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Implications of water resources management on the long-term regime of Lake Garda (Italy)

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A B S T R A C T

Amongst different climatic and anthropogenic drivers, water resources management can cause massive changes to the natural regime of a lake after its regulation, thereby affecting the quantity and quality of water intended for satisfying the multiple basin water requirements. Here, we investigate the multi-decadal variation of the water levels and outflows of Lake Garda, the largest in Italy, where the dam operational rules and the related basin water needs heavily altered the annual and seasonal trend of the lake regime since its regulation in 1951. Daily lake levels and outflows were first collected and digitized for the period 1888–2020, thus providing a unique database of 133 years that allowed a consistent comparison between natural and regulated periods. Statistical analyses highlighted a significant change of the inter-annual trend of the lake outflows, which passed from upward to downward after regulation, against a constant increasing trend of the water levels. Conversely, water levels showed a more remarkable shifts on a seasonal scale if compared to the outflows, revealing the influence of summer and winter basin water needs. Additional analyses on the inter-annual variation of the main downstream water demands regulated by the dam, i.e. the irrigation, hydropower and fluvial ecosystem requirements, outlined their relevance in changing the lake regime, influencing dam operational policies, which progressively limited the share of water released for ecosystem integrity. A comparison between the lake levels and outflows recorded for the pre-regulation and post-regulation periods of some selected European perialpine lakes finally highlighted different effects on the lake regime, drawing attention to the importance of defining the role of the dam operational policies within the current scenario of climate change and changing water demands.

1. Introduction

Lakes are one of the major global sources of renewable freshwater (Gleick, 1993), and they have been massively turned into regulated systems since the second half of the XX century (World Commission on Dams, 2000; Gleick, 2003). Despite the potentially high amount of water that can be allocated through lake regulation, efficient management of lake levels and outflows is an increasingly critical issue. Major water demands, like hydroelectricity production (Zarfl et al., 2015) and crop irrigation (Oki and Kanae, 2006), long-standing water interests, e.g. navigation and touristic activities, together with climate change and the need to ensure decent environmental standards for freshwater bodies (European Commission, 2000), challenge the way we manage key lake regulation systems, such as dams, to optimally benefit the human society and the natural environment (Moore et al., 2010). Dam construction, even on previously existing natural lakes, indeed determines relevant alterations both on the downstream riverine system and on the lake itself, affecting a variety of hydrological, geochemical and biological aspects (Ward et al., 1983; Nilsson et al., 2005; Magilligan and Nislow, 2005; Poikane et al., 2020).

Many studies discussed the long-term effects of lake regulation, also outlining the ecological impacts on the in-lake processes (Matzinger et al., 2007; Wei et al., 2009), on the littoral zones (Aroviita and Hämäläinen, 2008; Carmignani and Roy, 2017) and the downstream river (Nilsson et al., 1997; Vinson, 2001).

In general, the lake level regime can be affected at varying degrees by both climate and human-related factors, which have significantly changed within few decades, especially in the XX century. For instance, Khazaei et al. (2019) discussed and explained the drastic decline of Lake Urmia in terms of human-driven vegetation cover changes and the associated increase in irrigation water uses; however, Schulz et al. (2020) indicated climate change as the primary cause of the lake desiccation. Ever-growing agricultural activities, in fact, caused the lowering of the water levels of various lakes in the arid and semi-arid

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regions, additionally limiting the ecological flow releases in some cases (Haghighi and Kløve, 2017). Combined effects of climate and human drivers were found to affect water level variability in the Great Slave Lake (Gibson et al., 2006), in Lake Bosten (Guo et al., 2015) and in Poyang Lake (Mei et al., 2015).

Multiple water uses and their long-term changes are a distinctive feature of several European perialpine lakes (Fig. 1a), which were mostly dammed during the second half of the XX century to effectively address changes mainly in hydropower production, irrigation water needs and flood control. Very few of these lake systems succeeded in maintaining their natural conditions. On one hand, Lake Constance, having the largest catchment area among these perialpine lakes, felt more limited effects of water regulation despite the widespread presence of multiple water uses in the catchment (Hammerl and Gattenhoehner, 2003). On the opposite hand, Lake Garda, the largest in Italy, presents the highest ratio of lake surface per catchment area among such lakes, which entails a high sensitivity to regulation of its lake regime.

Lake Garda was turned into a multipurpose reservoir with inter-basin water transfers following the installation of several hydropower and irrigation schemes within the basin since 1920 (Fig. 1b), and especially after completion of the Salionze Dam in 1951. Existing studies on Lake Garda addressed its internal physical processes (Lovato and Pecenik, 2012; Amadori et al., 2018; Piccolroaz et al., 2019), water quality and ecological dynamics (Brivio et al., 2001; Giardino et al., 2007), at relatively short time scales. Few long-term studies mainly focused on the variation of its ecological and biological aspects (Salmaso, 2005, 2010; Salmaso et al., 2018b). Long-term investigations on the lake water level regime and its relation with the lake outflows are instead surprisingly lacking, despite the strategic role played by the largest Italian lake in water resources management (Berbenni et al., 1992).

Besides Lake Garda, few studies on regulated lakes specifically focused on joint changes in lake levels and outflow regimes associated with specific water uses and with their multi-decadal changes (Alemayehu et al., 2010; Moisello et al., 2013). Here, we aim to fill this gap by investigating the long-term (133 years) variation of the water levels and outflows of Lake Garda, and relating the outcomes to the changing downstream water uses that contributed to lake regime alteration.

We develop a 133 years-long record of daily lake levels and outflows from a variety of historical sources, on which we perform time series and statistical analysis. Differences between pre- (1888–1950) and post-regulation (1951–2020) periods as well as between different seasons are of particular interest, together with seasonal shifts resulting from changes in operational rules of Salionze Dam and in the related inter-annual variability of the basin water needs. A specific comparison between the main downstream water requirements regulated by the dam, i.e. for irrigation, hydropower and fluvial ecosystem health, boosts the discussion on their relative importance in determining the variation of the lake regime. Outcomes of this work allow to discuss management strategies for Lake Garda within the broader framework of other European perialpine lakes, and to provide support for future water resources management in the area.

2. Materials and methods

2.1. Study area

Lake Garda has an average surface area of 368 km^2 and water volume of 49 km^3. The efficient management of such large amount of water has been a long-debated issue, as contrasting and asynchronous water interests progressively emerged among the 42 municipalities located along its lakeshores and belonging to three administrative regions, i.e. Lombardia, Veneto and Trentino (Berbenni et al., 1992). The completion of the Salionze Dam in 1951 near the headwaters of the lake emissary, the Mincio River, allowed to manage the main downstream water needs

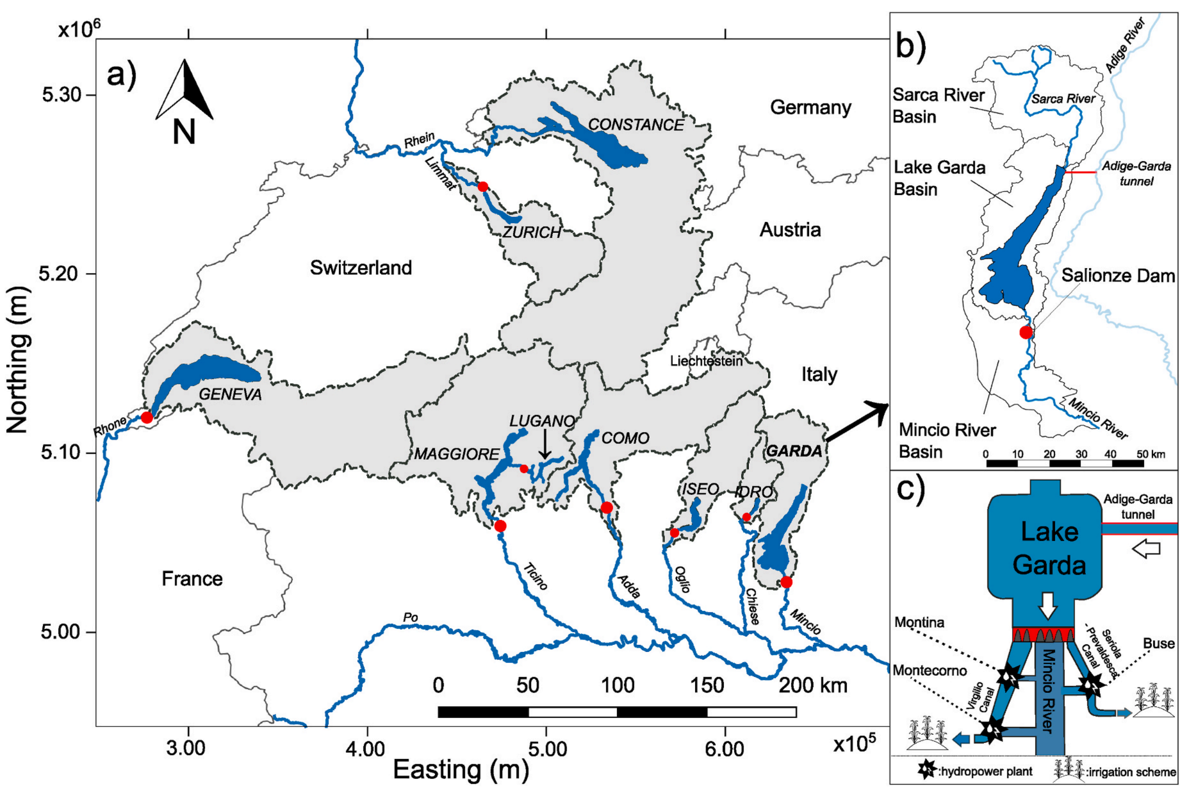

Fig. 1. a) Lake Garda location in the framework of the perialpine lakes considered in this study. Gray areas indicate the lake watersheds while red circles indicate their main regulation infrastructures, i.e. dams. Solid blue lines indicate the lake main outflows. b) Focus on the Sarca-Garda-Mincio basin and the inter-basin water transfer system of the Adige-Garda diversion tunnel. c) Sketch of the three watercourses downstream the Salionze Dam regulated to supply water for hydropower and irrigation seasonal demands. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of that period, i.e. flood prevention and crop irrigation, through the regulation of lake water levels. After 70 years of its completion, the Salionze Dam still guarantees an high level of flood protection, but is progressively showing difficulties in complying with other water needs (e.g. irrigation and hydropower production), which have massively increased in recent decades. First observations on the need and feasibility of regulating Lake Garda date back to 1833 (Lombardini, 1833), followed by other debates before the start of construction works of Salionze Dam in 1939, which was completed in 1951. The Salionze Dam (Fig. 1c) has six gates and three distinct outflow canals to allocate the total dam releases between the irrigation districts (grouped under two main consortiums named Consorzio Territori del Mincio and Consorzio Garda-Chiese) and hydropower plants (the Montecorno, Montina and Buse hydropower plants) located in the downstream Mincio River basin. More precisely, three gates release water into the Mincio River, two additional gates regulate the releases into the Virgilio Canal and one gate to the Seriola-Prevaldesca Canal. The Italian High Council of Public Works defined the first regulation rule in 1965, which was subsequently revisited in 1984, and in 2009, together with the Interregional Agency of the Po River (AIPo) and the Lombardia Region.

