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Hydrological impacts of dam regulation for hydropower production: The case of Lake Sibinacocha, Southern Peru

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A R T I C L E I N F O

Keywords:
Ecoflow
Hydrologic alteration
Dam
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A B S T R A C T

Study region: Vilcanota-Urubamba river basin, Southern Peru.
Study focus: Hydraulic infrastructure plays a fundamental role for energy production, drinking and irrigation water storage and flood control in regions with seasonal river flow. The high-Andean Lake Sibinacocha has been regulated since 1988 to increase energy production of the Machupicchu hydropower plant. In this study, river streamflow changes are evaluated by analyzing precipitation and discharge trends using indicators of hydrologic alteration and ecoflow for natural (1965–1987) and altered (1988–2016) flow regimes.
New hydrological insights for the region: For the altered flow regime, an ecodeficit of about 20% (compared to natural river flow) and an ecosurplus > 30% were found during the wet season (December-February) and dry season (June-August), respectively. These changes have reduced the risk of water shortage (dry season) and flood (wet season) and contribute to increasing water use including hydropower production, irrigation and drinking water. However, river alteration might lead to considerable impacts on riverine ecosystems.
Despite major limitations related to data scarcity and complex environmental processes in the basin, our results highlight the usefulness of combined methods of hydrological alteration and ecoflow to effectively evaluate water regime changes in regulated basins. An integrated scientific approach is necessary to address uncertainties and develop meaningful future water availability scenarios that guide hydropower projects with improved water and energy security considering minimal impacts on human and natural systems.

1. Introduction

Water is essential for human health and wellbeing and key to support diverse ecosystems (Keeler et al., 2012). Rivers provide essential ecosystem services that benefit human livelihoods directly (e.g. drinking water supply, hydropower production, irrigation, navigation) or indirectly (e.g. recreation, soil wetting and fertilization of floodplains) (Bhaduri et al., 2017; Brismar, 2002).

Worldwide, hydropower capacity has increased by 7% between 2017 and 2021 (IHA, 2022). Almost 90% of global power generation is dependent on water (Bhaduri et al., 2015; Larsen et al., 2019) which highlights the close connection between water and energy. The availability of water to produce hydropower depends on local climate in many regions of the world (Berga, 2016; Chala

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et al., 2019). However, climate change is expected to alter regional hydrological regimes threatening the development and operation of hydropower generation (Caceres et al., 2021).

In this context, hydraulic infrastructure (i.e. dams and reservoirs) plays an essential role for economic growth and water security in regions with high seasonal river flow providing key functions of water storage (during wet or low-demand periods) and release (during dry or peak-demand periods) (Bird and Wallace, 2001). Hydraulic infrastructure is designed to provide services such as drinking water provision, reduction of flood risks, and hydropower production, among others (Rakhmatullaev et al., 2010). Nevertheless, the presence of dams and reservoirs alters natural flow variability and biogeochemical processes, mainly through changes in the ecological parameters of the hydrological regime (Black et al., 2005; Gao et al., 2018; Christer et al., 2005; Timpe and Kaplan, 2017; Zhang et al., 2015). Hydraulic infrastructure can also lead to substantial social conflicts often associated with unequal power relations and control over water resources due to poor water governance (Boelens et al., 2019; Carey et al., 2012). Therefore, it is crucial to understand how hydraulic interventions change natural hydrological regimes (Passaia et al., 2020) to anticipate undesired effects and reduce adverse impacts from climate change (Moran et al., 2018). Consequently, strategic planning taking into account key drivers and potential changes of the hydrological regime is paramount to operate hydraulic infrastructure (Jiang et al., 2019). Such an endeavor can then support adaptive measures for sustainable hydropower management (Moran et al., 2018). Different methodologies based on static and dynamic hydrological metrics have been developed to analyze and quantify the degree of alteration of river flow regimes (Gao et al., 2018).

South America holds some of the largest drainage systems of the world, such as the Amazon, La Plata and Orinoco basins (Gioia, 1987) which are considerably altered by water infrastructure. Indicators of hydrologic alteration (IHA) combined with ecoflow methods have been used to quantify changes in the flow regime. IHA are composed by a set of parameters to compare the inter- and intraannual variation of the flow regime. Whereas, ecoflow is based on non-dimensional measurement of ecodeficit and ecosurplus considering flow duration curves (FDCs, see Section 2.5.1). The South American climate is complex due to the influence of tropical, subtropical and extratropical patterns (Garreaud, 2009) and interannual variability patterns which are strongly influenced by the El Niño-Southern Oscillation (ENSO) (Perry et al., 2014; Poveda et al., 2020; Salzmann et al., 2013). Glaciers are rapidly retreating which affects downstream water availability including hydropower production and regional economies (Carey et al., 2016; Vergara et al., 2007). A hydrological assessment for the upper Vilcanota-Urubamba river basin in Southern Peru suggests that future river discharge could decrease by 2–11% (7–14%) until 2050 (2100) because of the substantial loss of glaciers linked to climate change scenarios (Drenkhan et al., 2019). In the last decades, the increasing demand for energy and untapped potential (hydropower plants) is a critical factor for economic growth (Caceres et al., 2021; De Souza Dias et al., 2018; Timpe and Kaplan, 2017). Moreover, hydropower projects are growing in the Andes-Amazon region where regional governments are prioritizing the construction of dams for energy supply purposes raising concerns about potential environmental consequences (Anderson et al., 2018; Finer and Jenkins, 2012). In Peru, installed hydropower capacity has increased by 147% since 2005 and currently represents 36% of total energy capacity (15,340 MW) (MINEM, 2022; MINEM, 2015).

In South America, only a few studies at regional (Anderson et al., 2018; Pringle et al., 2000) and local scale (Almeida et al., 2020;

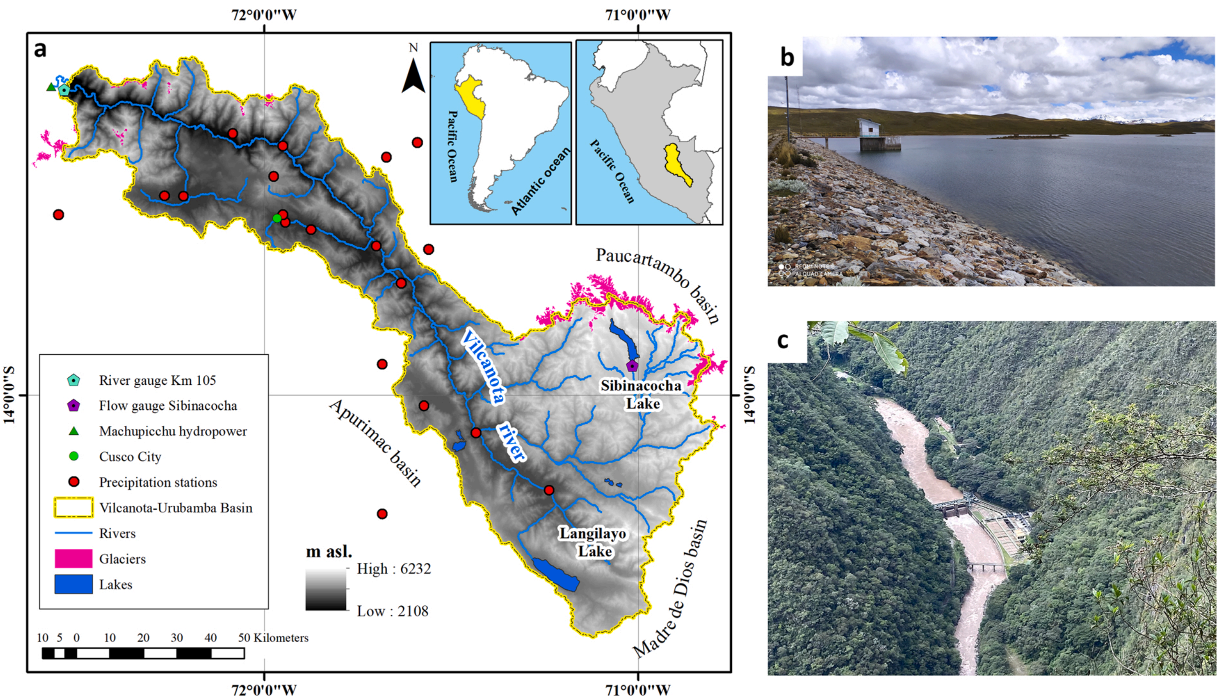

Fig. 1. Location of the Vilcanota-Urubamba river basin, b) Lake Sibinacocha and c) Machupicchu hydropower plant in the Urubamba river.

Jardim, . et al., 2020; Carolina Rocha Lessa et al., 2015; Passaia et al., 2020; De Souza et al., 2017) assess altered river regimes using indicators of hydrologic alteration or ecoflow. In the Pangor basin (Ecuador), changes in streamflow in the last decades (1963–2009) have been mostly linked to anthropogenic disturbances rather than direct climatic impacts due to substantial land cover changes (Molina et al., 2015). For the Peruvian Andes, only a few studies address hydrological alteration (Castello and Macedo, 2016; Ochoa-Tocachi et al., 2016; Vega-Jácome et al., 2018). Nevertheless, not all basins indicate major changes in streamflow due to land cover changes, as the Vilcanota-Urubamba river basin highlights. Here, less than 3% (1988–2001) and 6% (2001–2014) can be attributed to land cover changes with projections that suggest minor land cover changes below 1% for the next fifteen years (2030) (Aybar, 2016). To our knowledge, no studies exist for the Central Andes that examine hydrological alteration combining IHA and ecoflow methods to identify changes in the flow regime under hydropower regulation. In this study we address this gap by analyzing precipitation and discharge trends using indicators of hydrologic alteration and ecoflow for natural (1965–1987) and altered (1988–2016) flow regime series in the Vilcanota-Urubamba river basin (Southern Peru) to understand the drivers of hydrological change and provide useful information for future water resource planning.

