flow was generated. It was determined that the variation of the precipitation rates, temperature and their interaction between them generate changes in the flows, showing effects on the temporal and spatial variation of the basin.

Keywords: Hydrological response, climate change, climate patterns, hydrological modeling, HydroBID.

Resumen

Las cuencas de montaña son consideradas como los sistemas hidrológicos de mayor afectación por el cambio climático, estimándose impactos significativos en los recursos hídricos y las demandas de agua. Este estudio evalúa la respuesta hidrológica de una cuenca del altiplano peruano frente a cambios de los patrones de precipitación y temperatura. El conocer con anticipación el efecto del cambio climático sobre la oferta hídrica toma relevante importancia para la toma de decisiones en la planificación a corto, mediano y largo plazos del uso del agua y la gestión de los recursos hídricos. A partir de la implementación del Modelo Integrado de Cambio Climático y Recursos Hídricos (HydroBID) se evaluaron 30 escenarios climáticos que consideraron cambios en la precipitación entre -20 y +20 %, temperatura entre 0 y 6 °C, y combinaciones de éstos formulados según las proyecciones para el área de estudio disponibles en la literatura. Los resultados mostraron que por cada 10 % de incremento de la precipitación se produjo un aumento promedio de 23.4 % en el caudal; mientras que por cada 10 % de disminución de la precipitación se generó una reducción promedio del caudal de 16 %. Asimismo, se evidenció que por cada 1 °C de subida de la temperatura se generó en promedio un 5 % de reducción del caudal. Se determinó que la variación de las tasas de precipitación, temperatura y su interacción entre ellas generarían cambios en los caudales futuros, mostrando efectos en la variación temporal y espacial de la cuenca.

Palabras clave: respuesta hidrológica, cambio climático, patrones climáticos, modelización hidrológica, HydroBID.

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Introduction

Climate change has become a decisive topic and one of the greatest challenges to be faced, due to the vulnerability it generates in natural ecosystems and with greater incidence in mountain areas. They are recognized as the especially sensitive physical environments, where climate change could have considerable repercussions on water availability (Abdulla & Al-Shurafat, 2020; Beniston, 2012; Guo, Ma, Wang, & Lin, 2021; Mengistu, Bewket, Dosio, & Panitz, 2021; Budhathoki, Babel, Shrestha, Meon, & Kamalamma, 2021; Valdivia, Thibeault, Gilles, García, & Seth, 2013; Lozano-Povis, Alvarez-Montalván, & Moggiano, 2021). The uncertainty of the possible impacts of climate change —analyzed from global circulation models (MCG)— can be broad and its evaluation depends mainly on the temporal resolution and representativeness of the climate scenarios analyzed (Ndhlovu & Woyessa, 2020).

Numerous studies have shown the impacts of future climate change on water resources and their use, due to the alteration it generates in the processes of the hydrological cycle (Modi, Fuka, & Easton, 2021), in agriculture (Masia *et al*., 2021), population supply (Olabanji, Ndarana, Davis, & Archer, 2020), food security (Omar, Moussa, & Hinkelmann, 2021), hydroelectric power generation (Hidalgo *et al*., 2020), as well as socioeconomic indicators (Aghapour-Sabbaghi, Nazari, Araghinejad, & Soufizadeh, 2020), among others (Funes *et al*., 2021).

Sanabria, Marengo and Valverde (2009) analyzed the impact of change in the department of Puno, located in the extreme southeast of Peru, from regional climate models (HadRM3 and ETA CSS), defining probable climate scenarios for the period 2010-2100, in an extreme scenario A2 determined increases in precipitation by up to 2 mm / day in the rainy season and in a moderate scenario B2 conditions similar to the current pattern. They projected for scenarios A2 and B2 temperature increases between 2 °C and 4 °C, respectively, and at the northern end of Lake Titicaca up to 6 °C, constituting a first approximation of future climate change in the Peruvian Altiplano.

Llacza *et al*. (2021) projected climate scenarios to 2050 in Peru, from which it is extracted that for the Huancané River basin (CRH) there would be increases in precipitation up to 15 % in relation to the base period (1981-2005). In the summer and spring seasons, increases in precipitation similar to the annual period were observed, while for the winter season reductions by up to -15 %, and in spring increases greater than 15 %. They also projected average temperature increases between +2.4 and +2.8 °C. At the seasonal level, the largest increases were observed in winter, with values between +3.2 to 3.6 °C. The thermal range to 2050 showed significant changes from +0.2 to 0.4 °C. Finally, they determined that the Puno region is placed among the regions with the greatest changes in precipitation and temperature patterns.

Zubieta, Molina-Carpio, Laqui, Sulca and Ilbay (2021) found that for the period 2034-2064 the average temperature will increase in the range of 0.5 to 3.5 °C in relation to the base period (1984-2014), with greater incidence in the southern end of the Water System called Sistema Hídrico Titicaca-Desaguadero-Poopó-Salar de Coipasa (TDPS). They also observed increases between 3 and 6 % of the total annual future precipitation in the northern and central end of the TDPS, while in the extreme south a reduction in precipitation up to 3 % was forecast.

GIRH-TDPS (2021) found that the spatial distribution of precipitation changes focused to 2050 on an annual scale are between -15 to +15 % in much of the TDPS. For the CRH, precipitation reductions up to -15 % were observed on an annual scale and similar behavior for the wet period. Likewise, increases in the maximum and minimum temperature by up to 3.5 and 2.5 °C, respectively, were observed, with similar behaviors for the rainy period and intensifications of the increase for the dry period.

The possible impact of climate change on water resources and hydrological processes in basins has been studied extensively through the use of properly calibrated and validated hydrological models, as they allow to obtain quantitative for possible future conditions (Sha *et al*., 2014; Didovets *et al*., 2020; Her *et al*., 2019; Kour, Patel, & Krishna, 2016; Hakala *et al*., 2019; Bai, Liu, Liang, & Liu, 2015). An adequate estimation of the hydrological process is essential for decision-making, water management, as well as watershed planning due to the complexity of operational hydrological and hydraulic processes (Zhang, Wang, Wang, Li, & Wang, 2013).

In the CRH as in other basins of the Peruvian Altiplano, agricultural use constitutes the greatest demand for water, as agriculture is the main economic activity of the population (ANA, 2010). The other important water uses are population supply, aquaculture, industry and mining (ALT, 2020). In periods of water deficit, where the integral insufficiency of water makes it impossible to satisfy all types of water demand, as in the events that occurred in 2015 and 2016, where the CRH was declared in a state of emergency due to imminent danger of water deficit (D. S. No. 045-2015-PCM, 2015; D. S. No. 089-2016-PCM, 2016), there is frequent occurrence of conflicts over access to water in sufficient quantity and quality between the different uses and users of water in the basin, as well as economic losses in productive activities and health impact by the consumption of unsafe water.

Therefore, improving the knowledge of the impacts of climate change on the hydrological response of the CRH has a fundamental importance for the planning of water use, the management of water resources systems, as well as the prevention of the occurrence of social conflicts linked to water resources (Laqui, 2010; Defensoría del Pueblo, 2015). Because of this, this study proposes as its main objective to evaluate the hydrological response of the CRH against changes in precipitation and temperature patterns and the combination of them, estimated from the implementation of the Integrated Model of Climate Change and Water Resources (HydroBID).