Other hydraulic infrastructures have been installed in the XX century within its basin to comply with growing water demands. Starting from 1920, several irrigation schemes and hydropower plants were constructed in the Mincio River basin as well as in the upstream Sarca River catchment, thereby modifying also the natural regime of the main lake inflow. In addition, the construction of a flood diversion tunnel, bringing water from the Adige River to the lake during extreme flood events, makes Lake Garda also part of an inter-basin water transfer system. Finally, the long-standing tradition in tourism of the lake, averaging 20 million of mostly international visitors per year (Simeoni et al., 2019), further exacerbated water conflicts within the entire Sarca-Garda-Mincio system, especially during the summer season. Water requirements in such composite catchment differ between winter (October–March) and summer (April–September) seasons. Water uses in winter are dominated by hydropower, which characterise the whole year, while April–September is defined as the irrigation season, when crop water demands are paralleled by other recreational, touristic activities (e.g. fishery, navigation), with ecological water needs for the downstream freshwater ecosystem being also a concern. Resulting changes in Lake Garda annual regime in the last 70 years, though evident, haven't been quantified so far.

The variety of water uses related to Lake Garda is a common feature of several European perialpine lakes. Indeed, beginning with the impoundment of Lake Idro in 1923, one of the first lakes regulated in Europe (the first in Italy), the majority of these lakes were dammed during the second half of the XX century, mainly for delivering water for hydropower and agricultural purposes.

The main hydromorphological characteristics of Lake Garda are presented in Table 1 and compared with those of the other lakes belonging to the district known as deep subalpine lakes (DSL), i.e. Maggiore, Lugano, Como, Iseo, the smaller Lake Idro and three major European perialpine lakes, i.e. Zürich (Switzerland), Geneva (Switzerland-France) and Constance (Switzerland-Germany-Austria). In particular, Lake Geneva (Léman) has the highest values in terms of water volume and surface area, with a relatively high theoretical renewal time, while Lake Zürich presents the smallest average depth and a relatively low water volume, when compared to its catchment area. The relatively low average value of Lake Garda outflow, as compared to its water volume, defines its average theoretical renewal time as the longest of all the perialpine lakes (Ambrosetti et al., 2003).

2.2. Data collection

Historical data of Lake Garda daily water levels and outflows were collected and digitized starting from the existing historical documents partly available online and partly accessible at local municipal archives. Data obtained from the Italian Annual Hydrological books (Ministero dei Lavori Pubblici - Servizio Idrografico, 1917) were integrated with the Registry of hydrometric observations of the AIPo archive (located in the city of Mantova), starting from 1888. In particular, the observations recorded at the monitoring stations of Peschiera del Garda (southern part of the lake) and Monzambano (located in the Mincio River headwaters), which represent the two main historical stations adopted for monitoring the Lake Garda regime, cover the period 1888–2020. More precisely, the first hydrometer located in Peschiera del Garda was installed in 1860 and its daily value was recorded by reading the instrument notches. With regard to lake outflows, the rating curve originally constructed near the headwaters of the Mincio River (Ministero dei Lavori Pubblici - Servizio Idrografico, 1917), representative of the natural lake regime, was subsequently evaluated some 5 km downstream, in the municipality of Monzambano, after the construction of the Salionze Dam. Hence, the resulting database enabled the analysis of 133 years of recorded lake levels and outflows data, yielding an unprecedentedly long time-series of the pre-regulation (hereby also called "natural", from 1888 to 1950) and post-regulation ("regulated", from 1951 to 2020) periods. In addition, we quantified the downstream water uses (irrigation, hydropower and fluvial ecosystem health) starting from the daily outflow records of the three watercourses that origin from the Salionze Dam (i.e. the Mincio River, the Virgilio Canal and the Seriola-Prevaldesca Canal), each of which presents abstraction points along its watercourse (Fig. 1c). The tripartite outflow values were collected from the AIPo Registry of gate-opening manoeuvres for the available period 1955–2020 and water uses were subsequently estimated on the basis of the current dam management policy, which regulates the quantity of water that can be diverted into the three watercourses and consequently be abstracted for hydropower and irrigation purposes.

We finally collected and processed the available similar data for the

Table 1

Hydromorphological characteristics of the perialpine lakes considered in this study. Symbols: $\overline{d}$ = average lake depth; d_{max} = maximum lake depth; A = average lake surface area; A_c = catchment area; A/A_c = lake surface area per catchment area ratio; V = average lake volume; L = maximum length of the lake; W = maximum width of the lake, τ_w = theoretical renewal time, Cr = crypto depression. References: (1) Tolotti et al. (2018), (2) Salmaso and Mosello (2010).

Lake	Altitude(1)	$\overline{d}$(1)	d_{max}(1)	A(1)	A_c(1)	A/A_c	V(1)	L(1)	W(1)	τ_w(1)	Cr.(2)
	(m a.s.l.)	(m)	(m)	(km^2)	(km^2)	(%)	(km^3)	(km)	(km)	(year)	(m)
Garda	65	133	350	368	2290	16.07	49	51.9	17.5	30	285
Idro	368	77	124	11	617	1.70	0.9	8.3	1.9	1.2	–
Iseo	186	123	251	62	1842	3.36	7.6	25	4.4	4.1	65
Como	198	154	410	146	4508	3.24	22.5	4.5	45.7	4.3	212
Lugano	271	171	288	28	297	9.43	4.7	35	4.3	12.4	17
Maggiore	193	178	370	213	6599	3.20	37.5	64.4	10	4.1	177
Geneva	372	153	310	582	7975	7.27	89	72	13	11.4	–
Zürich	406	51	136	65	1757	3.70	3.4	40.6	3.8	1.2	–
Constance	539	101	252	493	10900	4.52	48	63	14	4.7	–

other eight lakes considered in this study and presented in Table 1, thus putting the long-term variation of the Lake Garda regime into the wider context of the European perialpine lakes. In this regard, the pre-regulation data of Lake Idro, Iseo, Como, Lugano and Maggiore were obtained from the Italian Annual Hydrology books (Ministero dei Lavori Pubblici - Servizio Idrografico, 1917), while data of Lake Geneva, Zürich and Constance were provided by the Federal Office for the Environment (FOEN). Regarding the post-regulation period, the average values of lake levels and outflows, along with the related range of the dam operational rules, were derived from different online sources, such as the portal www.laghi.net or www.hydrodaten.admin.ch/de/. Further detailed information were additionally obtained by consulting specific online documents, such as the summary sheets compiled by the FOEN, the report drawn up by Autorità del Bacino del fiume Po (2015) or the legislative document prepared by the State of Geneva for Lake Geneva (Etat de Genève, 1997). Further details can be found in the description of Table 4, which will be discussed in Section 4.

2.3. Data analysis

The historical lake level - outflow record has been first analysed through a series of statistical techniques and further put in relation with the reconstructed information on the main downstream water uses.

First, statistical tests were applied on monthly average values to evaluate the existence of significant trends, using methods adopted for the analysis of long-term time series of hydro-meteorological data (Yue et al., 2002; Partal and Kahya, 2006; Han et al., 2016; Brugnara and Maugeri, 2019; Yagbasan et al., 2020). Specifically, the significance of the long-term trends before and after the regulation of Lake Garda was assessed through the rank-based non-parametric Mann Kendall (MK) test (Mann, 1945; Kendall, 1948), along with its modified version (Modified Mann Kendall, MMK) proposed by Hamed and Rao (1998) which considers the possible influence of autocorrelated data. The Spearman's Rho (SR) method (Spearman, 1987; Sneyers, 1990) was used to check the agreement with the results obtained with the MK tests, as they have comparable power in detecting a monotonic trend (Yue et al., 2002). The magnitude, i.e. the slope, was further calculated through the Theil-Sen approach (Theil, 1950; Sen, 1968). A detailed description of the adopted statistical methods can be found in the Supplementary Material.

We then quantified the impact of the dam operational rules on the annual and monthly distribution of lake levels and outflows by computing the Empirical Cumulative Distribution Function (ECDF) as well as calculating the 1σ, 2σ and 3σ standard deviation limits from the mean, also highlighting seasonal patterns. The computation of these limits, which describe the 68th, 95th and 99.7th percentiles of the dataset, enabled to detect changes in the annual lake regime. Moreover,

Table 3
Statistical significance of the Mann Kendall (MK), Modified Mann Kendall (MMK) and Spearman's Rho (SR) tests for an α of 10%, 5% and 1%. The existence of a significant trend is labelled with "x". h = lake level, Q = lake outflow. The subscript "N″ or "R″ indicates the natural or regulated period. The test statistic S, the p-value p, the standardized test statistic Z, the Kendall's rank correlation coefficient τ and the rho coefficient ρ are also indicated.