2. Materials and methods

2.1. Study area

The Tropical Andes are home to more than 99% of all tropical glaciers in the world, of which around 70% are located in Peru (Condom et al., 2012; Rabatel et al., 2013; Yarleque et al., 2018). These glaciers have been subject of several studies to understand the possible consequences of glacier retreat on current and future water availability (Drenkhan et al., 2019; Kronenberg et al., 2016; Mark et al., 2017; Sagredo and Lowell, 2012). The Vilcanota mountain range is the second largest glacierized mountain range in Peru with an approximate glacier surface of about 255 km^2 in 2016, which has decreased by 48% since 1962 (INAIGEM, 2018). Glaciers in the upper Vilcanota feed the Vilcanota-Urubamba river basin (Fig. 1a) where glacier area has been reduced by 37% from 226 km^2 in 1988–142 km^2 in 2016. Consequently, glacier lakes have increased in area and number by about 16% and 18%, respectively, from 23 km^2 (460 lakes) in 1988–27 km^2 (544 lakes) in 2016 (Drenkhan et al., 2018). The lake Sibinacocha (dammed since 1988, Fig. 1b) drains into the Vilcanota-Urubamba river basin. Together with the Langui-Layo and Piuray lakes, Sibinacocha represents the main sources of water provision for human livelihoods, irrigation and energy production in the Cusco region (Salzmann et al., 2013; Drenkhan et al., 2019).

The Vilcanota-Urubamba river basin (Fig. 1a) covers an area of 9617 km^2 with an elevation range of 2136–6301 m asl. (Fernandez-Palomino et al., 2021). The climate is highly variable driven by complex orography. Precipitation distribution is highly seasonal, marked by a wet season in austral summer (November to March) when the Bolivian High generates easterly flow transporting moisture from the Amazon and a dry season in austral winter (April to October) due to strong westerlies (Drenkhan et al., 2018). At interannual timescale, ENSO represents an important driver of rainfall variability with dry conditions during warm phase (El Niño) events and an opposite behavior during the cold phase (La Niña) events (Rau et al., 2017; Rosas et al., 2016). However, the ENSO phenomenon and its feedback are not clearly understood and superimpose with other climatic features such as the Pacific Decadal Oscillation (PDO) (Vuille et al., 2008). In the study area, average annual precipitation accounts for of 749 mm (1985–2015) with about 80% of total rainfall occurring between the months of October to March which leads to a highly variable hydrological regime (Fernandez-Palomino et al., 2021).

Hydraulic and dam infrastructure has been established in the study basin (Fig. 2): (i) the Machupicchu I hydropower plant (Fig. 1c) was built in two stages with a total installed capacity of 107.2 MW, (ii) the Sibinacocha dam was constructed (located at 147 km southeast of the Cusco city and at an elevation of 4680 m asl.) in 1988 (formally inaugurated in June 1996) by the Energy Generation Company Machupicchu S.A. (EGEMSA) to guarantee the operation of the hydropower plant with a volume of 120 million m^3, (iii) the reconstruction of the Machupicchu II hydropower plant built in two phases with a total installed power of 192.45 MW (the debris flow in 1998 damaged the former hydropower plant), (iv) further downstream the Santa Teresa hydropower plant (Luz del Sur) started operation in 2015 with an installed capacity of 98 MW.

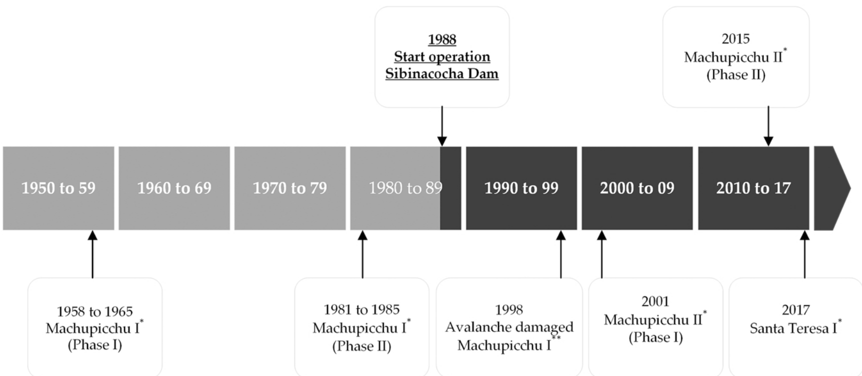

Fig. 2. Historical line of hydropower projects (*) and extreme flow event (**) developed in the study area.

2.2. Data

The flow and precipitation datasets (period: 1965–2016) used in this study belong to the National Hydrology and Meteorology Service of Peru (SENAMHI). The flow dataset corresponds to daily observations of the hydrometric station Km-105, which collects continuous data series in the lower Vilcanota-Urubamba river since 1964 (Fig. 1a). For lake Sibinacocha, daily outflow series are available from 1965 to 2020 provided by the Committee for Economic Operation of the Peruvian Interconnected Energy (COES, for its acronym in Spanish). The precipitation dataset for this study was obtained from monthly records of 19 rainfall stations, of which 12 stations are located in the study area and another seven stations in adjacent basins (Fig. 1a and Table 1). For the hydrological analysis, the flow and precipitation information was arranged considering the hydrological year from September (year i) to August (year i + 1), which matches with the beginning of the wet season.

2.3. Data processing

The flow and precipitation datasets were submitted to an exploratory data analysis (EDA) to summarize main data characteristics, and to detect outliers using univariate graphical techniques (histograms and boxplot). In addition, all precipitation information was quality-checked using a regional vector method (RVM) (Brunet-Moret, 1979). We selected the stations located in the study area, the quality of the stations was evaluated based on their correlation coefficient ($r^2>0.5$) and missing data were filled. To build the RVM, a minimum of three values per year/station and a minimum of three years in a station were required. The RVM assumes that annual rainfall in the same climate zone is pseudo-proportional, with a small random variation each year due to the rainfall distribution within the area (Villar et al., 2009). The RVM with the available data create a virtual station (vector) that is representative for the entire study area, under the concept of extended precipitation average (Rau et al., 2017). It uses the minimum squares method to find the yearly regional pluviometric indices Z_i and extended precipitation average *Pi*, through the following formula (Rau et al., 2017):

$$\sum_{i=1}^{N}\sum_{j=1}^{M}\frac{Pij}{Pi}-Z_i$$

Where; *i* is the year index, *j* is the station index, N is the number of years, and M is the number of stations. *Pij* is the annual precipitation for station *j* in the year *i*, *Pi* is the mean precipitation extended to the period of N years and $Z_i$is the regional pluviometric index for the year *i*.

Additionally, all monthly precipitation data was interpolated using an Inverse Distance Weighting (IDW) approach to estimate the mean areal precipitation of the Vilcanota-Urubamba basin river. Subsequently, the generated series were accumulated and precipitation anomalies were calculated using the difference of annual precipitation and the multiannual average of mean precipitation for each period.

2.4. Statistical analysis

The statistical analysis included (Table 2) the use of parametric tests, i.e. a linear regression (Montgomery et al., 2012) and Spearman Rho, and non-parametric tests, i.e. Man-Kendall (Mann, 1945; Kendall, 1955) and the distribution-free cumulative sum (McGilchrist and Woodyer, 1975). These tests were applied to determine the possible existence of statistically significant trends and the change-point in the flow and precipitation dataset, with significance confidence levels at 90%, 95%, and 99%. For the seasonal analysis, the data is organized in four quarters, i.e. September-November (SON), December-February (DJF), March-May (MAM), and

Table 1
Rainfall stations used in the study, the last column indicates the percentage of complete data between the years 1965–2016.

Station	Latitude	Longitude	Elevation (m asl.)	Available data (%)
Mollepata	-13.52	-72.55	2601	25.2
Calca	-13.33	-71.95	2926	51.3
Paucartambo	-13.32	-71.59	3042	76.9
Cay Cay	-13.60	-71.70	3150	97.3
Acomayo	-13.92	-71.68	3160	90.2
Pomacanchi	-14.03	-71.57	3200	52.6
Granja Kcayra	-13.56	-71.88	3219	98.4
Cusco	-13.54	-71.94	3288	49.4
Anta Ancachuro	-13.47	-72.22	3340	93.6
Perayoc	-13.52	-71.95	3429	12.2
Combapata	-14.10	-71.43	3464	56.3
Yucay	-13.30	-72.08	3481	27.7
Zurite	-13.47	-72.27	3506	33.3
Sicuani	-14.25	-71.24	3574	88.9
Urcos	-13.70	-71.63	3666	31.4
Ccatcca	-13.61	-71.56	3729	94.4
Colquepata	-13.36	-71.67	3729	99.2
Livitaca	-14.32	-71.68	3741	32.9
Chitapampa	-13.41	-71.97	4306	67.3

Table 2
Summary of the statistical analysis applied.

