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ORIGINAL PAPER

Assessing hydrological changes in a regulated river system over the last 90 years in Rimac Basin (Peru)

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Abstract Hydrological changes were assessed considering possible changes in precipitation and regulation or hydraulic diversion projects developed in the basin since 1960s in terms of improving water supply of the Rimac River, which is the main source of fresh water of Peru's capital. To achieve this objective, a trend analysis of precipitation and flow series was assessed using the Mann-Kendall test. Subsequently, the Eco-flow and Indicators of Hydrologic Alteration (IHA) methods were applied for the characterization and quantification of the hydrological change in the basin, considering for the analysis, a natural period (1920–1960) and an altered period (1961–2012). Under this focus, daily hydrologic information of the "Chosica R-2" station (from 1920 to 2013) and monthly rainfall information related to 14 stations (from 1964 to 2013) were collected. The results show variations in the flow seasonality of the altered period in relation to the natural period and a significant trend to increase (decrease) minimum flows (maximum flows) during the analyzed period. The Eco-flow assessment shows a predominance of Eco-deficit from December to May (rainy season), strongly related to negative anomalies of precipitation. In addition, a predominance of Eco-surplus was found from June to November (dry season) with a behavior opposite to precipitation, attributed to the regulations and diversion in the basin during that period. In terms of magnitude, the IHA assessment identified an increase of 51% in the average flows during the dry season and a reduction of 10% in the average flows during the rainy season (except December and May). Furthermore, the minimum flows increased by 35% with shorter duration and frequency, and maximum flows decreased by 29% with more frequency but less duration. Although there are benefits of regulation and diversion for developing anthropic activities, the fact that hydrologic alterations may result in significant modifications in the Rimac River ecosystem must be taken into account.

1 Introduction

The construction of hydraulic infrastructures for different uses has modified the flow regime, and it has changed the sediment and nutrients transportation, has modified the habitats, and has perturbed the migration routes of the aquatic biota (World Resources Institute 2005). Considering that seasonality, magnitude, and natural frequency of flows have established evolutionary adaptations of river biota (Bunn and Arthington 2002), it is expected that anthropogenic alterations of flows significantly affect and damage the structure and functioning of the ecosystem (Marcarelli et al. 2010; Ashton 2012).

At a global level, various investigations have shown that the predominant sources of flow alterations due to anthropogenic causes were reservoirs, water intake, changes in soil use, and climate (Ashton 2012). In general, some findings suggest that dams equalize natural flow regimes over large areas (Poff et al. 2007), reducing maximum flows and flow variability, while minimum flows tend to increase (Pyron and Neumann 2008; Mittal et al. 2014). In addition, some reservoir simulation models have shown different regulation effects as in the systems regulated by individual reservoirs, in contrast to multi-reservoir systems, experimenting this last one an intensified accumulated perturbation (Mcmanamay 2014).

Fresh water availability for priority uses such as human consumption and agriculture is one of the major concerns related to climate change consequences. The increase of global

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temperature could accelerate the hydrologic cycle, leading to a change in the spatial and temporal distribution of water resources (Labat et al. 2004), including the decrease of flows variability (Mittal et al. 2014) and changes in the intra-annual regime of flows, especially with seasonal changes (Arnell 1999).

Many research studies related to hydrologic alterations due to anthropogenic activities (Yang et al. 2012; Gao et al. 2012; Belmar et al. 2013) or due to climate change effects (Kim et al. 2011; Lee et al. 2014; Mittal et al. 2014; González-Zeas et al. 2015), and considering both effects over streamflow trends (Abeysingha et al. 2016) have been currently published in different countries. The main results found were the following: Kim et al. (2011) analyzed alterations in flow regime of Han River in South Korea, as a consequence of climate change whose results showed that climate change would increase the flow variability, with major surface runoff at the end of the summer, resulting from an increase in precipitation during that season. Mittal et al. (2014) concluded that the flow regime change resulting from the construction of reservoirs would increase due to the climate change effects (precipitation decrease, temperature increase, and extreme events intensification) and González-Zeas et al. (2015) predicted a significant decrease in the water availability due to reduction of water inflows in the Spanish basin under climate change scenarios. On the other hand, the research of Gao et al. (2012), which compared the results of the annual and seasonal Eco-flow to those corresponding to Indicators of Hydrologic Alteration (IHA), concluded that the combination of both methods provides an efficient measure of the change in flow regime of the Yangtze River in China. Hydrological research in the tropical Andes has increased over the last decades (Célleri 2010), most of them related to land use changes in natural or regulated basins (Buytaert et al. 2006; Roa-García et al. 2011; Ochoa-tocachi et al. 2016). Although no existing scientific studies were found about the hydrology alterations on the Rimac Basin, the closest study related to hydrological response of a catchment is the one done by Ochoa-tocachi et al. (2016); this study analyzed the hydrology response under land use changes of the Huamantanga catchment, which is located in the neighboring basin called Chillon, in a bioma similar to the one found in the upper Rimac Basin (Dry Puna). The results showed that the Huamantanga catchment is overgrazed, and it exhibits visible flashy hydrological responses; likewise, during rainfall events, flows are considerably unstable, with frequent peaks, quickly dropping to low flows in a time span of a few days.

The Rimac Basin, located in the central coast of Peru, is the main water source to supply the demand of the capital Lima (the second largest desert city in the world, after Cairo (WWF Perú 2014) with a population of 8,751,741 inhabitants (in 2014) representing about 30% of the total population of Peru (INEI 2014). In addition, based on the statistics described by WWF Perú (2014) related to total water availability of the Rimac Basin, 80% is used to cover the demand for domestic

use in the province of Lima. In this context, it is important to know the temporary evolution of the flow regime variations of the Rimac River (SEDAPAL 2012).

Lavado Casimiro et al. (2012) described flow and precipitation trends in the basins of the Pacific watershed of Peru, stating that the Rimac Basin was subject to changes in the last 35 years showing significant positive trends in the minimum flows, as well as negative trends in precipitation (1964–2004). These discrepancies show the different relationships between precipitation and flows that could be a signal of hydrologic alteration. Furthermore, studies assessing the hydrologic response to climate change by simulation of future scenarios until 2050 estimate a possible increase in water availability in the Rimac Basin (Vergara et al. 2011). In spite of this possible increase, water availability is more likely to be shortage due to a future demographic increase in the Rimac River Basin (Buytaert and De Bièvre 2012).

Although the tropical Andes delivers an abundant and sustained supply of clean fresh water (Buytaert et al. 2006; Roa-García et al. 2011), based on the high water demand related to the Rimac Basin since 1960, regulating infrastructures and hydraulic diversions were implemented in order to ensure water provision to supply current and future demands of the region. However, no study assessing the consequences of these interventions in the hydrologic alteration of the Rimac River has been done up to date. Thus, the purpose of this article is to assess the variations of flow regime of the Rimac River characterizing, quantifying, and explaining the hydrologic alterations after the implementation of regulations and hydraulic diversion projects in the Rimac Basin.

Likewise, the present study focuses on the assessment of hydrological changes in the regulated system of the Rimac Basin, considering climatic and anthropogenic causes, this last one specifically referring to anthropic interventions in the basin through regulation and transfer. This study aims to evaluate the changes and trends in precipitation and flow during the last 90 years, characterizing, quantifying, and explaining the hydrologic alterations, after the implementation of the regulations and hydraulic diversion projects in the Rimac Basin, and finally, analyzing the Hydroclimatic change implications for the ecosystem in the Rimac River. It is also important to mention that it is not our intent to describe or predict biological responses to hydrologic alteration. Instead, we hope that this tool will facilitate investigations into the effects of regulating infrastructure on hydrologic river alteration.