Materials and methods

Study area

The CRH is located between the coordinates 69.28º to 70.17º W and 14.48º to 15.37º S in the extreme south east of Peru. The drainage area delimited to the Puente Carretera Huancané station, near to the mouth of Lake Titicaca, covers an approximate area of 3 522 km^2 (Figure 1). The main course is 125 km long and the elevation ranges between 3 820 and 5 162 masl. The CRH is located in the rainy climatic zone, characterized by humid and warm summers and dry and cold winters (SENAMHI, 2020).

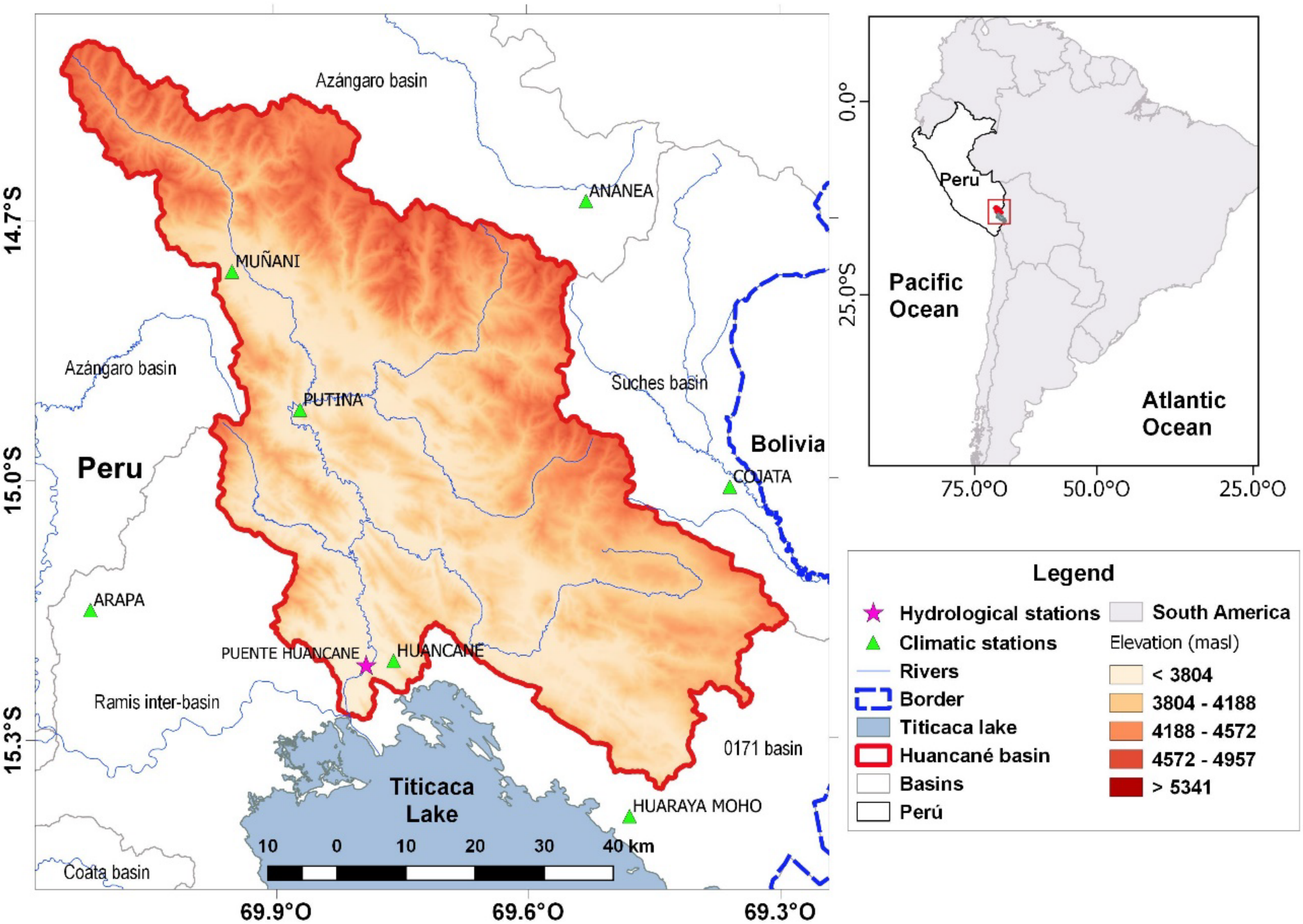

Figure 1. Location of the Huancané River basin and hydroclimatic stations used.

The average annual rainfall is 699.5 mm. The rainy season is between November and April, which concentrates approximately 80 % of the total annual rainfall. In the dry period between May and October, the remaining 20 % of the total rainfall occurs (Andrade, 2018). The average multi-year temperature is 7.71ºC. The average annual maximum temperature reaches values between 9.0 °C and 16.5 °C. The average annual minimum temperature shows values between -9.0 °C and 3.0 °C. The highest temperature values are recorded in the transition season from dry to wet (spring) and the lowest values occur in the dry season (winter). The total annual potential evapotranspiration is 1 160 mm, the highest values are observed in the dry period and the lowest values in the rainy season (Laqui *et al*., 2019).

The average annual flow is 19.3 m^3/s, in the rainy season a maximum flow of 59.1 m^3/s is recorded and in the dry season there is a minimum flow of 2.8 m^3/s. The main crops of the CRH are natural pastures, cultivated pastures, potatoes, fodder oats and beans, which shows the great agricultural potential of the Peruvian Altiplano (ANA, 2010).

Hydrometeorological stations in the CRH

Daily precipitation and temperature data were collected from seven weather stations and daily flow records from the Puente Carretera Huancané station, all managed by the National Service of Meteorology and Hydrology of Peru (SENAMHI), the data period selected for hydrological analysis was between 1977 and 2013 (Figure 1, Table 1). These records were subjected to analysis, critique and data processing through the Standard Normal Homogeneity Test (SNHT) available in R's

CLIMATOL package (Guijarro *et al.*, 2017; Guijarro, 2018) and the missing precipitation and temperature data were completed using data from neighbor stations with the use of this same package and the experience of previous studies (Montero-Martínez, Santana-Sepúlveda, Pérez-Ortiz, Pita-Díaz, & Castillo-Liñan, 2018; Domonkos *et al.*, 2020).

Table 1. Location of the Huancané River basin and hydroclimatic stations used.

Season	Location			Variable
	Latitude (°)	Longitude (°)	Altitude (masl)	
Huaraya Moho	-15.39	-69.48	3 890	*P*, *T*
Huancané	-15.20	-69.75	3 890	*P*, *T*
Cojata	-15.03	-69.36	4 380	*P*
Putina	-14.91	-69.87	4 878	*P*
Muñani	-14.77	-69.95	3 948	*P*, *T*
Ananea	-14.68	-69.53	4 660	*P*
Crucero	-14.36	-70.03	4 183	*P*
Huancané Bridge	-15.12	-69.47	3 860	*Q*

P = total daily precipitation

T = average daily temperature

Q = average daily flow

Future climate scenarios

Climate change, as the IPCC points out, is caused by the increase in Greenhouse Gas (GHG) emissions, which is inducing significant climate alterations (IPCC, 2013), as evidenced by the results of global climate models that analyze different climate change scenarios. In this research, future climate scenarios were proposed taking into account climate change predictions analyzed from data obtained from global climate models and published in Sanabria *et al*. (2009), Zubieta *et al*. (2021), Llacza *et al*. (2021) and GIRH-TDPS (2021) which are summarized in Table 2. The scenarios consider annual and seasonal variations in precipitation and temperature between extreme maximums and minimums, which generated rainy and dry scenarios, as also proposed by Hidalgo *et al*. (2020), while the physical and environmental conditions of the CRH defined for the current scenario remained constant for future scenarios.