Statistical analysis	Equation	Description
Man-Kendall	$\sum_{i=1}^{n-1}\left[\sum_{j=i+1}^{n}\mathrm{sgn}(Ri-Ri)\right]$	n time series values (X_1, X_2, X_3, …., X_n) are replaced by their relative ranks (R_1, R_2, R_3,…., R_n) (starting at 1 for the lowest up to n).
Linear regression	$b=\frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sum_{i=1}^{n}(x_i-\overline{x})^2}$	Time (x) and the variable of interest (y).
Spearman Rho	$\rho=S_{xy}/(S_yS_x)^{0.5}S_x=\sum_{i=1}^{n}(X_i-\overline{X})^2Sy=\sum_{i=1}^{n}(Y_i-\overline{Y})^2S_{xy}=\sum_{i=1}^{n}(X_i-\overline{X})(Y_i-\overline{Y})$	Xi (time), Yi (variable of interest), x and y refer to the ranks ($\overline{X}$,$\overline{Y}$ Sx and Sy have the same value in a trend analysis).
Distribution-free cumulative sum	$V_k=\sum_{i=1}^{k}\mathrm{sgn}(x_i-x_{median})$	Time series data (X_1, X_2, X_3, …., X_n).

June-August (JJA) to average flow and a cumulative volume for precipitation are calculated. For the annual analysis, the totalized precipitation and the average flow were estimated using the hydrological year. Additionally, we considered the maximum (AMMAX) and minimum (AMMIN) average monthly flow.

2.5. Hydrologic alteration

One of the most robust approaches to determine hydrologic alteration is the specific comparison of pre-impact (natural) and post-impact (altered) flow data (McManamay et al., 2012). The natural period was defined based on the water resources management projects implemented in the study area (Fig. 2) considering 1965–1987 as a natural period and 1988–2016 as the altered period. Therefore, the ecoflow method and the IHA indicators were used to characterize and quantify the hydrological change of the flow regime in the Vilcanota-Urubamba river basin.

2.5.1. Ecoflow

In this study, we used the ecoflow method based on non-dimensional measurements of ecodeficit (i.e. the amount of water that is needed but unavailable for ecological flow) and ecosurplus (i.e. the amount of water that exceeds the ecosystem requirement), which are constructed using flow duration curves (FDCs) (Gao et al., 2012, 2018). The FDCs were estimated based on the daily flow record of VRB, and provide a measure of the percentage of time duration during which a specific flow equals or exceeds a value. The Qi flow is graphed with the corresponding excess probability Pi, calculated by the following formula:

$$p_i=\frac{i}{(n+1)}$$

Where; i is the rank (position) corresponding to each flow after being arranged in descending order and n is the total number of days.

Therefore, annual and seasonal FDCs (Fig. 3) of each year were estimated to analyze changes in the flow regime. The FDCs for the natural period (1965–1987) were used to obtain the 25th and 75th percentile FDCs. For the annual ecoflow, ecosurplus is defined as the area between the 75th percentile FDC and the annual FDC, which occurs when the FDC of a given year is above the 75th percentile

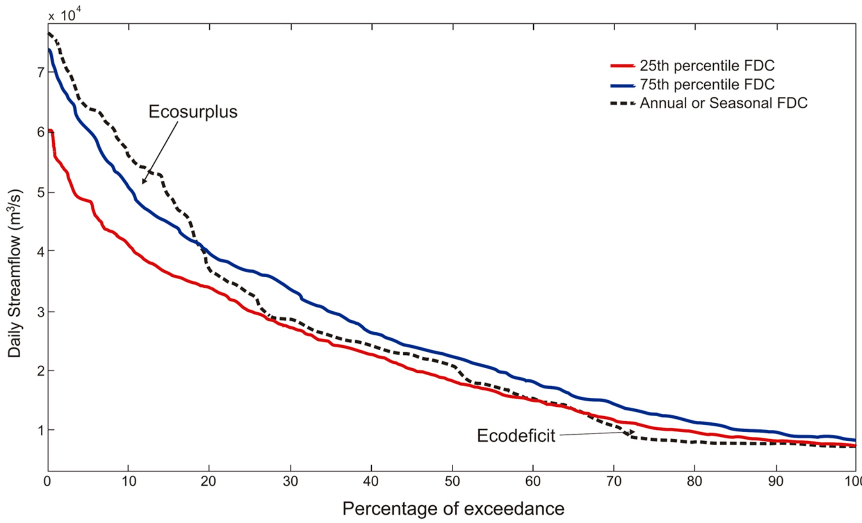

Fig. 3. Definition of ecoflow according to Gao et al., (2012, 2018) based on a flow duration curve (FDC).

FDC. Conversely, when the FDC is below the 25th percentile FDC, the area between the 25th percentile FDC and the annual FDC is defined as the ecodeficit. For the seasonal ecoflow, we proceeded similarly to the annual ecoflow assessment, with the difference that the accumulated values of quarterly periods were considered. All ecodeficit and ecosurplus values were divided by the annual average or seasonal flow to make them non-dimensional. The ecosurplus represents the amount of water in excess (gain), and the ecodeficit corresponds to the amount of water that is not available (loss) due to the alteration of the flow regime.

2.5.2. Indicators of Hydrologic Alteration

The Indicators of hydrologic alteration (IHA) were formulated by Richter et al. (1996) to compare the inter- and intraannual variation of the flow regime. They include 33 parameters (Table 3) lumped into five groups: (i) magnitude of monthly hydrological conditions, (ii) magnitude and duration of annual hydrological extreme conditions, (iii) date of annual extreme hydrological conditions, (iv) frequency and duration of high and low pulses, and (v) rate and frequency of changes in hydrological conditions. We used the software IHA (TNC, 2009) to compare the hydrological series before (natural period) and after (altered period) the construction of the reservoir. All parameters were included in the analysis except for the days with zero-flow conditions that did not occur in the study period. We adopted a presumptive standard with a moderate level of ecological protection (flow changes ranging from 10% to 20%) established by Richter et al. (2011).

Finally, in order to assess the changes in the flows during the natural and altered period with respect to the total flows, the anomalies were determined at monthly scale expressed as:

$$Anomaly(\Delta) = evaluationperiod - referenceperiod$$

Where; Δ is the anomaly expressed in m^3/s; evaluation period is the natural and altered flow in m^3/s and the reference period is the average flow of the entire series in m^3/s.

3. Results

3.1. Data analysis

The flow boxplot at seasonal level shows a symmetric distribution (Fig. 4a) with some atypical values (e.g. 1100 m^3/s) (Fig. 4b). These values represent the extreme hydrological events that occurred in January 2010 due to various consecutive days of precipitation (Lavado et al., 2010). Based on this technical support, all the historical flow data were considered. Daily discharge in the study area is highly variable, with a minimum of 20 m^3 /s in the dry season and up to 1100 m^3/s in the wet season (1985–2016 period). Km-105 station shows an unimodal seasonal flow regime (Fig. 4a), with high flow during December-April, and low flow in the remaining months. Fig. 5 shows the amplitude range of annual and seasonal precipitation per year. The annual precipitation ranges from 466 mm to 934 mm. During MAM, precipitation varies from 73 mm to 257 mm. In SON, precipitation ranges from 53 to 215 mm. JJA (DJF) shows the lowest (highest) values of precipitation between 1 and 60 mm (208–542 mm).

3.2. Statistical analysis

Annual and DJF precipitation series show significant positive trends at 95% and 99% confidence level for all applied tests (Table 4). Analyzed flow changes show an increasing trend of maximum and minimum flows of the Vilcanota-Urubamba river basin (Table 5). This trend was also detected during SON at 90% (Mann-Kendall) and at 95% (Spearman Rho) confidence level, and during JJA at 99% confidence level for all statistical tests. Clear changes in the mean for the AMMIN, AMMAX, SON, and JJA flows were detected in the hydrological years 1997–98 (99%), 1998–99 (90%), 1978–79 (90%), and 1988–89 (99%), respectively.

Table 3
Summary of the different hydrological parameters that comprise the Indicators of Hydrologic Alteration (IHA).

Group	Description	Hydrological indicators
Group 1	Magnitude of monthly flow (12)	Mean value for each calendar month (January, February, March, April, May, June, July, August, September, October, November and December)
Group 2	Magnitude and duration of annual extreme flows and base flow condition (11)	Annual minimum 1-day, annual minimum 3-day, annual minimum 7-day, annual minimum 30-day, annual minimum 90-day; annual maximum 1-day, annual maximum 3-day, annual maximum 7-day, annual maximum 30-day, annual maximum 90-day; mean base flow index.
Group 3	Timing of annual extreme flow conditions (2)	Julian date of annual 1-day minimum; julian date of annual 1-day maximum
Group 4	Frequency and duration of high and low Pulses (4)	Number of low pulses each year; mean duration of low pulse with each year; number of high pulses each year; mean duration of high pulse with each year.
Group 5	Rate and frequency of flow changes (3)	Rise rate; fall rate; number of flow reversals.

Notes: Adapted from (Richter et al., 1996).