1.1 Study area and data processing

The study area is the upper basin of the Rimac River (Fig. 1), located in the central coast of Peru (76°0′ to 76°45′ W and 11°25′ to 12°0′ S) where elevations range from 921 to 5585 m a.s.l. Politically, the study area is located in the province of
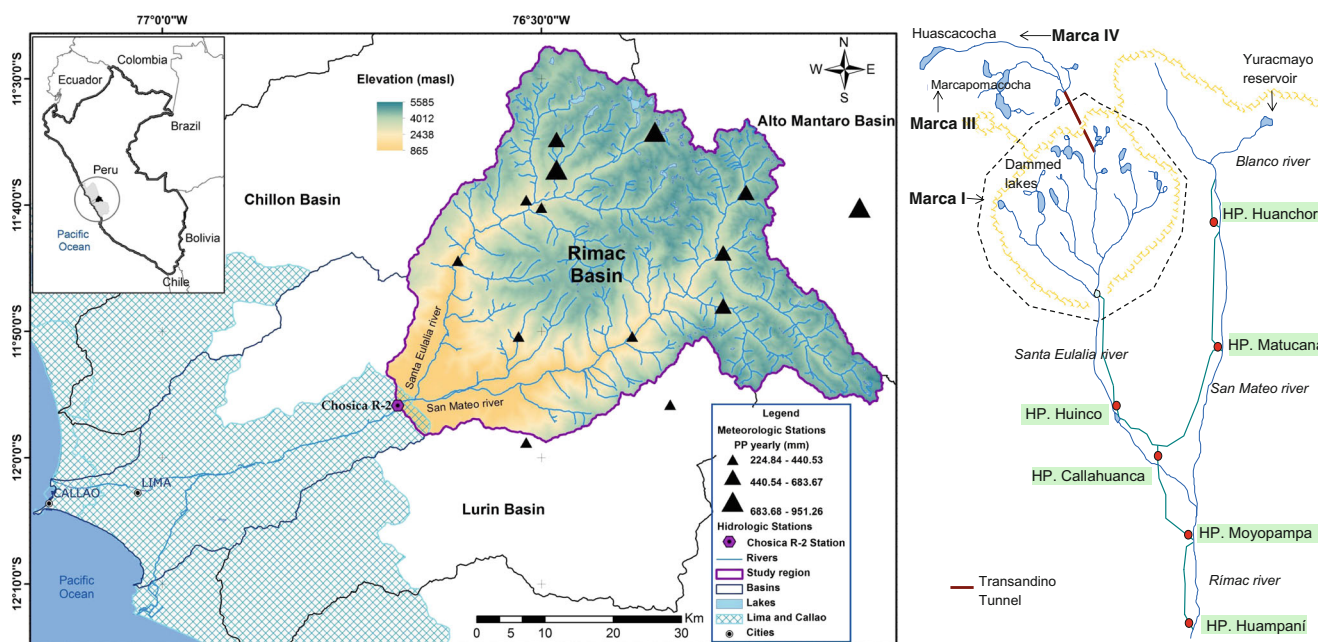
Fig. 1 Location of pluviometric stations and the hydrological station "Chosica R-2" in the study area (*left*), and outline of the spatial distribution of the infrastructure projects in Rimac Basin detailed in Fig. 2 (*right*)

Huarochirí, and a small part belongs to the provinces of Lima and Yauli in the departments of Lima and Junín, respectively.

The study area has a drainage area of 2303 km², and it is hydrographically located in the Pacific central watershed. The Rimac Basin is bounded by the Chillon River Basin to the north, the Mantaro and the Mala River Basins to the east, and the Lurin River Basin to the south. The upper basin of the Rimac River is composed of two subbasins denoted by the Santa Eulalia and the San Mateo River Basin, which join together near the city of Chosica (see Fig. 1) and form the Rimac River Basin. The Rimac River runs through the city of Lima and is the main source of water for this city, with the water abstraction system located downstream of the gauging station used in this study ("Chosica R-2").

The precipitation in the study area is characterized by a strong seasonality, with major precipitation from November to April, which is similar in the entire basin. In addition, there is a significant spatial variation with average values lower than 68 mm in the lower zone, and values over 848 mm in the upper zone resulting in a strong correlation between the precipitation and the altitudinal gradient of the basin.

Currently, in the Rimac Basin, the main source of water is the precipitation with an annual average of 512 mm (1964–2013) followed by scarce contribution from glaciers in the headwaters of the Rimac Basin. These water contributions are regulated by 15 lake reservoirs, Yuracmayo reservoir, hydraulic diversions, small lakes with a volume less than 0.25 MCM, and hundreds of natural springs and wetlands.

In the last century, the study area has changed in terms of land-use, caused mostly by the suburban sprawl and

consequently less cultivated areas and increase of economic activities located in the basin, basically artisanal mines and hydropower plants. The bigger hydrological changes were caused by different projects oriented to supply, storage, and use of hydrologic resources developed in the study area since 1930, but with a higher development after 1960 (Fig. 2). The outlined projects are (i) the Grathon Tunnel with 12 km long that has operated since 1962 in order to drain water lost due to filtration in the galleries of the mining companies operating in the zone. It has a maximum capacity of 10 m³/s and discharges an average of 5 m³/s, in low water periods (June–November); (ii) 15 lakes reservoirs in the upper zone of the subbasin of the Santa Eulalia River, with a total volume of 77 MCM, with 4 of the lakes regulated during 1920s to 1930s, representing around 9 MMC and two of these with the bigger volume were constructed during 1920s, representing around 6.4 MMC; (iii) the Transandino Tunnel with 10 km long, which transfers an average of 6 m³/s of water from Marcapomacocha Lake located in the neighboring Mantaro Basin to Milloc lake located in the Santa Eulalia subbasin (Marca I project, since 1966); (iv) the Yuracmayo reservoir operating since 1994 in the San Mateo subbasin with a capacity of 48 MCM; (v) diversions and regulations of the Marcapomacocha system with the enhancement of the Marca I project through the addition of water from two rivers from the Mantaro Basin, reaching a contribution capacity of 157 MCM (Marca III project); and (vi) the Huasacocha reservoir with a storage capacity of 48.6 MMC, whose outflows contribute with an average of 2.6 m³/s to increase water availability in Marca III system and consequently increase flow in Chosica R-2 station (Marca IV project) (see Figs. 1 and 2).

Fig. 2 Historic line of the projects developed in the study area. *Green bars* represent the Natural Period and *blue bars* the Altered Period
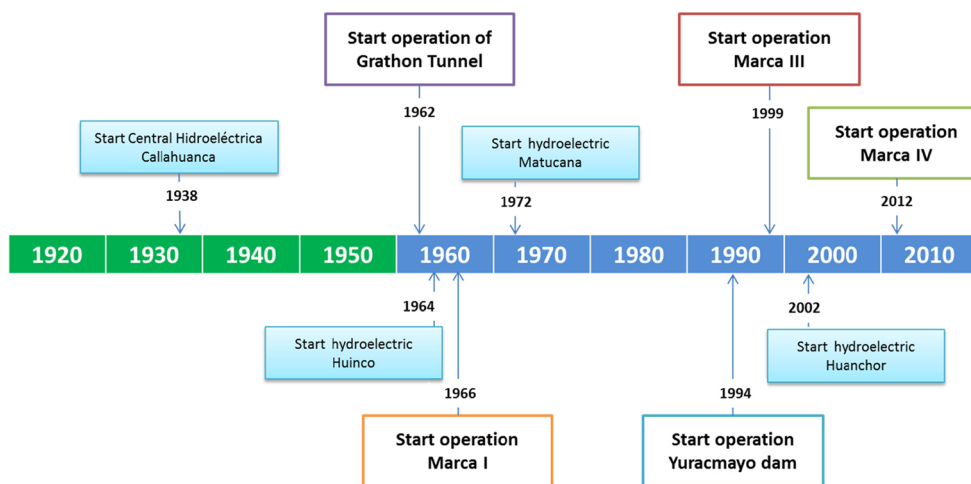
In addition, in the study area, there are six hydropower plants installed before (4) and after (2) Chosica R-2 gauging station, and these plants belong to private enterprises; therefore, it was not possible to have access to detailed information related to the outflow, but it is known that they use a near constant flow and the bigger of them ("Huinco") uses an inflow average of 11 m^3/s (see Fig. 1).

Concerning glaciers in the highest elevations of the study area, we found 12 glaciers belonging to La Viuda Mountain range over 4900 m a.s.l. with a current area of 6 km^2, which had a retreat of 23 km^2 from 1970 to 2007 (ANA-PERU 2012), with a noticeable retreat from 1970 to 1980 related to surface (Suarez et al. 2010).