Table 2. Summary of climate change scenarios for the study area available in the literature.

Climate models	Scenarios	Precipitation	Temperature	Reference
ETA CCS HadRM3 REgCM3	A2	+2 mm/day	+2 to +4°C	Sanabria *et al*. (2009)
	B2	No change	+1 to +2°C	
ACCESS1-0 HadGEM2-EN MPI-ESM-LR	CPR 8.5	Up to 15 %	+2.4 to +2.8 °C	Llacza *et al*. (2021)
EC-EARTH HadGEM2-EN IPSL-CM5B-LR MIROC5 MPI-ESM-LR	CPR 8.5	3 to 6 %	+0.5 to +3.5 °C	Zubieta *et al*. (2021)
MPI-ESM-MR MPI-ESM-LR MIROC-ESM HadGEM2-EN GFDL-CM3 CCSM4 ACCESS1-0 Era-Interim	CPR 8.5	-6 %	+3.3 °C (maximum) +2.5 °C (minimum)	GIRH -TDPS (2021)
	CPR 4.5	-2 %	+2.5 °C (maximum) +2.0 °C (minimum)	

GIRH-TDPS (2021) found that the spatial distribution of precipitation changes centered to 2050 on an annual scale are between -15 to +15 % to a great extent of the TDPS. For the CRH, precipitation reductions up to -15 % were observed on an annual scale and similar behavior for the wet period. Likewise, increases in the maximum and minimum temperature up to 3.5 and 2.5 °C, respectively, were observed, with similar behaviors for the rainy period and intensifications of the increase for the dry period.

The predictions mostly refer to an increase in precipitation rates, however, in order to evaluate the hydrological response of the CRH to precipitation reductions, a range of variation of -20 to +20 % was considered with intervals of increase and decrease of ±10 %, resulting in precipitation variations of -20, -10, +10 and +20 %. Regarding the variation of the temperature, the scenarios considered a maximum increase of 6 °C with increases of 1 °C. Table 3 presents the climate change scenarios that result from the combination of the four scenarios for precipitation and the seven scenarios for temperature. In total, 28 scenarios were proposed that consider proportional changes at the monthly level, divided into 14 wet scenarios from 1 to 14, and 14 dry scenarios from 15 to 28. As well, scenarios 28 and 29 were considered, which include seasonal changes in precipitation (displacement), with increases of +20 % for the January, February and March (EFM) quarter (scenario 29) and +20 % for the October-March semester (O-M) (scenario 30).

Table 3. Characteristics of precipitation and temperature change scenarios.

Scenario		Precipitation	Temperature	Reference
Number	Condition			
1 to 7	Wet	+10 %	0 to 6 °C	Zubieta *et al*. (2021)
8 to 14		+20 %		Llacza *et al*. (2021)
15 to 21	Drought	-10 %		
22 to 28		-20 %		GIRH-TDPS (2021)
29	Displacement	+20 % EFM	0 °C	Llacza *et al*. (2021)
30		+20 % O-M		

Note: EFM corresponds to the January-March quarter. O-M refers to the October-March semester. The wet condition refers to scenarios that consider increased precipitation, while the dry condition refers to scenarios that include precipitation reduction.

Hydrological modelling

The Integrated Climate Change and Water Resources Model (HydroBID) was applied, which is based on the well-known model "Generalized Watershed Loading Functions – GWLF" (Haith, 1985; Haith, Mandel, & Wu, 1996). GWLF has been tested and used in watersheds around the world (Mukundan, Acharya, Gelda, Frei, & Owens, 2019; Qi *et al*., 2017; Qi, Kang, Shen, Wang, & Chu, 2019). In HydroBID the basin is divided into several sub-basins (41 sub-basins for the CRH) which are predefined, together with the current networks and the uses and types of land in the Analytical Hydrological Database (AHD). The impacts of climate change on water resources can be simulated at scales as small as an individual watershed or across all basins within an entire watershed (Moreda, Miralles-Wilhelm, Muñoz, & Coli, 2014a; Moreda, Miralles-Wilhelm, & Muñoz, 2014b).

The watershed in HydroBID is conceptually represented in saturated and unsaturated soil layers, as used in the GWLF model (Figure 2). The model calculates runoff and base flows by catchment: runoff is generated in the form of excessive infiltration and the base flow is a gradual release of the saturated layer. After taking into account runoff from precipitation events, any volume of water exceeding the calculated evaporation volume infiltrates the unsaturated layer. Over time, the infiltrated water seeps from the unsaturated layer down to replenish saturated storage. Water within the saturated layer enters the stream channel as the base flow, where it combines with runoff from the basin and any inlets from the upstream basins to provide the flow volume of the stream for the day. It should be noted that the saturated layer, or the water available as a base flow, can be depleted by filtration into a deeper underground aquifer (Moreda *et al*., 2014a, Moreda *et al*, 2014b).