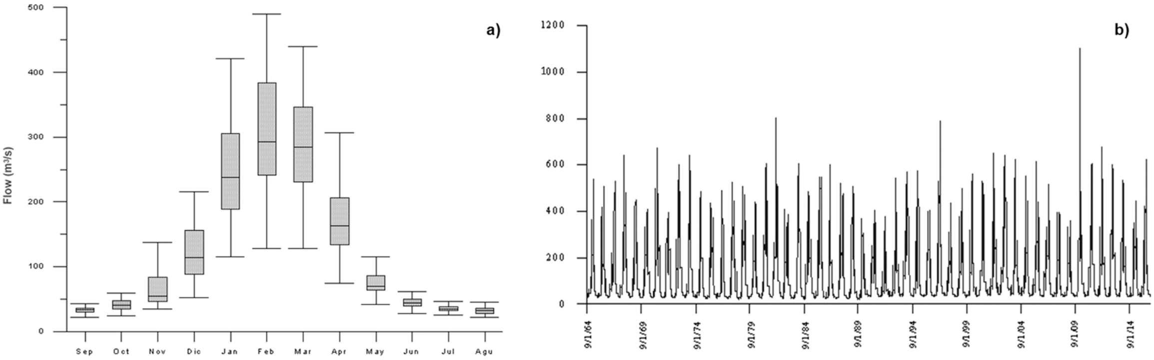

Fig. 4. a) Flow boxplot and b) interannual flows of Vilcanota-Urubamba river basin (1965–2016).

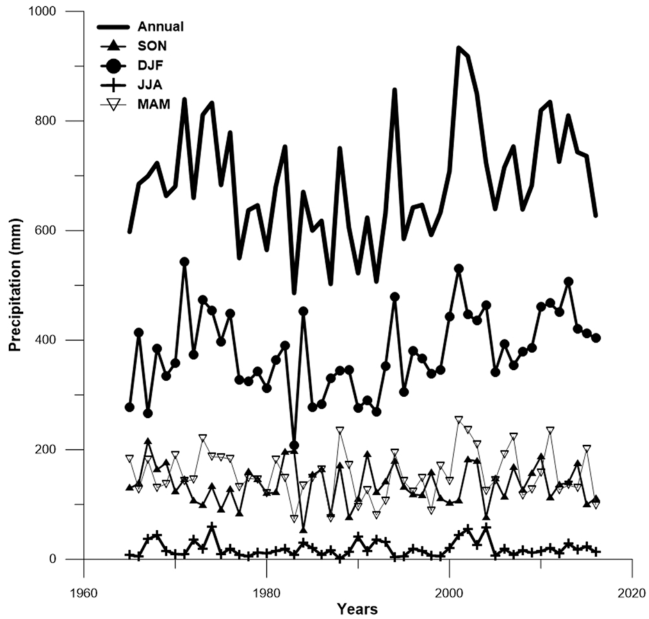

Fig. 5. Amplitude range of the annual and seasonal precipitation of the Vilcanota-Urubamba river basin (1965–2016).

Table 4
Observed precipitation trend changes and change-point for parametric (c,b) and non-parametric tests (a,d).

	Mann-Kendall[a]	Spearman Rho[b]	Linear Regression[c]	Cusum[d]
Annual	(+) **S*** *	(+) **S*** *	(+) **S*** *	**1998–99** * *
SON	NS	NS	NS	
DJF	(+) **S*** **	(+) **S*** **	(+) **S*** **	**1998–99** * **
MAM	NS	NS	NS	
JJA	NS	NS	NS	

Notes: * ** confidence level at 99%, * * confidence level at 95%, * confidence level at 90%. S: Significant, NS: No Significant, December-January-February (DJF), b) March-April-May (MAM), c) June-July-August (JJA) and d) September-October-November (SON).

3.3. Hydrologic alteration

3.3.1. Ecoflow

At the interannual scale, ecoflow analysis revealed (Fig. 6) a temporal variation in low annual flows (ecodeficits) that matches with negative anomalies of average annual precipitation in most years and it is opposite in other years. However, in some years, large ecodeficits are not justified by minor negative precipitation anomalies. The high annual flows (ecosurplus) show a relatively different behavior, not strictly associated with positive precipitation anomalies. This behavior could particularly be observed between 1999 and

Table 5
Observed flow trend changes and change-point for parametric (c,b) and non-parametric tests (a,d).

	Mann-Kendall[a]	Spearman Rho[b]	Linear Regression[c]	Cusum[d]
Annual	NS	NS	NS	
AMMIN	(+) **S*** **	(+) **S*** **	(+) **S*** **	**1997–98** * **
AMMAX	(+) **S***	(+) **S*** *	(+) **S*** *	**1998–99** *
SON	(+) **S***	(+) **S*** *	NS	**1978–79***
DJF	NS	NS	NS	
MAM	NS	NS	NS	
JJA	(+) **S*** **	(+) **S*** **	(+) **S*** **	**1988–89** * **

Notes: * ** confidence level at 99%, * * confidence level at 95%, * confidence level at 90%. S: Significant, NS: No Significant, December-January-February (DJF), b) March-April-May (MAM), c) June-July-August (JJA) and d) September-October-November (SON), maximum (AMMAX) and minimum (AMMIN) average monthly flow

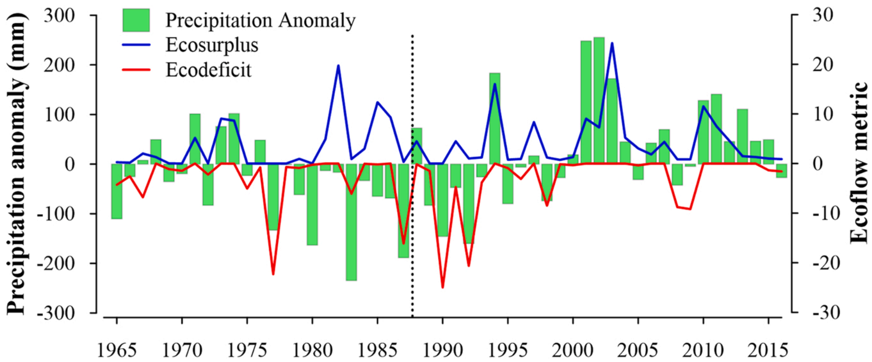

Fig. 6. Relationship between annual ecoflow and precipitation anomalies The dotted line indicates the separation of the natural and altered periods.

2000 and in a lower degree some years after (2003–2005, 2008–2009, and 2012). For the natural period 1981–1986, high annual flows (ecosurplus) were observed which did not match the precipitation anomalies for the same period. This mismatch could suggest an error during the data flow collection. Nonetheless, all flow data recorded during 1981–1986 was considered for the analysis since information with a record length of at least twenty years is required for evaluation of both, the natural and altered period. Moreover, Km-105 was the only hydrometric station that provided flow data in the study area before the construction of the Sibinacocha dam.

At the seasonal scale, Fig. 7a and b show the changes in the ecoflow for DJF and MAM. Ecodeficits occurred in most years with variable magnitudes related to negative precipitation anomalies, and more ecodeficits during the altered period were observed particularly in MAM. Ecosurplus values were smaller in magnitude, without notable variation between the compared periods (natural and altered flow), following positive precipitation anomalies. In JJA and SON (Fig. 7c and d) a lower number of ecodeficit occurred during the altered period than in the natural period, while the predominance of ecosurplus is observed since 1988 (altered period), which is not related to the values of precipitation anomalies. Overall, in the altered period, the low flows (ecodeficits) are most likely associated with negative rainfall anomalies in DJF and MAM, while high flows (ecosurplus) which occurred during JJA and SON, are likely related to the operation of the Sibinacocha dam.

3.3.2. Indicators of hydrologic alteration

At the interannual scale, an average increase of 5.3 m^3/s from June to November and an average reduction of 35.2 m^3/s from January to February were observed for the altered period (1988–2016) compared to the natural period (1965–1987). Table 6 shows the percentage of change of the 32 IHA parameters.

For monthly flow (group 1), a positive change between 12% and 27% was observed from July to November. This trend matches with the ecosurplus presented in Fig. 7c and d, which cannot be explained by precipitation regime (Fig. 8). For December, a flow increase (+7%) can be observed, while ecodeficit with considerable flow reduction can be found for January (−18.4%) and February (−7.4%) (Fig. 7a). Between March and May the change ratios were positive and in the range of + 2.1% to + 7.1%. For the extreme flows condition (Group 2), there was an increase in the percentage number of days of minimum flow with an absolute variation higher than 10%. The timing of annual extreme flow conditions (Group 3) showed a variation in the date of maximum and minimum flows occurrence during the altered period. In the frequency and duration of high and low pulses (Group 4), a reduction in extreme low flow events was observed in terms of duration and frequency for the altered period, while extreme high flow events increased their frequency but reduced their duration. The rate and frequency of flow changes (Group 5) decreased due to lower increase in flows during the high flow events.