Based on the information related to water resources management projects implemented in the study area (Fig. 2), 1920–1960 period was considered as a Natural Period, because it was the period with less interventions in the basin, and 1961–2013 was considered as the Altered Period.

The flow and precipitation datasets used in this study belong to the National Hydrology and Meteorology Service of Peru (SENAMHI). The flow dataset corresponds to the records of the hydrometric station called "Chosica R-2" that was chosen due to the fact that it collects water from the study area and its 94-year daily information record (1920–2013). Chosica R-2 has an automatic and a conventional station providing hourly information from the Rimac River discharges; the collection of the flow data is made by water level measurements converted into discharge using the rating curve, this last is estimated based on the measurements of discharge by a current meter using a cableway, considering a weekly frequency during dry season and once a month during rainy season, having a different rating curve for wet and dry season due to the particularities of both seasons. It is important to mention that the rating curve used is recalibrated yearly and the measurements procedures are based on the Guide to Hydrological Practices of the World Meteorological Organization. The precipitation dataset for this study was obtained from monthly records of 14 rainfall stations located in the study area with information available from 1964 to 2013. The rainfall stations selected for this study have monthly records with 70 to 95% of the series complete, and the gaps were filled using Regional Vector Method (RVM) (Hiez 1977; Brunet-Moret 1979) (Table 1); in the case of flow data, the record did not have gaps. In order to facilitate the hydrologic assessment, the flow and precipitation information was structured as water year: September (year$_i$)–August (year$_{i+1}$).

2 Methodology

2.1 Data processing

Both precipitation and flow dataset used in this study were subject to an exploratory data analysis (EDA), and in the case of the precipitation, the monthly series were filled before the interpolation. Regarding to precipitation, the Regional Vector Method and the outlier detection method were used for the EDA and the infilling was made by the RVM. A few outlier data were found, in which case the data was compared with the data of the nearest stations to verify the coherence, removing from the series the incoherent outliers. Additionally, precipitation data were infilled using stations from the neighboring basins, and based on the classification of the stations in groups done by the RVM, the stations were distributed into four groups (the group of each station is numbered in Table 1) and the infilling was made by month and by station in each group.

The basic idea of the RVM is the following: instead of comparing between stations by correlation or double mass, a fictional station (a vector) for all the stations of the area is created, which is compared with every station; to calculate this "vector station," the RVM applies the concept of extended precipitation average to the respective period. Under this concepts, it is used the minimum square method to find the yearly regional pluviometric indices "Zi" and extended precipitation average

Table 1 Pluviometric stations used in the present study (source: SENAMHI)

Station	Coordinates		P_{mean} (mm)	Elev. (m a.s.l.)
	Latitude (°S)	Longitude (°W)		
Autisha[1]	−11.735	−76.607	224.84	2171
Matucana[1]	−11.839	−76.378	283.08	2479
Canchacalla[1]	−11.845	−76.531	289.06	2554
Santiago de Tuna[1]	−11.983	−76.517	317.02	2921
Sheque[2]	−11.666	−76.499	440.53	3214
Carampoma[2]	−11.655	−76.515	401.46	3489
Rio Blanco[3]	−11.735	−76.259	523.48	3550
San José de Parac[3]	−11.800	−76.258	625.82	3866
Chalilla[4]	−11.933	−76.333	331.13	4050
Yauli[4]	−11.667	−76.083	951.26	4141
Tingo[4]	−11.617	−76.483	876.20	4200
Casapalca[4]	−11.648	−76.233	683.67	4214
Milloc[4]	−11.570	−76.350	911.33	4398
Mina Colqui[4]	−11.583	−76.483	673.94	4600

The number next to the name of the station represents the group to which belongs the station, based on RVM

P_{mean} multiannual mean precipitation of each station, *Elev.* elevation

"Pj," which is calculated by minimizing the expression in Eq. (1) (Hiez 1977; Vauchel 2005 for more detail about RVM).

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

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 in the j station in the year i, Pj is the mean precipitation extended to the period of N years and finally Zi is the regional pluviometric index for the year i.

Regarding flow dataset, several extreme values were found in the maximum annual series for the natural period (around 40 values, greater than 200 m³/s [75 percentile]). However, according to the results of the atypical data detection test of Grubbs (Barnett and Lewis 1984), none of those values were considered as atypical at 95% of confidence, so all flow data record was considered in the analysis.

2.2 Precipitation-flow changes and trends

Before analyzing changes and trends in precipitation, it was needed to estimate the mean areal precipitation of the Rimac Basin; for that purpose, the spatial interpolation technique was conducted by the Inverse Distance Weighted (IDW) method (Ware et al. 1991) based on the previously infilled monthly precipitation data of the 14 stations under analysis. Subsequently, the generated series were accumulated to obtain an annual series considering that the water year and the Mann–Kendall nonparametric test (Mann 1945; Kendall 1975) were used to analyze the trend of the series, comparing two periods:

the analyzed period of the research done by Lavado Casimiro et al.(2012) (1969–2004) and the analyzed period of this research (1964–2013) in order to assess the differences.

To estimate the precipitation anomalies, the differences between annual precipitation and multiannual average of the mean precipitation over the study area were calculated for the period of 1964–2012.

Concerning to flow changes, an analysis of monthly flow data during the period from 1920 to 2013 was made, considering the analysis of maximum, minimum, and average flow and its trends using Mann–Kendall test. Likewise, the intra-annual variation in flows was analyzed comparing the altered period with the natural period, through a multi-temporal average of the monthly flows in both periods.

Additionally to the independent analysis of precipitation and flow, an analysis was made to evaluate the precipitation–flow relationship, analyzing the trend for both series altogether and for the yearly runoff ratio (flow/precipitation); in both cases, it was used the Mann–Kendall test only for the period 1964–2012 considering the precipitation data availability, all this with the objective of analyzing the possible influence of climatic variability in flow alteration.

2.3 Hydrologic alteration

To assess the impact of the flow regime changes, it is necessary to analyze the indicators in order to understand the ecological health of the river and the degree of hydrologic alteration. Due to the complex nature of predicting hydrologic changes induced by the regulation of reservoirs, many approaches link the reservoir operation with downstream flows.

Most of these approaches are based on assessing the flow information based on periods before and after the construction of the reservoir (Richter et al. 1996; Gao et al. 2009; Mittal et al. 2014).

In this sense, the Eco-flow method described by Vogel et al. (2007) appears as a simple method to assess the flow regimen alteration, with a nondimensional measurement of Ecodeficit and Ecosurplus, but as this method uses duration curves, it cannot consider the time when a particular event occurs or its duration (Gao et al. 2012). In consequence, a complementary analysis with the use of the Indicators of Hydrologic Alteration method was needed, which has the capacity of quantifying the flow regime alteration (Richter et al. 1996).

Considering the abovementioned, this study used two methods to assess the variations in flow regime of the Rimac River: (i) the Eco-flow (Eco-surplus and Eco-deficit) and (ii) the estimation of the Indicators of Hydrologic Alteration (IHA).

2.3.1 Eco-flow

The Eco-flow (Gao et al. 2009) is based on the Eco-surplus and Eco-deficit estimation, and these measurements in turn were calculated considering flow duration curves (FDC).

The FDC were estimated based on the daily flow record of the Rimac River and provided a measurement of the time percentage during which a specific flow is equalized or exceeded. For this purpose, Qi flow is graphed versus the corresponding excess probability (pi). This last one was estimated based on Eq. (2):

$$p_i = i/(n + 1) \tag{2}$$

where i is the rank (position) corresponding to every flow after being organized in descending order and n is the total number of days. According to the abovementioned, the FDC were calculated for each year within the established period, based on the data corresponding to the water year and season (quarterly), as appropriate.

Regarding Eco-flow assessment, a natural period represented by the interval 1912 to 1960 was considered, because it was a period with the minimum disturbance resulting from the regulation and transfer activities in the basin (Fig. 2). An altered period represented by the interval 1961 to 2012 was also considered because it was a period influenced by regulating and diversion projects.