	S	P	Z	τ	$\alpha_{10\%}$	$\alpha_{5\%}$	$\alpha_{1\%}$	
								MK
h_N	$8.50 \cdot 10^{3}$	$1.98 \cdot 10^{-1}$	1.29	$3.18 \cdot 10^{-2}$				
h_R	$2.08 \cdot 10^{4}$	$1.03 \cdot 10^{-2}$	2.56	$5.91 \cdot 10^{-2}$	x	x		
Q_N	$2.58 \cdot 10^{4}$	$2.19 \cdot 10^{-6}$	4.83	$1.28 \cdot 10^{-1}$	x	x	x	
Q_R	$-4.04 \cdot 10^{4}$	$6.44 \cdot 10^{-7}$	−4.98	$-1.15 \cdot 10^{-1}$	x	x	x	
	S	p	Z	τ	$\alpha_{10\%}$	$\alpha_{5\%}$	$\alpha_{1\%}$	
								MMK
h_N	$8.50 \cdot 10^{3}$	$6.31 \cdot 10^{-1}$	0.48	$3.18 \cdot 10^{-2}$				
h_R	$2.08 \cdot 10^{4}$	$5.24 \cdot 10^{-2}$	1.94	$5.91 \cdot 10^{-2}$	x			
Q_N	$2.67 \cdot 10^{4}$	$3.63 \cdot 10^{-2}$	2.09	$1.23 \cdot 10^{-1}$	x	x		
Q_R	$-4.04 \cdot 10^{4}$	$2.63 \cdot 10^{-3}$	−3.00	$-1.15 \cdot 10^{-1}$	x	x	x	
	S	p	ρ		$\alpha_{10\%}$	$\alpha_{5\%}$	$\alpha_{1\%}$	
								SR
h_N	$6.21 \cdot 10^{7}$	$1.98 \cdot 10^{-1}$	0.049					
h_R	$9.00 \cdot 10^{7}$	$1.03 \cdot 10^{-2}$	0.089		x	x		
Q_N	$3.92 \cdot 10^{7}$	$2.19 \cdot 10^{-6}$	0.18		x	x	x	
Q_R	$1.15 \cdot 10^{8}$	$6.44 \cdot 10^{-7}$	−0.17		x	x	x	

Table 2
Statistics of the Lake Garda water levels and outflows series for the natural and regulated periods, for the entire year and for the irrigation and winter seasons. Lake levels are indicated in accordance to the reference zero of 64.027 m a.s.l. σ = standard deviation, CV = coefficient of variation. Δ_{max} = maximum range, the difference between the absolute maximum and minimum values in the period; Δ_{mean} = mean range, the difference between the mean annual maximum and minimum values in the period.

Lake level		Pre-regulation			Post-regulation		
		annual	irrigation	winter	annual	irrigation	winter
Max	(m)	+1.96	+1.96	+1.88	+2.12	+1.53	+2.12
Min	(m)	−0.038	+0.053	−0.038	+0.080	+0.080	+0.090
Mean	(m)	+0.84	+0.97	+0.72	+0.92	+0.95	+0.89
Median	(m)	+0.82	+0.98	+0.67	+0.94	+1.00	+0.94
σ	(m)	0.35	0.33	0.32	0.30	0.29	0.31
CV	(–)	0.41	0.34	0.44	0.33	0.31	0.35
Δ_{max}	(m)	2.00	1.91	1.92	2.04	1.45	2.03
Δ_{mean}	(m)	0.88	0.67	0.69	0.84	0.69	0.71
Outflow		Pre-regulation			Post-regulation		
		annual	irrigation	winter	annual	irrigation	winter
Max	($m^3 \cdot s^{-1}$)	133.0	133.0	127.1	190.0	170.0	190.0
Min	($m^3 \cdot s^{-1}$)	14.7	15.2	14.7	6.0	7.0	6.0
Mean	($m^3 \cdot s^{-1}$)	60.0	68.1	51.5	53.0	67.0	39.0
Median	($m^3 \cdot s^{-1}$)	57.4	68.1	47.8	50.0	65.0	30.0
σ	($m^3 \cdot s^{-1}$)	23.3	22.6	21.0	31.3	26.7	29.2
CV	(–)	0.39	0.33	0.41	0.59	0.40	0.75
Δ_{max}	($m^3 \cdot s^{-1}$)	117.8	117.4	112.4	184.0	163.0	184.0
Δ_{mean}	($m^3 \cdot s^{-1}$)	59.2	46.5	45.0	98.5	79.6	73.4

Table 4
Lake levels and outflows variation due to regulation and related dam management policies of the European perialpine lakes considered in this study. Symbols: h_{ref} hydrometer reference zero of the lake (the current place of the hydrometer is also indicated above the related value); $\overline{h}$ = average lake water level referred to its h_{ref}; $\overline{Q}$ = average lake outflows; Δh_R = operational range of lake levels referred to the related h_{ref}; ΔQ_R = operational range of lake outflows. "n.d" = not defined. The name and the year of the completion of the dam are finally indicated in the last column. References: (1) Ministero dei Lavori Pubblici - Servizio Idrografico, 1917, (2) courtesy of AIPo, (3) www.comunitadelgarda.it, (4) Autorità del Bacino del fiume Po (2015), (5) ARPAL Bulletins (www.arpalombardia.it) (6) www.oglioconsorzio.it, (7) courtesy of FOEN, (8) Micotti et al. (2010), (9) ARPA Lombardia (2016), (10) Etat de Genève (1997).

Lake	h_{ref}(m a.s.l.)	Natural → regulated		Management		Dam
		$\overline{h}$(m a.s.l.)	$\overline{Q}$($m^3 \cdot s^{-1}$)	Δh_R(m a.s.l.)	ΔQ_R($m^3 \cdot s^{-1}$)	
Garda (1, 2, 3, 4)	Peschiera 64.027	64.87 → 64.95 (1888–1950) (1951–2020)	60 → 53 (1888–1950) (1951–2020)	64.18 ÷ 65.43	6 ÷ 200	Salionze (1951)
Idro (1, 2, 3, 4, 5)	Idro 359.97	367.30 → 368.67 (1917–1923) (1932–2019)	29 → 36 (1923) (1934–1989)	367.00 ÷ 368.50	2.5 ÷ 100	Idro (1923)
Iseo (1, 2, 4, 6)	Sarnico 185.15	185.45 → 185.68 (1895–1930) (1933–2019)	66 → 54 (1926–1930) (1937–2019)	184.85 ÷ 186.25	6.5 ÷ 440	Sarnico (1933)
Como (1, 2, 4)	Malgrate 197.37	197.95 → 197.74 (1917–1941) (1946–2019)	167 → 158 (1921–1943) (1946–2018)	196.97 ÷ 198.67	n.d.	Olginate (1946)
Lugano (7, 8)	Melide 271	270.51 → 270.49 (1923–1962) (1965–2019)	25 → 22 (1906–1962) (1963–2019)	n.d.	2 ÷ 190	Rocchetta (1963)
Maggiore (1, 7, 8, 9)	Sesto Calende 193.016	193.17 → 193.43 (1917–1941) (1943–2019)	320 → 282 (1921–1942) (1943–2015)	192.52 ÷ 194.52	n.d.	Miorina (1943)
Geneva (7, 10)	St-Prex 372	372.05 → 372.06 (1930–1994) (1995–2019)	250 → 250 (1919–1994) (1995–2017)	371.70 ÷ 372.30	50 ÷ 550	Seujet (1995)
Zürich (7)	Zürich 406	405.97 → 405.93 (1892–1950) (1951–2019)	99 → 95 (1906–1950) (1951–2019)	405.45 ÷ 406.60	50 ÷ 200	Letten (1951)
Constance (7)	Romanshorn 396	395.62 (1930–2019)	359 (1959–2019)	Not Regulated		

we computed a centered moving average of daily lake levels and outflows to highlight the most impacted months by the dam operational rules, and carried out a targeted analysis for the 1st of April and the 1st of October (first and last days of the irrigation season), taken as representative of the relevant seasonal changes of the downstream water demands.

We finally quantified the annual water volumes associated to each downstream water use from the total recorded outflows referring to the