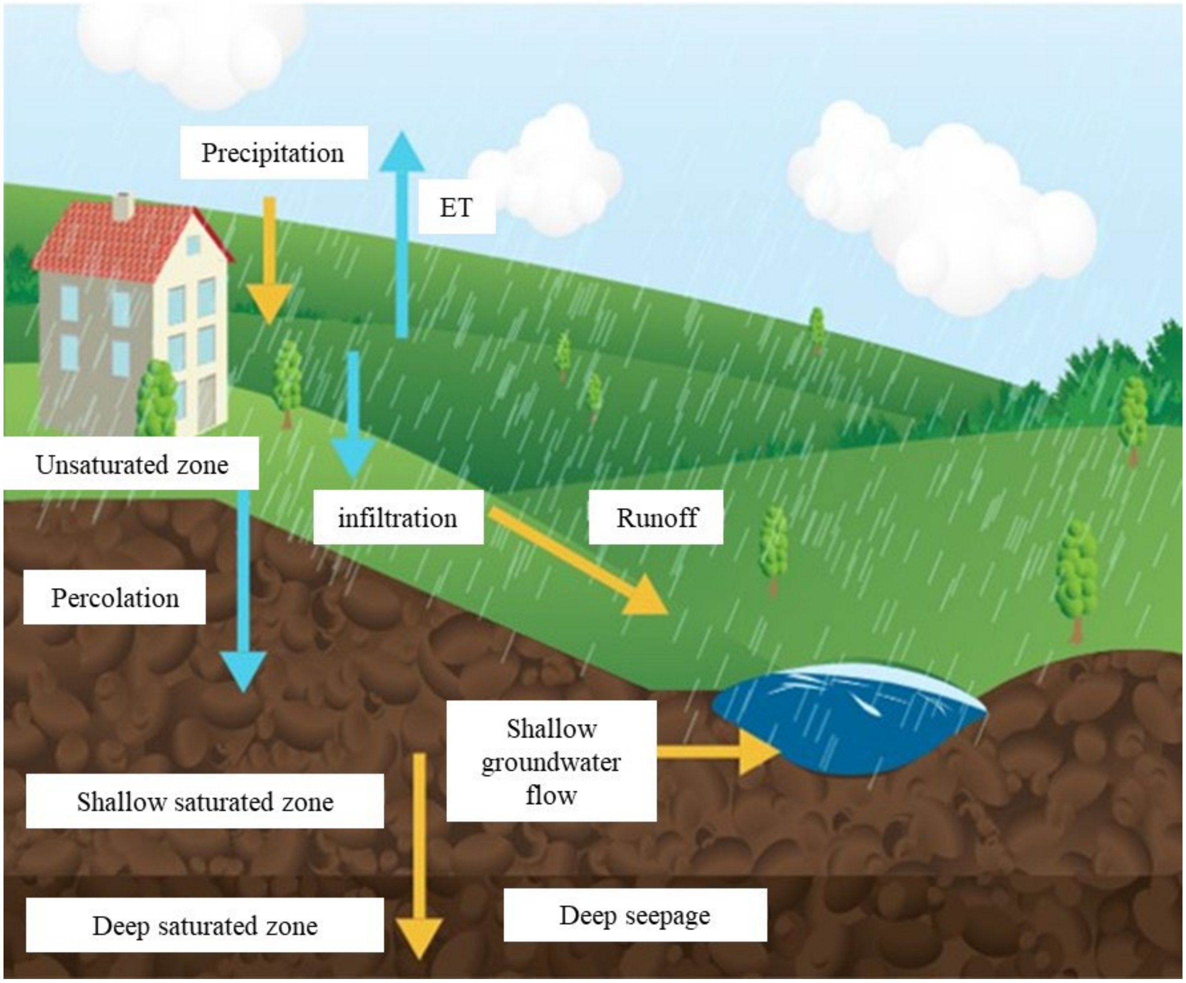

Figure 2. Conceptual scheme of the GWLF model implemented in HydroBID (modified from Moreda *et al*., 2014a).

The main parameters of HydroBID recommended by Moreda *et al*. (2014) as a result of the implementation of the model in different basins of Latin America and the Caribbean, are described in Table 4.

Table 4. HydroBID's main calibration parameters.

Parameter	Description	Suggested value
Stream velocity	Estimated average stream velocity	0.5 m/s
Latitude	Location of the centroid of the basin	
Start of growing season	Julian date of the start day of the growing season	
End of the growing season	Julian date of the last day of the region's growing season	
AWC	Available water content (AWC)	10 cm
CN	Curve number. It controls the amount of the initial abstraction and is used to calculate water retention in the basin	
Coefficient *R* (*R*)	Recession coefficient	0.01
Permeability (*S*)	Permeability coefficient to determine deep infiltration from the saturated layer	0.005
Growing Season *ET* Factor (*ET-EC*)	Evapotranspiration factor during the growing season	1.0
Latency Station *ET* Factor (*ET-EL*)	Evapotranspiration factor during the latency season (when not growing)	1.0
Percentage of impermeable coverage (*ICP*)	Estimated percentage of the impermeable portion of the basin as a percentage	2 %

Two distinct periods of hydroclimatic data were selected. For the calibration process, 75 % of the data corresponding to the period March 1977 to December 1990 were used and 25 % of the remaining data were used for the validation stage (January 1991 to November 1998). Also, to minimize the uncertainty of the initial conditions of the models, the first year of the hydroclimatic records were considered as a warm-up period, as recommended by Niraula Kalin, Srivastava and Anderson (2013) and Kim, Kwon and Han (2018). For the simulation of future scenarios of precipitation and temperature change, the parameters calibrated and validated in the period March 1977 to November 1998 were used.

The daily mean flow records of the Puente Huancané station were used to evaluate the performance of HydroBID to estimate flows, through the use of the Nash-Sutcliffe efficiency coefficient (NSE) (Nash & Sutcliffe, 1970), the correlation coefficient (R) and the overall volume error (*OVE*), which were compared with the criteria of Moriasi *et al*. (2007) to determine their performance, as also suggested by Sheikh-Goodarzi, Jabbarian-Amiri, Azarnivand and Waltner (2021) and Stephens, Marshall and Johnson (2019):

$$NSE = \left(1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right) \quad (1)$$

$$R = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2 (P_i - \bar{P})^2}} \quad (2)$$

$$ove = \frac{\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} O_i}{\sum_{i=1}^{n} O_i} \quad (3)$$

Where O_i and P_i are the observed and simulated flow rate at time i, $\bar{O}$ and $\bar{P}$ are the averages of the observed and simulated flows, respectively. *NSE* varies between -∞ and 1.0 being 1.0 the optimal. *R* varia from 0 to 1.0. Values of "OVE" below 10 % are considered as very good.

To analyze the effect of precipitation and temperature on the hydrological response of the CRH, the analysis of variance (ANOVA) was used, for this purpose the percentage of change of precipitation and the rate of change of temperature were established as factors (independent variables), while the percentage of change of the flows of the future scenarios in relation to the base period was defined as the dependent variable corresponding to scenarios 1 to 28. For the determination of the effect of the factors and their interaction on the hydrological response, the p-values (Pr(>F)) compared with a significance level of 0.01 were taken into account. P-values less than the significance level will show evidence of the effect of the parameters and their interaction on the dependent variable.

Results

Model performance

The manual calibration carried out through the change of the initial values of the parameters of the HydroBID model for the period 1 March 1977 to 31 December 1990 (Table 5), shows the good capacity of HydroBID in simulating the average flows in the CRH. The performance statistics in calibration and validation (Table 6) show values of *NSE* greater than 0.75 and *OVE* less than -10 %. The model presents a better performance in the validation stage reaching performance values higher than those obtained in the calibration stage.

Table 5. Calibrated parameters of the HydroBID model for the period March 1977-December 1990.

Parameter	Value
CN	0.95
AWC	0.5
R	0.025
S	0.025
ET-EC	1
ET-EL	1
ICP	1.0

CN = curve number
AWC = available water content (*AWC*)
R = recession coefficient
S = permeability coefficient
ET-EC = evapotranspiration factor during the growing season
ET-EL = evapotranspiration factor during the latency season
ICP = Percentage of waterproof coverage

Table 6. HydroBID performance measures during calibration and validation periods.

Stage	**Daily values**			**Monthly values**		
	NSE	***R***	***OVE* (%)**	***NSE***	***R***	***OVE* (%)**
Calibration	0.76	0.87	2.16	0.86	0.93	2.12
Validation	0.76	0.88	8.77	0.88	0.95	8.76

Slight differences (underestimation) were observed between the simulated and observed values, mainly in the dry season (Figure 3). Average daily and monthly flows were generated for the base period from January 1984 to December 2013, observing a marked seasonality of the rainy and dry periods, with a maximum value of 56.96 m^3/s in February and a minimum of 0.26 m^3/s in August.