Once FDC were estimated for the natural period (1912–1960), 25 and 75 percentiles were calculated, considering the rank between both percentiles as the adaptation rank of river ecosystem. Then, each annual or seasonal FDC belonged to the altered period (1961–2012) were graphed over the 25 and 75 percentiles mentioned before, establishing the Eco-surplus as the area composed of each FDC over the 75 percentile and the Eco-deficit as the area composed of each FDC under 25 percentile. The values of Eco-surplus and Eco-deficit were divided by the annual average or seasonal flow, respectively, in order to estimate the percentage corresponding to Eco-surplus and Eco-deficit. Figure 3 shows an example of the Eco-flow estimation using the Rimac Basin flow record.

2.3.2 Indicators of Hydrologic Alteration

The IHA, developed by Richter et al. (1996), are used to characterize the intra and interannual flow variations, based on the five characteristics of the flow regimes: magnitude of monthly flows; magnitude and duration of annual extreme flows, date of annual extreme flows; frequency and duration of the high and low pulses; and the rate and frequency of flow changes (Mathews and Richter D. 2007).

The IHA were estimated using the IHA Software (Mathews and Richter D. 2007), considering a daily data record of flow (1920–2012) and taking into account the natural period (1912–1960). The IHA comprising 33 parameters are divided into five groups. Group #1 (12 parameters) is composed of the percentage change between natural period and altered period of monthly average flows. Group #2 (12 parameters) is composed of the changes in the days of minimum and maximum flow, estimated by mean of the moving average of appropriate length (1, 3, 7, 30, and 90 days), calculated for every possible period included within the water year, expressed by 1, 3, 7, 30, and 90 days of minimum and maximum flows, apart from the base flow index. Group #3 (2 parameters) is represented by the change in the date of minimum and maximum flow expressed in the number of days since January 1. Group #4 (4 parameters) shows the changes in the count and duration of high and low pulses, taking into account that 1 day will be considered as low pulse if it is lower than the median of the period less 25% (first quartile) or high pulse if it is higher than the median of the period plus 25% (third quartile). Finally, Group #5 (three parameters) shows how fast and frequent the flow increases or decreases based on the rise and fall rates by the number of reversals. For further information related to IHA, look at the IHA manual (The Nature Conservancy 2009).

2.4 Characterization of the drivers of trends in flow

In this section, changes in climate variables were evaluated in terms of its trends in time, focusing our analysis on precipitation. In addition, the results of other studies were used to evaluate the possible influence of temperature on the flow alteration found in the Rimac Basin.

Additionally, a complementary analysis of the transfer of water to the Rimac Basin was made using flow data collected

Fig. 3 Definition of Ecosurplus and Ecodeficit for Eco-flow analysis. Based on Rimac flow data for the year 1968, according to Gao et al. (2012)
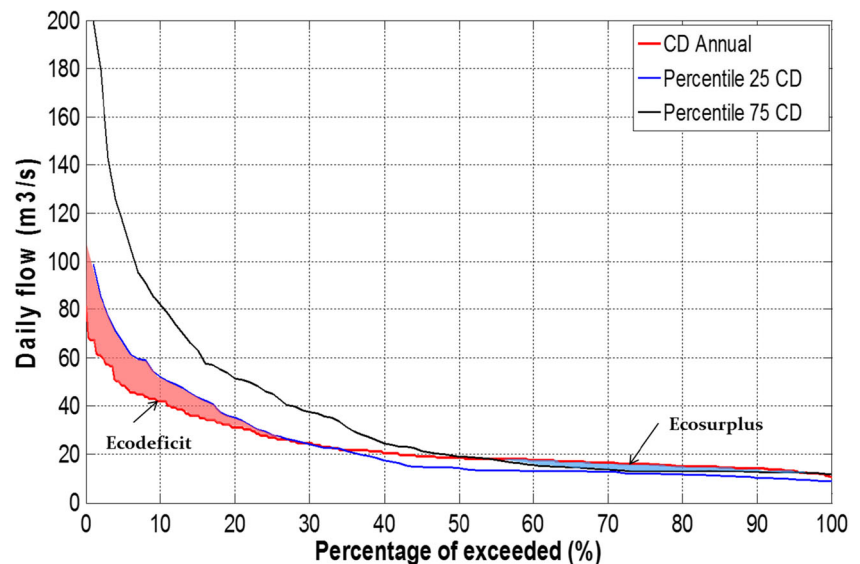
from the "Trasandino" tunnel outflow, evaluating the evolution and trends of inter basin water transfer.

2.5 Implications of Hydroclimatic change for the Rimac Basin Ecosystem

The implications of the Hydrologic alterations found in this study for the Rimac Basin Ecosystem were assessed based on the results of the seasonal Ecobalance analyzed with the precipitation anomalies and considering the knowledge available around the world about the general impacts of the flow regimen changes on ecosystems of rivers.

3 Results and discussion

3.1 Precipitation-streamflow changes and trends

3.1.1 Precipitation changes and trends

At interannual scale, the precipitation shows high variability over time, with years with low precipitation like 1989 and 1991 in terms of water years (Fig. 4). Also, it was found that since 2005, there is a signal of sustained increase in the magnitude of annual precipitation. This increase has influenced the significant positive trend at 90% of confidence found in the precipitation series for the study period of this research (1964–2013), in contrast with the significant negative trend for the period ranging from 1969 to 2004, reported by Lavado Casimiro et al. (2012). This difference shows how the strong interannual variability of the Andes precipitation can influence the trend signal. In addition, in the assessment of trends on a seasonal basis (DJF, MAM, JJA, SON) (not shown in the paper), the JJA months present a negative trend, while

the other seasons present significant positive trends at 90% of confidence.

3.1.2 Flow changes and trends

There was an evident intra-annual variation in the Rimac River flows during the altered period (1961–2012) in contrast to the natural period (1920–1960), with an average increase in flow by 8 m^3/s from June to November corresponding to the dry season and an average decrease in flow by 13 m^3/s from February to March corresponding to the rainy season, as a consequence of the regulation projects that have been implemented in the basin since 1962 (5 up to 2012). However, the seasonal behavior with the highest flows in March remains for both periods (Fig. 5).

Regarding the trend assessment of the median, minimum, and maximum flows of the Rimac River made by the Mann-Kendall test, a significant decreasing trend (negative) was identified in the maximum flows of the Rimac River, in contrast to the significant increasing trend (positive) in the minimum flows at a 99% of confidence, which matches the results of Lavado Casimiro et al. (2012). It was estimated an average change ratio per year of −0.7 m^3/s for the maximum flows and 0.1 m^3/s for the minimum flows. In addition, the median shows a significant increasing trend, with bigger variations in the altered period (Fig. 6). Also, in the case of the altered period, there was an increase of 37% in the minimum flows and an average reduction of 29% in the maximum flows, in comparison with the natural period.

In general terms, these results indicate the evolution of the minimum and maximum flows from 1920 to 2012, and the changes found were influenced by the regulation activities in the study area. It is also important

Fig. 4 Variation and trend (by water year) of precipitation. *Black line* is the linear trend for the period 1964 to 2012 and *gray line* is the linear trend for the period 1969–2004
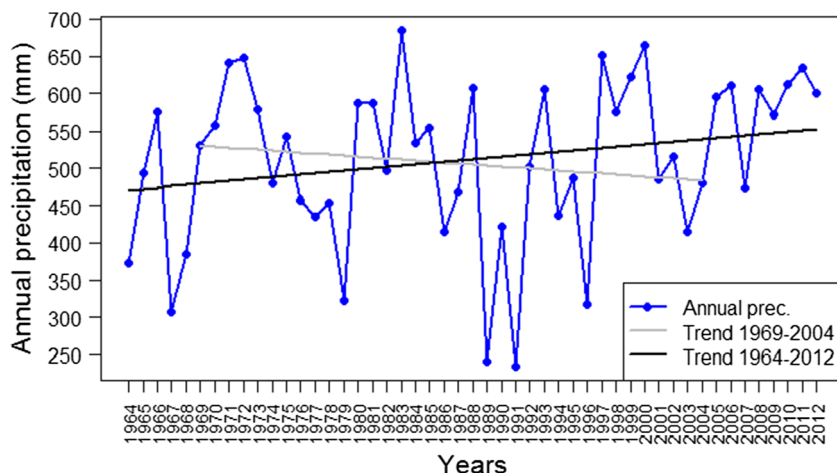
to note the low minimum and maximum flows from 1989 to 1991, which will be analyzed in the following items of this study.

3.1.3 Precipitation-flow relationship in the altered period

The relationship between precipitation and flow was estimated only in the altered period considering the precipitation data available (1964–2012 as hydrological year). Using determination coefficient, it was estimated that rainfall explain in 49% the flow at annual resolution. Additionally, in order to evaluate the interaction between precipitation and flow, the runoff coefficient (RC) (flow-precipitation ratio) was estimated for each year since 1964, considering the water year. Thus, Fig. 7 shows the time series of RC highlighting a positive not significant trend (0.02 of Sen Slope); also in this figure, it is shown that some years (1985, 1986 in greater extent and 2001, 2002) were found RC values over 1. These values indicate that in some years, the anthropic influence in the Rimac Basin was higher than in other years; more detailed analysis is presented in the next sections of this study.

3.2 Hydrologic alteration

3.2.1 Eco-flow

Inter-annual eco-flow assessment The long-term annual flow change assessment was made by the Eco-balance method (Fig. 8). Temporary variations in the annual low flows of the Rimac River (Ecodeficit) were found, related to the negative anomalies of average annual precipitation for the study area, considering 1964–2013 period. This relationship suggests that during the mentioned period, the negative balances in the annual flow are caused by a negative anomaly in precipitation. However, the annual high flows of Rimac River (Eco-surplus) show a behavior not related to the positive precipitation anomalies, in particular since the 1980s; this behavior would be explained by the regulation projects implemented during that period (mainly Marca III and Marca IV, see Fig. 2). Thus, it is reasonable to assume that in terms of transfer impacts on the flow regimen, the implementation of Marca I did not have as considerable impacts as the Marca III and Marca IV projects, considering an interannual scale.

Fig. 5 Intra-annual variability of the Rimac River flow for the natural period-NP (*black dotted line*) and the altered period -AP (*blue continuous line*)
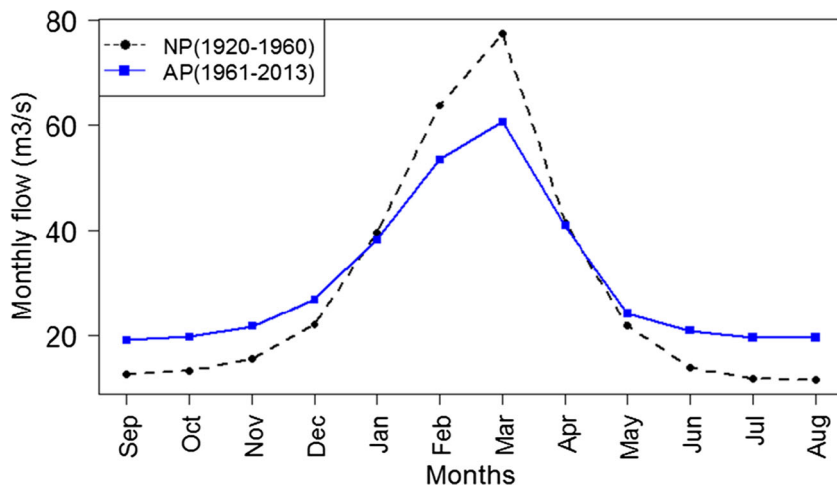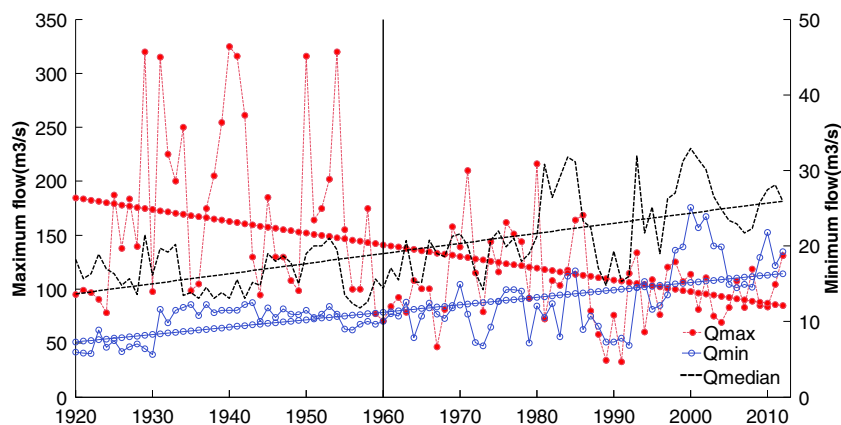
Fig. 6 Trends in maximum, minimum, and median flows in the Rimac River. The *vertical black line* represents the division between natural and altered period

Furthermore, it is important to state that the extremely low flows (1981 and 1991) are related to the significant negative anomalies of the precipitation in those years, indicating that until 2000, the basin low flows depended on the precipitation, which is analyzed in the following item at a seasonal timescale.

Complementarily, an Eco-surplus (ES) and Eco-deficit (ED) decadal statistical assessment was made (Fig. 9). The results showed that the high flow values (Eco-surplus) and its decadal variability have increased since 1970, while the low flows values and its variability have decreased, except the apparent variation in the 1980s and 1990s caused by a severe flow deficit from 1989 to 1991 and a moderate flow deficit from 1993 to 1994 (see Fig. 9).

Seasonal Eco-flow assessment Considering the dry season (June, July, and August—JJA; September, October, and November—SON) and the rainy season (December, January, and February—DJF; March, April, and May—MAM), the seasonal assessment identified the seasons of the year when the Eco-deficit and Eco-surplus appear more frequently (Fig. 10), and the corresponding boxplots complement this analysis (Fig. 11).

Since 1960 (altered period), it can be clearly observed that almost all ED appear in DJF and MAM (Fig. 10a, b) fully related to the negative precipitation anomalies. Also, during these seasons, ES are scarce and nearly related to the positive precipitation anomalies.

The opposite results were found in JJA and SON, with a clear increase and predominance of the ES since 1960 that are not related to little to null values of precipitation anomalies in JJA, and a different behavior between ES and the precipitation anomalies in SON, probably due to the major influence of the reservoirs management during these seasons (Fig. 10c, d).

It is important to highlight that in JJA and SON, there were two important time intervals, the first one (between 1960 and 1990) under the influence of Grathon Tunnel and Marca I infrastructure, with more variable ES and less magnitude in contrast to the second one (between 1991 and 2012), which had more stability and magnitude in the ES as a consequence of the implementation of the Yuracmayo dam, the Marca III, and Marca IV projects (see Fig. 2).

Also, the eco-flow boxplots at a seasonal level (Fig. 11) showed an evident high variability of the ES in DJF during the study period, with a minor variation from

Fig. 7 Runoff coefficient trend in the altered period.S.S.: Sen's Slope
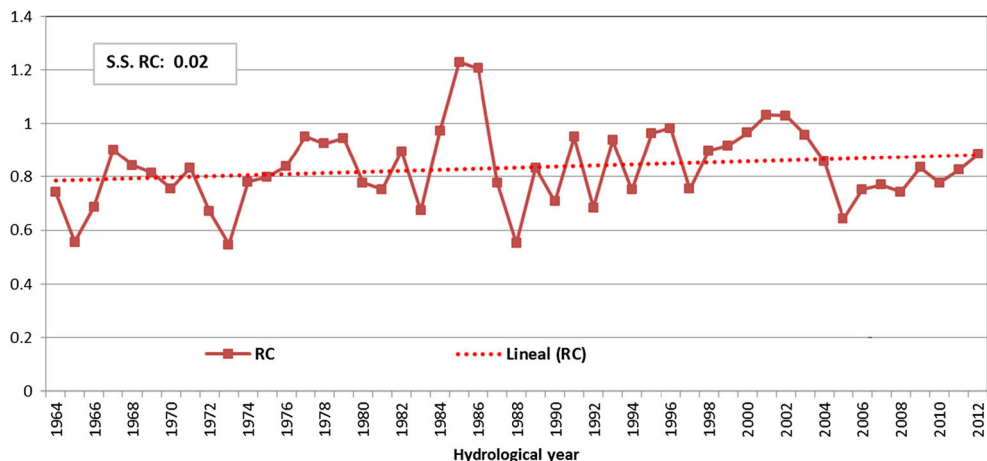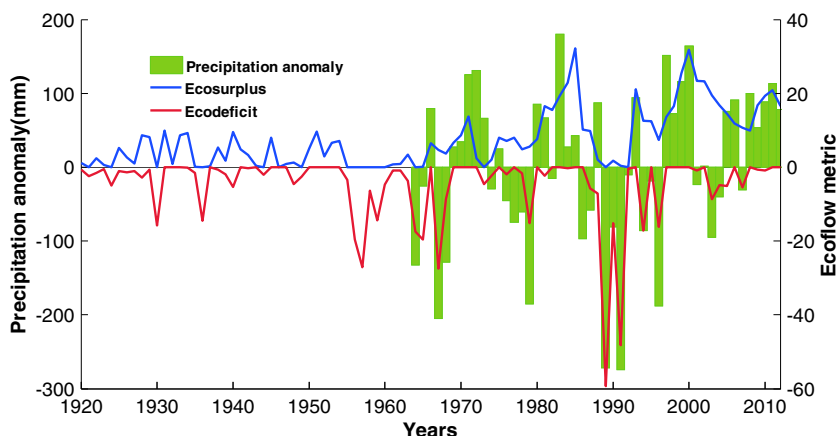
Fig. 8 Annual Eco-flow change and precipitation anomalies

1960 to 1970 and an increase in the values since 1980, while the ED has reduced its value and variability in the last decades. In MAM, the ES showed increasing value and variability since 1960, while the ED had more variability from 1990 to 2009. The ES values and variability have increased in JJA and SON since 1970 due to the influence of Grathon Tunnel and Marca I projects (see Fig. 2), apart from a dramatic decrease in ED variability and values, being practically zero since 1960.

In addition, the correlation between Eco-flow and precipitation was assessed for the period 1964–2012, and the results are shown in Table 2. In the table, it is observed that (i) during the rainy season (DJF and MAM), there is a significant positive (negative) correlation between ES (ED) and precipitation at 95% of confidence, with a stronger correlation with ED. These results confirm and strengthen the graphic deduction of the previous section: The low flows in this season are mainly caused by negative anomalies in precipitation, and (ii) during the dry season, correlations are weak. In JJA, there is no correlation with the ES and the weak significant correlation with the ED is not representative because the ED is almost zero; even though, there is a significant weak positive correlation between ES and precipitation in SON. These results indicate that the flow changes in JJA and SON are influenced by other factors such as reservoir operations.

3.2.2 Indicators of Hydrologic Alteration

Table 3 shows the percentage of change of the 32 IHA for the study periods (natural period and altered period). It shows us more detailed changes in the flow regime.

In the Group #1, the months from June to November showed high positive alterations, with values from +42% to +63%, indicating a flow increase during these months, consistent with the ES behavior in this period (Figs. 10c, d). On the other hand, the months from December to February showed a +32% of change in December and negative changes less than −10% for the two other months, so that we can state that the small ES showed in Fig. 10a results from an increase in flows in December and that the ED results from a decrease in flows in January and February. Also, from March to May, there are change ratios of −21% in March and −7% in April, resulting in severe ED showed in Fig. 10b, while the rate of 7% in May results in small ES showed in the same figure.

In the Group #2, the indicators related to number of days of minimum flow have increased in a percentage between +17 and +44%, compared with the natural period, while the indicators of the number of days of maximum flow showed a decrease in a percentage between −18 and −35%. Also, the base flow index increased an average of +43%.

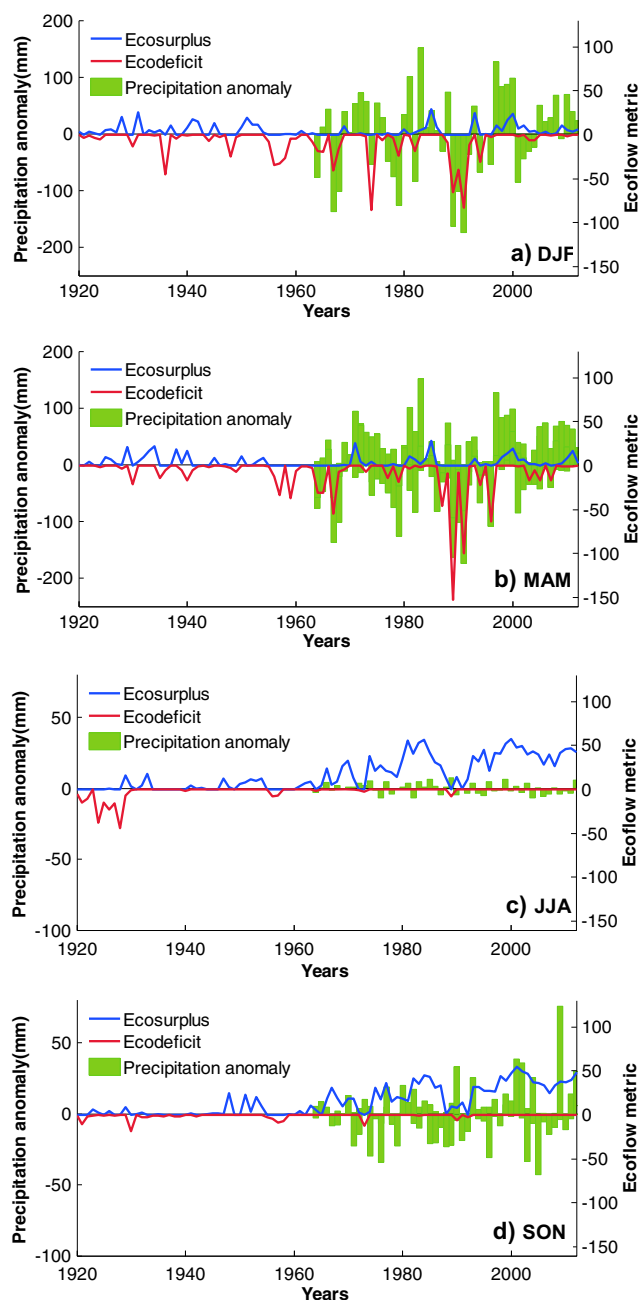**Fig. 9** *Boxplot* of decadal changes for Ecosurplus and Ecodeficit
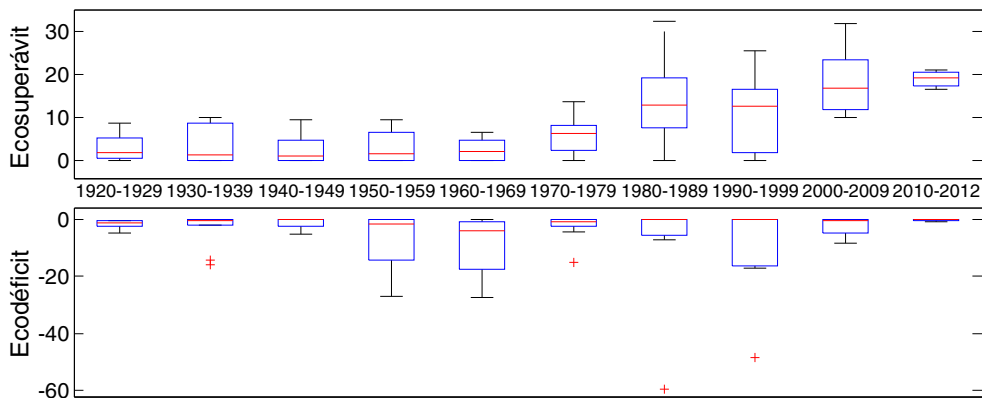
Fig. 10 Seasonal Eco-flow change and precipitation anomalies in **a** DJF, **b** MAM, **c** JJA, and **d** SON

In the Group #3, a small negative alteration lower than −4% on the dates of maximum and minimum flows was found. This alteration implies the occurrence of minimum flows a day before in average, during March, and the occurrence of maximum flows 4 days before in September, compared with the natural period.

In the Group #4, there was a reduction in the extreme low flows in terms of duration and frequency, of −86 and −75%, respectively, while extreme flood increased its frequency by +25% but decreased its duration by −65%. These results indicate a more stable flow for the altered period.

Finally, in Group #5, there is a decrease in the rise rate by −30%, involving a lower rise rate of flows during an increasing event, which seems to be influenced by the basin regulation.

3.3 Characterizing the drivers of trends in flow

In this study, we evaluated the trends and changes in flow regime of the Rimac River in the altered period, due to precipitation data availability (1965–2013). Main results of this study suggest that the principal drivers of flow change are the regulation and transfer in the basin. Thus, climate variables as precipitation or temperature did not show as big changes as flow did, according to Fig. 4 (for precipitation) and in agreement with Lavado Casimiro et al. (2013) who reported a temperature increase not significant of 0.09 °C per decade in the 1965–2007 period.

Nevertheless, it was not possible to analyze in detail the different drivers to detect flow alteration in this river, because of the nonavailability of data records of water transfer and operating rules of the reservoirs located upstream of the basin.

However, in the last years, a clear increasing in the flow water transfer measured in the Trasandino tunnel was found (see Fig. 12), as consequence of the operation of the Marca III project. It is possible to appreciate an unusual increase of annual mean flow in this location since 1999. Under this scenario and considering the increasing water demand for human consumption, in a large city like Lima (~8,751,741 inhabitants) with a population rate increase of 1.4% in the last 10 years, it is advisable that the future projects oriented to increase water availability will contribute to hydrological alterations.

3.4 Hydroclimatic change implications in the Rimac Basin

The results of this document show that the major changes in the flow regimen of Rimac River were related to the decrease in maximum flows during the rainy season, the increase in minimum flows during the dry season, the decrease in the flow rise speed, low pulses in smaller quantities and duration, and a major quantity of high pulses with less duration. These changes are not related to precipitation trends due the fact that while the precipitation trend is positive during the rainy season, the maximum flows have decreased, and during the dry season, there are opposite trends in precipitation between JJA (negative) and SON (positive) against an increase in minimum flows during this season. These results show the disagreement between precipitation and flows in the Rimac Basin as a consequence of the regulation and diversion of the basin, in agreement with the findings of Lavado Casimiro et al. (2012). It leads us to the conclusion that the alterations in the flows of the Rimac Basin due to anthropogenic activities are more significant than alterations due to climate variability.

Fig. 11 *Boxplot* of seasonal
decadal changes in Eco-flow: **a**
DJF, **b** MAM, **c** JJA, and **d** SON
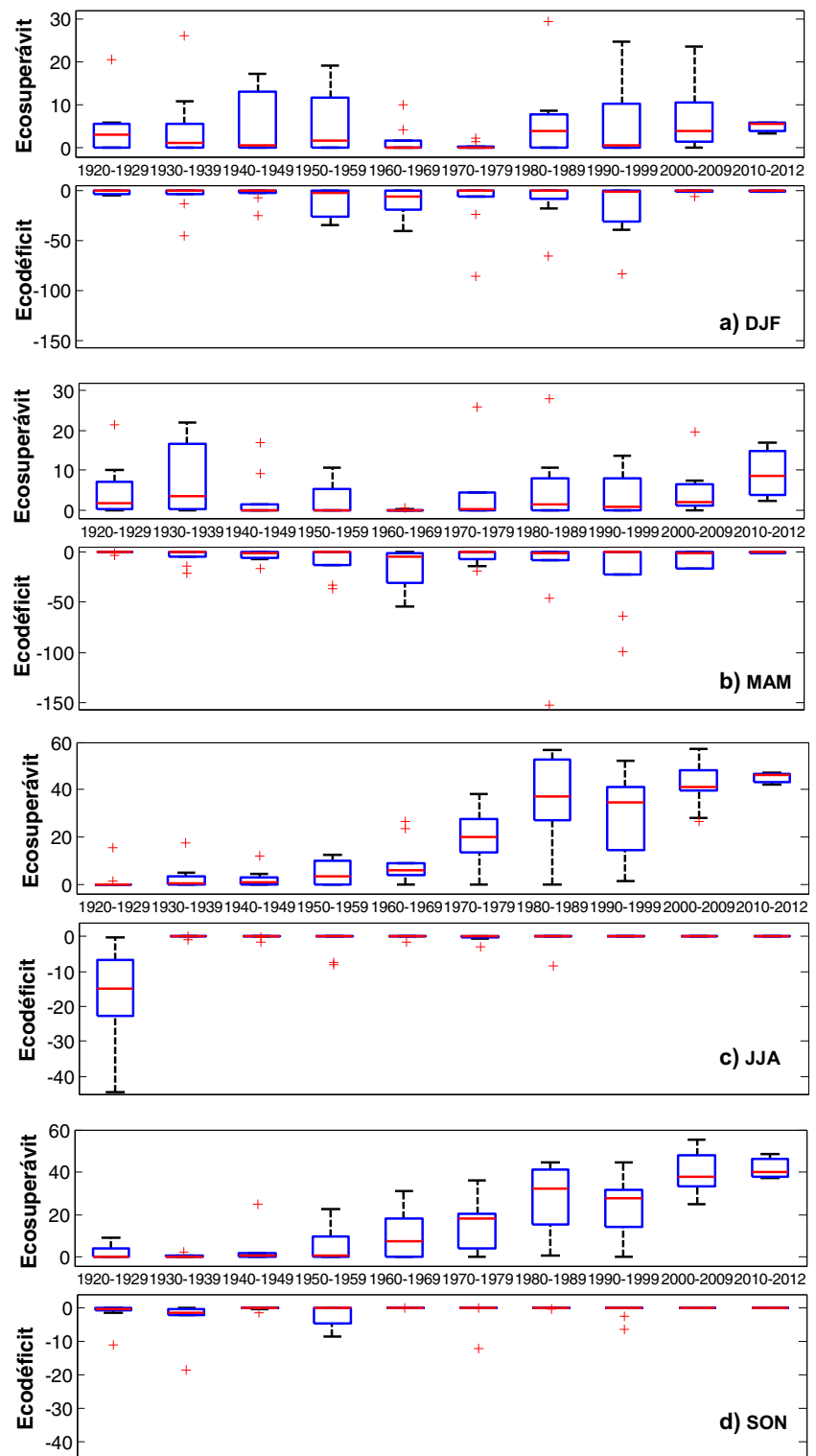
The alterations in the natural flow regimen may involve the alteration in life cycles of many species (Martínez and Fernández 2010) due to each ecosystem characteristics. To understand the implications of the change of flow regimen of the Rimac River in the aquatic ecosystem and to discern the implications of the effects of other factors such as climate and soil use changes, among others, it would be necessary to have information about biological aspects of the Rimac River before and after hydrologic alterations. However, in general, the response of the aquatic biodiversity to the alterations found would be similar as in other parts of the world. In this sense,

Table 2 Correlation coefficients between Eco-flow and seasonal precipitation

Correlation	DJF		MAM		JJA		SON	
	ES	ED	ES	ED	ES	ED	ES	ED
r	0.351	−0.662	0.433	−0.609	−0.030	0.285	0.284	0.134

Values in italics are statistically significant at 95% of confidence

ES Ecosurplus, ED Ecodeficit

Table 3 Changes in the IAH for both periods of analysis: Natural (1920–1960) and Altered (1961–2012)

Parameters IAH	1920–1960	1961–2012	% of change
Group of parameters #1			
Mean in September	13.03	19.4	48.89
Mean in October	13.05	19.5	49.43
Mean in November	14.27	20.4	42.96
Mean in December	17.62	23.31	32.29
Mean in January	35.25	32.98	−6.44
Mean in February	52.98	48.75	−7.98
Mean in March	68.25	53.6	−21.47
Mean in April	38.95	36.1	−7.32
Mean in May	20.75	22.23	7.13
Mean in Jun	13.05	20.8	59.39
Mean in July	12.19	19.35	58.74
Mean in August	12	19.5	62.5
Group of parameters #2			
1 day minimum	10.65	12.45	16.9
3 days minimum	11.06	14.79	33.73
7 days minimum	11.08	15.47	39.62
30 days minimum	11.63	16.71	43.68
90 days minimum	12.65	18.01	42.37
1 day maximum	159.5	104.6	−34.42
3 days maximum	146.7	98.77	−32.67
7 days maximum	134.1	87.31	−34.89
30 days maximum	93.29	68.28	−26.81
90 days maximum	64.52	53.2	−17.54
Base flow index	0.3627	0.5176	42.71
Group of parameters #3			
Date of minimum	241	240	−1
Date of maximum	66.5	63	−3.5
Group of parameters #4			
Low pulse count	4	1	−75
Low pulse duration	7	1	−85.71
High pulse count	4	5	25
High pulse duration	14.5	5	−65.52
Group of parameters #5			
Rise rate	2	1.4	−30
Fall rate	−1.5	−1.5	0
Number of reversals	74	164	121.62

Numbers in italics are changes higher than 10%

some of the potential harmful impacts of hydrologic alterations in the ecosystem of the Rimac River would be related to (i) reduction of habitat availability for aquatic organisms, as well as alterations in net primary production and patterns of organic matter production with changes even more important than those found due to water temperature changes (Marcarelli et al. 2010), all this as consequence of maximum flows decrease during the rainy season, (ii) modification of the stream bed morphology and physical conditions of the habitat, and increase in the transport of bottom sediments from the Rimac River to the Coast, causing sedimentations in these places due to an increase in minimum flows during the dry season, (iii) increase of stress in the aquatic ecosystem due to a decrease in speed rise of flows, (iv) more frequency and duration of anaerobic stress for plants and major transport of bottom sediments due to low pulses in smaller quantities and duration, and (v) more frequent stress in plants due to soil moisture and more high pulses with less duration (The Nature Conservancy 2009).

Additionally, it is important to comment that there is a marked difference in the perception of advantages and disadvantages of regulating and transfer projects by the community in the study area. In this sense, advantages are perceived by all the population, while disadvantages are perceived by the communities which live in the middle and head of the basin, particularly the people who live close to the rivers. The main advantages perceived are related to fresh water availability to supply the demand of the big population of Lima, the increase of hydropower energy availability to supply population demand, and the flood risk reduction, while the main disadvantages are related to the reduction of aquatic biodiversity in the river, historically used for people feeding.

In spite of the benefits of the anthropogenic actions in the Rimac Basin to supply water for consumption, supply of energy, and to reduce the flood risk, it is very important to bear in mind the environmental cost it represents, since hydrologic alterations may put at risk not only the survival of a large number of aquatic biota but also the ecosystem sustainability. So, it is necessary to maintain an equilibrium between the ecosystem and the benefit of the users of water resources, which has been demonstrated
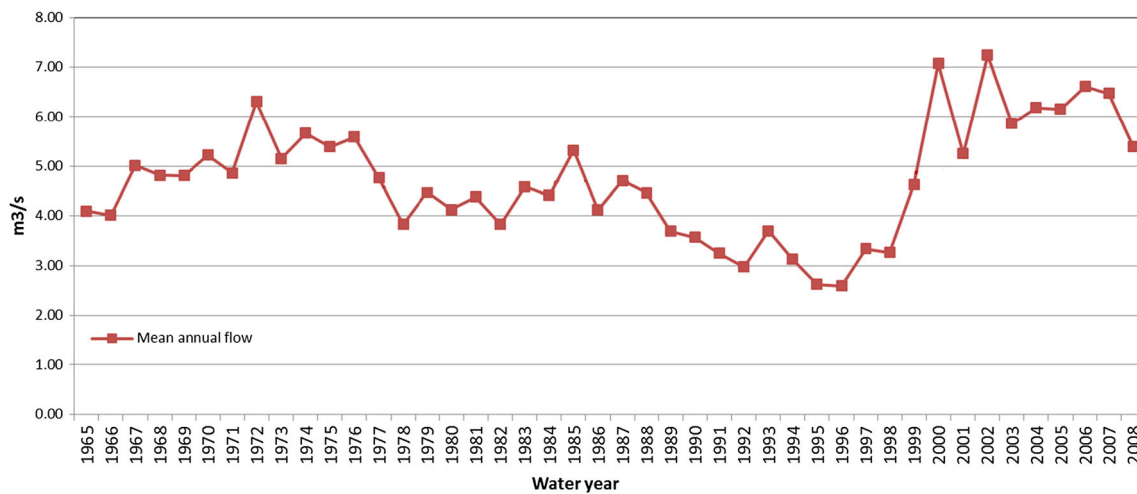
Fig. 12 Temporal evolution of flow discharges in the "Trasandino" tunnel considering water years for the period 1965–2008

to be possible in Cohen Liechti et al. (2014), where it was reached a compromise between energy production and environmental sustainability.

In this sense, the procedures developed in this study may be the basis for developing a standard hydrologic methodology of ecological flow regime estimation in Peruvian rivers, considering that the success in the conservation of the biodiversity and functionality of our rivers depends on our ability to protect or restore the main aspects of the natural flow regime (Richter et al. 1996; Bunn and Arthington 2002) in order to preserve the ecosystem of the rivers and surviving modes in benefit of the population welfare.

4 Summary and conclusions

This study assesses for the first time the hydrologic alterations as a consequence of the regulation and hydraulic diversion activities in the Rimac River Basin, located in the central coast of Peru. For this purpose, the interannual flow variation was characterized through the Eco-flow method, and the hydrologic alterations were quantified by the IHA, as well as assessing the correlation of the changes in the flow with the precipitation variability over the study area. This analysis was possible thanks to the availability of daily flow information for a long period (1920–2013, 94 years), and the comparison between flow and rainfall information (1965–2013, 49 years).

Based on the results of the seasonal assessment, we can conclude that in the Rimac River, the Eco-deficit occurred during the rainy season as a result of reservoirs storage installed in the study area and due to significant negative anomalies in the precipitation during this period. Also, Eco-surplus predominated during the dry season, in spite of the shortage of precipitation with negative trend in JJA

and a behavior opposite to precipitation anomalies in SON, mainly due to the reservoirs discharge with a major influence of reservoirs regulation in JJA (dry season). More conclusions are detailed below:

- It is evident that there are variations in the seasonality of monthly flows in the altered period in contrast to the natural period, with an increase in flows during the dry season and a decrease in flows during the rainy season, and also a significant negative (positive) trend for the maximum (minimum) flows throughout the assessment period (1920–2013).

- At an interannual time scale, and based on the Eco-flow assessment, it is deducted a significant increase in flows during the altered period, which is evident due to the increase in Eco-surplus and decrease in Eco-deficits, with more emphasis since 1990. It is also clear that a decrease in flows is predominant (Eco-deficit) during the rainy season (DJF, MAM) which is strongly related to negative precipitation anomalies, and also an evident increase in flows (Eco-surplus) during the dry season (JJA, SON) that is not related to the precipitation variations since it results from regulating and diversion projects implemented in the study area.

- The quantification of the alteration in flow regimen using the IHA illustrates that flow variations during the dry months were +51% on average, while during the rainy months (January–May), they were −10% on average. Also, low pulses varied by +35% with less duration and frequency, and high pulses varied by −29% with more frequency but less duration.

- The changes in the flow regime of the Rimac River would have positive impacts on the reduction of flood hazards and the improvement in the coverage of water demands, mainly for human consumption and irrigation; however, they would also result in negative impacts on the equilibrium of the ecosystem of the river.

– In general, the Eco-flow method and IHA are complementary and facilitate the deep assessment of the changes in the flow regime of the Rimac River in qualitative and quantitative terms, and the Eco-flow has the advantage of showing the relationship with other variables such as precipitation.

As a perspective for future studies we have the hydrologic alterations assessment in the Alto Mantaro Basin as a result of water diversion to the Rimac River Basin; the assessment of the precipitation trends found in the basin and the relationship with global climate patterns, as well as the development of hydrologic models to assess future alterations based on climate scenarios and changes in soil use.

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