Finally, the Sibinacocha outflow series were used to validate the influence of the dam on river discharge at Km-105 (Fig. 9a). Before the lake was dammed in 1988, high lake outflows occurred during January-March (peak outflow: 6.0 m^3/s in January) and low

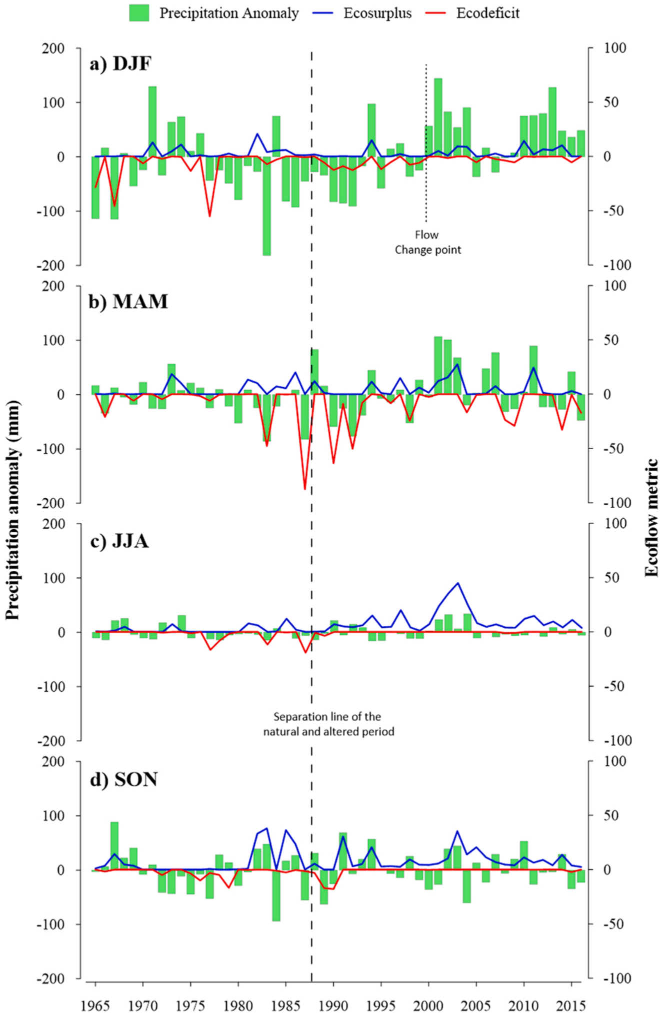

Fig. 7. Seasonal ecoflow and precipitation anomalies for the four quarters a) December-January-February (DJF), b) March-April-May (MAM), c) June-July-August (JJA) and d) September-October-November (SON).

outflows during July-September (minimum outflow: 0.8 m^3/s in September). Conversely, this behavior reversed after 2002, with high lake outflows during July-November (peak outflow: 6.27 m^3/s in September) and low outflows during December-June (minimum outflow: 0.37 m^3/s in March), following river flow regulation to meet the demand for the Machupicchu and Santa Teresa hydropower plants. In addition, monthly flow anomalies at Km-105 were computed for the entire period (1965–2016) based on parameter group 1 of Table 6. The anomalies for the period before the construction of the dam (1965–1987) were positive during January-April (peak anomaly: 7.1 m^3/s in January), and negative from May to October (minimum anomaly: −4.9 m^3/s in August). This flow pattern clearly changed for the altered period (1988–2016) with positive anomalies prevailing from May to September and December (peak anomaly: 4.2 m^3/s in August) and negative anomalies from January to April (minimum anomaly: −6.0 m^3/s in January). These patterns are consistent with observed outflows at Sibinacocha dam (Fig. 9a).

4. Discussion

This study analyzes the hydrological impact of dam regulation on hydropower production in a high-mountain basin in southern Peru. Based on instrumental precipitation records (period 1965–2016), our data suggest that annual and wet season (DJF) precipitation has increased since 1998–99 (Table 4). These findings stand in contrast to the results of Salzmann et al. (2013), who observed a decreasing precipitation trend for the Vilcanota region during the period 1965–2009. However, the comparability between both studies is limited due to the different number of stations considered (a total of 19 stations in this research compared to only one station in the other study). Furthermore, the analyzed precipitation trends in the Andes often lack strong significance (cf. Salzmann et al., 2014) and do not show clear unique patterns (Arias et al., 2021; Rabatel et al., 2013; Vuille et al., 2003) due to large spatial variability and limited process understanding. Results need therefore to be carefully revised. We also observed strong negative precipitation

Table 6
Changes in IHAs for the natural (1965–1987) and altered (1988–2016) period, the percentage changes expressed in bold represent changes in ± 10%.

Parameters IHA	1965–1987	1988–2016	**Change**
Group of parameters 1	**(m^3/s)**		**%**
September	28	35.5	**26.8**
October	33.6	40.2	**19.5**
November	47.9	53.5	**11.7**
December	94.3	100.8	7.0
January	263	214.7	**-18.4**
February	299.3	277.2	-7.4
March	279	285	2.2
April	153	157	2.6
May	65.5	70.2	7.2
June	42.9	43.8	2.0
July	31.5	36.4	**15.6**
August	27.6	34.2	**23.8**
Group of parameters 2	**(m^3/s)**		**%**
1-day minimum	25.5	31.9	**24.9**
3-days minimum	25.8	32.1	**24.2**
7-days minimum	26	32.7	**25.9**
30-days minimum	27.5	33.8	**22.7**
90-days minimum	34.7	37.9	9.2
1-days maximum	525.3	542.8	3.3
3-days maximum	490.7	504.2	2.8
7-days maximum	428.1	458.7	7.2
30-days maximum	347.2	364.7	5.0
90-days maximum	283.8	286.2	0.9
Base flow index	0.23	0.26	
Group of parameters 3	**(Julian Days)**		
Date of minimum	244	238	
Date of maximum	55	52	
Group of parameters 4			
Low pulse count	4	2	
Low pulse duration	8.5	2.3	
High pulse count	4	5	
High pulse duration	7.5	5	
Group of parameters 5			
Rise rate	5	4.2	**-16.0**
Fall rate	-2.6	-2.8	9.0
Number of reversals	117	128	9.4

Notes: Numbers in bold indicate changes greater than 10%.

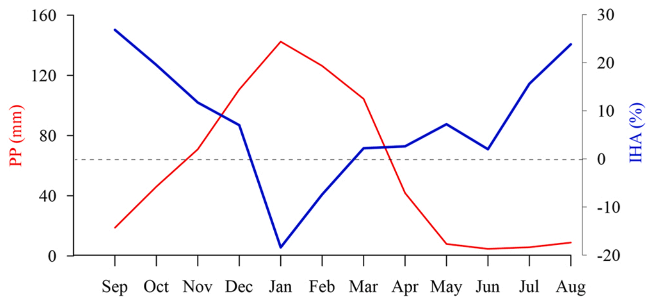

Fig. 8. Seasonal precipitation and percentage flow changes between the altered period (1988–2016) and the natural period (1965–1987).

anomalies for the hydrological years 1980, 1983, and 1987 and high positive anomalies during 2001–2003 several of which match with pronounced ENSO events (Fig. 6). The influence of ENSO on precipitation patterns in the Vilcanota mountain range was previously analyzed by Perry et al. (2014) using in-situ stations and satellite information. They concluded that precipitation would likely decrease during La Niña events and increase during El Niño events, which represent a distinct pattern compared to other Andean regions, such as the Cordillera Blanca further north (Vuille et al., 2008). This particular pattern in the Vilcanota region could be associated to the influence of coupled climatic-oceanic processes, including changes in the tropical Atlantic sea surface temperature (Lavado Casimiro et al., 2013; Rau et al., 2017). Our results follow this pattern indicating an increase in the flow during the hydrological year 1997–1998 that matches with a strong El Niño event.

Table 5 shows the flow trend and change-point in the study area for 1965–2016. The observed change-point for the AMMAX in the

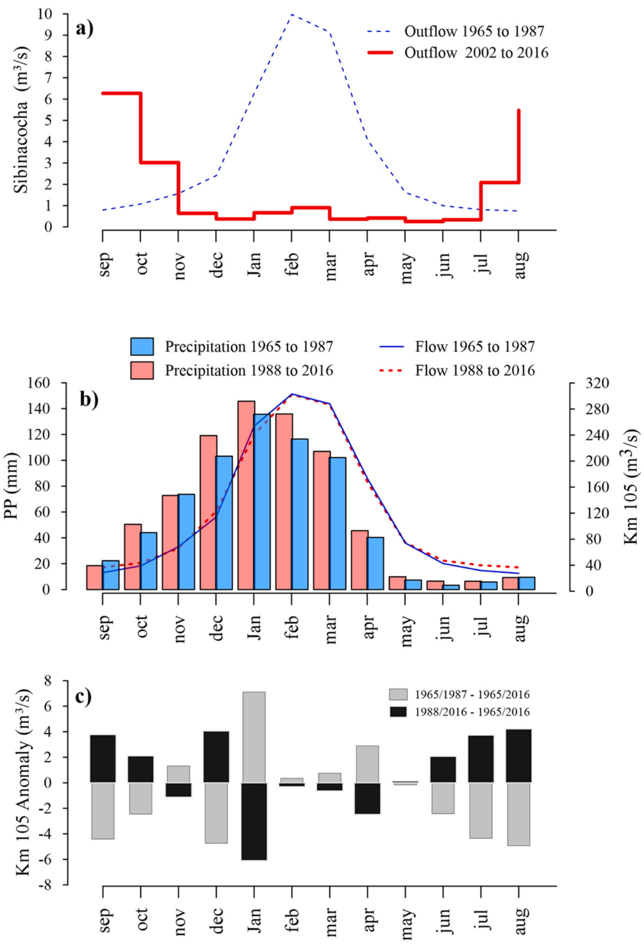

Fig. 9. a) Comparison of flows before Sibinacocha dam operation (1965–1987) and flows from 2002 to 2016, b) comparison of basin average precipitation and flows in "Km-105" station before (1965–1987) and after (1988–2016) Sibinacocha dam operation, c) flow anomalies in "Km-105" station before (1965–1987) and after (1988–2016) Sibinacocha dam operation, with respect to reference period (1965–2016).

hydrological year 1998–99 is related to a positive precipitation trend at 90% confidence found during DJF (Table 4). Changes in mean flow in the hydrological year 1978–79 (90% confidence) during SON are attributed to precipitation variability. This mean change was also displayed in 5-year moving average curves of SON flow and precipitation (result not shown in the paper), which exhibited strong negative anomalies during 1968–1978 in both variables. Our findings suggest that dam operation was the main factor that controlled the hydrological flow regime variability in the Vilcanota-Urubamba river basin. As from 1988 to 89 when dam operation had started, we found a significant increasing trend of dry season (JJA) flow despite of distinct precipitation patterns (Fig. 8) in line with Drenkhan et al. (2015), who reported positive (non-significant) discharge anomalies for the period 1958–2013. Considerable flow increase during the dry season is associated with increasing water release to meet drinking, irrigation, and hydroelectric water demand. Additionally, the average precipitation during the altered period (Fig. 9b) reveal an increase by more than 10 mm between December and February, that might influence the baseflow. Fernandez-Palomino et al. (2021) found important baseflow contribution to the water yield, which confirms the role of baseflow, and the contribution of groundwater on the modulation of the flow regime during the dry season.