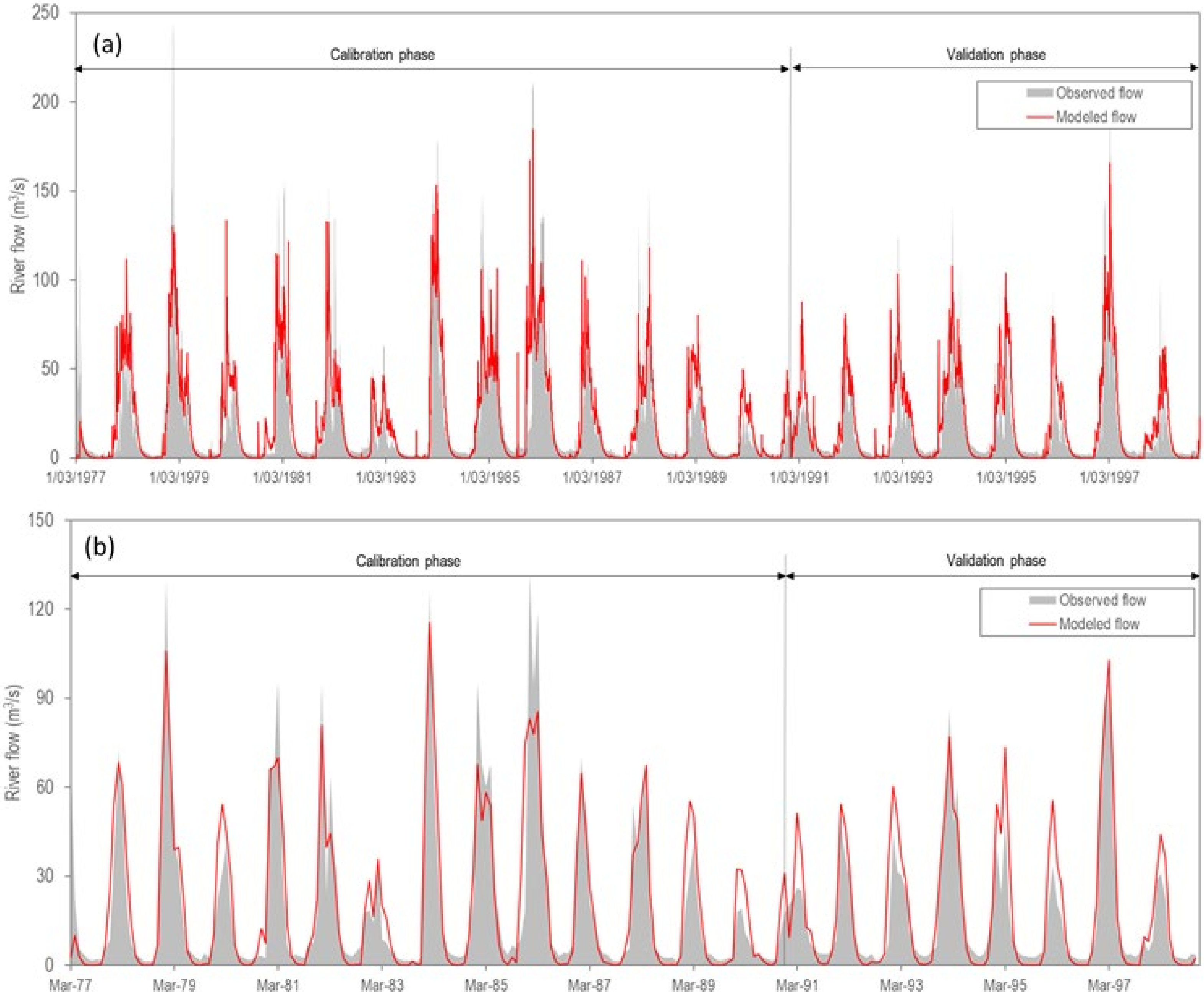

Figure 3. Flow rates observed and simulated at the Puente Huancané station for the calibration and validation period (a) daily (b) monthly.

Hydrological response to climate change scenarios

In relation to the wet scenarios (1 to 7), Figure 4 shows that only in two of them (1 and 2) were observed flow increases for the entire period (January – December) with annual average values of 26 and 20 %, respectively (1 and 2), in relation to the base period. While in the rest of the scenarios (3 to 7) there were increases only in the rainy period, and decrease in flows in times of dryness, with a maximum up to -37 % for the July-September period (JAS) in scenario 7. The average annual change in flows for scenarios 3, 4, 5 and 6 reached values of 14, 9, 3, -2 and -7 %, respectively, in relation to the base period (Table 7). For wet scenarios with +20 % increases in precipitation, all seven scenarios recorded flow increases in the range of 12 to 47 % relative to the base period. In five of them (scenarios 8, 9, 10, 11 and 12) increases were observed for all months in the rainy period, while in two (scenarios 13 and 14) there were reductions in flows in JAS of -7 and -15 %, respectively. Scenario 8 shows a significant increase in flows in all months, with an annual average of 47 % and increases > 100 % for the periods of July-August-September and October-November-December. This suggests that under scenario 8 there would be a greater water supply in the CRH for the rainy and dry period.

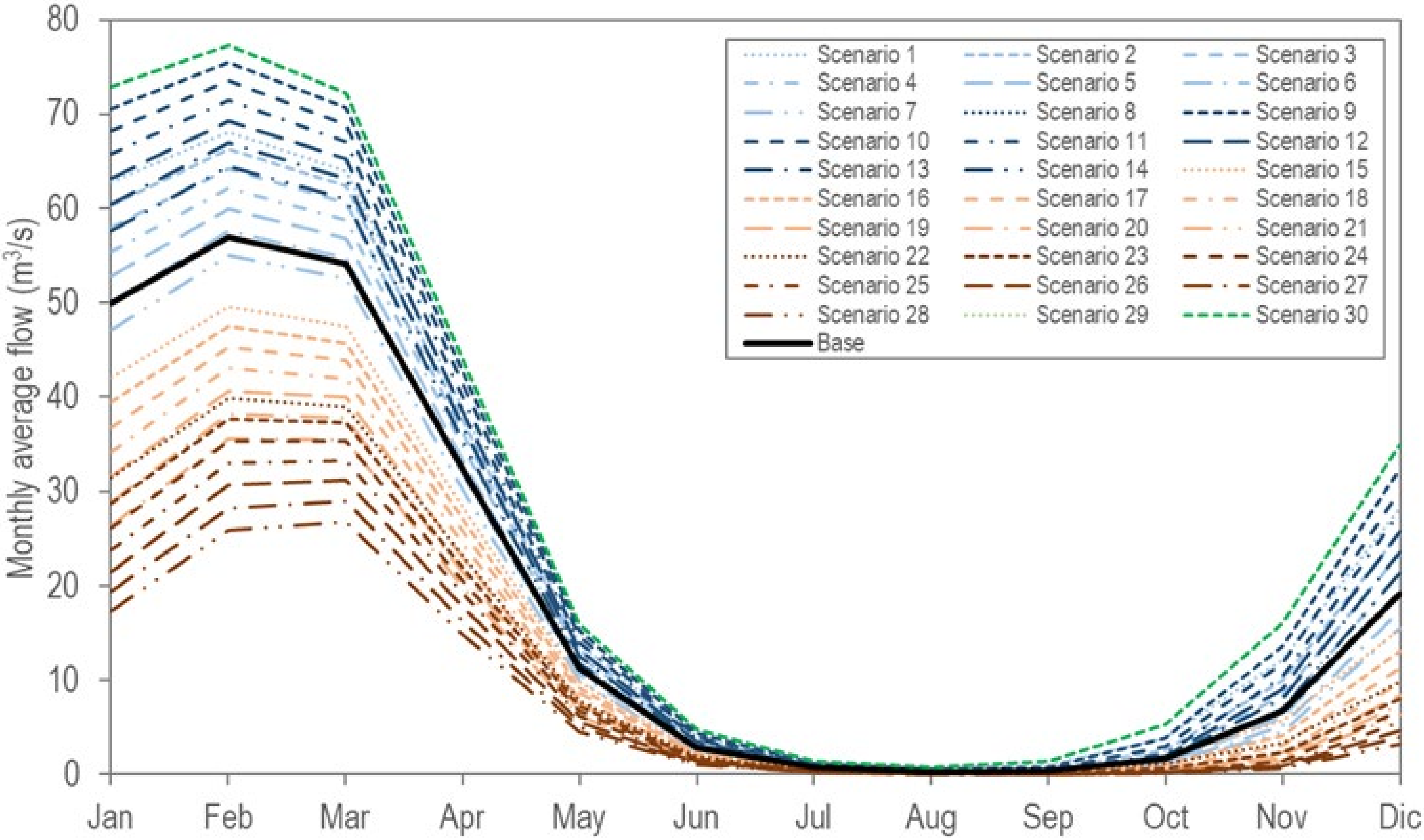

Figure 4. Hydrogram of monthly average flows (multi-year average) of the CRH for different climate change scenarios.

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Table 7. Seasonal percentage changes in flows in the CRH under different climate change scenarios.

Variable	Scenario	Months				Annual
		EFM	AMJ	JAS	OND	
Flow rate (m^3/s)	Base	53.68	15.52	0.45	6.99	19.71
Seasonal change (%)	Scenario 1	21 %	22 %	> 100 %	60 %	26 %
	Scenario 2	17 %	17 %	38 %	39 %	20 %
	Scenario 3	14 %	12 %	-2 %	22 %	14 %
	Scenario 4	9 %	7 %	-16 %	8 %	9 %
	Scenario 5	5 %	2 %	-24 %	-4 %	3 %
	Scenario 6	1 %	-3 %	-31 %	-14 %	-2 %
	Scenario 7	-4 %	-9 %	-37 %	-24 %	-7 %
	Scenario 8	38 %	39 %	>100 %	>100 %	47 %
	Scenario 9	35 %	34 %	84 %	81 %	40 %
	Scenario 10	31 %	29 %	34 %	62 %	34 %
	Scenario 11	27 %	24 %	13 %	47 %	29 %
	Scenario 12	23 %	19 %	2 %	33 %	23 %
	Scenario 13	18 %	13 %	-7 %	20 %	17 %
	Scenario 14	14 %	8 %	-15 %	8 %	12 %
	Scenario 15	-14 %	-12 %	15 %	-17 %	-14 %
	Scenario 16	-18 %	-17 %	-30 %	-34 %	-19 %
	Scenario 17	-22 %	-21 %	-50 %	-46 %	-25 %
	Scenario 18	-26 %	-26 %	-56 %	-54 %	-29 %
	Scenario 19	-30 %	-31 %	-60 %	-61 %	-34 %
	Scenario 20	-35 %	-36 %	-63 %	-66 %	-39 %
	Scenario 21	-39 %	-41 %	-66 %	-70 %	-43 %
	Scenario 22	-31 %	-29 %	-22 %	-48 %	-33 %
	Scenario 23	-36 %	-34 %	-55 %	-61 %	-38 %
	Scenario 24	-40 %	-38 %	-65 %	-69 %	-43 %
	Scenario 25	-44 %	-43 %	-69 %	-75 %	-48 %
	Scenario 26	-48 %	-47 %	-71 %	-79 %	-52 %
	Scenario 27	-52 %	-52 %	-74 %	-82 %	-56 %
	Scenario 28	-57 %	-56 %	-76 %	-85 %	-60 %
	Scenario 29	38 %	39 %	>100 %	>100 %	47 %
	Scenario 30	38 %	39 %	>100 %	>100 %	47 %

In the case of dry scenarios (15 to 21), reductions in flows were observed, presenting average values in the range of -14 to -43 %, the greatest reduction was presented in scenario 21 that considers the maximum increase in temperature. Likewise, a reduction in flows was observed in all months, with a higher incidence in the dry period (AMJ and JAS) reaching values up to -70 %. In scenarios 22 to 28, a generalized reduction in flows (monthly and annual) was found, the average reduction values are in the range of -33 to -60 % with the highest incidence in the dry period (-85 %). The extreme dry scenario (28) projected seasonal reductions in flows in the range of -56 to -85 %, with greater incidence in the dry period.

The scenarios that consider seasonal changes in precipitation by +20 % in the EFM (29) and EFM – OND (30) periods show behaviors of increased flows, in both scenarios they reach average change values of 47 % and in the periods of JAS and OND changes greater than 100 %.

Impact on water contribution

The water contribution constitutes the graphic representation of the average annual runoff, which allows to identify the basins with the greatest contribution to the flow. At the level of the 41 sub-basins of the CRH for the base scenario, it was found that the maximum water contribution reached 2.94 cm/year in the extreme southeast of the basin, this mainly due to the climatic conditions of that area, such as greater precipitation and lower rates of evapotranspiration due to its proximity to

Lake Titicaca, since the geomorphological conditions, soil, vegetation and topographical are similar to the rest of the CRH (Figure 5). The changes in precipitation and temperature did not generate changes in the spatial behavior of the water contribution, since for the extreme wet and dry scenarios, the greatest water contributions were also presented in this area. However, for the extreme wet scenario (8) important changes were found in the magnitude of the water contribution, reaching values up to 4.59 cm/year, while for the extreme dry scenario (28) a significant reduction in the water contribution was observed with a maximum value of 1.60 cm/year.

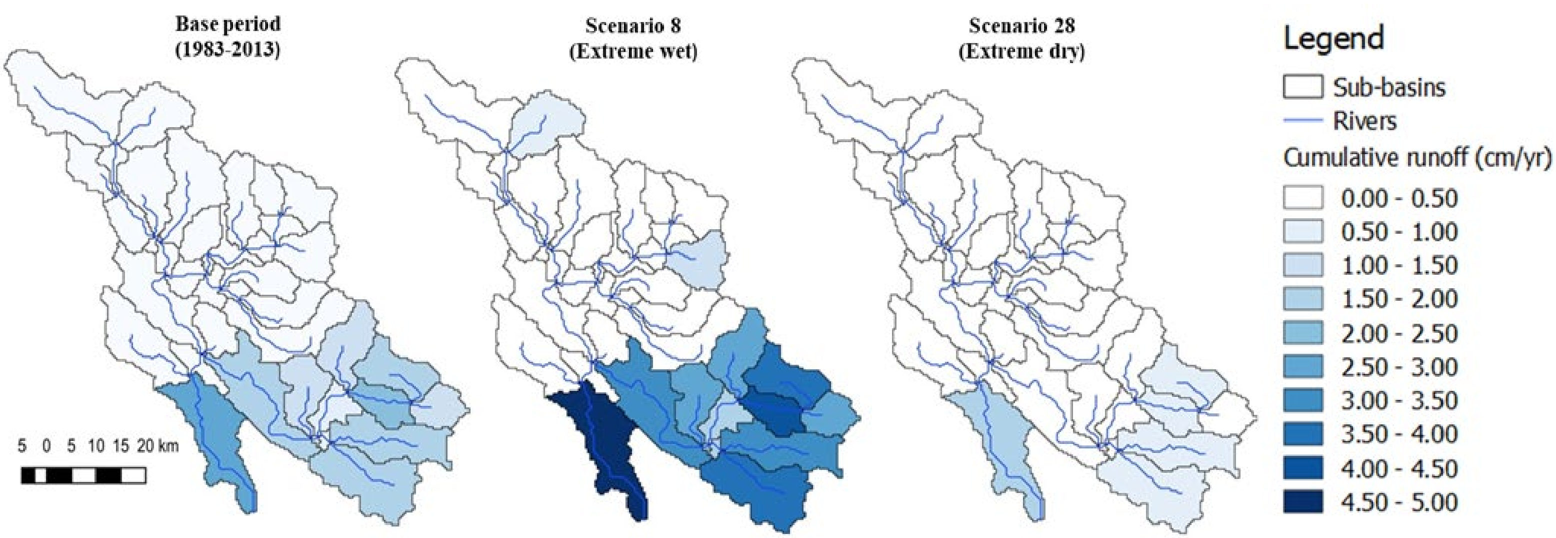

Figure 5. Spatial variation of the water contribution in the CRH, for the current and projected periods.

Contribution of factors in changing hydrological response

The analysis of variance (ANOVA) to quantify the relative contribution of precipitation and temperature in the change of hydrological response in the CRH, determined that there is a significant influence ($p < 0.01$) of changes in precipitation and temperature, in the hydrological response in 28 climate change scenarios analyzed (Table 8). Also, the existence of significant interaction between precipitation and temperature was evidenced, as well as its influence on the hydrological response.

Table 8. Significance of the factors in the change of the hydrological response.

Answer: change	**Sum of squares**	**Degrees of freedom**	**Value of *F***	***Pr* (> *F*)**	**Significance**
Precipitation	25 226.7	1	56 525.602	< 2.2e-16	***
Temperature	3 001.2	1	6 724.782	< 2.2e-16	***
Precipitation: Temperature	29.7	1	66.604	2.213e-08	***
Residual	10.7	24			

Code meaning:
0
'***' = 0.001
'**' = 0.01
'*' = 0.05
'.' = 0.1
' ' = 1

Discussion

The HydroBID model, both at daily and monthly time, presents *NSE* and *R* values greater than 0.75 and 0.87, respectively. While *OVE* registers values less than 8.77, so the performance of the model can be qualified as very good (Moriasi *et al*., 2007). The high performance presented by HydroBID at the *CRH* is consistent with the results obtained with other hydrological models such as GR2m, GR4j and SWAT that also showed a very good performance in flow modeling (Llauca, Lavado-Casimiro, Montesinos, Santini, & Rau, 2021; Asurza, Ramos, & Lavado-Casimiro, 2018; Fernández, 2017; Asurza *et al*., 2020). The model shows a good ability to reproduce the behavior of seasonality, as well as an adequate estimation of maximum and minimum flows, this is reflected in the reduced value of *OVE*. The slight difference in the performance statistics, 2.3 % for NSE and 2.1 % for *R*, in the calibration and validation stages of the model, suggest the existence of a reduced variability of the flows between both periods.

As well, it was observed that the values of the calibrated *R* and *S* parameters are greater than the values suggested by Moreda *et al*. (2014b), which can be attributed to the different conditions existing in the basins of the Altiplano compared to other hydrographic regions, such as their location at the high dry puna, the predominance of mountains and hills, the scarce vegetation cover and a marked seasonality of precipitation and temperature that control the hydrological behavior (Ochoa-Tocachi *et al*., 2016). Despite this, the very good performance obtained in the hydrological modelling of the CRH to represent daily flow records is a good example that a model with a semi-distributed approach, such as HydroBID, can be implemented quite successfully for the simulation of flows, as also demonstrated in different studies carried out by Moreda *et al*. (2014a); Wyatt, Moreda, Miralles-Wilhelm and Muñoz (2014); Moreda, Coli, Lord and Corrales (2016a); Moreda and Coli (2016b); Moreda and Coli (2017), and Arbuet *et al*. (2021).

Changes in hydrological response in wet scenarios (1 to 14) are expected to result in increases in flows. However, the results of this research show that not all wet scenarios showed increases in flows. This is the case of scenarios 6 and 7, where despite having considered an increase in precipitation by +10 %, a reduction in flows was observed in relation to the base period, which could be attributed to the impact generated by the increase in temperature at 5 °C and 6 °C, respectively. These are possible scenarios to occur according to the predictions of Sanabria *et al*. (2009), Zubieta *et al*. (2021), Llacza *et al*. (2021) and GIRH-TDPS (2021). These results are explained, from the direct effect that the increase in temperature has on evapotranspiration rates (Laqui *et al*., 2019) and therefore on the hydrological response of the basin, even more so in regions where the annual amounts of evapotranspiration (1 160 mm / year) are bigger than the precipitation (699.5 mm / year).

From Figure 6, it can be described that in the CRH an increase in precipitation of +10 % would generate on average an increase in flow by 23.4 %, while a reduction in precipitation by -10 % would result in an average decrease of 16% in flow. Likewise, it was evidenced that for every 1 °C of temperature increase, an average of 5 % reduction in flow was generated, which suggests that the variation in precipitation rates, temperature and their interaction are the generators of changes in the flows of the CRH. As well as other variables of the hydrological cycle process, such as evapotranspiration, where temperature is one of the variables with the highest incidence for its estimation in the Altiplano (Zubieta *et al*., 2021; Shi *et al*., 2020; Lin *et al*., 2018; Laqui *et al*., 2019), even more so when the method of estimating these variables is mainly dependent on temperature, as in HydroBID which uses the Hamon method (Hamon, 1961).