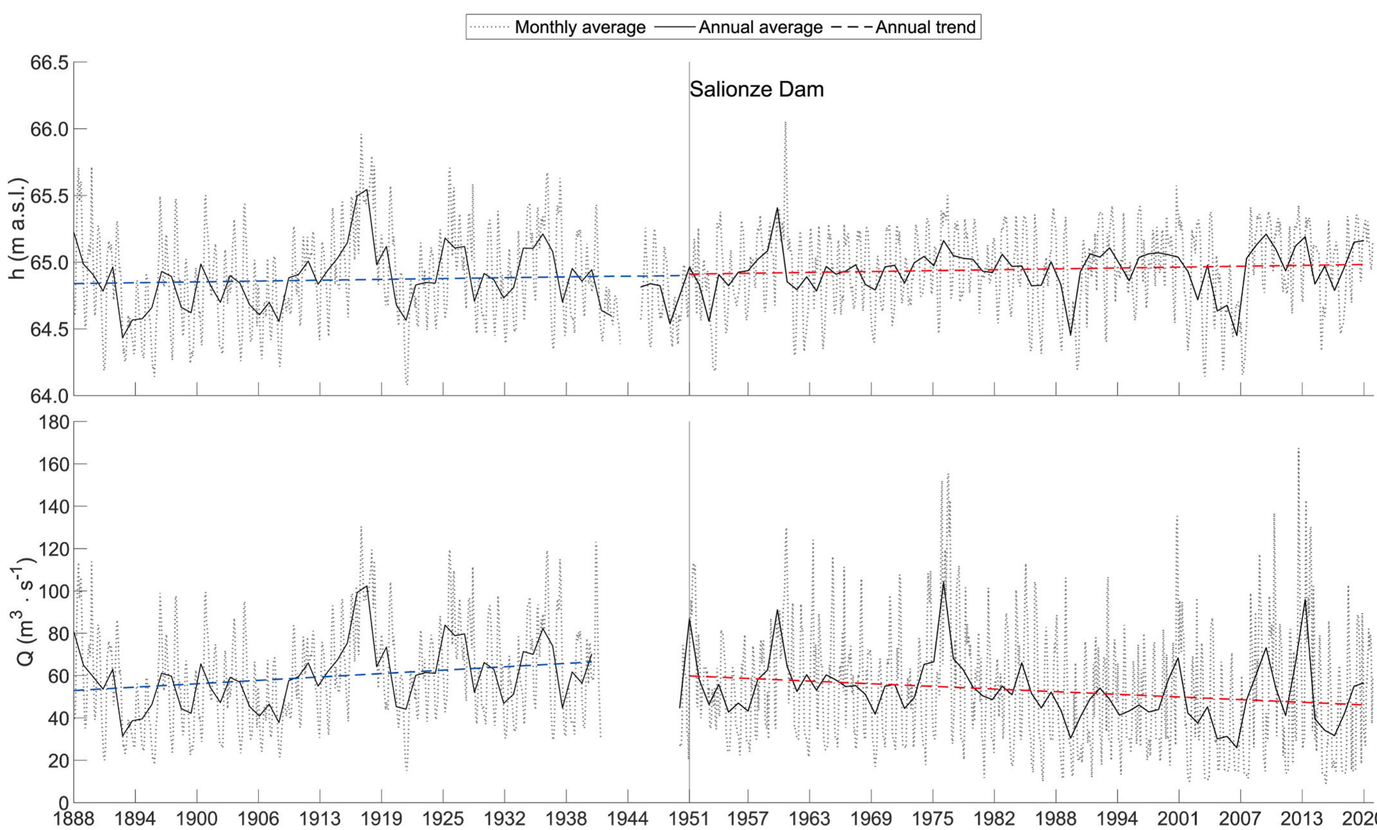

Fig. 2. Multi-decadal trend of the Lake Garda water levels and outflows for the period 1888–2020. The construction of the Salionze Dam (1951) is highlighted by a solid vertical line, separating the pre-regulated (1888–1950) and post-regulated (1951–2020) periods. The monthly and annual averages are showed by dotted gray and solid black lines, respectively. Long-term trends are denoted for the two periods by dashed blue and red straight lines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

official operational rules that are used to manage the outflows from the Salionze Dam. These rules (entirely reported in the Supplementary Material, Table 6.1) prescribe the outflow ranges that can legally be released for each downstream water use (irrigation, hydropower, river ecosystem) on a seasonal basis and as function of the lake water level. They essentially prioritize releases for irrigation over hydropower in summer and regulate hydropower water demands in winter. A Minimum Environmental Flow (MEF) for safeguarding river ecosystem health in the downstream Mincio River is legally set at 6 $m^3 \cdot s^{-1}$ on a purely hydrological basis. The influence of irrigation, hydropower and ecosystem water uses on the lake level variations was finally obtained by comparing the recorded annual lake levels with the hypothetical levels that could be calculated assuming the absence of hydropower and of irrigation water uses. The mean annual lake levels corresponding to these two scenarios were computed from the recorded mean annual levels by adding the ratio of the annual water volumes for each water use to the Lake Garda surface area.

3. Results

3.1. Long-term trends and statistics in lake levels and outflows

The variations and long-term trends of the level and outflow of Lake Garda from 1888 to 2020 are shown in Fig. 2, which highlights the impact of the Salionze Dam construction in 1951. While the pre-regulation period is characterized by a similar upward trend for both the lake level and outflow, in the post-regulation period lake outflows show a clear downward trend, as opposed to the persistently increasing trend of the water level. Across the entire regulation period, the average lake outflow decreased by 6.8 $m^3 \cdot s^{-1}$ (from 59.8 $m^3 \cdot s^{-1}$ to 53.0 $m^3 \cdot s^{-1}$) (Table 2). Such difference is of the same order of magnitude (11% higher) than the established downstream MEF requirement of the Mincio River.

A significant change is also observed in terms of the outflow variability, as the standard deviation σ increases from 23.3 $m^3 \cdot s^{-1}$ to 31.3 $m^3 \cdot s^{-1}$. Lake regulation also determined an average water level increase of +0.08 m (from +0.84 m to + 0.92 m), together with a reduction of 0.04 m of the mean range of variability Δ_{mean} (from 0.88 m to 0.84 m), which corresponds to a decrease of some 14.8 Mm^3 of the active lake storage with respect to the natural period. The higher impact of dam management on the lake outflows variability, compared to that of lake levels, is further shown by the coefficient of variation (CV in Table 2), with similar values for both the lake level and outflow series before regulation (0.41 and 0.39, respectively), but a much higher difference after dam construction (0.33 and 0.59, respectively).

On a seasonal scale, considerable modifications of Lake Garda regime are observed for the winter season, with a relevant increase of +0.17 m (from +0.72 m to + 0.89 m) of the lake level and a significant decrease of 12.5 $m^3 \cdot s^{-1}$ (from 51.5 $m^3 \cdot s^{-1}$ to 39.0 $m^3 \cdot s^{-1}$) of the lake outflow. Such variations mainly reflect the need of constantly storing water into the lake during the low stressed winter season, in terms of water requirements, to supply the higher water uses of the summer season.

The MK and MMK trend tests highlight the existence of significant trends both in terms of lake levels and outflows after the regulation, while a significant trend is detected only in terms of lake outflows before the regulation (Table 3). Precisely, in the MK test, the null hypothesis H_0 of the existence of no trend is rejected for an α level of 5% and 1% respectively for the regulated lake levels (h_R) and outflows (Q_R). For the natural period, the null hypothesis is accepted in terms of lake levels and rejected for the outflows with an α level of 1%. In addition, the Kendall's rank correlation coefficient τ is lower for the natural lake level and outflow as compared to the values evaluated for the regulated period, which further indicates the higher influence of the operational rules of the Salionze Dam on imposing a modification in the lake regime natural trends. Outcomes of the MK test are supported by those of the MMK test, which reveal the substantial absence of autocorrelation in the data series. A consistent decrease of the p and Z values for the post-regulation period emerges from the MMK test as compared to the values obtained by the MK test. The MK and MMK tests in terms of natural lake outflows indicate the rejection of the null hypothesis for an α level of 1% and 5%, respectively.

Results given by the MK approach are additionally confirmed by the SR test, as significant trends at the same α level of the MK and MMK tests are found for both the natural and regulated periods. In addition, the SR ρ coefficient confirms the upward and downward trends calculated in the MK and MMK tests as well as the higher strength of the regulated values with respect to the pre-regulation values. In terms of trend magnitude, the Sen's slope s indicates a mild increase of both the lake levels ($s = 0.100$ cm $\cdot y^{-1}$) and outflows ($s = 0.295$ $m^3 \cdot s^{-1} \cdot y^{-1}$) for the pre-regulation period that reflects the natural lake behaviour. Instead, while the slope of the regulated outflow turns to a meaningful negative trend ($s = -0.224$ $m^3 \cdot s^{-1} \cdot y^{-1}$), the lake level maintains an upward trend ($s = 0.129$ cm $\cdot y^{-1}$).

3.2. Lake regime frequency distributions

Regulation of lake regime addressed the need of increasing the water stored into Lake Garda during the winter season for releasing a larger amount of water during the summer season. This has affected the frequency distributions (ECDF) of lake levels and outflows (Fig. 3a–d). During the irrigation season (Fig. 3a) the lake levels ECDF reveals the existence of a relevant shift of the highest water levels approximately in accordance with the maximum management level, which is 65.4 m a.s.l. (+1.40 m above the reference zero). Conversely, during the winter season (Fig. 3b) a relevant difference appears between the entire distributions before and after regulation, with a median value reduced by 0.20 m (from 64.9 m a.s.l. to 64.7 m a.s.l.), reflecting the increasing need of using the lake to store water before the irrigation season.

A coherent behaviour is shown by lake outflows (Fig. 3c–d), with a consistent reduction of the median value (by 20 $m^3 \cdot s^{-1}$) during the winter season and a shift of the extreme values towards the minimum (6 $m^3 \cdot s^{-1}$) and maximum (200 $m^3 \cdot s^{-1}$) releases set by management regulations, which are established to ensure the MEF for fluvial ecosystem health and to prevent floods, respectively. Regulated lake outflows below the median value of the ECDFs are systematically reduced compared to the natural distribution, a behaviour that is particularly evident in winter (Fig. 3d). This reflects the marked reduction of downstream releases towards the minimum environmental flow requirements set for the downstream Mincio River.

The annual time series of the median and of the 1σ, 2σ, 3σ confidence intervals of the daily distributions (Fig. 3e–h) provides additional insight into the effect of dam management rules on the seasonal lake regime. Lake levels variability was highly reduced after regulation, as it emerges especially observing the upper 3σ limit: the mean difference between the upper 3σ and 2σ limits reduces from 0.47 m to 0.10 m after regulation, during the main period of water storing in the lake (January–March). As also suggested by Fig. 3a–b, such alteration reveals that lake regulation is conceived to reduce the lake levels fluctuation (especially from January to July), setting a lake level that supplies the main downstream water requirements.

The σ intervals of regulated lake outflows are also highly modified, and show an impulsive step-function pattern that was absent in the natural regime (Fig. 3g–h). The same step-function pattern could be already observed in the red ECDFs in Fig. 3c–d, and it is determined by the possibility offered by the dam to rapidly modify water releases. In this respect, high flow events considerably contribute to the increase of the difference between the upper 2 and 3σ limits before and after dam construction, which change from 31.3 $m^3 \cdot s^{-1}$ to 56.2 $m^3 \cdot s^{-1}$ (Fig. 3g–h).

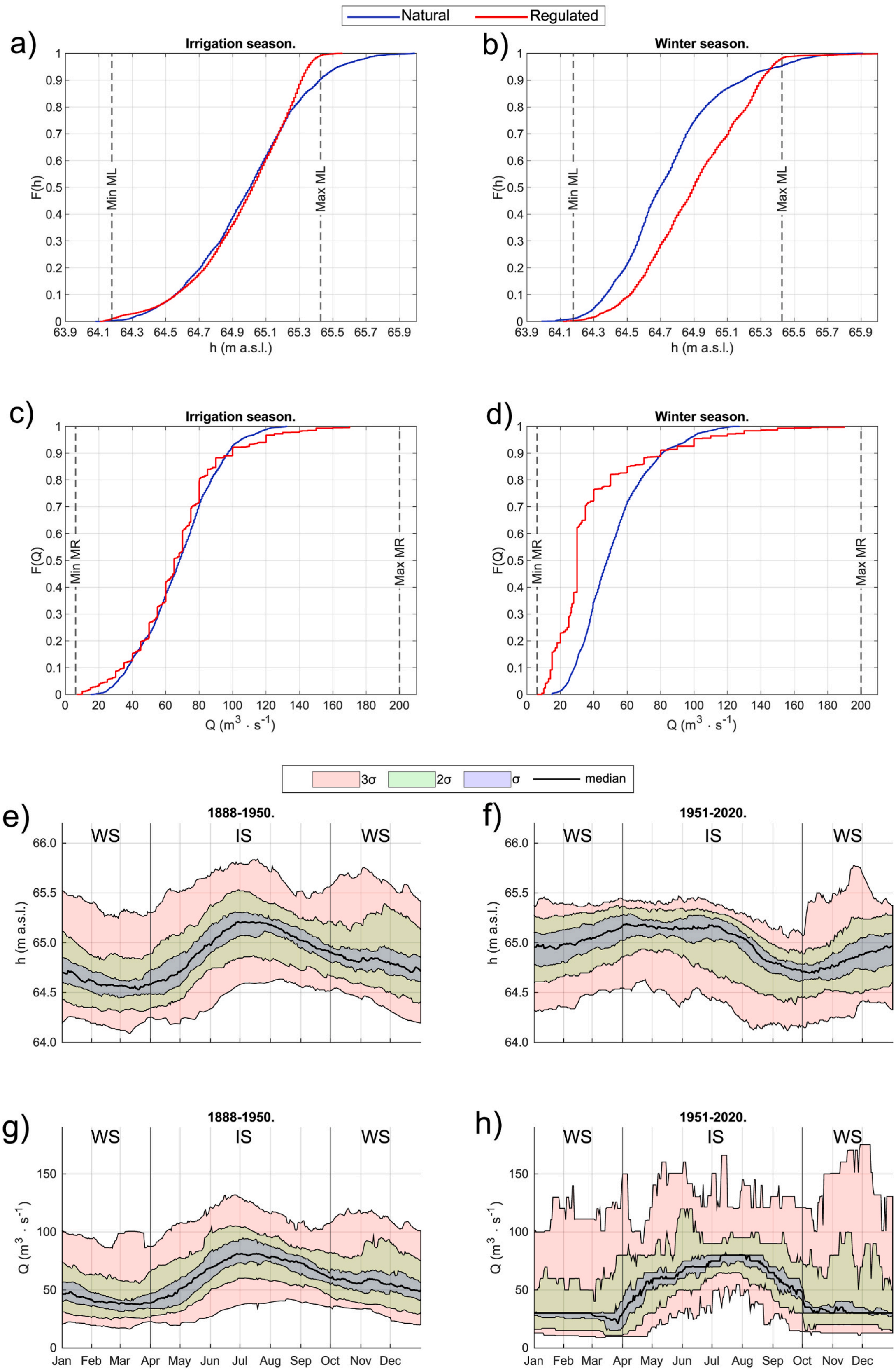

Fig. 3. Variability of Lake Garda water levels and outflows before and after the regulation. a)-d): Empirical Cumulative Distribution Functions (ECDF). The maximum and minimum management levels (ML) and releases (MR) imposed by the operational rules of the Salionze Dam are indicated through vertical dashed lines. Precisely, "Min ML" and "Max ML" corresponds to +0.15 m and +1.40 m above the reference zero of 64.027 m a.s.l.; "Min MR" and "Max MR" corresponds to 6 $m^3 \cdot s^{-1}$ and 200 $m^3 \cdot s^{-1}$. e)-h): Confidence intervals (3σ, 2σ and 1σ; σ = standard deviation) of daily lake levels (e,f) and outflows distributions (g,h). The solid line indicates the median value for each considered period.

3.3. Seasonal and annual shifts

The regulation of Lake Garda has determined seasonal as well as annual changes of the lake regime, with higher values of lake levels recorded at the beginning of the irrigation season and lower values of dam releases registered throughout the year.

The computation of the 20-year centered moving average of daily water levels (Fig. 4a) indicates lower values from January to June and considerably higher values from July to November. The seasons of the year when maximum and minimum lake levels occur have shifted, with the maximum value moving from July to June and the minimum value from March to middle September. Such transition is also detected by the average lake levels recorded on the two dates that set the transition from the winter and irrigation seasons and viceversa, i.e. the 1st of April and the 1st of October. For the whole considered time period such values display an opposite tendency following lake regulation (Fig. 4b–c). The maximum lake level at the beginning of the irrigation season was recorded in 1965–1979, during which the average value was constantly higher than +1.12 m above the reference zero, a value that was reached again only in 2019 (Fig. 4b). A significant reduction of lake level fluctuation is also apparent, especially for the 1st of October, as the excursion drops from 0.34 m (period 1888–1950) to 0.12 m (period 1951–2020).

The lake levels' rate of change between consecutive years (Fig. 4, d-e), allows to detect specific changes of the lake regime in response to both natural (e.g. extreme floods and snow melt) and anthropic (e.g. installation of hydraulic infrastructures) factors. Fig. 4e suggests that the response of the lake levels to autumn flood events within the regulated period is quite similar to that registered in the natural period, as the level increase of +0.04 m between 1950 and 1951 is comparable with the

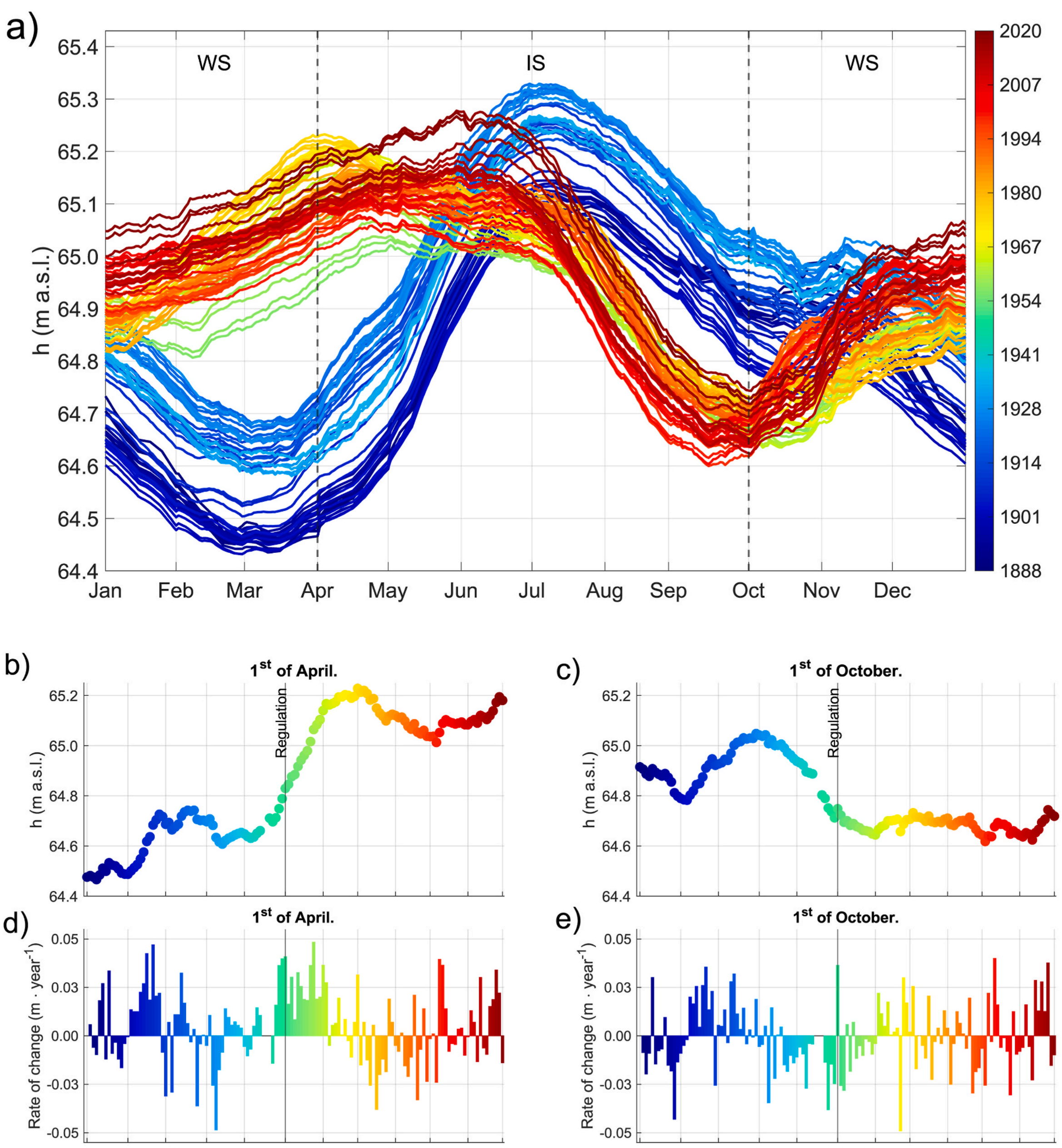

Fig. 4. a) Centered moving average on 20 years of daily Lake Garda water levels for the period 1888–2020. Start dates of the irrigation (1st of April, IS) and winter seasons (1st of October, WS) are denoted by dashed lines. b), c): long-term series of lake levels at IS and WS, respectively; d), e): rate of change of lake levels for consecutive years at IS and WS, respectively. The vertical line indicates the year of the Salionze Dam construction (1951).

values for 2000–2001 and 2018–2019 periods. For the pre-regulation period, the highest rate of change of water levels is likely to be associated to the extreme snowfall recorded in 1909 within the Garda basin, as some 0.55 m of total snowfall were recorded the 10–11 of February, thus influencing the lake regime with the subsequent snow melt. At a first look, intra-annual shifts of lake outflows (Fig. 5a) appear less dramatic, as the highest values are detected in June–July both before and after the regulation. However, water releases are clearly lower throughout the winter season, as well as at the end of the irrigation season in October, particularly in the last decade (red color, 2011–2020). As a result, besides the first annual minimum typically occurring in March, a second, similar minimum appears in October after the regulation, which is then followed by a sharp increase, likely associated to the autumn floods. Average outflow values for April 1st and October 1st show a relevant reduction at the end of the 1980s, especially for the 1st of October (Fig. 5b–c). Since hydropower is the only downstream water use during the winter season, such decrease of the lake outflow (22 $m^3 \cdot s^{-1}$, from 56.85 $m^3 \cdot s^{-1}$ to 34.85 $m^3 \cdot s^{-1}$ during 1987–2007) is likely associated to the operation of the Montina hydropower plant, built in 1988 immediately downstream the Salionze Dam (see Fig. 1c). The absolute value of the rate of change increases after lake regulation, from an average of 0.96 $m^3 \cdot s^{-1}$ to 1.81 $m^3 \cdot s^{-1}$ (April 1st) and from 0.95 $m^3 \cdot s^{-1}$ to 1.23 $m^3 \cdot s^{-1}$ (October 1st).

The modification of the natural relationship between the lake levels and outflows is highlighted in Fig. 6, where we report their correlation based on a 10-year centered moving average data analysis for the 1st of April and the 1st of October. We can recognize the existence of three different periods of lake regime, in accordance with the change of dam management rules and the related variation of the basin water requirements, which in turn caused an increase of irrigation schemes and

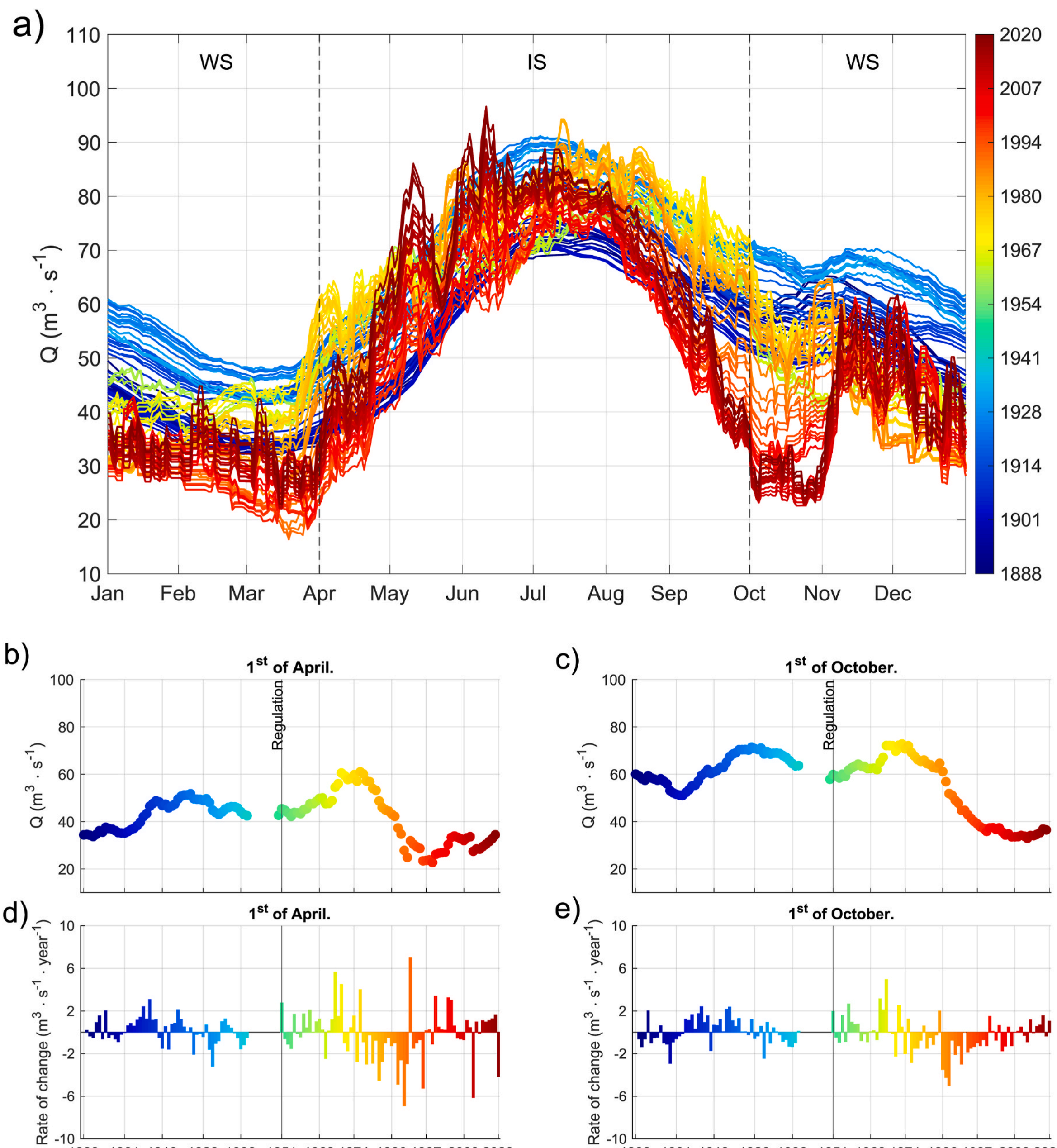

Fig. 5. a) Centered moving average on 20 years of daily Lake Garda outflows for the period 1888–2020. Start dates of the irrigation (1st of April, IS) and winter seasons (1st of October, WS) are denoted by dashed lines. b), c): long-term series of lake outflows at IS and WS, respectively; d), e): rate of change of lake outflows for consecutive years at IS and WS, respectively. The vertical line indicates the year of the Salionze Dam construction (1951).

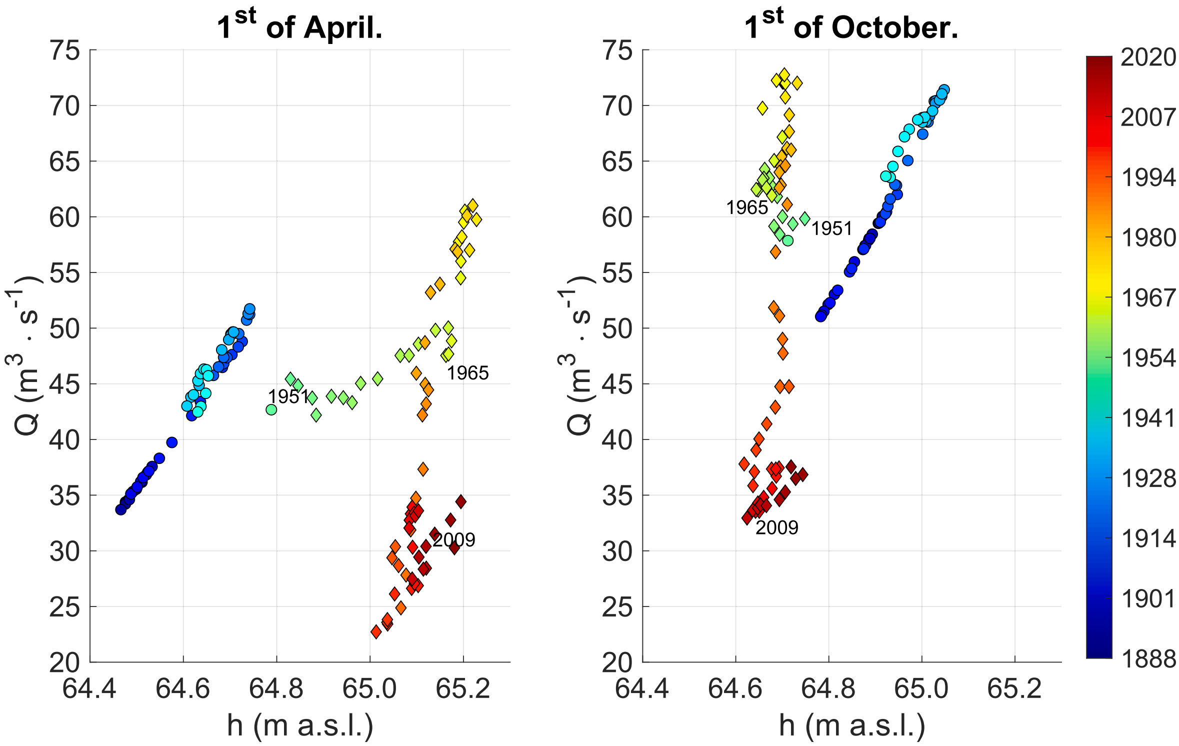

Fig. 6. Shifts in the lake level-outflow correlation throughout the years for the beginning of the irrigation (1st of April) and winter (1st of October) seasons, respectively.

hydropower exploitation.

Precisely, a first common trend can be observed for the pre-regulation period (1888–1950) for both the 1st of April and the 1st of October, showing a clear positive correlation between lake levels and outflows that reflects the natural lake behaviour (dark-light blue markers in Fig. 6). After the construction of the Salionze Dam, a second, transitional period is observed until 1965 (green markers in Fig. 6), which highlights the lack of a definite management scheme of the dam. This is particularly apparent for the 1st of April, as the correlation shifts toward higher values of lake levels. In the period 1966–2020, the relationship between outflows and lake levels at the beginning of both the irrigation and the winter seasons is quite different with respect to the pre-regulation trend, and gets nearly vertical in the (h,Q) plane (yellow-red markers in Fig. 6). Specifically, the range of variation of lake levels shrinks, while the range of outflow values greatly increases. This mainly reflects the constant increase of water requirements within the Sarca-Garda-Mincio system, stressing the high accuracy needed for regulating the lake regime. Lastly, a further change of the relationship between lake level and outflow is detectable in the last decade, especially at the beginning of the winter season, as a consequence of the application of the new dam management rule operated by AIPo from 2009.

3.4. *Influence of water uses on the lake regime*

The variation of the annual water volumes released by the Salionze Dam to supply irrigation, hydropower and fluvial ecosystem requirements are represented in terms of cumulative curves and percentage of use in Fig. 7a–b. Construction of the Montina hydropower plant in 1988 has increased the average share of water released for hydropower purposes by 16% (8.7 $m^3 \cdot s^{-1}$) and caused a strong reduction of the annual volume released only to support fluvial ecosystem integrity from an average of 50.8% of the total outflows in 1955–1987 to 22.3% in 1988–2020. Such considerable decrease affects by roughly two thirds a 12 km-long stretch of the Mincio River, at the end of which the Montecorno powerplant releases the turbinated water back into the river, while the rest (nearly one third) of the water used for hydropower production is reintroduced into the river channel a little further (some 500 m) downstream the Salionze dam (Fig. 1c). Reduction of ecological water releases has been also consistently affected by the nearly constant increase of the annual water volumes released for irrigation, which represents a consumptive water use. Abstraction for irrigation increased from 27.5% (1955–1987) to 42.8% (1988–2020) of the total annual outflow (Fig. 7b).

To isolate the effect of each specific water use on the Lake Garda water levels, we plot in Fig. 7c the hypothetical mean annual levels computed by assuming the absence of downstream hydropower or irrigation water demands, together with the recorded mean annual levels. Under these hypothetical scenarios, oscillations of annual lake levels would have been increasing after 1988, with maximum annual oscillation ranges of 0.26 m (only hydropower water use) and 0.23 m (only irrigation water use). Moreover, the absence of hydropower or irrigation releases would have increased the lake level by, respectively, 7 cm and 10 cm after the construction of the Montina hydropower plant. This allows to single out the effect of these downstream water uses on the lake levels variability. The hypothetical absence of water abstractions for hydropower and irrigation would correspond up to $1.2 \cdot 10^8$ m^3 and $1.5 \cdot 10^8$ m^3 of water volume into the lake, respectively, considering that a 1 cm increase in the Lake Garda water level corresponds to some 3.7 Mm^3 of additional water stored in the lake. Fig. 7c also shows that the hypothetical absence of the irrigation and hydropower water uses would cause the exceedance of the maximum management level (i.e. +1.40 m above the reference level), which is presently fixed mainly for touristic purposes, up to 0.54 m and 0.42 m, respectively.

4. Discussion

The multi-decadal analysis of the Lake Garda water levels and outflows reported in Section 3 has outlined the influence of water uses evolution on the lake regime modification. We now provide an interpretation of the key outcomes and discuss their implications for future

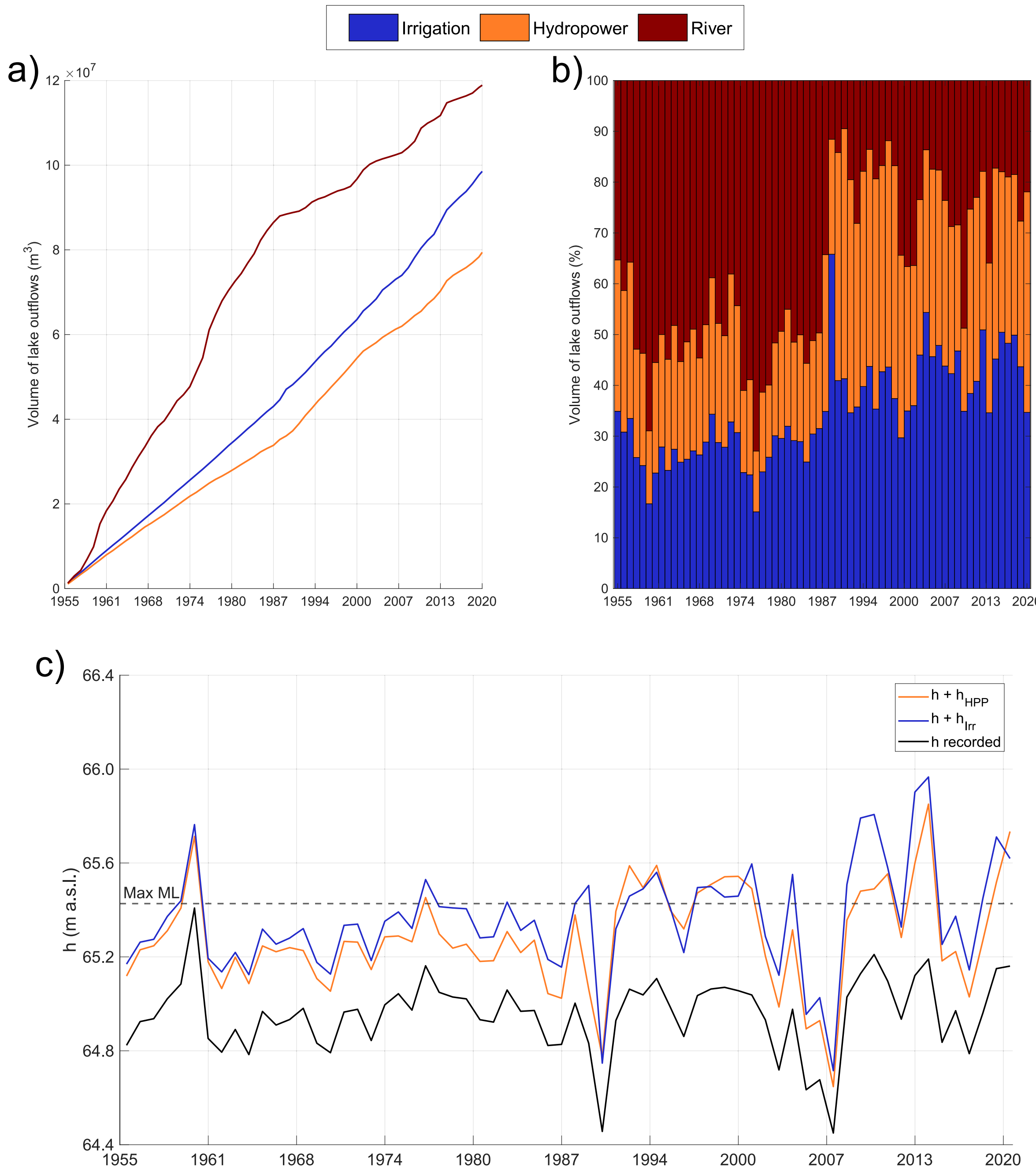

Fig. 7. a) Cumulative curves for hydropower, irrigation and fluvial ecosystem health ("river") requirements downstream the Salionze Dam. b) Percentage of the annual water volume released for the different water uses. c) Comparison between the recorded annual lake levels (black line) and the values estimated by assuming the absence of hydropower and irrigation releases (orange and blue lines, respectively). The maximum management level of the Salionze Dam ("Max ML" = +1.40 m above the reference zero) is also indicated by a black dashed line. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

lake water management also in the broad context of the European perialpine lakes district.

The long-term analysis of the Lake Garda regime reveals a remarkably different response to regulation between water levels and outflows, from both annual, monthly and averaged daily records. Specifically, the Salionze Dam has changed the inter-annual trend of the lake outflow from upward to downward, while maintaining a constantly increasing tendency of the lake levels. This is also reflected in the significant modification of the natural, pre-regulation lake levels-outflows relation. Such shift occurred to the lake levels and outflows at the seasonal scale in response to the changes in downstream water demands both in winter and summer. Furthermore, the increased variability of the lake outflows compared to that of lake levels can be explained by the strict dependence of lake outflows on the gate-opening maneuvers, while lake levels are likely to be influenced by other lake water budget components, such as the inflows or the evaporation rate. Despite a general decrease of total lake outflows showed in Fig. 2 after the Salionze Dam construction, we highlighted a corresponding increasing trend of downstream human water uses. Such behaviour can be associated with changes in agricultural practices, extension of irrigated areas with low-efficiency distribution schemes and overall changing in the seasonal precipitation regime of the region (Brunetti et al., 2000), likely to have increased the irrigation water demand. Preliminary analyses carried out by Valerio (2018) indicate that increasing the present irrigation distribution efficiency has the potential of saving up to 40% of the water currently abstracted for agriculture.

A particular concern emerging from our analysis is the marked reduction of releases from the Salionze dam to sustain ecosystem water needs in the downstream Mincio River, which are now determined on a purely hydrological basis. Dam construction and operation is known to highly reduce the downstream flow rates, variability, thus posing threats to the riverine ecological integrity, as the release of a minimum constant flow doesn't represent a sufficient condition to sustain the fluvial aquatic biodiversity (Poff et al., 1997). Coherently, the present minimum environmental flow of the Mincio River should shift towards a more variable flow regime. In this respect, the long-term information of pre-regulation outflows regime reconstructed within this work represent a key element to better support the ecological flows paradigm. Indeed, although reintroducing natural flow conditions in highly regulated systems might be questionable (Acreman et al., 2014), understanding the pre-impacted flow regime variability remains essential to identify the role of hydrological alterations in freshwater ecological systems and, ultimately, to support fluvial ecosystem health under future hydro-climatic changes and socio-economic developments (Poff, 2018). In this regard, a promising approach for complex systems with multiple, competing water demands like Lake Garda is provided by optimization algorithms, flexible supporting tools that are explored by an increasing number of studies for finding optimal water allocation policies in regulated freshwater systems (Nicklow et al., 2010; Ahmad et al., 2014; Horne et al., 2016), also adopting historical data (Hejazi et al., 2008).

Regulation strategies of Lake Garda can be further analysed in the light of contemporary regulation processes that characterized other regulated lakes of the European perialpine region.

In addition to a variety of comparative studies that discussed ecological and water quality aspects for addressing future management policies in the area, e.g. Bresciani et al. (2011); Salmaso et al. (2018a), here we drew attention to published hydrological information of lake levels and outflows for seven regulated and one nearly unregulated lake in the European perialpine region (Table 4), to place the response of Lake Garda regime in a broader framework.

Dam construction and operations have implied an average increase of lake levels for lakes Garda, Idro, Iseo and Maggiore, and to a decrease or constant variation for lakes Zürich, Como, Lugano and Geneva. All regulated lakes showed a decrease of the average lake outflows. The behaviour of Lake Idro cannot be assessed, because few pre-regulation data are available, before its impoundment in 1923. The comparative analysis shows that changes in the lake regime are, in some measure, associated with both dam construction and modifications of the lake management rules, which in many cases were not fixed contextually. As an example, for Lake Geneva almost identical average values of lake level and outflow are recorded before and after its present regulation system (i.e. the Seujet Dam, completed in 1995), but a strong reduction of the lake variability is registered. In fact, a significant change of the lake level and outflow regimes is observed since the 1970s, and it might be attributed to different modifications within the basin, including hydropower plant construction and the related concession contracts (Ruiz-Villanueva et al., 2015). Also the establishment of Lake Lugano new regulation rule in 1977, i.e. 15 years after the construction of the Rocchetta Dam, is considered as a breaking point for the lake regime (FOEN, 2017). Overall, lake dam management strategies have been influenced by different types of operational rules, either rigidly fixing minimum and maximum management thresholds of lake levels and outflows, such as for Lake Garda, or progressively adapting the thresholds in accordance to the different seasonal lake regime, as set for Lake Maggiore, for which lake outflows are changed as a function of the lake levels and inflows (Castelletti and Soncini-Sessa, 2006).

We finally summarize the key limitations of and the developments suggested by our work, which is based on the consistent reconstruction of long-term Lake Garda water level and outflow consistent record from multiple data sources including historical registries since 1888. As data collection and systematization is critical to the implementation of a meaningful time series analysis (Han et al., 2016), an intrinsic characteristic of the long historical record that we assembled for this work is related to the use of different methods and instruments for recording the Lake levels and outflows in different periods, with uncertainties that are hard to be quantified in detail, especially during the first decades, i.e. 1888-1916.

Uncertainties in the developed record might be reduced by developing a comprehensive hydrological analysis of the lake. This is, however, surprisingly lacking so far for Lake Garda, despite the fundamental interest for its management at a national level. The present analysis focuses on the recorded lake levels regardless of the actual interaction among the different components of the water balance, which should be analysed in the future to isolate climatic effects from human-caused modifications of the lake regime. Climatic drivers may indeed play an important role, as a clear decreasing trend of annual and seasonal precipitation was detected in northern Italy during the last century (Brunetti et al., 2000). Evapotranspiration, groundwater fluxes and snow melt are known to be relevant for the lake hydrological budget (Berbenni et al., 1992; Longinelli et al., 2008), but no comprehensive and targeted quantification of these fluxes is presently available. Floods from the main lake inflow, i.e. the Sarca River, can increase the Lake Garda level up to 0.5 m, corresponding to 1.85 Mm^3 of additional water stored into the lake. Furthermore, the pronounced hydropower regulation within the Sarca River basin since the second half of the XX century (Carolli et al., 2021) are likely to have affected the timing of the water released into the lake, shifting the annual peaks from summer to winter. Relevant effects of the alpine reservoirs were for instance studied by Moisello et al. (2013) for the management of Lake Como and by Loizeau and Dominik (2000) for the evolution of the Upper Rhone River regime and its possible implications in terms of sedimentation and oxygenation of Lake Geneva. Further analyses should be carried out also in relationship with the effect determined by the opening of the Adige-Garda tunnel, which can transfer up to 500 $m^3 \cdot s^{-1}$ into Lake Garda and has historically discharged a maximum volume of 79 Mm^3 in 1965, with an increment of 21.42 cm of the lake level. Thus, although this tunnel has not relevant implications in terms of the annual lake water budget, consistent effects might occur in terms of timing of regulation rules of the lake (Berbenni et al., 1992).

5. Conclusion

In this paper we analysed 133 years of the Lake Garda water levels and outflows from a water management perspective, investigating the implications of lake regulation in relationship with the basin water uses evolution.

The multi-decadal (1888–2020) time series showed opposite trends of the lake level and outflow as an effect of the dam construction in 1951, with a specific significant decreasing trend in terms of the outflows. Furthermore, a relevant annual shift of the lake regime was observed on a seasonal scale, as the lake regime observed during the winter season has been increasingly influenced by the multiple summer water requirements, determining higher amount of water stored particularly during January–March to be released mostly during July–September. Analyses of the main downstream water needs confirmed the major influence of the irrigation and hydropower water requirements on the Lake Garda water levels variation. The importance of developing a detailed water budget model to optimize the dam operational rules was then outlined, indicating the need of analysing climatic and hydrological drivers as well as stakeholders interests in a unique perspective. A particularly critical element is the progressive decrease of the share of water releases to sustain the downstream river ecosystem health. A comparison with the long-term variation of the water levels and outflows of other European perialpine lakes finally pointed out the relevance of carrying out a comparative and integrated study for regulated lakes to design efficient management policies of the available lake water resources in the current global change context.

CRediT

Luigi Hinegk: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft preparation, Visualization. Luca Adami: Conceptualization, Methodology, Investigation, Validation, Supervision, Writing – review & editing. Guido Zolezzi: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. Marco Tubino: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113893.

References

Acreman, M., Arthington, A.H., Colloff, M.J., Couch, C., Crossman, N.D., Dyer, F., Overton, I., Pollino, C.A., Stewardson, M.J., Young, W., 2014. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Front. Ecol. Environ. 12, 466–473. https://doi.org/10.1890/130134.

Ahmad, A., El-Shafie, A., Razali, S.F.M., Mohamad, Z.S., 2014. Reservoir optimization in water resources: a review. Water Resour. Manag. 28, 3391–3405. https://doi.org/10.1007/s11269-014-0700-5.

Alemayehu, T., McCartney, M., Kebede, S., 2010. The water resource implications of planned development in the Lake Tana catchment, Ethiopia. Ecohydrol. Hydrobiol. 10, 211–221. https://doi.org/10.2478/v10104-011-0023-6.

Amadori, M., Piccolroaz, S., Giovannini, L., Zardi, D., Toffolon, M., 2018. Wind variability and Earth's rotation as drivers of transport in a deep, elongated subalpine lake: the case of Lake Garda. J. Limnol. https://doi.org/10.4081/jlimnol.2018.1814.

Ambrosetti, W., Barbanti, L., Nicoletta, S., 2003. Residence time and physical processes in lakes. J. Limnol. https://doi.org/10.4081/jlimnol.2003.s1.1.

Aroviita, J., Hämäläinen, H., 2008. The impact of water-level regulation on littoral macroinvertebrate assemblages in boreal lakes. In: Ecological Effects of Water-Level Fluctuations in Lakes. Springer, pp. 45–56. https://doi.org/10.1007/s10750-008-9471-4.

ARPA Lombardia, 2016. Progetto di sperimentazione del DMV sul fiume Ticino sublacuale. This document is written in Italian. ARPA. https://www.ticinoconsorzio.it/attachments/article/18/1/DMVTicino_Rapporto/Finale.pdf.

Autorità del Bacino del fiume Po, 2015. Attività del tavolo tecnico per l'individuazione degli invasi utili alla laminazione delle piene al fine della definizione dei piani di laminazione. schede riassuntive delle modalità di regolazione dei grandi laghi prealpini. This document is written in Italian. AdBPo. http://www.adbpo.it/PDGA_Documenti_Piano/Attuazione_del_Piano/Piani_Laminazione/Relazione_Finale/ALLEGATO_A_SCHEDA_LAGHI.pdf.

Berbenni, P., Bertelli, P., Occhi, R., Bottazzi, S., 1992. Usi plurimi delle acque del Garda. La disciplina dei livelli del lago, Comunità del Garda – Civiltà Gardesana. Consorzio Universitario di Economia Industriale e Manageriale - Verona. This document is written in Italian.

Bresciani, M., Stroppiana, D., Odermatt, D., Morabito, G., Giardino, C., 2011. Assessing remotely sensed chlorophyll-a for the implementation of the Water Framework Directive in European perialpine lakes. Sci. Total Environ. 409, 3083–3091. https://doi.org/10.1016/j.scitotenv.2011.05.001.

Brivio, P., Giardino, C., Zilioli, E., 2001. Determination of chlorophyll concentration changes in Lake Garda using an image-based radiative transfer code for landsat TM images. Int. J. Rem. Sens. 22, 487–502. https://doi.org/10.1080/014311601450059.

Brugnara, Y., Maugeri, M., 2019. Daily precipitation variability in the southern Alps since the late 19th century. Int. J. Climatol. 39, 3492–3504. https://doi.org/10.1002/joc.6034.

Brunetti, M., Buffoni, L., Maugeri, M., Nanni, T., 2000. Precipitation intensity trends in northern Italy. Int. J. Climatol. 20, 1017–1031. https://doi.org/10.1002/1097-0088(200007)20:9{\textless}1017::AID-JOC515{\textgreater}3.0.CO;2-S.

Carmignani, J.R., Roy, A.H., 2017. Ecological impacts of winter water level drawdowns on lake littoral zones: a review. Aquat. Sci. 79, 803–824. https://doi.org/10.1007/s00027-017-0549-9.

Carolli, M., Gelmini, F., Pellegrini, S., Deriu, M., Zolezzi, G., 2021. Prioritizing reaches for restoration in a regulated Alpine river: locally driven versus hydro-morphologically based actions. River Res. Appl. 37, 17–32. https://doi.org/10.1002/rra.3737.

Castelletti, A., Soncini-Sessa, R., 2006. A procedural approach to strengthening integration and participation in water resource planning. Environ. Model. Software 21, 1455–1470. https://doi.org/10.1016/j.envsoft.2005.07.013.

Etat de Genève, 1997. Règlement sur la manœuvre de l'ouvrage de régularisation du niveau du lac Léman à Genève (l 2 15.03, art. 1,11. This document is written in French. Etat de Genève. https://www.vd.ch/fileadmin/user_upload/themes/environnement/eau/fichiers_pdf/DIRNA_EAU/Reglement_regularisation_niveau_lac_Leman.pdf.

European Commission, 2000. The Water Framework Directive 2000/60.

FOEN, 2017. Statistica Sulle Piene - Rapporto Della Stazione Tresa - Ponte Tresa, Rocchetta. https://www.hydrodaten.admin.ch/lhg/sdi/hq_studien/hq_statistics/2167_hq_Bericht.pdf. This document is written in Italian.

Giardino, C., Brando, V.E., Dekker, A.G., Strömbeck, N., Candiani, G., 2007. Assessment of water quality in lake Garda (Italy) using hyperion. Remote Sens. Environ. 109, 183–195. https://doi.org/10.1016/j.rse.2006.12.017.

Gibson, J., Prowse, T., