Hydrological regime index for non-perennial rivers

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Abstract. The hydrological regime is an integrated basin response that constitutes an established paradigm for environmental flows (E-Flows) to mimic, as all its components influence aquatic life, and consequently fluvial ecosystems. It has been widely described that human activities and climate change modify the natural hydrological regime. These changes in non-permanent rivers generally tend towards greater intermittency, a condition that limits the applicability of hydrological alteration indices. The general aim of the paper was to develop an aggregated impact index, the Hydrological Regime Index (HRI) suitable for flow alteration assessment in non-permanent rivers. The HRI is composed of the flow magnitude attenuation, timing of maximum flow and interannual flow variation impact factors. The HRI is based on simple conceptualisations and uses monthly flow data, allowing its applicability in basins with limited information. The HRI was suitable to evaluate the impacts on the river regime of both the Desaguadero-Salado-Chadiluevú-Curacó River which is severely dammed with intermittent runoff and the Colorado River with permanent runoff. In all the cases, the HRI successfully distinguished different impacts on the hydrological regime under natural, low, and high impoundment conditions. Thus, the HRI constitutes a very useful tool for determining E-Flows and quantifying impacts due to water or land use changes.

1 Introduction

River networks expand and contract in response to the hydrological regime. Hydrological expressions can manifest in one or all of the four dimensions, longitudinal, transversal, vertical, and temporal. These dimensions define the connectivity of the fluvial system throughout the basin (Stanley et al., 1997; Amoros and Bornette, 2002; Gordon et al., 2004; Doering et al., 2007). The hydrological regime of a river can generally, and despite other considerations, be defined in terms of how the flows are distributed throughout the year. A main concern is whether the flows are permanent, intermittent, and/or ephemeral (Sauquet et al., 2021).

Arid and semi-arid basins typically present intermittent runoff in some sectors of the drainage network. This intermittence can be of different duration and extent (Datry et al., 2014; Boulton et al., 2017; Tramblay et al., 2021). Extensive semi-arid basins are hardly fully activated since they usually do not depend solely on a climatic configuration. In contrast, there exist other factors such as relief or geographical location that determine the occurrence of precipitation. Therefore, in large complex terrain basins, the headwaters of the drainage network are generally located in a mountainous sector that favours the occurrence of precipitation due to the orographic effect. Consequently, the hydrological forcing of the basin typically occurs in the headwaters and almost none is manifested in the lower part (Viviroli and Weingartner, 2004). Moreover, higher temperatures result in important evapotranspiration losses which accentuate the hydrological deficit of the lower part of the basin. Therefore, runoff is made up of allochthonous flows. Between these events and depending on whether there is groundwater discharge that maintains a base flow, the riverbeds can dry up.

Snow-fed rivers present a well-defined hydrological regime in terms of flow timing and magnitude, with a pronounced peak flow when snow is melting and low winter flow during the snow accumulation phase. However; all these hydrological expressions are strongly modified by flow regulation, usually by the construction of dams to supply water for multiple uses such as irrigation, recreation, domestic and hydroelectric generation (Magilligan et al., 2013). These effects are accentuated by the use of low-efficiency irrigation systems, such as gravity-fed surface irrigation practices (McMahon and Finlayson, 2003; Masseroni et al., 2017) and contribute to the reduction of hydrological connectivity within the basin.

In addition, the human-caused impact on the hydrological regime of snow-fed rivers caused by the damming of large reservoirs may be greater than the impact of climate change (Arheimer et al., 2017). This poses a challenge in the necessity to define environmental flows (E-Flows). Regardless of the large number of approaches and methods available for their estimation, there exists a consensus that E-Flows must mimic the hydrological regime, given its structural and functional role in fluvial ecosystems (Richter et al., 1996; Poff et al., 1997). In this sense, hydrological methods that include the description of the natural hydrological regime are the most used (Arthington, 2012). However, knowing how the hydrological regime is influenced is also a critical component in the determination of E-Flows employing holistic approach methods. Moreover, tools for defining E-Flows must be developed within transboundary fluvial systems that exhibit fragmented water governance (Best, 2019; Wineland et al., 2021).

The resulting major disturbances of flow regulation on the hydrological regime may include changes in the magnitude of flows (i.e. flow attenuation), time delay of peak flows, loss of intra-annual variability, and reduction or loss of the hydrological connectivity in the basin (Callow and Smettem, 2009; Steward et al., 2012; Magilligan et al., 2013; Torabi Haghighi et al., 2014). Hydropower and flood management typically reduce flow variability and can affect the timing of peak flows, while irrigation management usually reduces flow magnitude due to crop water use.

Several conceptualizations and metrics have been proposed to assess the effects of dams on the hydrological regime (e.g. Richter et al., 1996, 1997 and 1998; Olden and Poff, 2003; Magilligan and Nislow, 2005; Poff et al., 2007; Gao et al., 2009; Radinger et al., 2018; Döll and Schmied, 2012; Richter et al., 2012; Torabi Haghighi and Kløve, 2013; Torabi Haghighi et al., 2014; Singh and Jain, 2020; Zhou et al., 2020; Sauquet et.al., 2021; Arthington, 2022; De Girolamo et al., 2022; McManamay et al., 2022; Wang et al., 2022). In general, these indices of hydrological alteration (IHA) include many parameters whose statistics serve as indicators of flow alteration and may be used as operation rules for reservoirs when downstream flows are analysed (Harman and Stewardson, 2005). However, the intercorrelation among the parameters may result in statistical redundancy (Poff and Zimmerman, 2010) and different methodologies such as principal component analysis (PCA) have been applied to identify subsets of more representative hydrological parameters (Gao et al., 2009). Furthermore, the complexities involved in the explicit use of these parameters in optimization models for reservoir operation, have led in the proposal of subset of parameters based on the flow duration curve (FDC) to define seasonal ecodeficit/ecosurplus (Vogel et al., 2007) and the development of different linear and nonlinear strategies to constrain these parameters (Wang et al., 2015; Li et al., 2018).

In semi-arid regions the usual scarcity of data, such as the lack of detailed and distributed information (e.g., discontinuous flow records and lack of daily data), and the intermittent flow conditions, limit the use of IHA (Leone et al., 2023; Gómez-Navarro et al, 2024). Indeed, indices based only on flow statistics, including for example the interquartile variation range (IQR), the coefficient of variation (CV) or the FDC, used as proxies for the seasonality of flows, among others; may not be suitable when no flow conditions are present. They require very detailed information not always available or is irrelevant to the dominant processes occurring in the basin. For example, the typical IHA parameters such as the number of high or low pulses, means of all positive or negative differences between consecutive daily means do not necessarily reflect the presence of allochthonous flows or interactions with groundwater. Similarly, those parameters based on complex theoretical functions of flow distribution have limited representativeness when runoff is not of a natural origin (e.g. only dam discharges, drainage flows). Moreover, the difficulty in standardizing flows through statistical proxies (e.g. CV, IQR, FDC) for a given period when the average flow rate equals zero. Therefore, new approaches to evaluate the modification of hydrological regimens in non-perennial rivers are needed. First and as indicated, the necessity to mathematically resolve relationships that adjust to intermittent flow scenarios. Second, to possess the capability to implement the index in a temporal and/or spatially distributed manner to assess the hydrological connectivity in extensive basins, which is a fundamentally important factor for the quantification of E-flows.

In this context, the Desaguadero Salado Chadileuvú Curacó (DSCC) River provides a representative case study because it is an extensive semi-arid basin severely dammed which has undergone noticeable changes in its hydrological expression over the past century mainly due to the fragmented water governance along its transboundary water systems (Dornes et al., 2016). The fluvial system of the DSCC river develops over an extensive basin, with a highly heterogeneous relief, where winter snowfall in the mountain area constitutes the main hydrological input function with a variability strongly influenced by the El Niño-Southern Oscillation (ENSO) climate pattern (Compagnucci and Vargas, 1998; Compagnucci and Areneo, 2007; Montecinos and Aceituno, 2003; Masiokas et al., 2006; Prieto et al., 2001; Araneo and Companucci, 2008; Barros et al., 2008; Cortés et al., 2011; Penalba and Rivera, 2016; Rivera et al., 2017; Lauro et al., 2019).

This configuration determines a complex and non-linear hydrological basin response, which is modified by high impoundment conditions. Thus, those years characterized as the warm or positive phase of ENSO (El Niño) led to heavy snowfall and above-normal runoff that may exceed the storage capacity of the reservoirs, have less effect on the hydrological regime downstream the reservoirs and a greater basing connectivity is observed. On the contrary, years characterised as the negative phase of ENSO (La Niña) result in less snowfall and lower than normal streamflow which strongly modify the hydrological regime downstream since almost no flow exceeds the storage capacity of the reservoirs, hence flows do not activate the lower part of the DSCC River basin.

Since the flow regime is an integrated basin response, a comprehensive approach should be used to evaluate its temporal and spatial distribution under both permanent and no-permanent flow conditions in areas with data scarcity. The hydrological metric must be capable of describing the flow under natural (i.e. low modified) and modified conditions to varying degrees. For example, in the tributaries of the DSCC River the index must possess the ability to adequately discriminate between the hydrological conditions observed upstream and downstream of the main hydraulic structures. In the DSCC River, additional hydrological characteristics emerge that must be suitably assessed, such as river reaches with or without interaction with groundwater, contributions from tributaries with modified flows, and the influence of wetland storage in the hydrological regime. These characteristics also have an important impact on the hydrological connectivity of the basin.

Therefore, to address the deficiency wherein numerous metrics inadequately assessed the alterations in the hydrological regime under no flow conditions, the objective of this study was to investigate the effect of flow regulation on the hydrological river regime by the development of a simple and dimensionless index that is applicable across different regimes but especially under no flow conditions with minimal data requirements.

2 Study Area

The DSCC River basin is the largest basin that extends entirely in Argentina. The DSCC River basin is located in the central-west part of Argentina lying to the east of the of the Cordillera de los Andes (CA) mountain range with a north–south orientation (27° 47' S, 38° 50′ S). The basin belongs to the Colorado (CO) River that drains into the Atlantic Ocean (Figure 1). It encompasses partially or totally the provinces of Catamarca, La Rioja, San Juan, Mendoza, San Luis and La Pampa. The total area is approximately 315,000 km^2 and includes the sub-basins of the Vinchina-Bermejo (VB), Jáchal (JL), San Juan (SJ), Mendoza (MZ), Tunuyán (TY), Diamante (DT) and Atuel (AT) rivers. The DSCC River basin located in the CA piedmont is defined by mountain ranges such as the Cordillera Principal, the Cordillera Frontal and the Precordillera to the West and North, the Sierras Orientales and Sierras Pampeanas to the East, whereas the lower basin is developed on flat terrain as part of the occidental area of the Pampean region (Ramos, 1999). This orographic configuration determines that the CA is the headwaters of the DSCC River basin, where winter precipitation due to the orographic lifting of Pacific air masses by the mountains, constitutes the principal hydrological forcing of the basin (Bruniard, 1986). The rest of the basin is isolated from the influences of wet air masses driven by the extratropical high-pressure systems of the Atlantic and Pacific Oceans, a condition that results in an arid climate to the North and semiarid to the South (Prohaska, 1976). These conditions generate a north-south precipitation gradient that ranges from values around 100 to 350 mm per year respectively, however this precipitation does not contribute to the average hydrological expression of the lower basin of the DSCC River which is strongly defined by the allochthonous snowmelt runoff from de CA (Dornes et al., 2016).

The tributaries drain the eastern slope of the CA through well-defined valleys and canyons towards the piedmont. All the tributaries have a defined snow-fed hydrological regimen, given that neither the glacier cover at the middle CA is significant nor the summer precipitation. Northern sub-basins have considerably less runoff than the central and southern sub-basins as is the case of the VB River with a mean discharge value around 1 $m^3 s^{-1}$, and JL River with an average annual flow of 10 $m^3 s^{-1}$. The SJ River is the tributary with the greatest discharge with a mean annual flow of 65 $m^3 s^{-1}$ as a consequence of the development of the basin over a large part of the CA covering a mountain front of more than 200 km. It is followed by the MZ River with 44 $m^3 s^{-1}$, whereas the TY, DT, and AT have 27, 31, and 34 $m^3 s^{-1}$ respectively. The tributaries show both a great interannual flow variability that is consistent with varying snowmelt processes occurring in a complex mountain environment and a defined synchronicity with above and below-average flows strongly related to positive and negative ENSO episodes (Compagnucci and Vargas, 1998, Aceituno and Vidal, 1990; Waylen and Caviedes, 1990; Masiokas et al., 2006; Araneo and Villalba, 2014). The maximum flow magnitudes observed in 1980s, 1992, 1995, 2005, and 2006 and to a lesser degree in 2008 were associated with El Niño episodes. On the opposite, the last decade showed very low flow values, according to the dominance of negative ENSO phases (La Niña), with the exclusion of 2015 classified as an El Niño episode that resulted in average flow values (Table 1). As a consequence, lesser natural flows are seen in all the tributaries for the current conditions Tributary streams reach their confluence with the DSCC River usually through depositional sediments forming alluvial fans where the reduction of the terrain slope and the discharge of alluvial local aquifers, led to the occurrence of extensive wetlands. The DSCC River initiates as the outlet of the Lagunas de Guanacahe (LG) wetland, which is fed by the VB, SJ and MZ Rivers (see Figure 1), however as these tributaries are highly dammed, the DSCC River has modified flows, showing a tendency for increased intermittency. The DSCC River follows a North-South trajectory along approximately 1.450 km until its mouth in the CO River at the Pichi Mahuida point in La Pampa province (38° 49′ S and 64° 59′ W) and is distinguished by being an axial collector that receives on its right bank all its tributaries aforementioned and connecting important wetlands (Bereciartua et al., 2009; Chiesa et al., 2015), such as LG, Bañados del Tunuyán (BT), Bañados del Atuel (BA) and Lagunas de Puelches (LP). Between these wetlands and until its mouth in the CO River, the DSCC River has different names. Thus, it is called Desaguadero River (DSCC-I) between LG and BT, Salado River (DSCC-II) between BT and BA, Chadileuvú River (DSCC-III) between BA and LP, and Curacó River (DSCC-IV) from LP to the CO River.

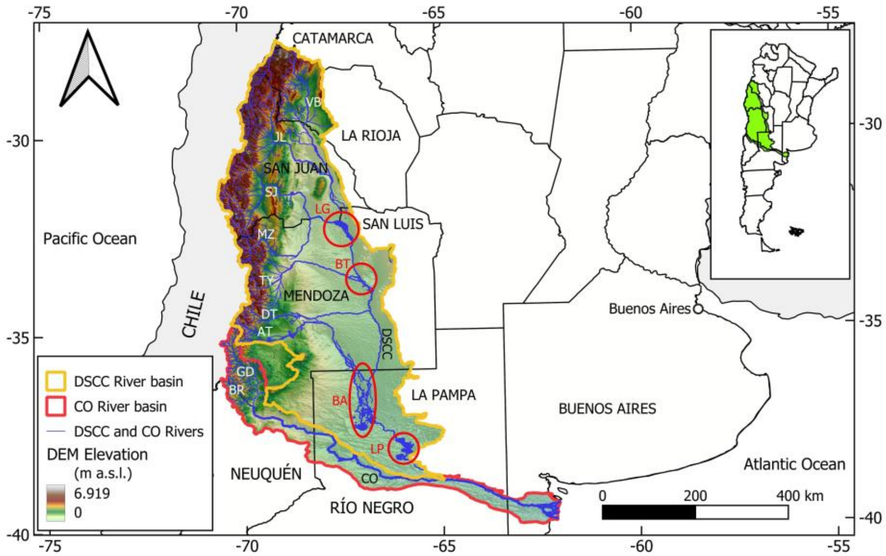

Figure 1: Location of the Desaguadero-Salado-Chadileuvú-Curaco (DSCC) and Colorado (CO) River basins. VB: Vinchina-Bermejo River, JL: Jachal River, SJ: San Juan River, MZ: Mendoza River, TY: Tunuyán River, DT: Diamante River, AT: Atuel River, GD: Grande River, and BR: Barrancas River. Circles and ellipse indicate main wetlands: Lagunas de Guanacache (LG), Bañados del Tunuyán (BT), Bañados del Atuel (BA), and Lagunas de Puelches (LP).

The wetlands of the DSCC River are epigenic as a result of the fluvial contributions with null groundwater discharge. They are characterized by extensive flooded areas with numerous channels and lagoons, and acquire an ecological relevance due to their location in a semi-arid region and for being hydrological regulation nodes of the basin. The LG, BT, and BA wetlands are located at the distal part of extensive alluvial fans developed at the confluence of the corresponding tributary with the DSCC River, therefore their hydrological expression depends more on the flow contribution of the tributary than on the DSCC River. On the other hand, the LP wetland is characterized by the presence of extensive lagoons (e.g. La Brava, La Leona, La Julia, La Dulce, Urrelauquen, and La Amarga) all of them linked by the DSCC River.

Table 1: Mean annual discharge for the gauging stations (GS) in the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) and Colorado (CO) Rivers. [H]: historical period, [C]: current period, [N]: natural flow (upstream the reservoirs), [M]: modified flow (downstream the reservoirs). VB: Vinchina-Bermejo River, JL: Jáchal River, SJ: San Juan River, MZ: Mendoza River, TY: Tunuyán River, AT: Atuel River, GD: Grande River, and BR: Barrancas River. VIN: Vinchina, PAC: Pachimoco, PLT: Paso las Tunitas, EEN: El Encón, GUI: Guido, VDU: Valle de Uco, LJA: La Jaula, MCO: Monte Comán, ESO: El Sosneado, CAA: Cañada Ancha, LAN: La Angostura, CAR: Carmensa, PTU: Puesto Ugalde, ADD: Arcos del Desaguadero, SLT: Salto de la Tosca, CAN: Canalejas, STI: Santa Isabel, LRF: La Reforma, PUE: Puelches, PM2: Pichi Mahuida 2, LGR: La Gotera, BAR; Barrancas, BRQ: Buta Ranquil, and PMA: Pichi Mahuida (PMA).

River	Sub-basin	GS	ID	Lat S	Long. W	Elevation (m a.s.l.)	Mean annual Discharge ($m^3 s^{-1}$)	Record period
DSCC	VB	VIN	1001	28.75	68.25	1480	1.3 [H, N]	1967-1981
							0.4 [C, M]	2016-2023
	JL	PAC	1204	30.21	68.83	1160	14.6 [H, N]	1921-1928
							9.6 [H, N]	1936-1990
	SJ	km 43.7	1208	31.52	68.94	934	65.2 [H, N]	1909-2014
		km 101	1211	31.25	69.18	1245	55.6 [H, N]	1971-2005
							30.7 [C, N]	2010-2023

		PLT	1408	32.12	68.16	531	16.8 [H, M]	1937-1951
		EEN	1219	32.23	67.81	518	11.8 [H, M]	1993-2023
							0.9 [C, M]	2010-2023
	MZ	GUI	1413	39.92	69.24	1408	43.6 [H, N]	1956-2023
							32.8 [C, N]	2010-2023
		CAC	1412	33.02	69.12	1250	50.2 [H, N]	1909-1990
	TY	VDU	1419	33.78	69.27	1199	27.0 [H, N]	1954-2023
							17.5 [C, N]	2010-2023
	DT	LJA	1423	34.67	69.32	1457	31.2 [H, N]	1971-2023
							19.1 [C, N]	2010-2023
		MCO	1451	34.57	67.87	521	7.5 [H, M]	1990-2023
							3.0 [C, M]	2010-2023
	AT	ESO	1428	35.08	69.60	1603	36.0 [H, N]	1972-2023
		CAA	1415	35.19	69.78	1680	9.4 [H, N]	1940-2023
		LAN	1403	35.10	68.87	1302	34.4 [H, N]	1906-2023
							24.0 [C, N]	2010-2023
		CAR	1453	35.19	37.73	438	7.1 [H, M]	1985-2023
							3.9 [H, M]	2010-2023
		PTU	4404	36.00	67.19	343	6.6 [H, M]	1980-2023
							2.0 [C, M]	2010-2023
	DSCC	ADD	1424	33.40	67.15	450	15.9 [H, M]	1941-1951
							0, 1[C, M]	2010-2023
		SLT	1605	34.09	66.71	404	5.1 [H, M]	1944-1950
							0.2 [C, M]	2017-2023
		CAN	1452	33.17	66.50	356	13.0 [H, M]	1987-2023
							1.1 [C, M]	2010-2023
		STI	4403	36.28	66.85	310	37.5 [H, M]	1980-2023
							1.2 [C, M]	2010-2023
		LRF	---	37.55	66.23	243	30.2 [H, M]	1980-2023
							0.4 [C, M]	2010-2023
		PUE	---	38.15	65.91	222	22.2 [H, M]	1982-2023
							0.0 [C, M]	2010-2023
		PM2	---	38.82	64.99	125	12.0 [H, M]	1982-2023
							0.0 [C, M]	2010-2023
CO	GR	LGT	1427	35.87	69.89	1454	100.2 [H, N]	1973-2023
	BR	BAR	2001	36.80	69.89	950	34.0 [H, N]	1960-2023
	CO	BRQ	2002	37.07	69.74	850	140.9 [H, N]	1940-2023
							79.1 [H, N]	2010-2023
		PMA	1801	38.82	64.98	122	133.6 [H, N]	1918-1990
							59.3 [C, M]	2010-2023

The DSCC River basin has twelve large reservoirs; all located on its tributaries (Figure 2 and Table 2). Currently, El Tambolar (ETA) on the SJ River is under construction and there is more planned such as El Baqueano (EBA) on the DT River. None of them were built for flood control; instead, they were built for irrigation purposes and hydropower generation. The prevalent use of inefficient gravity-fed surface irrigation systems determines that irrigation demands are unusually high with respect to natural supply (Llop et al., 2013). As a result of these impoundments and reservoir operation, none of the tributaries contributes in natural regimen to the DSCC River. Further, in the DSCC River, two small dams (Azud Norte, AZN, and Azud Sur, AZS) were built to generate impoundment conditions and prevent erosion in the LG wetland. The CO River, has the Dique Punto Unido (DPT) diversion dam used for irrigation and water consumption, and the Casa de Piedra (CDP) reservoir that regulates the different water allocations in the lower basin.

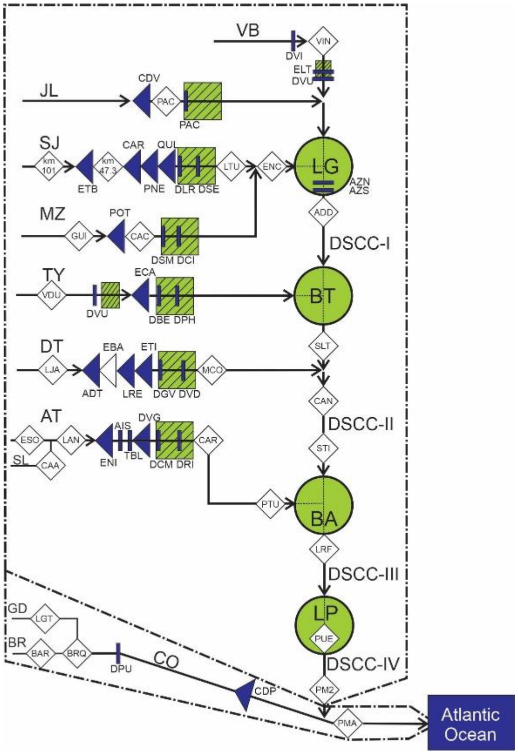

Figure 2: Schematic diagram of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and Colorado (CO) River basins showing the location of its reaches, tributaries, wetlands, gauging stations, reservoirs, diversions dams and irrigated areas. DSCC-I: Desaguadero River, DSCC-I: Salado River, DSCC-III: Chadileuvú River, and DSCC-IV: Curacó River. Circle: wetlands. Dark triangles: main reservoirs. White triangle: projected reservoir. Rectangles: diversion or flood control dams. Shaded squares: irrigation areas. Diamonds: gauging stations. More descriptions are depicted in Figure 1, and Tables 1 and 2.

The runoff in the DSCC River is allochthonous due to the reduced rainfall that dominates the lower basin with high flow records strongly associated with El Niño episodes, such as in the 1980s decade when the DSCC River drainage network was fully active with discharges to the CO River. The historical information is not synchronous, given that it is generally only available during runoff periods, and it indicates highly modified annual hydrographs along the DSCC River. The current situation with lower snowfalls shows an even more severe hydrological condition exhibiting nearly no flow throughout its length. Thus, as a consequence of the described flow regulation in the tributaries, the DSCC River remains dry. Furthermore, no groundwater discharge is observed from outside the alluvial plain. Groundwater flow follows the regional gradient of the river and it is majorly constrained to the alluvial plain of the DSCC River where the phreatic aquifer is fed by fluvial recharge (Páez Campos and Dornes, 2021).

Table 2: Subbasins, reservoirs and diversion dams in the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River basin and in the Colorado (CO) River basin. Elevation obtained from the Digital Elevation Model (DEM). *Diversion and flood control dam. DVI: Dique Vinchina, ELT: Embalse Lateral, DVU: Dique Villa Unión, CDV: Cuesta del Viento, PAC: Pachimoco, ETA: El Tambolar, CAL: Caracoles, PTN: Punta Negra, QUL: Quebrada de Ullúm, DLR: Dique La Rosa, DSE: Dique San Emiliano, POT: Potrerillos, DSM: Dique San Martín, DCI: Dique Cipolletti, DVU: Dique Valle de Uco, ECA: El Carrizal, DBE: Dique Benegas, DPH: Dique Phillps, ADT: Agua del Toro, LRE: Los Reyunos, ETI: El Tigre, DGV: Dique Galileo Vitali, DVI: Dique Vidalino, ENI: El Nihuil,

AIS: Aisol, TBL: Tierras Blancas, VGR: Valle Grande, DCM: Dique Canal Marginal, DRI: Dique Rincón del Indio, AZN: Azud Norte, AZS: Azud Sur, Dique Punto Unido (DPU) and CDP: Casa de Piedra.

River	Subbasin	Area (km^2)	Max. Elevation (m a.s.l.)	Min. Elevation (m a.s.l.)	Reservoirs and diversion dams	Vol Reservoirs (hm^3)
DSCC	VB	35,850.2	5,195	532	DVI*	< 1
					ELT*	< 1
					DVU*	< 1
	JL	34,716.6	5,296	695	CDV	206
					PAC*	< 1
	SJ	38,813.3	4,850	555	ETA	605
					CAL	565
					PTN	450
					QUL	440
					DLR*	< 1
					DSE*	< 1
	MZ	17,861.7	6,556	539	POT	180
					DSM*	< 1
					DCI*	< 1
	TY	21,384.2	4,766	476	DVU*	< 1
					ECA	327
					DBE*	< 1
					DPH*	< 1
	DT	8,638.2	4,082	413	ADT	380
					LRE	255
					ETI	70
					DGV*	< 1
					DVI*	< 1
	AT	54,832.5	3,118	298	ENI	384
					AIS*	< 1
					TBL*	< 1
					VGR	164
					DCM*	< 1
					DRI*	< 1
	DSCC	102,842.4	1,612	214	AZN*	10
					AZS*	138
Total		**314,939.1**	**6,556**	**214**		
CO		47,458.9	3,230	0	DPU*	< 1
					CDP	400

The consequent absence of hydrological connectivity of the DSCC River with the upper basin where snowmelt runoff occurs, leads to a pronounced hydrological deficit in the lower basin which has considerable ecological effects and results in the lack of contribution to the CO River. Figure 3 illustrates the annual hydrographs for both the available historical information and the current period (2010-2023) of the tributaries and the DSCC River.

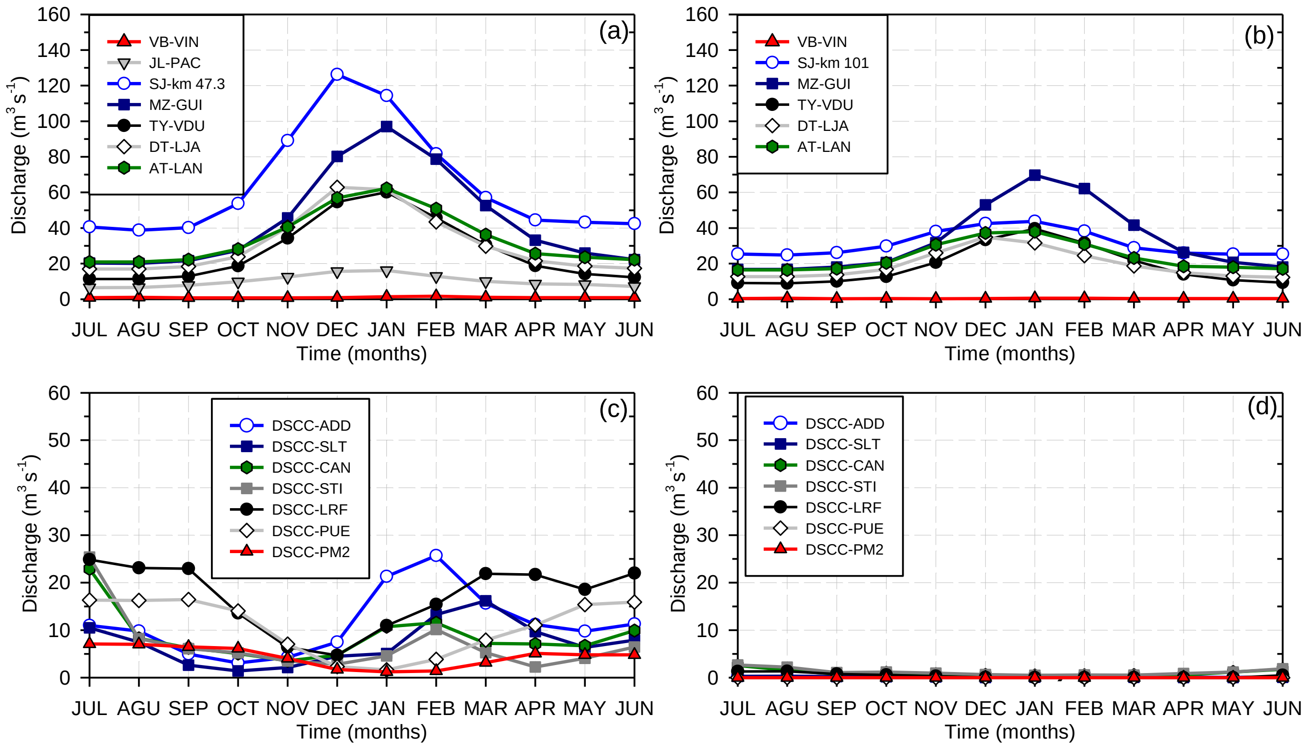

Figure 3: Annual hydrographs of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River. a) Historical flows in natural regime of the tributaries of the DSCC, b) Current flows (2010-2023) in natural regime of the tributaries of the DSCC, c) Historical flows in modified regime of the DSCC, and d) Current flows (2010-2023) in modified regime of the DSCC River. Rivers, gauging stations, and historical and actual periods detailed in Table 1.

3. Materials and methods

3.1 Development of the hydrological regime index

To evaluate the effects of flow regulation on the hydrological river regime in different hydrological conditions but mainly in intermittent rivers, a single impact index, the Hydrological Regime Index (HRI) was developed. The HRI incorporates the main components of the hydrological regime (i.e. flow attenuation, time shifting of maximum flow and inter-annual variability). It is based on the comparison of the annual distribution of monthly flow records in natural or low modified with modified regimes (i.e. upstream vs downstream of a reservoir) which represent the long-term pattern of water flow and therefore the hydrological regime. Since the HRI is not a site-specific measurement, this approach makes it suitable for no flow conditions and to evaluate the limitation or loss of hydrological connectivity due to flow impoundment along the river network.

To facilitate the comparison of the flow records and similar to the concept of the unit river approach used by Torabi Haghighi and Kløve (2013), the flows are scaled to have an equal flow rate (U) of 100 million cubic meters (MCMs) per year. Therefore, the scaled monthly flows (Q_{sm}) are calculated as the contribution to the annual flow following Eq. (1):

$$Q_{sm} = \frac{Q_m}{Q_a} \times U \quad (1)$$

where Qm is the monthly flow and Qa is the annual average flow rate of the river. This scaling allows rivers with different flow rates to be compared in terms of the annual hydrological regime. A uniform regulated o dry river has a Qsm of exactly 8.333 MCM of total flow.

Similar to the approach applied by Torabi Haghighi et al (2014), but using simpler functions adapted to intermittent flows to describe the time lag and interannual variability, the HRI is detailed as follows in Eq. (2):

$$HRI = MIF \times (TIF + VIF) \quad (2)$$

where *HRI* varies between 1 (natural or unmodified flow) and 0 (completely modified flow). *MIF*: Magnitude Impact Factor, *TIF*: Timing Impact Factor, and *VIF*: Variation Impact Factor.

MIF is of equal importance to the sum of TIF and VIF because flow magnitude is the main controlling factor of the hydrological regime. For example, for a no-flow condition, MIF is 0 and HRI must be 0 (i.e. completely modified flow). The maximum impact of TIF or VIF is 0 and their sum is 1 when no changes in timing and intra-annual variability are observed.

Flows downstream of multipurpose reservoirs typically result in values of lower magnitude due to different water consumption. The extreme cases are when there are no downstream flows (MIF=0) or when the upstream and downstream flows are equal (MIF=1). Since MIF is calculated based on average values over long o representative periods, is very rare to have larger flow values downstream of a reservoir. However, if this is the case, MIF is set equal to 1. Therefore, MIF was calculated as the ratio between modified to natural flows as in the following Eq. (3):

$$MIF = Q_{aM} / Q_{aN} \quad (3)$$

where Q_{aM} is the mean annual modified flow (e.g. downstream of the reservoir) and Q_{aM} is the mean annual flow in natural regime (e.g. upstream of the reservoir).

The TIF was calculated based on the time delay in monthly maximum discharge (TD) along the hydrological year between the natural (e.g. upstream of the reservoir) and modified flows. The maximum TD value is 6 months corresponding with a seasonal inverted maximum flow, therefore the following conditionals are applied in Eq. (4) and (5):

$$\text{if } TD = |TQ_{mN.max} - TQ_{mM.max}| \leq 6;\ TD = |TQ_{mN.max} - TQ_{mM.max}| \quad (4)$$

$$\text{if } TD = |TQ_{mN.max} - TQ_{mM.max}| > 6;\ TD = 12 - |TQ_{mN.max} - TQ_{mM.max}| \quad (5)$$

where $TQ_{mN.max}$ and $TQ_{mM.max}$ are the time (i.e. month number within the hydrological year) of occurrence of the monthly natural and modified maximum flow respectively.

To scale the TIF to a maximum value of 0.5 (i.e. natural flow) and a minimum value of 0 (i.e. maximum TD) applying a linear relationship with a slope of 0.0833 is calculated as following Eq. (6):

$$TIF = 0.5 - 0.0833 \times TD \quad (6)$$

Regardless of the type and operation of the reservoir, the resulting downstream flow is more uniform, which represents a loss of interannual variability. Complete regulation implies a constant flow rate, which can be equal to the average annual flow rate or have a lower value up to a flow rate equal to zero. Therefore, the VIF is calculated based on the annual sum of the deviations from a straight or constant flow line for both the natural and modified flow. These values are the Monthly Regime Index (MRI) and are totalized in the Annual Regime Index (ARI). Both, the MRI and ARI are computed using the scaled hydrographs (Eq. 1), therefore if the Qm is constant (i.e. uniform regime); the Qsm= 8.333, and MRI=ARI=0. The following conditions are applied in Eq. (7, 8 and 9):

If $Q_{sm} = 8.333; MRI = 0$ (7)

If $Q_{sm} > 8.333; MRI = |Q_{sm} - 8.333|$ (8)

$$ARI = \sum_{i=1}^{12} MRI_i \quad (9)$$

The Annual Regime Index for natural flows (ARI_N) typically varies between 30 to 55 for snow-fed regimes. Modified flows can have values of the Annual Regime Index (ARI_M) between 0 (i.e. equal value all the months) and a maximum value of 91.67 when a dry river has runoff occurring only in one month (i.e. ephemeral river). To scale the VIF between 0.5 (i.e. natural flows) and a minimum value of 0 (i.e. maximum flow regime modification) the Relation Regime Index (*RRI*) between the natural and modified flows is defined in Eq. (10):

$$RRI = ARI_M / ARI_N \quad (10)$$

The following conditions must be considered. If the observed annual flow variability downstream is lower than the one upstream (i.e. RRI<1), the RRI value is scaled so that VIF varies between 0 and 0.5. On the contrary, if the flow variability downstream is larger than the one upstream (i.e. RRI>1) it means that a drastic modification occurred to the streamflow given by dam management or by the contribution of no natural flow such as drainage discharges from irrigation areas. In this case, VIF equals 0. To avoid a drastic change between values of RRI=1 (VIF 0.5) and RRI>1 (VIF=0) a transition function was introduced to consider an increase in the non-natural variability of less than 20% as indicated in the following Eq. (11, 12 and 13):

If $0 < RRI \leq 1; VIF = 0.5 \times RRI$ (11)

If $1 < RRI \leq 1.2;\ VIF = -2.5 \times RRI + 3$ (12)

If $RRI > 1.2$; $VIF = 0$ (13)

Finally, seven different impact classes were defined for different values of HRI using percentiles as indicated in Table 3. The two classes at the lower and upper extremes have an extension of 10% in relation to the 20% that the middle classes present. This was implemented to highlight severe and drastic impacts or low impact conditions respectively.

Table 3: Hydrological Regime Index (HRI) impact classes

Range	Impact class
0.0 ≤ HRI < 0.1	Drastic
0.1 ≤ HRI < 0.2	Severe
0.2 ≤ HRI < 0.4	High
0.4 ≤ HRI < 0.6	Moderate
0.6 ≤ HRI < 0.8	Incipient
0.8 ≤ HRI < 0.9	Low
0.9 ≤ HRI < 1.0	Extremely Low

3.2 Data set

The HRI was applied in the DSCC river basin, which is currently characterized by its hydrological discontinuity and intermittent flows. Therefore, natural flows were evaluated in the tributaries upstream the main reservoirs, whereas modified flows downstream the main reservoirs were analyzed by comparing them with flow records registered upstream. Similarly, in the lower basin of the DSCC River and considering the significant distance from the reservoirs, the modified flows were analyzed by comparing flow periods in natural regime with those in a modified condition under low impoundment conditions (i.e. reservoirs with storage capacity < 2 hm^3, see Table 2) and high impoundment conditions (i.e. reservoirs with greater storage capacity, >100 hm^3).

Moreover, to validate the applicability of the index, the HRI was also applied to the CO River with a defined hydrological connectivity throughout the basin and permanent runoff in natural regimen, and with both low and high impoundment conditions.

In the tributaries of the DSCC River, the HRI was calculated on those rivers with flow in natural regime by comparing at least two gauging stations located upstream of the main reservoirs. The gauging stations were selected for their proximity, to ensure that there are no significant contributions from streams or interactions with groundwater. If the distances are larger, the criterion was based on the allochthonous nature of the flows, meaning that there are no evident contributions in the analyzed section that cause increased flows at the downstream gauging station. Based on the above and the availability of information, the MZ River at GUI and CAC (1956-90) and AT River at ESO plus the contribution of the Salado (SL) River at CAA respect to the records downstream in LAN (1972-03), were evaluated. In the CO River basin, the HRI for natural flows was implemented in the headwaters (LGT and BAR) with respect to the monthly flows registered in BRQ, and in the main channel between BRQ and PMA gauging stations, for the 1976-2011 and 1940-1971 periods respectively.

Furthermore, to assess the HRI performance in evaluating the impact of reservoirs on flow conditions, the HRI was applied in the DSCC River basin in two sectors, in the tributaries and the lower reaches of the DSCC River, based on flow data availability. The comparison between the flow records downstream of the reservoirs with those upstream in natural or low modified flow regime, was discriminated between periods characterized by low impoundment conditions during which water for irrigation was primarily sourced from diversion and small dams, and periods characterized by high impoundment conditions that represent current conditions (Table 4). In this case, only in the SJ River (km 47.3 vs PLT) was possible to evaluate the effect of a low impoundment condition from 1937 to 1950 and in the CO River (BRQ vs PMA) for the 1940-1971 period. For the current impoundment conditions, the modification of the hydrological regime was analysed in the majority of the tributaries of the DSCC River (SJ, MZ, DT and AT) in two periods, the historical available records until 2010 and the 2010-2023 time series that represent both the current impoundment and climate conditions. In the SJ River, the sum of natural or low modified flows at SJ-km 47.3 or SJ-km 101 and in the MZ River at MZ-GUI were compared with those observed downstream of QUL, PTN, CAL, ETA and POT reservoirs in SJ-EEN (modified flow) for the two indicated periods extending from 1993 to 2023. In the DT River, the natural or low modified flows at DT-LJA were compared with modified flows recorded downstream of ETI, LRE and ADT reservoirs in DT-MOC for the historical and current periods, while in the AT River the natural or low modified flows at AT-LAN were contrasted with the modified flows registered downstream of VGR and ENI reservoirs at AT-CAR and AT-PTU for the 1985-2023 and 1980-2010 time series respectively splitting the analyses in the two previously indicated periods.

Similar approach was applied in the CO River, where for low impoundment conditions natural or low modified monthly flows recorded in BRQ were compared with the modified observed in PMA downstream of DPU diversion dam for the 1972-1990 period. For high impoundment conditions, flows recorded in BRQ were contrasted with flows in PMA downstream of CDP reservoir, for the available historical (1994-2010) and current (2010-2023) periods. Missing records in PMA between 2015-2018 and 2023 were completed with CDP flow discharges while the flow contributions of the DSCC River in the 1980s were subtracted.

Table 4: Detail of the gauging stations (GS) located upstream [us] and downstream [ds] of reservoirs and periods with common available data used to calculate the Hydrological Regime Index (HRI) for modified flows in the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and the Colorado (CO) River. San Juan (SJ) River at km 47.3, km 101, Paso las Tunitas (PLT) and El Encón (EEN), Mendoza (MZ) River at Guido (GUI), Diamante (DT) River at La Jaula (LJA) and Monte Comán (MCO), Atuel (AT) River at La Angostura (LAN), Carmensa (CAR) and Puesto Ugalde (PTU), CO River at Buta Ranquil (BRQ), Pichi Mahuida (PMA) and Casa de Piedra (CDP). [N] and [M], natural and modified flows, [*] and [+] low and high impoundment conditions, [H] and [C] historical and current conditions respectively.

River	Tributaries	GS [us, N]	GS [ds, M]	period
DSCC	SJ	Km 47.3	LTU	1937-1951 [H*]
	SJ+MZ	Km 47.3 + GUI	EEN	1993-2010 [H^{+}]
	SJ+MZ	Km 101 + GUI	EEN	2010-2023 [C^{+}]
DSCC	DT	LJA	MCO	1990-2010 [H^{+}]
	DT	LJA	MCO	2010-2023 [C^{+}]
DSCC	AT	LAN	CAR	1990-2010 [H^{+}]
	AT	LAN	CAR	2010-2023 [C^{+}]
	AT	LAN	PTU	1990-2010 [H^{+}]
	AT	LAN	PTU	2010-2023 [C^{+}]

CO	BRQ	PMA	1972-1990 [H*]
	BRQ	PMA	1994-2010 [H$^+$]
	BRQ	PMA/CDP	2010-2023 [C$^+$]

In the DSCC River, the lack of records with natural flows and the intermittence of the current flow records determined that the application of the HRI relied on a temporal comparison. If 1988, which activated the entire fluvial system, is considered as an approximate representation of the natural or low modified regimen, it is possible to compare it with current flow conditions (2010-2023). Logically, 1988 represented a year of extraordinary flows that yield greater attenuations when compared to the current flows. Consequently, the 1982-1992 time series was utilized as the reference period, given that its records encompass both flood years and low-water years. As a result of data availability, the STI, LRF, PUE, and PM2 gauging stations located in the lower DSCC River basin were used.

The information is available at the national hydrological information system (SNIH) of the Secretaría de Infrestructura y Política Hídrica de Argentina, https://snih.hidricosargentina.gob.ar, in the hydrological database of La Pampa province (BDH) of the Secretaría de Recursos Hídricos de La Pampa, https://bdh.lapampa.gob.ar , and in the Colorado River Interjurisdictional Committee (COIRCO), https://www.coirco.gov.ar.

4. Results

4.1 Hydrological regime index in natural flow

The performance of the HRI was first evaluated for rivers with flow in natural regimes in both the tributaries of the DSCC River and in the CO River (Figure 4). In this case, the average monthly flows in natural regime recorded at a given gauging station were compared with those recorded upstream.

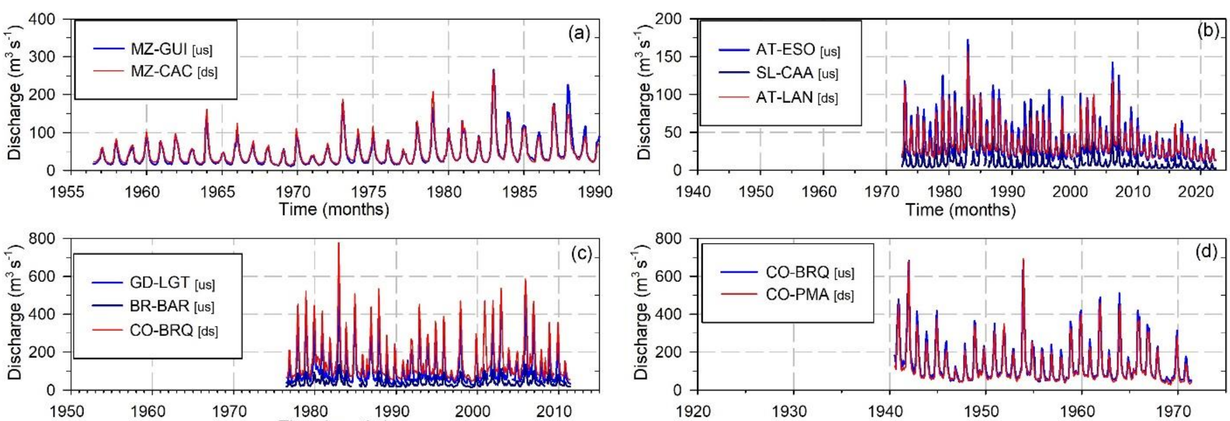

Figure 4: Chronological monthly flows in natural regime of the tributaries of the Desaguadero-Salado-Chadleuvú-Curacó (DSCC) River and in the Colorado (CO) River used to calculate the Hydrological Regime Index (HRI). [us]: upstream, [ds]: downstream. a) Mendoza (MZ) River at GUI and CAC, b) Atuel (AT) River at ESN, Salado (SL) River at CCA, and AT-LAN, c) Grande (GD) River at LGT, Barrancas (BR) River at BAR, and CO River at BRQ, and d) CO River at BRQ and PMA.

For all the rivers analysed in natural regime, high HRI values indicating low impacts were observed (Table 5 and Figure 5). In the MZ River, the comparison between flows recorded in GUI and CAC gauging stations for the period 1956-1990, previous to the construction of the POR reservoir, showed that there was no flow attenuation between GUI and CAC gauging stations. CAC had a slightly higher average annual flow value, possibly as a result of the contribution of streams between both stations, since they were located approximately 17.5 km from each other. Therefore, MIF was set equal to 1. There was no time delay (TIF=0.5) and a slightly lesser interannual flow variation was seen in CAC (VIF=0.476). The resulting HRI of 0.98 indicates an extremely low modification of the hydrological regime.

In the AT River, the analysis was carried out from the monthly flows recorded in ESO plus the contributions from its tributary the Salado (SL) River in CAA, and compared with the flow records in LAN located approximately 90 km downstream of both gauging stations. Both rivers join in the place called Las Juntas located at the foot of an extensive alluvial fan where significant flow losses occur and therefore lower flows are recorded in LAN. This resulted in an important attenuation of the flow magnitude (MIF= 0.785), however smaller impacts were seen in the timing and flow variability (TIF= 0.417 and VIF= 0.386). The HRI equals 0.63 and indicates an incipient modification of the hydrological regime.

In the headwater of the CO River basin, the monthly flows for the 1976-2011 period of the GD River in LGT plus those of the BR River in BAR were contrasted, with the flows recorded at the BRQ gauging station, located 160 and 37 km downstream respectively (see Figure 2). Due to contributions from small streams in the river section between the gauging stations analysed, the average annual flow is 5 % larger downstream in BRQ. Therefore, no flow attenuation was observed and the MIF equalled 1. In addition, no temporal differences were observed in the maximum flows (TIF=0.5) and a slightly lower interannual variability (VIF=0.475) was seen. The HRI equals 0.98 and shows that hydrological regime in natural conditions presented an extremely low modification between the analysed gauging stations. In the CO River, the monthly flows recorded in BRQ were compared with those of the PMA gauging station located 150 km downstream for the 1940-1971 period. Flows showed a low magnitude attenuation downstream that resulted in a MIF=0.883. The timing of maximum flows did not change (TIF=0.5) and the loss of interannual variability was very low (VIF=0.493). These impact factors resulted in a HRI=0.88 that indicates a low impact on the hydrological regime for the CO River in natural regime.

Table 5: Hydrological Regime Index (HRI) for natural flows in the tributaries of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and in the Colorado (CO) River. Qma: mean annual flow. [us]: upstream, [ds]: downstream. MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. Mendoza (MZ) River at Guido (GUI) [us] and Cacheuta (CAC) [ds], Atuel (AT) River at El Sosneado (ESO) [us], Salado (SL) River at Cañada Ancha (CAA) [us], and AT River at La Angostura (LAN) [ds], Grande (GD) River at La Gotera (LGT) [us], Barrancas (BR) River at Barrancas (BAR) [us], CO River at Buta Ranquil (BRQ) [ds and us] and Pichi Mahuida (PMA) [ds].

River	Series	Qma ($m^3 s^{-1}$) [us]	Qma ($m^3 s^{-1}$) [ds]	MIF	TIF	VIF	HRI	Impact class
MZ	1956-90	44.4 (GUI)	46.2 (CAC)	1	0.5	0.475	0.98	Extremely Low
AT+SL	1972-23	36 (ESO) + 9.5 (CAA)	35,7 (LAN)	0.785	0.417	0.386	0.63	Incipient
GD+BR	1976-11	111.1 (LGT)+39.2 (BAR)	158.1 (BRQ)	1	0.5	0.475	0.98	Extremely Low
CO	1940-71	136.3 (BRQ)	120.4 (PMA)	0.883	0.5	0.493	0.88	Low

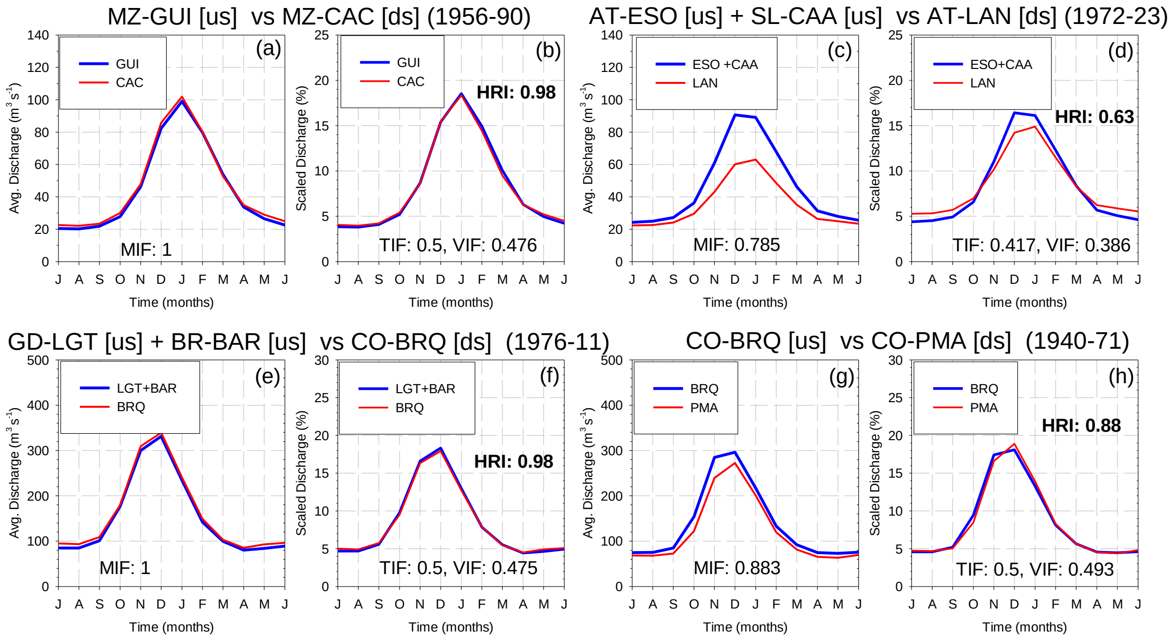

Figure 5: Hydrological Regime Index (HRI) for flows in natural regime in the tributaries of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and in the Colorado (CO) River. Annual and scaled hydrographs between gauging stations located upstream [us] and downstream [ds]. MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. a and b) Mendoza (MZ) River at GUI and CAC, c and d) Atuel (AT) River at ESO, Salado (SL) River at CAA, and AT River and LAN, e and f) Grande (GD) River at LGT, Barrancas (BR) River at BAR, and CO River at BRQ, and g and h) CO River at BRQ and PMA.

4.2 Hydrological regime index with low impoundment conditions

On the DSCC River basin, most of the main reservoirs were built on its tributaries in the second half of the 20th century. Previously, there were only small water diversion dams with little or no impoundment conditions (see Table 2). The present analysis is thus restricted to the periods with flow records upstream and downstream of the diversion dams. This is the case of the SJ River with flow records in SJ-km 47.3 and SJ-LTU located upstream and downstream of Dique la Roza (DLR) and Dique San Emiliano (DSE) diversion dams respectively for the period 1937-1951. Since the period under analysis was characterized by a significant flood in 1941/42 that contrasted with the low flows observed before and after (Figure 6), the HRI was determined for the entire period (1937-1951), for the period with high flows 1941-1946, and for the periods with low flows 1937-1940 and 1946-1951 (Table 6 and Figure 7).

In the CO river, the analysis was applied by comparing the average monthly flows in BRQ with those registered in PMA gauging station located downstream the Dique Punto Unido (DPU) diversion dam for the 1972-1990 period. PMA is located 550 and 360 km downstream of BRQ and DPU respectively. Flows showed a low magnitude attenuation downstream that resulted in a MIF=0.879. The timing of maximum flows did not change (TIF=0.5) and the loss of interannual variability was very low (VIF=0.464). These impact factors resulted in a HRI=0.84 that indicates a low impact on the hydrological regime.

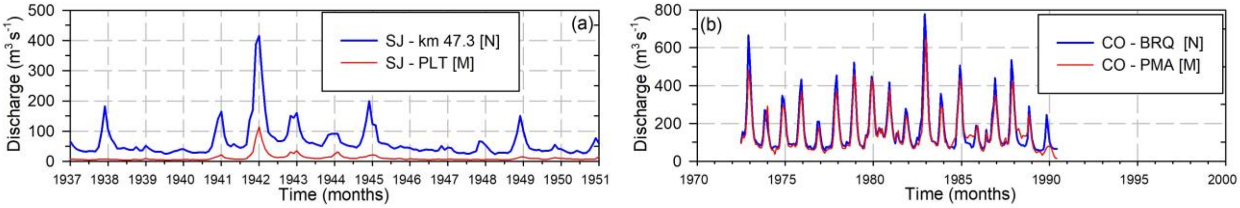

Figure 6: Chronological monthly flows in natural [N] and modified [M] regime used to calculate the Hydrological Regime Index (HRI) with low impoundment conditions in the tributaries of the Desaguadero-Salado-Chadleuvú-Curacó (DSCC) River and in the Colorado (CO) River a) San Juan (SJ) River at km 47.3 and PLT gauging stations upstream and downstream of Dique la Roza (DLR) and Dique San Emiliano (DSE) diversion dams respectively, b) CO River at BRQ and PMA gauging stations upstream and downstream of Dique Punto Unido (DPU) diversion dam respectively.

For the complete period, the MIF=0.270, TIF=0.417 and VIF=0.489 resulted in a HRI=0.24 that indicates a high impact on the hydrological regime downstream the SLR diversion dam. However, if the previous and post flood conditions that better represent the average flow conditions, are evaluated, the attenuation of the flow magnitude is very large (MIF=0.057). No differences in timing were observed (TIF=0.417), but they contrasted with the drastic loss of natural variability downstream (i.e. increase unnatural variability), where very low flows and only present during the summer season, differed from the almost null and zero flows registered in the reset of the year (VIF=0). These impact factors determined an HRI =0.02 that illustrates a drastic impact condition. Finally, if only the period with the highest flows is analysed, MIF=0.371, TIF=0.417 and VIF=0.449. It gives an HRI=0.32 that corresponds to an equally high impact condition to the hydrological regime.

Table 6: Hydrological Regime Index (HRI) for modified flows with low impoundment conditions in a tributary of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and in the Colorado (CO) River. Qma: mean annual flow. [N]: natural flow, [M]: modified flow. [us]: upstream, [ds]: downstream. MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. San Juan (SJ) River at km 47.3 and Paso las Tunitas (PLT) located [us] and [ds] of Dique de la Roza (DLR) and Dique San Emiliano (DSA) diversion dams respectively. CO River at Buta Ranquil (BRQ) and Pichi Mahuida (PMA) located [us] and [ds] of Dique Punto Unido (DPU) diversion dam respectively.

River	Series	Qma ($m^3 s^{-1}$) [N, us]	Qma ($m^3 s^{-1}$) [M, ds]	MIF	TIF	VIF	HRI	Impact class
SJ	1937-51	62.2 (km 47,3)	16.8 (PLT)	0.270	0.417	0.489	0.24	High
SJ	1937-40, 1947-51	45.9 (km 47,3)	2.6 (PLT)	0.057	0.417	0	0.02	Drastic
SJ	1940-46	80.1 (km 47,3)	29.7 (PLT)	0.371	0.417	0.449	0.32	High
CO	1972-1990	165.1 (BRQ)	145.2 (PMA)	0,879	0,5	0,464	0,85	Low

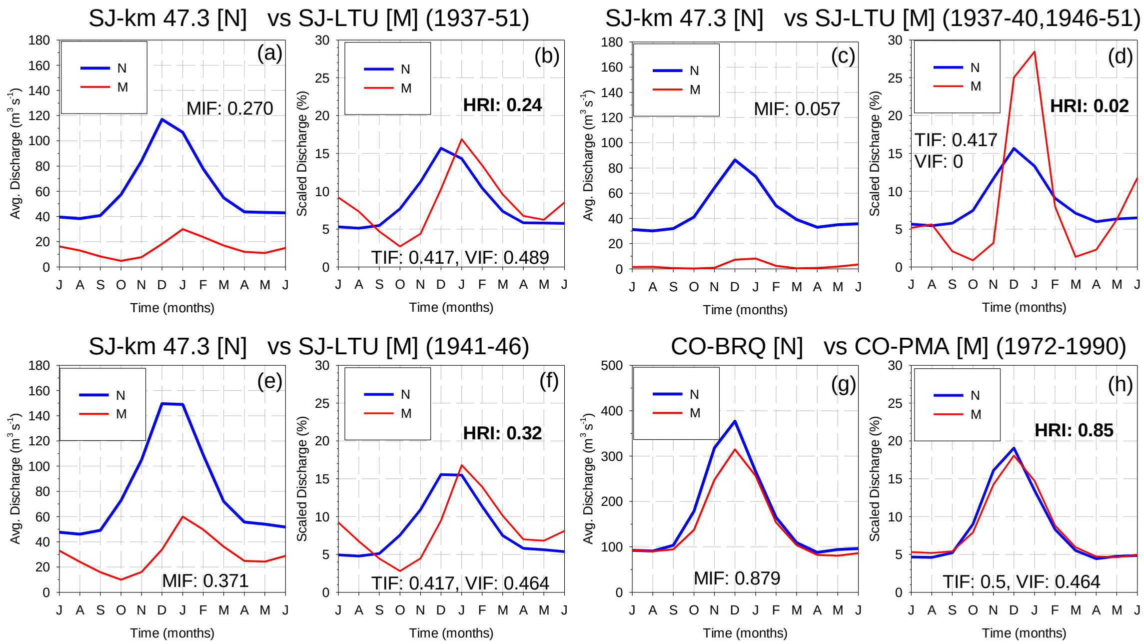

Figure 7: Hydrological Regime Index (HRI) for low impoundment conditions. Annual and scaled hydrographs in natural [N] and modified [M] flows. MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. a-b) San Juan (SJ) River at km 47-3 [N] and PLT [M] complete period (1937-51), c-d) SJ River at km 47-3 [N] and PLT [M] low flow periods (1937-1940 and 1946-1951), e-f) SJ River at km 47-3 [N] and PLT [M] high flow period (1941-1946), and g-h) Colorado (CO) River at BRQ [N] and PMA [M] (1972-1990).

4.3 Hydrological regime index with high impoundment conditions

The comparison of flow conditions upstream (i.e. natural regime) and downstream (i.e. modified regime) of the main reservoirs in the tributaries of the DSCC River and in the CO River revealed a different degree of modification of the hydrological regime (Figure 8). In the tributaries, downstream of the reservoirs and adjacent to irrigation areas, runoff is intermittent. However, this runoff is not natural and stems from both direct and diffuse drainage contributions of irrigation surpluses due to the use of highly inefficient gravity irrigation systems. Therefore, flows show significant attenuation or an intermittent condition with an inverted hydrological regime as they predominantly occur in winter. This runoff vanishes downstream and does not contribute to the DSCC River.

Furthermore, in the current period characterized by reduced natural flows, the aforementioned effects are more pronounced. The reduction in flows exhibited a marked synchronicity in all the tributaries of the DSCC River and in the CO River, where consistently lower snowfall amounts in the CA were attributable to the predominance of La Niña episodes.

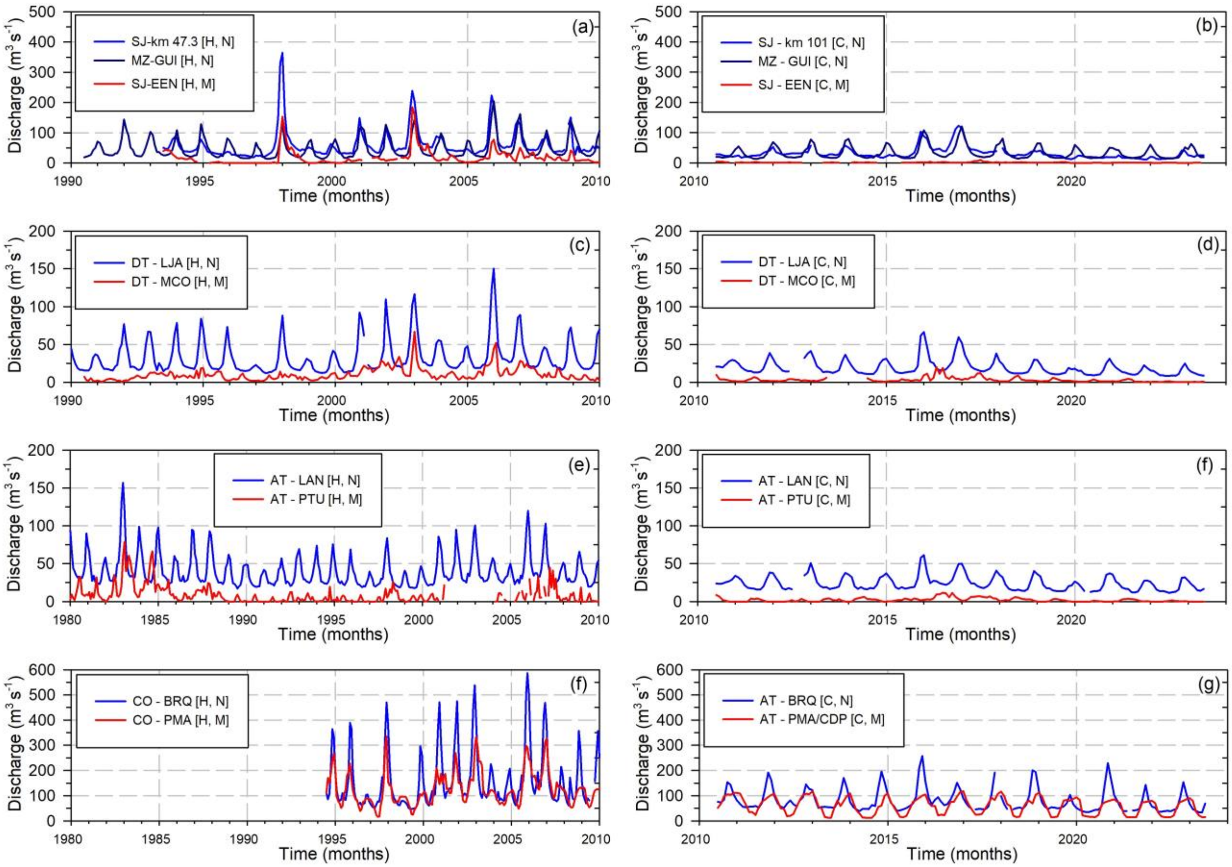

Figure 8: Chronological monthly flows in natural [N] and modified [M] regime of the tributaries of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and in the Colorado (CO) River for available historical [H] and current [C] (2010-23) periods. a) San Juan (SJ) River at km 47.3 [H, N], Mendoza (MZ) River at GUI [H, N] and SJ River at EEN [H, M], b) SJ at km 101 [C, N], MZ River at GUI [C, N] and SJ River at EEN [C, M], c) Diamante (DT) River at LJA [H, N] and MCO [H, M], d) DT River at LJA [C, N] and MCO [C, M], e) Atuel (AT) River at LAN [H, N] and PTU [H, M], e) AT River at LAN [C, N] and PTU [C, M], f) CO River at BRQ [H, N] and PMA[H, M], g) CO River at BRQ [C, N] and PMA completed with Casa de Piedra (CDP) reservoir discharges [C, M]

The HRI values determined by comparing the flows upstream and downstream of the main reservoirs for the historical and current periodsare shown in Table 7 and Fig. 9. For the SJ River, the natural flows in km 47.3 plus the contribution of the MZ River in GUI were contrasted with flows observed in the SJ River in EEN located downstream the of the QUL, DLR and DSE (in SJ River), POT, DSM and DCI (in MZ River) reservoirs and diversion dams, for the 1993-2010 period. In this condition, the mayor impact factor was the strong flow magnitude attenuation (MIF=0.174). In contrast, no changes in the maximum flow timing (TIF=0.5) and lover effects in the interannual variability were observed (VIF=0.449). The resulting HRI =0.15 indicates a severe impact on the hydrological regime. However, when current conditions are analysed (2010-2023), the lower natural flows and the inclusion of the PTN and CAL reservoirs plus the construction ETA in the SJ River, and the lack of contributions from the MZ River, exacerbated the effects downstream in EEN. Flows became intermittent (MIF=0.014), with a strong effect in the timing given by the prevalence of winter flows (TIF=0) that resulted in a non-natural variability (VIF=0). Consequently, the hydrological regime impact is classified as drastic with a HRI =0.

In the DT River, flows upstream the ADT, LRE, ETI, DGV, and DVI reservoirs and diversion dams, showed downstream in MCO a high impact on the flow regime for the historical period (HRI=0.24) as a result of a MIF=0.369, TIF=0.417 and VIF= 0.225 values. For current conditions with no changes in the impoundment conditions, the lower natural flows resulted in a stronger attenuation (MIF= 0.157), a marked delay on the occurrence of maximum flows (TIF=0.08) and a larger and non-natural interannual variability due to the prevalence of winter flows (VIF= 0). The resulting HRI=0.16 indicates drastic effects on the hydrological regime in MCO.

In the AT River, flows downstream the ENI, AIS, TBL, VGR and DRI reservoirs and diversion dams, showed for the historical period a severe impact on its hydrological regime in CAR with HRI= 0.1. The marked attenuation (MIF=0.239) and the dominance of winter flows (TIF= 0) were the main factors modifying the hydrological regime. For the current conditions, the inclusion of the DCM diversion dam and the lower natural flows worsened the impact on the hydrological regime downstream the reservoirs. The HRI degraded to a value of 0.07 indicating a drastic flow regime modification. In PTU, located 120 km downstream of CAR, the HRI for the historical period equalled 0.01 which indicates a drastic impact on the hydrological regime, showing significant flow attenuation, changes in timing and interannual variability (MIF=0.128, TIF=0 and VIF= 0.110). For current conditions, the flow intermittence is more pronounced given by MIF=0.083, TIF=0 and VIF= 0 values, which resulted in an HRI= 0 that indicates a maximum drastic impact.

The CO River showed for the historical period and incipient impact (HRI=0.62) on the hydrological regime of the flows in PMA located downstream of the CDP and DPU reservoir and diversion dam. The flow attenuation resulted in a MIF= 0.791, no changes were registered in the timing (TIF=0.5), however a marked reduction of the interannual flow variability (VIF=0.279) was observed presumably due to the filling of the CDP reservoir at the beginning of the period considered. In the current condition with the same impoundment infrastructure, the lower natural flows resulted in a similar attenuation (MIF= 0.759) and, larger delay in maximum monthly values (TIF= 0.333) but a lower effect in the flow variability (VIF=0.423). The resulting HRI equalled 0.57 indicating a moderate effect on the natural hydrological regimen in PMA.

Table 7: Hydrological Regime Index (HRI) for modified flows in the tributaries of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and the Colorado (CO) River with high impoundment conditions. Qma: mean annual flow. us: upstream, ds: downstream. MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. San Juan (SJ) River at km 47.3, km 101 and El Encón (EEN), Mendoza (MZ) River at Guido (GUI) and Cacheuta (CAC), Diamante (DT) River at La Jaula (LJA) and Monte Comán (MCO), Atuel (AT) River at La Angostura (LAN), Carmensa (CAR) and Puesto Ugalde (PTU), and CO River at Buta Ranquil (BRQ), Pichi Mahuida (PMA) and Casa de Piedra (CDP).

River	Series	Qma (m^3/s) [N, us]	Qma (m^3/s) [M, ds]	MIF	TIF	VIF	HRI	Impact class
SJ+MZ	1993-10	60.1 (km47.3) + 48.1 (GUI)	18.8 (EEN)	0.174	0,5	0,382	0,15	Severe
	2010-23	30.7 (km101) + 32.8 (GUI)	0.9 (EEN)	0.014	0	0	0	Drastic
DT	1990-10	31.2 (LJA)	7.5 (MCO)	0.369	0.417	0.225	0.24	High
	2010-23	19.1 (LJA)	3.0 (MCO)	0.157	0.080	0	0.01	Drastic
AT	1985-10	37.7 (LAN)	9.0 (CAR)	0.239	0	0.419	0.10	Severe
	2010-23	24.0 (LAN)	3.9 (CAR)	0.163	0	0.457	0.07	Drastic
AT	1980-10	39.7 (LAN)	5.1 (PTU)	0.128	0	0.110	0.01	Drastic
	2010-23	24.0 (LAN)	2.0 (PTU)	0.083	0	0	0	Drastic

CO	1994-10	158.1 (BRG)	125.0 (PMA)	0.791	0.5	0.279	0.62	Incipient
	2010-23	79.1 (BRQ)	59.3 (PMA/CDP)	0.750	0.333	0.423	0.57	Moderate

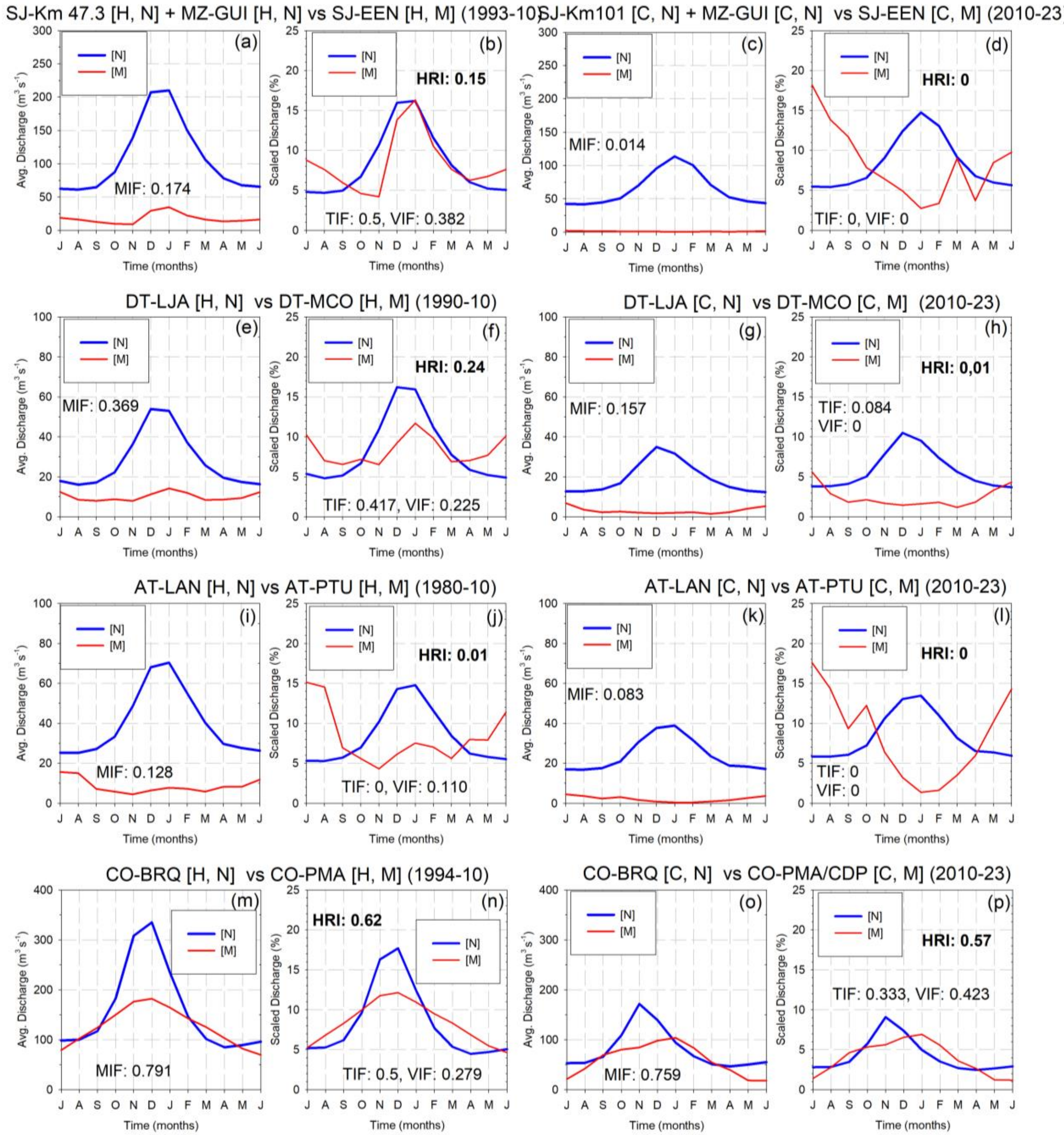

Figure 9: Hydrological Regime Index (HRI) of the tributaries of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River and in the Colorado (CO) River with high impoundment conditions for available historical [H] and current [C] (2010-23) periods. Annual and scaled hydrographs in natural [N] and modified [M] flows. MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. a-b) San Juan (SJ) River at SJ-km 47.3 [H, N] plus Mendoza (MZ) River at MZ-GUI [H, N] vs SJ-

EEN [H, M], c-d) SJ- km 101 [C, N] plus MZ-GUI [C, N] vs SJ-EEN [C, M], e-f) Diamante (DT) River at DT-LJA [H, N] vs DT-MCO [H, M], g-h) DT-LJA [C, N] vs DT-MCO [C, M], i-j) Atuel (AT) River at AT-LAN [H, N] vs AT-PTU [H, M], k-l) AT-LAN [C, N] versus AT-PTU [C, M], m-n) CO River at Buta Ranquil (BRQ) [H, N] vs Pichi Mahuida (PMA) [H, M], and o-p) CO River at Buta Ranquil (BRQ) [C, N] vs Pichi Mahuida (PMA) and Casa de Piedra [C, M].

Although the DSCC River does not have large reservoirs, the severe flow regulation on its tributaries, results in the DSCC River being dry. Flows are only present as runoff pulses associated with ENSO episodes that eventually exceed the storage capacity of the reservoirs as occurred during the 1980s and particularly in 1988 when the fluvial network of the DSCC River was entirely activated. Similar effects, though to a lesser extent, were observed in 1998 and 2006. Fig. 10 depicts the longest time series available of monthly flows located in the lower part of the DSCC River basin. Based on these hydrological expressions, both the historical or reference period (1982-1992) with flows in natural regime and the current period (2010-2023) characterized by their intermittent and very attenuated flow conditions, are indicated.

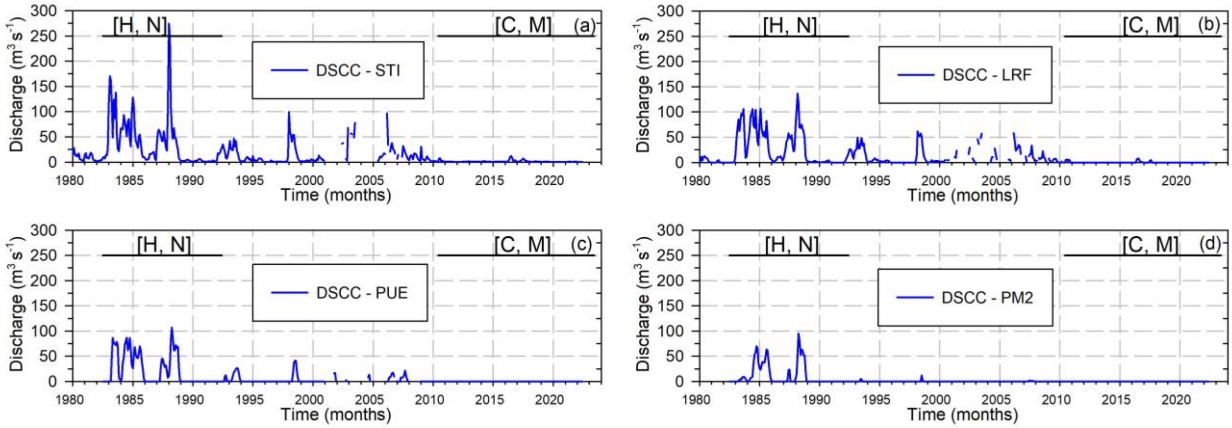

Figure 10: Chronological monthly flows in the lower part of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River basin with high impoundment conditions. Straight lines indicate the historical [H] period (1982-1992) in assumed natural [N] regime and the current [C] period (2010-2023) with modified [M] regime. a) DSCC River at Santa Isabel (STI), b) DSCC River at La Reforma (LRF), c) DSCC River at Puelches (PUE), and d) DSCC River at Pichi Mahuida 2 (PM2).

Table 8 and Fig. 11 compare both periods and indicate the values of the impact factors of the HRI in different gauging stations of the lower basin of the DSCC River. For the historical period, flows in STI exhibited a rather complex annual hydrograph with maximum flows in summer season. This is the result of the prolonged travel time of allochthonous flows caused by the extensive river network relative to its headwaters (> 1000 km), along with both anthropogenic (upstream reservoirs) and natural (LG and BT wetlands) flow regulation. In contrast, current conditions have an almost uniform hydrograph that demonstrates a drastic flow attenuation (MIF= 0.032). The predominance of winter flows resulted in a TIF=0,084 whereas the intermittence of flows culminated in a non-natural intrerannual variability that led to a VIF=0. Consequently, the resulting HRI= 0.003 indicates a drastic impact with a maximal modification of flow regimen.

Downstream, the natural flows in LRF showed the combined effect of flow attenuation given by the regulation of BA wetland and the contribution of the AT River. This regulation resulted also in a complex hydrograph with summer and winter flows slightly more uniform than those observed in STI. However, for the current conditions, intermittent conditions with much attenuated winter flows were observed, The MIF= 0.013, TIF= 0.167 and VIF= 0 indicate the attenuation of the flows, their intermittency and winter occurrence. These impact factors resulted in an HRI= 0.002 showing a drastic impact on the hydrological regime.

As can be observed in both PUE and PM2 gauging stations, the annual hydrograph of the historical period showed highly predominance of winter flows given by the natural flow regulation of the LP wetland. On the contrary, no flows were observed for the current conditions along the 13 years considered. In consequence, all the impact factors and the resulting HRI values equalled 0, indicating a drastic impact on the hydrological regime in both gauging stations.

Table 8: Hydrological Regime Index (HRI) for modified flows in the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River with high impoundment contitions. Qma: mean annual flow. [N]: historical period (1982-92), [C]: current period (2010-23). MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. DSCC River at Santa Isabel (STI), La Reforma (LRF), Puelches (PUE) and Pichi Mahuida 2 (PM2).

River	Qma ($m^3 s^{-1}$) [H]	Qma ($m^3 s^{-1}$) [C]	MIF	TIF	VIF	HRI	Impact Class
DSCC-STI	37.5	1.2	0.032	0.084	0	0.003	Drastic
DSCC-LRF	30.2	0.4	0.013	0.167	0	0.002	Drastic
DSCC-PUE	22.2	0	0	0	0	0	Drastic
DSCC-PM2	12.0	0	0	0	0	0	Drastic

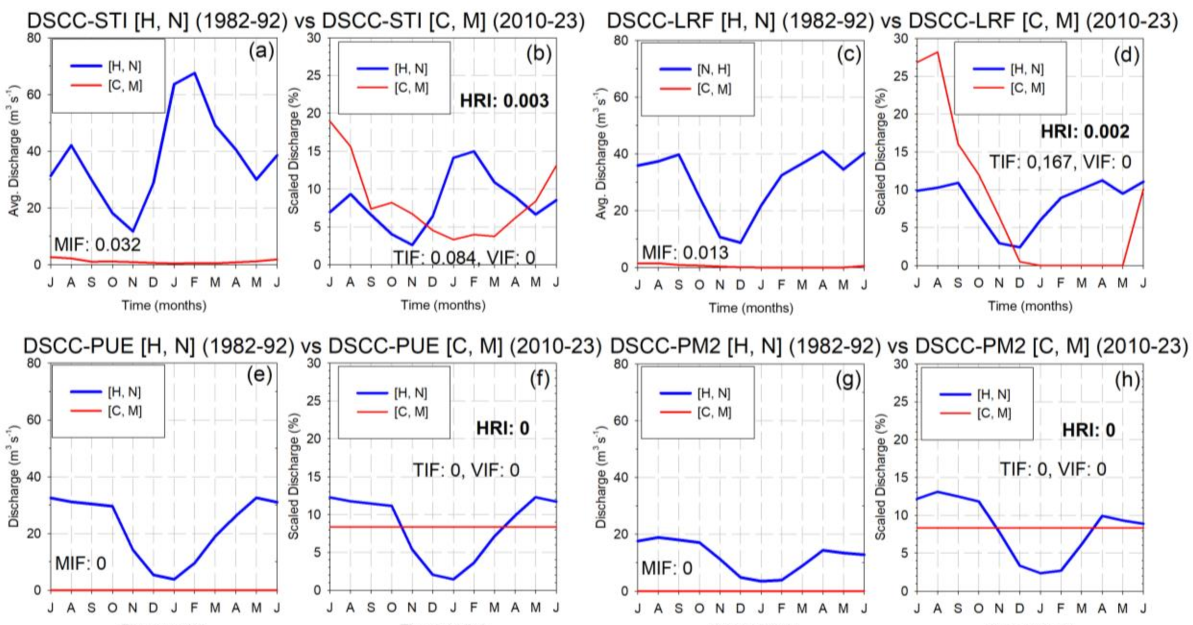

Figure 11: Hydrological Regime Index (HRI) of the lower basin of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) River with high impoundment conditions. Annual and scaled hydrographs for the historical [H] period (1982-92) with natural flows [N] and current [C] period (2010-23) with modified [M] flows. MIF: Magnitude Impact Factor, TIF: Timing Impact Factor, and VIF: Variation Impact Factor. a-b) DSCC River at Santa Isabel (STI) [H, N] versus [C, M], c-d) DSCC River at La Reforma (LRF) [H, N] versus [C, M], DSCC River at Puelches (PUE) [H, N] versus [C, M], and DSCC River at Pichi Mahuida 2 (PM2) [H, N] versus [C, M].

5. Discussion

Hydrological river regime is a spatial and temporally integrated basin response; therefore, a comprehensive approach should be used to assess the impacts due to both anthropogenic interventions such as river regulation and water diversion for different uses and change in climate conditions.

As described, there are several point measurements of change in the flow regime. They are usually based on simple characteristics or statistics of the river flow hydrograph, such as mean, maximum and minimum flow values, CV, and flow frequency for a given percentage of time, whereas flow variation is usually addressed by establishing ratios between some of these parameters or by the average flow in a given season. These metrics do not necessarily represent the flow distribution over the hydrological or water year in different conditions. Indeed, under prolonged flow intermittency, some of the statistics are not applicable (e.g. CV cannot be mathematically solved under no flow conditions, the FDC is a straight line of zero flow for the period considered). Similarly, the occurrence of unnatural variability (e.g. contributions of temporally lagged drainage from irrigated areas) may not necessarily be captured by seasonal averages or be assumed as natural unless compared with the upstream flow when a local or point evaluation index is used. Furthermore, the fact that many metrics are based on local measurements limits the study of temporal and spatial hydrological variability, such as the analysis of hydrological connectivity that is typically diminished or lost in semi-arid basins under conditions of drastic flow alteration. This determines that the hydrological regime at a downstream location has no relationship with that upstream, a phenomenon that can hardly be evaluated with specific site measurements.

The proposed HRI is a single and dimensionless metric that considers the impacts on the annual distribution of flows, which is the more general definition of the hydrological regimen. Therefore, monthly mean flows are used to evaluate the different impact factors. This method allows its application in large basins, where daily flow variations do not necessarily represent the river-aquifer interaction, the activation of a wetland, or the maintenance of ecosystem functions downstream of the reservoirs. Additionally, this approach allows addressing the usual lack of daily flow data especially during no flow periods, a condition that complicates the identification of pulses or the determination of runoff resumption. Furthermore, it is not a specific measurement but is based on the comparison of flow records between upstream and downstream locations, a feature that allows for the assessment of not only changes due to hydraulic infrastructure but also the effects of tributaries, groundwater interaction, and the storage impacts of wetlands. Therefore, it is a flexible method based on the comparison of sites or time series of the flow magnitude (i.e. flow attenuation), the timing of maximum flow (i.e. peak flow occurrence) and annual flow variation (i.e. the temporal pattern of flow variability). Conceptually, the HRI is similar to the index proposed by Haghighi Toraby and Kløve (2013) and Haghighi Toraby et al (2014), however, a simpler approach is used to compute the river regime indexes. HRI does not use conceptual hydrographs and somehow complex functions to represent the monthly river regime. Instead, the differences between the natural o reference regime and a uniform regime representing full regulation or no flow conditions are calculated.

The HRI, due to its low data requirements and the identification of impact factors through the contrast between upstream and downstream flows, demonstrated its effectiveness as an indicator to discriminate both the spatial and temporal impacts on the hydrological regime in the DSCC and CO Rivers in both continuous and discontinuous flow conditions and different degrees of regulation or impoundment conditions. For natural regime, the synchronous comparison of flows between upstream and downstream gauging stations in the tributaries of the DSCC River showed the sensitivity of the HRI. The HRI values indicated incipient or extremely low impacts on the hydrological regime as a result of minimal or no attenuation of flows, minimal time lag of the maximum flow and a reduced loss of interannual variability. The analysis could have been done using the asynchronous comparison of flow series; however, this criterion was applied to consider uniform hydrological conditions. In the case of the AT River, the incipient modification resulted from the streamflow losses in the alluvial fan at Las Juntas along with the significant distance (> 100 km) separating the gauging stations. Aside from the applicability or the approximation employed to determine HRI for flows in a natural regime, it is verified that HRI can be a useful management tool to assess impacts caused by changes in land and water use.

This approach was validated in the CO River with higher flows. In its tributaries, the natural flow inputs of the GD and BR Rivers, did not show a modification downstream in BRQ neither in the flow attenuation, nor in the timing or in the flow variability. The resulting HRI indicated an impact extremely low on the hydrological regime. Similarly, on its main channel between BRQ and PMA, the impact on the hydrological regime was classified as low, even though both gauging stations are located 550 km apart and there was water allocation for consumption and irrigation.

The HRI applied to low impoundment conditions demonstrated its sensitivity to different hydrological conditions. When extreme flows occurred, presumably associated with the ENSO episode, such as those in 1941/42, flows exceeded the capacity of the water diversion dam and the impact on the hydrological regime downstream was high. On the contrary, with average natural flows, the impact observed downstream of the diversion dam was drastic. This showed that the operation of these hydraulic structures played an important role as well, mainly due to the high seasonal demands given by the low efficiency of gravity-fed irrigation systems.

For high impoundment conditions, the HRI adequately discriminated the reduced or no flow observed downstream of the reservoirs in the DSCC River. The HRI values indicated severe and drastic impacts in all the tributaries. Moreover, the different impacts were quantified and identified, such as the severe attenuation of the flow magnitude with an average MIF value for all the tributaries of 0.228, and the inversion of the regime with winter flows and zero summer flows that resulted in very low values or equal to zero of TIF and VIF. This indicates that the runoff observed immediately downstream of the irrigation areas is not natural runoff but rather comes from irrigation drains. Towards downstream the modification of the hydrological regime worsened and flow becomes more intermittent until runoff disappears.

For the current conditions characterized by lower natural flows, and considering that the reservoir conditions did not change, except in the SJ River, a degradation of HRI values was observed in all tributaries. Although these values could be attributed to climate change that resulted in lower flows, the HRI impact factors demonstrated that water management for irrigation is the main cause of the drastic alteration of the snow-fed flow regimen observed in the tributaries. The MIF impact factor resulted in values close to or lower than 50 % of the values obtained in the historical series, as a result of the reservoir operation for irrigation purposes with a total diversion of water stored during the crop growing season and water storage in the rest of time. The effects of hydropower management that may influence the frequency and duration of flow pulses as well as the rate and frequency of changes in the flow, cannot be properly assessed because the flow downstream of the irrigation areas is not natural but rather comes from drainages or eventual water releases. This resulted in values of TIF and VIF equal to 0 or between the historical and current series. The exception is CAR with the same VIF values, which due to its location immediately downstream of the irrigation area, already presented unnatural variability in the historical series. As indicated for historical periods, the incidence in the modification of the hydrological regime is given by the high water demands of the gravity irrigation systems due to their low efficiency. Thus, in years of lower natural contributions, the impact on the hydrological regime is more evident. In the DSCC River, the lack of flow determined that the HRI values were equal to zero indicating a drastic impact in all the gauging stations.

In the CO River, lower natural flows also resulted in a degradation of the HRI indicating a moderate impact in relation to the incipient impact observed in the historical period. Changes in natural runoff also showed an advance in the occurrence of maximum flows due to both a shorter extension of the snow accumulation period and a rapid ablation of snow. Therefore, downstream of the CDP reservoir, similar values of attenuation and intra-annual variability were observed with a small increase in the temporal lag of the maximum monthly flows.

From a basic visual examination, it is obvious that the absolute lack of runoff indicates a drastic modification of the hydrological regime in the DSCC River that would not require the use of hydrological metrics. Nevertheless, the HRI allows us to both quantify the degree and discriminate the type of impact (i.e. attenuation of flows, time lag of maximum flows and reduction of variability) on the natural hydrological regime even when there are prolonged periods with no flow conditions. As an illustration of these capabilities, Figure 12 details the contrasting hydrological expressions of the DSCC River between the current and the fully activated river network (1988), where the HRI was applied. The surface of water obtained with the Modified Normalized Difference Water Index (MNDWI) (McFeeters, 1996) using Landsat 4-5 images from Sep to Dec 1988 and Landsat 8 images for the hydrological year 2021/22, demonstrates that in 1988 (i.e. natural flows), there was a distinctly defined longitudinal and transversal hydrological connectivity throughout the alluvial flood plain. It is observed that all the tributaries contributed to the DSCC River except the VB River which due to its low discharge values and intermittent flows were not identified by the MNDWI. The DSCC River exhibited activation across all sections and wetlands. Owing to the limited availability of satellite imagery and the sporadic runoff observed in the Curacó River in September of 1988 (see Fig. 10), the MNDWI was unable to recognize the intermittent runoff registered in the Curacó River that flowed into the CO River. In comparison, the present spatial extent of the fluvial system of the DSCC River indicates that merely the natural flows in the tributaries located upstream of the reservoirs were recognized by the MNDWI. Therefore, no flows were detected downstream of the irrigation zones, apart from the altered and intermittent flows in sections of the SJ, DT, and AT Rivers and groundwater discharge from the alluvial fans of the tributaries along its first sections (DSCC-I or Río Chadileuvú and DSCC-II or Río Salado).

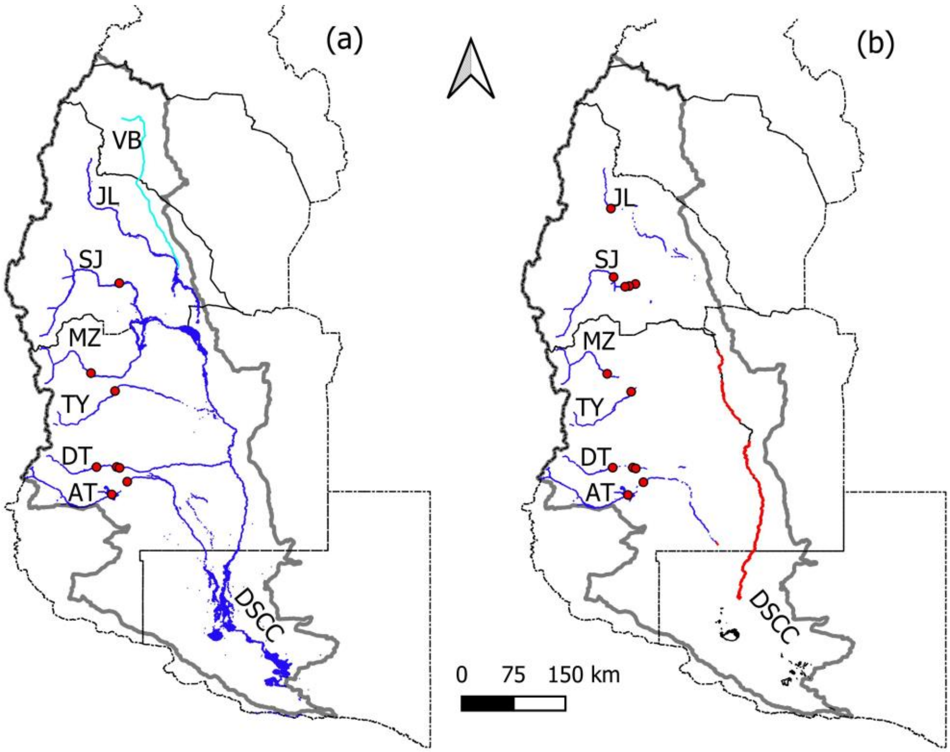

Figure 12: Comparison of contrasting hydrological expressions of the Desaguadero-Salado-Chadileuvú-Curacó (DSCC) fluvial system obtained with the Modified Normalized Difference Water Index (MNDWI) using optical Landsat satellite imagery (https://earthexplorer.usgs.gov/), row and path: 229-86 and 87, 230-83 to 86, 231-82 to 84, and 232-80 to 84 where the Hydrological Regime Index (HRI) was applied. a) Maximum areal extension in 1988. Blue lines: indicate the connectivity between tributaries (JL, SJ, MZ, TY, DT and AT Rivers) and the DSCC River with all the wetlands activated, light blue line: indicates the VB River but either due to low flows, intermittent runoff or lack of available images, the MNDWI did not identify it, b) Current expression of the drainage network corresponding to 2021/22. Blue lines: indicate tributaries only active upstream of the main reservoirs. Red lines: indicate water in the DSCC river in its first sections (DSCC-I or Río Chadiluevú and DSCC-II or Río Salado), a product of groundwater discharge (< 1 $m^3 s^{-1}$) of alluvial fans. No active wetlands are observed. Red dots: main reservoirs.

As detailed, the absence of runoff limits the utilization of hydrologic alteration metrics, as the majority of the parameters cannot be determined. For instance, the magnitude timing parameters remain unchanged due to all the average monthly flow are equal to zero, and this holds true for the magnitude duration (e.g. means of the annual maxima or minima). Likewise, this applies to magnitude frequency parameters such as the number of high or low pulses or their duration. Additionally, the parameters that assess the frequency rate of change (e.g. means of all positive or negative differences between consecutive daily means, or the number of rises or falls) remain unchanged.

In this context, the HRI based on temporal or spatial monthly flow comparisons overcomes these limitations and therefore constitutes an essential tool for the definition of E-Flows and for assessing the effectiveness of both structural and non-structural management measures that may be adopted to restore the environmental degradation of the fluvial ecosystems of the DSCC River caused by the absence of runoff. Moreover, remote sensing data could serve as an indicator of the impact factors of the HRI, such as flow attenuation, the timing of occurrence of maximum flow, or interannual variability, and it could also aid in monitoring ecohydrological processes, provided that representative relationships between the remote sensing products and impact factors are identified.

Climate change is another critical factor of regime modification whose effects can be evaluated with the HRI. The current period has exhibited reduced runoff due to diminished snowfall in the basin, and predictions for the study area indicate a decrease in snowfall alongside an increase in rainfall. However, according to Arheimer et al (2017), the anthropogenic influence on the snow-fed hydrological regime of the DSCC River has been found to be detrimental in relation to the potential consequences of climate change on the input function of the basin. Therefore, for sustainable freshwater management, the proposed HRI will contribute to focus on the adaptation to climate change and other environmental stressors (Poff and Matthews, 2013) such as the lack of integrated water resources management in the basin.

6. Conclusions

An index, the HRI, is presented to evaluate the modifications of the hydrological regime in non-permanent rivers. The usually drastic flow alterations in rivers of semiarid regions, where runoff can alter between a permanent or intermittent flow condition, require a new approach to properly evaluate the modification of the hydrological regime in these basins which typically have limited information. The HRI constitutes an aggregate impact index that facilitates its application in either spatial or temporal analysis. It can be applied at different points along the drainage network and is based on the comparison of flow measurements upstream and downstream of the locations, while the comparison of different time series makes it suitable to evaluate variations in impoundment conditions, changes in land use or the effects of climate change.

The HRI evaluates three impacts on the hydrological regime: the attenuation of the flows, the time lag, and the change in the intra-annual variability. It is based on the comparisons of monthly data which enhances its applicability in areas with limited information regarding other indices that utilize daily data.

The HRI was suitable for evaluating drastic flow alterations in the DSCC River under both permanent and non-permanent flow conditions across all the tributaries and in its main channel. Its application identified that, in addition to the impoundment conditions, the operation of the reservoirs constitutes one of the main modifying factors of the hydrological regime within the basin. Additionally, the application of the HRI in the CO River under natural and modified flow conditions while maintaining permanent runoff, validated the method and showed the ability of the HRI to discriminate impacts between different hydrological conditions.

The performance of the HRI in the DSCC river basin, characterized by the defined lack of hydrological connectivity between the upper basin, where the hydrological processes governing the generation of snowmelt runoff in the mountainous area are not related with those in the lower basin, where evaporative processes prevail, indicates that it is a valuable tool for E-Flow definition and environmental impact assessment.

Data availability

All raw data is accessible in the digital databases indicated or it can be provided by the corresponding authors upon request.

Author contributions

PFD: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft preparation, writing – review and editing. RNC: data curation, visualization, review and editing.

Competing interests

The authors declare that they have no conflict of interest.

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