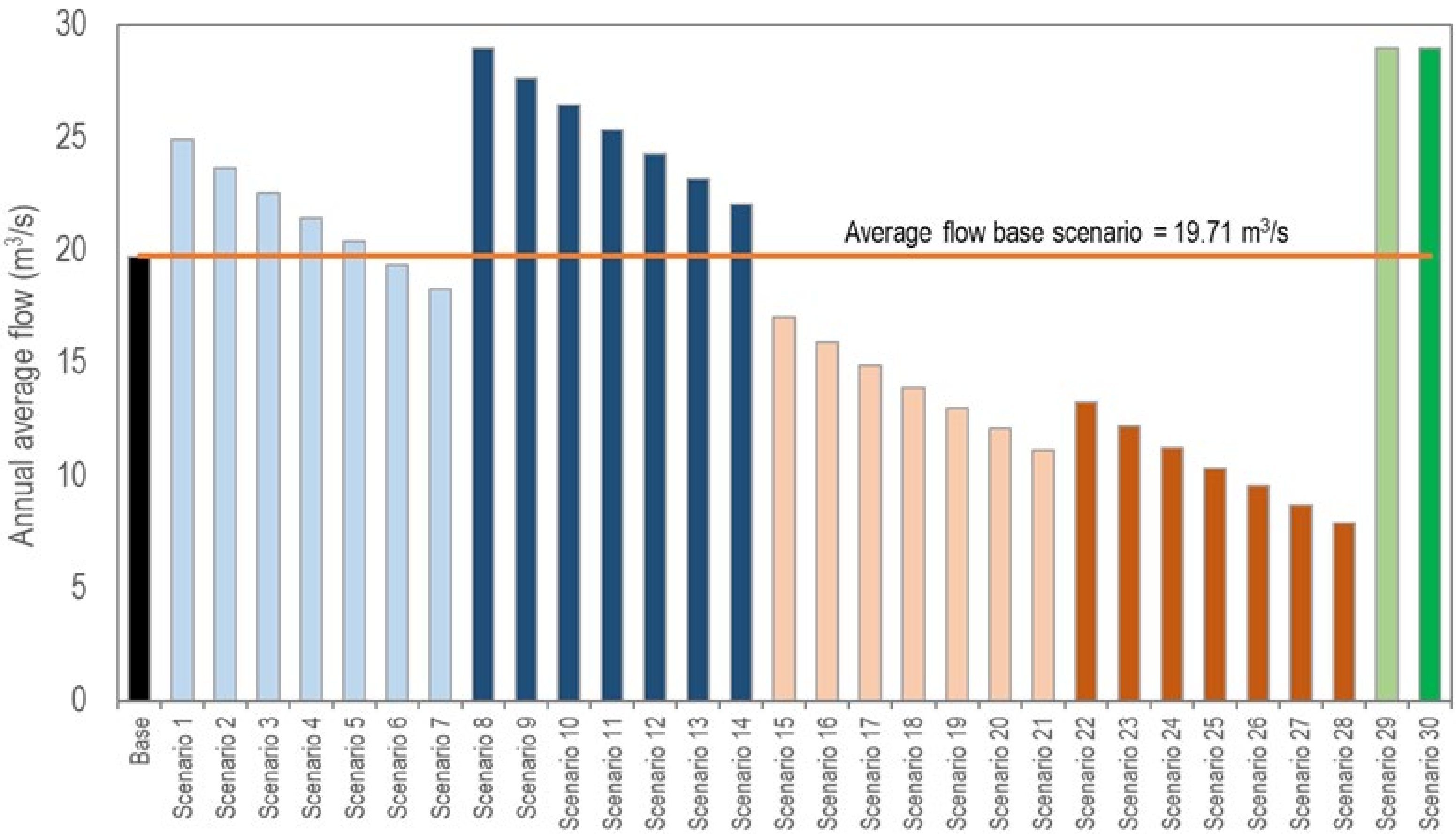

Figure 6. Average annual flows (multi-year average) for different climate change scenarios.

The largest increases in flows are recorded in the rainy period, which is closely related to the increase in precipitation and the decrease in evapotranspiration rates, due to the high values of relative humidity and the reduction of the available energy due to the presence of cloudiness (Núñez-González, Velázquez-Pérez, Pelayo-Cortés, & Barboza-Jiménez, 2019). In the dry period, the decrease in flows would be due to the absence of precipitation and the increase of the evapotranspiration rates as a result of the temperature increase (Zeng *et al*., 2021). Although the predictions mostly point to the increase in precipitation and temperature rates in the Puno region and the TDPS (Sanabria *et al*., 2009; Zubieta *et al*., 2021; Llacza *et al*., 2021; GIRH-TDPS, 2021), these still have a high level of uncertainty. Huerta and Lavado-Casimiro (2021) determined that the change in runoff evaluated from climate projections of the global climate models ACCESS 1.0, HadGEM2-ES and MPI-ESM-LR, showed important differences. Thus, for the ACCESS 1.0 model, a reduction in runoff up to -10 % was observed and for the other two models increases in runoff between 15 and 25 %. Therefore, it was convenient to include in the evaluation scenarios of reduction of precipitation rates, in order to show their impacts and improve the knowledge of the interaction of these factors in the hydrological response of the CRH.

On the other hand, it was also observed the existence of a relative similarity in the changes of the flows in different scenarios (scenarios 1-12, 2-13, 3-14, 19-22, 20-23 and 21-24), which, despite having different changes in precipitation and temperature, show approximate changes in the flows. This suggests that the interaction of precipitation and temperature changes also generates changes in hydrological response, as does precipitation and temperature when analyzed individually. In relation to scenarios 29 and 30 that consider seasonal changes and the beginning of the rainy period, no changes were observed in the magnitude of seasonal flows, which can be attributed to the fact that these changes in precipitation were made only for the rainy period.

Evaluating HydroBID with the variations in precipitation and temperature according to the proposed climate scenarios, the resulting flows and water contribution show coherence, since for the scenarios of increased precipitation greater amounts of flow and water contribution are observed compared to the base period (1993-2013). While for the scenarios of precipitation reduction, a decrease in flows and water contribution rates is observed in relation to the base period. The coherence of the results of the hydrological modelling is also represented in the evident changes in the slope of the monthly mean flow hydrograms (**Figure 4**), where wet scenarios have a greater slope to the base period and lower slopes for dry scenarios.

The high level of significance ($p < 0.01$) obtained in the ANOVA shows evidence of the existence of a high level of influence from precipitation and temperature on the flows of the CRH, however, it should be taken into account that the interaction of both climatic variables also generates important changes in the flows, which is evidenced in the comparison of some scenarios, that despite including different rates of change in precipitation and temperature offer approximate results.

The hydrological response for most of the climate scenarios analyzed shows that there are no significant water availability problems in the CRH due to the effects of climate change, however, it could be affected if there are significant increases in water demands, so it is necessary to establish mitigation and adaptation strategies to climate change. While this is urgent, it is also a rather complex task due to the great uncertainty of the impact of climate change and the effectiveness of adaptation measures and actions (Pearce-Higgins *et al*., 2022).

Proposals for potential climate change adaptation interventions in a water system should start from the identification of all combinations of hydroclimatic forcings, typically the changes in temperature and precipitation that generate the failure of the water system as pointed out by Sant'Anna, Tilmant and Pulido-Velazquez (2022). Therefore, having determined the impact of precipitation and temperature changes on the hydrological response of the CRH, it can be suggested that the interventions called Nature-Based Solutions (SbN) constitute a good alternative for adaptation to climate change, due to the ability to reduce and compensate for the impacts experienced by the anthropogenic influence on the climate system (Holden *et al*., 2022). These interventions include the restoration and protection of riverbanks, wetlands and headwaters in order to reduce erosion and increase water production in the basin.

Conclusions

The performance of the HydroBID model in the simulation of flows in the CRH can be described as very good when reproducing the flow regime. The change in +10 % of precipitation generated on average an increase in flow by 23.4 %, while a reduction in precipitation by -10 % resulted in an average decrease of 16 % in flow. However, it was also evidenced that for every 1 °C increase in temperature, an average of 5 % reduction in flow was generated, which suggests that the variation in precipitation rates, temperature and their interaction would lead to changes in the flows of the CRH.

The impact of the change in precipitation and temperature patterns on the water resources of the CRH is significant for the 30 proposed scenarios, showing effects on temporal and spatial variation, generating increases in the magnitude of flows in the rainy season and decrease in dry seasons. Likewise, it would be expected the increase in the water contribution in the 41 sub-basins of the CRH for wet scenarios and a reduction in the water contribution for dry scenarios.

In general, for most wet scenarios, those with the highest probability of occurrence according to the predictions made in previous research, there are no problems of water availability in the CRH due to the effects of climate change, however, the high level of uncertainty involved in the use of global climate models for the conditions of the Peruvian Altiplano must be taken into account, which can be improved from the use of regional climate models. However, this situation could change if there are significant increases in the water demands of the CRH that currently reach 33.83 hm^3 (ANA, 2010), this situation was not analyzed in the research, and should be addressed in future research that also considers intervention scenarios with measures and actions included in SbN.

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