For this study, the relatively short precipitation records, including inconsistent or missing data, that represent a limitation to fully understand precipitation trends and related impacts on river flow in this region. Similarly, we found inconsistency in flow data. Annual high-flow anomaly (ecosurplus) observed between 1981 and 1986 (natural period) most likely corresponds to inhomogeneities related to flow data collection or calibration errors. Nonetheless, we decided to use the entire dataset, as Km-105 represents the only gauge in the study area with a minimum series of > 20 years of daily flow data, which is a necessary benchmark to evaluate significant alteration in the hydrological regime. These data limitations reveal a clear need for a well-established and strategically distributed network of in-situ stations that increases our understanding of the flow regime and its potential changes in view of the combined impacts from climate change and human interventions. Such an effort is necessary for urgently needed robust development of future scenarios of water resource changes in the Vilcanota-Urubamba river basin to support local decision-making and climate change adaptation. New data collection strategies are required that use alternative, often more flexible and cost-effective approaches such as low-cost sensor technology, participatory monitoring and frameworks that deal with high uncertainties (Drenkhan et al., 2022; Muñoz et al., 2021).

Our results of hydrological alteration induced by dams are in line compared to other studies in the Andes region (Vega-Jácome et al., 2018) and beyond (Li et al., 2020; Pfeiffer and Ionita, 2017; Yin et al., 2020). Low and high flows were altered (Group 2) since 1-day, 3-day, 7-day, and 30-day minimum flows increased by more than 20%. Similar to this, 1-day, 3-day, 7-day, weekly, monthly and 3-monthly maximum flow statistics increased by up to 7%. This low flow increase is related to the increase in monthly mean flows (Group 1) during the dry season (JJA). We also observed a reduction in the low flow pulses (Group 4) for both counts and duration during the post-dam period, possibly associated with the release of water during the dry season. Our results highlight that the major changes in the flow regimen of the Vilcanota-Urubamba river basin were rather related to the increase of flows during the dry season (JJA) than to precipitation changes as shown in Fig. 7c, Table 6 (Group 1) and Fig. 8. These results show a divergence between precipitation and flows in the Vilcanota-Urubamba river basin due to the regulation of the basin associated with the operation of the dam (1988). In this study, we have not assessed the associated ecological impacts downstream due to dam operation and hydrological alteration. Richter et al. (2011) affirm that if is not possible to establish a relationship between hydrological alterations and possible ecological impacts; instead, it is possible to adopt a ̈presumptive standard ̈ ranging from 10% to 20% (moderate level of ecological protection) of hydrologic alteration, beyond which there may be relevant impacts on ecological functions. Based on this criterion, the hydrological changes identified in the Vilcanota-Urubamba river basin may generate ecological impact. More studies need to confirm this hypothesis, however only a limited body of studies includes impacts of hydrological changes on biological communities (e.g. Ochoa-Tocachi et al., 2016), and none of them cover our study area. Future studies require to integrated biota response and river ecosystems to these alterations, including their relationship with e.g. the morphology, nutrient cycling, sediment transport, groundwater, the risk of climate change and flow variability. A better grasp of such responses and processes combined with robust approaches to address uncertainties would allow for developing more meaningful future water availability scenarios to improve water and energy security in the Peruvian Andes. Understanding the hydrologic alteration of streamflow is therefore important to design appropriate strategies for improved water resources management and ecosystem conservation. An integrated evidence-based scientific approach is necessary that tackles with social-environmental risks concerning environmental degradation, climate change and socio-economic development (Drenkhan et al., 2022) associated with the construction and management of dams. Such an approach must support decision-making to promote infrastructure projects that have minimal impacts on natural ecosystems while maximizing future options for sustainable water and energy use.

5. Conclusions

This study evaluated for the first time a combined assessment of streamflow alteration as a consequence of hydropower regulation in the Vilcanota-Urubamba river basin, Southern Peru. Our multi-decadal (1965–2016) analysis of interannual flow variability (ecoflow method) highlights that at seasonal timescale an ecodeficit of about 20% (compared to average natural river flow) occurred during the wet season (DJF) as a result of water storage regulation of Lake Sibinacocha during the altered period (1988–2016). Meanwhile, an ecosurplus of $> 30\%$ (compared to average natural river flow) predominated during the dry season (JJA), as a result of additional lake water outflow for hydropower production in absence of rainfall in the altered period.

Our analysis confirms that the operation of Lake Sibinacocha was the main factor of hydrological flow regime alteration in the Vilcanota-Urubamba river basin during the dry season (JJA).

These findings provide useful insights for local and regional water resource planning and adaptation given combined and increasingly adverse impacts from climate, land use, and land cover changes. However, there an evident lack of data collection and limited knowledge hampers a detailed process understanding to conduct systematic research on hydrological alteration in the Peruvian Andes. These limitations are further exacerbated by challenges of complex hydrometeorological processes linked to high spatial and temporal gradients and variability.

Our approach compares the performance of two methods (Indicators of Hydrologic Alteration and ecoflow) and shows that both are complementary and effective in evaluating the water regime in a regulated high-Andean basin. Therefore, this methodology provides a reference for assessing hydrological alteration in Peru and beyond with similar basin conditions. This framework may be used as a case to develop a standard procedure of ecological flow regime estimation applied to other river basins in the region.

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CRediT authorship contribution statement

Cinthya Bello: Conceptualization, Data curation, Methodology, Software, Formal analysis, Writing – original draft. **Wilson Suarez:** Conceptualization, Visualization, Supervision, Writing – review & editing. **Fabian Drenkhan:** Supervision, Writing – review & editing. **Fiorella Vega:** Methodology, Software, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101319.

References

Almeida, R.M., Hamilton, S.K., Rosi, E.J., Barros, N., Doria, C.R.C., Flecker, A.S., Fleischmann, A.S., Reisinger, A.J., Roland, F., 2020. Hydropeaking operations of two run-of-river mega-dams alter downstream hydrology of the largest amazon tributary. Front. Environ. Sci. 8, 120. https://doi.org/10.3389/fenvs.2020.00120.

Anderson, E.P., Jenkins, C.N., Heilpern, S., Maldonado-Ocampo, J.A., Carvajal-Vallejos, F.M., Encalada, A.C., Rivadeneira, J.F., Hidalgo, M., Cañas, C.M., Ortega, H., Salcedo, N., Maldonado, M., Tedesco, P.A., 2018. Fragmentation of Andes-to-Amazon connectivity by hydropower dams. Sci. Adv. 4, 1–7. https://doi.org/10.1126/sciadv.aao1642.

Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P.W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R.P., Armour, K., Bala, G., Barimalala, R., Berger, S., Canadell, J.G., Cassou, C., Cherchi, A., Collins, W., Collins, W.D., Connors, S.L., Corti, S., Cruz, F., Dentener, F.J., Dereczynski, C., Di Luca, A., Diongue Niang, A., Doblas-Reyes, F.J., Dosio, A., Douville, H., Engelbrecht, F., Eyring, V., Fischer, E., Forster, P., Fox-Kemper, B., Fuglestvedt, J.S., Fyfe, J.C., Gillett, N.P., Goldfarb, L., Gorodetskaya, I., Gutierrez, J.M., Hamdi, R., Hawkins, E., Hewitt, H.T., Hope, P., Islam, A.S., Jones, C., Kaufman, D.S., Kopp, R.E., Kosaka, Y., Kossin, J., Krakovska, S., Lee, J.-Y., Li, J., Mauritsen, T., Maycock, T.K., Meinshausen, M., Min, S.-K., Monteiro, P.M.S., Ngo-Duc, T., Otto, F., Pinto, I., Pirani, A., Raghavan, K., Ranasinghe, R., Ruane, A.C., Ruiz, L., Sallée, J.-B., Samset, B.H., Sathyendranath, S., Seneviratne, S.I., Sörensson, A.A., Szopa, S., Takayabu, I., Tréguier, A.-M., van den Hurk, B., Vautard, R., von Schuckmann, K., Zaehle, S., Zhang, X., Zickfeld, K., 2021. In: Zhai, V., P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–144. https://doi.org/10.1017/9781009157896.002.

Aybar, C. 2016. Modelamiento de la escorrentía en cuencas de montaña: caso de estudio río Vilcanota. Tesis de pregrado, Universidad Nacional Mayor de San Marcos, Facultad de Ingeniería Geológica, Minera, Metalúrgica y Geográfica, Escuela Profesional de Ingeniería Geográfica. Repositorio institucional Cybertesis UNMSM. 〈https://hdl.handle.net/20.500.12672/5936〉.

Berga, L., 2016. The role of hydropower in climate change mitigation and adaptation: a review. Engineering 2, 313–318. https://doi.org/10.1016/J.ENG.2016.03.004.

Bhaduri, A., Subramanian, S.V., Green, P.A., Tickner, D., Parker, H., Moncrieff, C.R., Oates, N.E.M., Ludi, E., Acreman, M., 2017. Managing rivers for multiple benefits-a coherent approach to research, policy and planning, 5, 1–8 Front. Environ. Sci. |. https://doi.org/10.3389/fenvs.2017.00004. 〈www.frontiersin.org〉, 5, 1–8.

Bhaduri, A., Ringler, C., Dombrowski, I., 2015. Rabi Mohtar & Waltina Scheumann (2015) Sustainability in the water-energy-food nexus 40, 5–6. https://doi.org/10.1080/02508060.2015.1096110.

Bird, J., Wallace, P., 2001. Dams and development - an insight to the report of the world commission on Dams. Irrig. Drain. 50, 53–64. https://doi.org/10.1002/ird.11.

Black, A.R., Rowan, J.S., Duck, R.W., Bragg, O.M., Clelland, B.E., 2005. DHRAM: a method for classifying river flow regime alterations for the EC Water Framework Directive. Aquat. Conserv. Mar. Freshw. Ecosyst. 15, 427–446. https://doi.org/10.1002/aqc.707.

Boelens, R., Shah, E., Bruins, B., 2019. Contested knowledges: large dams and mega-hydraulic development. Water 11, 1–27. https://doi.org/10.3390/w11030416.

Brismar, A., 2002. PROFILE River Systems as Providers of Goods and Services: A Basis for Comparing Desired and Undesired Effects of Large Dam Projects 29, 598–609. https://doi.org/10.1007/s00267–001-0058–3.

Brunet-Moret, Y., 1979. Homogénéisation des précipitations. Cah. L'ORSTOM Série Hydrol. 16, 147–170.

Caceres, A.L., Jaramillo, P., Matthews, H.S., Samaras, C., Nijssen, B., 2021. Hydropower under climate uncertainty: characterizing the usable capacity of Brazilian, Colombian and Peruvian power plants under climate scenarios. Energy Sustain. Dev. 61, 217–229. https://doi.org/10.1016/j.esd.2021.02.006.

Carey, M., French, A., O'Brien, E., 2012. Unintended effects of technology on climate change adaptation: an historical analysis of water conflicts below Andean Glaciers. J. Hist. Geogr. 38, 181–191. https://doi.org/10.1016/j.jhg.2011.12.002.

Carey, M., Molden, O.C., Rasmussen, M.B., Jackson, M., Nolin, A.W., Mark, B.G., 2016. Impacts of Glacier Recession and Declining Meltwater on Mountain Societies. https://doi.org/10.1080/24694452.2016.1243039.

Carolina Rocha Lessa, A., Aurélio dos Santos, M., Edwin Lewis Maddock, J., dos Santos Bezerra, C., 2015. Emissions of greenhouse gases in terrestrial areas pre-existing to hydroelectric plant reservoirs in the Amazon: the case of Belo Monte hydroelectric plant. Renew. Sustain. Energy Rev. 51, 1728–1736. https://doi.org/10.1016/j.rser.2015.07.067.

Castello, L., Macedo, M.N., 2016. Large-scale degradation of Amazonian freshwater ecosystems. Glob. Chang. Biol. 22, 990–1007. https://doi.org/10.1111/gcb.13173.

Chala, G.T., Ma'Arof, M.I.N., Sharma, R., 2019. Trends in an increased dependence towards hydropower energy utilization—a short review. Cogent Eng. 6, 1–14. https://doi.org/10.1080/23311916.2019.1631541.

Christer, N.A.R.C., Mats, D., Carmen, R., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308 (80), 405–408. https://doi.org/10.1126/science.1107887.

Condom, T., Escobar, M., Purkey, D., Pouget, J.C.J.C., Suarez, W., Ramos, C., Apaestegui, J., Tacsi, A., Gomez, J., 2012. Simulating the implications of glaciers' retreat for water management: a case study in the Rio Santa basin, Peru. Water Int. 37, 442–459. https://doi.org/10.1080/02508060.2012.706773.

De Souza, N.C.R., Fontes, A.S., da Luz, L.D., Pinheiro, S.M.C., 2017. Identificação do grau de impacto de barragens sobre o regime hidrológico em rios do semiárido: Uma avaliação do método DHRAM. Rev. Bras. Recur. Hidr. 22. https://doi.org/10.1590/2318-0331.011716093.

De Souza Dias, V., Pereira Da Luz, M., Medero, G.M., Tarley, D., Nascimento, F., 2018. An Overview of Hydropower Reservoirs in Brazil: Current Situation, Future Perspectives and Impacts of Climate Change. Water 5, 1–18. https://doi.org/10.3390/w10050592.
Drenkhan, F., Carey, M., Huggel, C., Seidel, J., Oré, M.T., 2015. The changing water cycle: climatic and socioeconomic drivers of water-related changes in the Andes of Peru. Wiley Interdiscip. Rev. Water 2, 715–733. https://doi.org/10.1002/wat2.1105.
Drenkhan, F., Guardamino, L., Huggel, C., Frey, H., 2018. Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes. Glob. Planet. Change 169, 105–118. https://doi.org/10.1016/j.gloplacha.2018.07.005.
Drenkhan, F., Huggel, C., Guardamino, L., Haeberli, W., 2019. Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin. Sci. Total Environ. 665, 465–483. https://doi.org/10.1016/j.scitotenv.2019.02.070.
Drenkhan, F., Buytaert, W., Mackay, J.D., Barrand, N.E., Hannah, D.M., Huggel, C., 2022. Looking beyond glaciers to understand mountain water security. Nat. Sustain. https://doi.org/10.1038/s41893-022-00996-4.
Fernandez-Palomino, C.A., Hattermann, F.F., Krysanova, V., Vega-Jácome, F., Bronstert, A., 2021. Towards a more consistent eco-hydrological modelling through multi-objective calibration: a case study in the Andean Vilcanota River basin, Peru. Hydrol. Sci. J. 66, 59–74. https://doi.org/10.1080/02626667.2020.1846740.
Finer, M., Jenkins, C.N., 2012. Proliferation of hydroelectric dams in the andean amazon and implications for andes-amazon connectivity. PLoS One 7, 1–9. https://doi.org/10.1371/journal.pone.0035126.
Gao, B., Yang, D., Zhao, T., Yang, H., 2012. Changes in the eco-flow metrics of the Upper Yangtze River from 1961 to 2008. J. Hydrol. 448–449, 30–38. https://doi.org/10.1016/j.jhydrol.2012.03.045.
Gao, B., Li, J., Wang, X., 2018. Analyzing changes in the flow regime of the yangtze river using the eco-flow metrics and IHA metrics. Water 10, 1–27. https://doi.org/10.3390/w10111552.
Garreaud, R.D., 2009. The Andes climate and weather. Adv. Geosci. 22, 3–11. https://doi.org/10.5194/adgeo-22-3-2009.
Gioia, C.J., 1987. The great waterways project of South America. Proj. Apprais 2, 243–250. https://doi.org/10.1080/02688867.1987.9726637.
IHA, 2022. IHA's 2021–2022 Annual Report chronicles key achievements from a landmark year. (London, United Kingdom).
INAIGEM, 2018. Informe de la situacion de los glaciares y ecosistemas de montaña. Huaraz.
Jardim, P.F., Melo, M.M.M., Ribeiro, L., de, C., Collischonn, W., Paz, A.R. da, 2020. A modeling assessment of large-scale hydrologic alteration in south american pantanal due to upstream dam operation. Front. Environ. Sci. 8, 1–15. https://doi.org/10.3389/fenvs.2020.567450.
Jiang, C., Zhang, Q., Luo, M., 2019. Assessing the effects of the Three Gorges Dam and upstream inflow change on the downstream flow regime during different operation periods of the dam. Hydrol. Process. 33, 2885–2897. https://doi.org/10.1002/hyp.13535.
Keeler, B., Polasky, S., Brauman, K., Johnson, K., Finlay, J., ONeill, A., Kovacs, K., Dalzell, B., 2012. Linking water quality and well-being for improved assessment and valuation of ecosystem services. Proc. Natl. Acad. Sci. 109, 18619–18624. https://doi.org/10.1073/pnas.1215991109.
Kendall, M.G., 1955. Rank correlation methods. Rank correlation methods, second ed..,. Hafner Publishing Co., Oxford, England.
Kronenberg, M., Schauwecker, S., Huggel, C., Salzmann, N., Gurgiser, W., Kaser, G., Drenkhan, F., Frey, H., Gir, C., Ayros, E., Perry, B., Rohrer, M., 2016. The projected precipitation reduction over the Central Andes may severely a ff ect Peruvian glaciers and hydropower production. Energy Procedia 97, 270–277. https://doi.org/10.1016/j.egypro.2016.10.072.
Larsen, M.A.D., Petrovic, S., Engström, R.E., Drews, M., Liersch, S., Karlsson, K.B., Howells, M., 2019. Challenges of data availability: analysing the water-energy nexus in electricity generation. Energy Strateg. Rev. 26, 1–14. https://doi.org/10.1016/j.esr.2019.100426.
Lavado, W., Silvestre, E., Pulache, W., 2010. Tendencias en los extremos de lluvias cerca a la ciudad del Cusco y su relación con las inundaciones de enero del 2010. Rev. Peru. Geo Atmosférica RPGA 2, 89–98.
Lavado Casimiro, W.S., Labat, D., Ronchail, J., Espinoza, J.C., Guyot, J.L., 2013. Trends in rainfall and temperature in the Peruvian Amazon-Andes basin over the last 40years (1965-2007). Hydrol. Process 27, 2944–2957. https://doi.org/10.1002/hyp.9418.
Li, M., Liang, X., Xiao, C., Zhang, X., Li, G., Li, H., Jang, W., 2020. Evaluation of reservoir-induced hydrological alterations and ecological flow based on multi-indicators. Water 12, 1–17. https://doi.org/10.3390/w12072069.
Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13, 245–259. https://doi.org/10.2307/1907187.
Mark, B.G., French, A., Baraer, M., Carey, M., Bury, J., Young, K.R., Polk, M.H., Wigmore, O., Lagos, P., Crumley, R., McKenzie, J.M., Lautz, L., 2017. Glacier loss and hydro-social risks in the Peruvian Andes. Glob. Planet. Change 159, 61–76. https://doi.org/10.1016/j.gloplacha.2017.10.003.
McGilchrist, C.A., Woodyer, K.D., 1975. Note on a distribution-free CUSUM technique. Technometrics 17, 321. https://doi.org/10.2307/1268068.
McManamay, R.A., Orth, D.J., Dolloff, C.A., 2012. Revisiting the homogenization of dammed rivers in the southeastern US. J. Hydrol. S. 424–425, 217–237. https://doi.org/10.1016/j.jhydrol.2012.01.003.
MINEM, 2015. Evoluciones en el Sector Eléctrico 1995 - 2015 (Lima, Peru).
MINEM, 2022. Anuario estadistico de electricidad (Lima, Peru).
Molina, A., Vanacker, V., Brisson, E., Mora, D., Balthazar, V., 2015. Multidecadal change in streamflow associated with anthropogenic disturbances in the tropical Andes. Hydrol. Earth Syst. Sci. 19 (10), 4201–4213. https://doi.org/10.5194/hess-19-4201-2015.
Montgomery, D., Peck, E., Vining, G., 2012. Introduction to Linear Regression Analysis, fifth ed. Wiley, New Jersey.
Moran, E.F., Lopez, M.C., Moore, N., Müller, N., Hyndman, D.W., 2018. Sustainable hydropower in the 21st century. Natl. Acad. Sci. 115, 11891–11898. https://doi.org/10.1073/pnas.1809426115.
Muñoz, R., Huggel, C., Drenkhan, F., Vis, M., Viviroli, D., 2021. Comparing model complexity for glacio-hydrological simulation in the data-scarce Peruvian Andes. J. Hydrol. Reg. Stud. 37, 1–17. https://doi.org/10.1016/j.ejrh.2021.100932.
Ochoa-Tocachi, B.F., Buytaert, W., De Bièvre, B., Célleri, R., Crespo, P., Villacís, M., Llerena, C.A., Acosta, L., Villazón, M., Guallpa, M., Gil-Ríos, J., Fuentes, P., Olaya, D., Viñas, P., Rojas, G., Arias, S., 2016. Impacts of land use on the hydrological response of tropical Andean catchments. Hydrol. Process. 30, 4074–4089. https://doi.org/10.1002/hyp.10980.
Passaia, O.A., Siqueira, V.A., Brêda, J.P.L.F., Fleischmann, A.S., de Paiva, R.C.D., 2020. Impact of large reservoirs on simulated discharges of brazilian rivers. Rev. Bras. Recur. Hidr. 25, 1–9. https://doi.org/10.1590/2318-0331.252020190084.
Perry, L.B., Seimon, A., Kelly, G.M., 2014. Precipitation delivery in the tropical high Andes of southern Peru: New findings and paleoclimatic implications. Int. J. Climatol. 34, 197–215. https://doi.org/10.1002/joc.3679.
Pfeiffer, M., Ionita, M., 2017. Assessment of hydrologic alterations in elbe and rhine rivers, Germany. Water 9, 1–18. https://doi.org/10.3390/w9090684.
Poveda, G., Espinoza, J.C., Zuluaga, M.D., Solman, S.A., Garreaud, R., van Oevelen, P.J., 2020. High impact weather events in the andes. Front. Earth Sci. https://doi.org/10.3389/feart.2020.00162.
Pringle, C.M., Freeman, M.C., Freeman, B.J., 2000. Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical–temperate comparisons. Bioscience 50, 807–823. https://doi.org/10.1641/0006-3568(2000)050[0807:REOHAO]2.0.CO;2.
Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J.L.L., Basantes, R., Vuille, M., Sicart, J.-E.E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Ménégoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M., Wagnon, P., 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. Cryosphere 7, 81–102. https://doi.org/10.5194/tc-7-81-2013.
Rakhmatullaev, S., Huneau, F., Coustumer, P., Le, Motelica-Heino, M., Bakiev, M., 2010. Facts and perspectives of water reservoirs in central asia: a special focus on Uzbekistan. Water 2, 307–320. https://doi.org/10.3390/W2020307.
Rau, P., Bourrel, L., Labat, D., Melo, P., Dewitte, B., Frappart, F., Lavado, W., Felipe, O., 2017. Regionalization of rainfall over the Peruvian Pacific slope and coast. Int. J. Climatol. 37, 143–158. https://doi.org/10.1002/joc.4693.
Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A Method For Assessing Hydrologic Alteration Within Ecosystems. Conserv. Biol. 10, 1163–1174. https://doi.org/10.2307/2387152.
Richter, B.D., Davis, M.M., Apse, C., Konrad, C., 2011. A presumptive standard for environmental flow protection. River Res. Appl. 28 (8), 1312–1321. https://doi.org/10.1002/rra.1511.

Rosas, G., Gubler, S., Oria, C., Acuña, D., Avalos, G., Begert, M., Castillo, E., Croci-Maspoli, M., Cubas, F., Dapozzo, M., Díaz, A., van Geijtenbeek, D., Jacques, M., Konzelmann, T., Lavado, W., Matos, A., Mauchle, F., Rohrer, M., Rossa, A., Scherrer, S.C., Valdez, M., Valverde, M., Villar, G., Villegas, E., 2016. Towards implementing climate services in Peru – the Project CLIMANDES. Clim. Serv. 4, 30–41. https://doi.org/10.1016/j.cliser.2016.10.001.

Sagredo, E.A., Lowell, T.V., 2012. Climatology of Andean glacieRs: A Framework to understand glacier response to climate change. Glob. Planet. Change 86–87, 101–109. https://doi.org/10.1016/j.gloplacha.2012.02.010.

Salzmann, N., Huggel, C., Rohrer, M., Silverio, W., Mark, B.G., Burns, P., Portocarrero, C., 2013. Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, southern Peruvian Andes. Cryosph 7, 103–118. https://doi.org/10.5194/tc-7-103-2013.

Timpe, K., Kaplan, D., 2017. The changing hydrology of a dammed Amazon. Sci. Adv. 3, 1–13. https://doi.org/10.1126/sciadv.1700611.

TNC, 2009. Indicators of Hydrologic Alteration User's Manual.

Vega-Jácome, F., Lavado-Casimiro, W.S., Felipe-Obando, O.G., 2018. Assessing hydrological changes in a regulated river system over the last 90 years in Rimac Basin (Peru). Theor. Appl. Climatol. 132, 347–362. https://doi.org/10.1007/s00704-017-2084-y.

Vergara, W., Deeb, A., Valencia, A., Bradley, R.S., Francou, B., Zarzar, A., Grünwaldt, A., Haeussling, S., 2007. Economic impacts of rapid glacier retreat in the Andes. Eos Trans. Am. Geophys. Union 88, 261–264. https://doi.org/10.1029/2007EO250001.

Villar, J.C.E., Ronchail, J., Guyot, J.L., Cochonneau, G., Naziano, F., Lavado, W., de Oliveira, E., Pombosa, R., Vauchel, P., 2009. Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador). Int. J. Climatol. 29, 1574–1594. https://doi.org/10.1002/joc.1791.

Vuille, M., Bradley, R.S., Werner, M., Keimig, F., 2003. 20th century climate change in the tropical Andes: Observations and model results. Clim. Change 59, 75–99. https://doi.org/10.1023/A:1024406427519.

Vuille, M., Kaser, G., Juen, I., 2008. Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation. Glob. Planet. Change 62, 14–28. https://doi.org/10.1016/j.gloplacha.2007.11.003.

Yarleque, C., Vuille, M., Hardy, D.R., Timm, O.E., De la Cruz, J., Ramos, H., Rabatel, A., 2018. Projections of the future disappearance of the Quelccaya Ice Cap in the Central Andes. Sci. Rep. 8, 1–11. https://doi.org/10.1038/s41598-018-33698-z.

Yin, X., Zhang, J., Chen, J., 2020. The Impact Of Multi-projects On The Alteration Of The Flow Regime In The Middle And Lower Course of the Hanjiang River, China. Water 12, 1–21. https://doi.org/10.3390/w12082301.

Zhang, Q., Gu, X., Singh, V.P., Chen, X., 2015. Evaluation of ecological instream flow using multiple ecological indicators with consideration of hydrological alterations. J. Hydrol. 529, 711–722. https://doi.org/10.1016/j.jhydrol.2015.08.066.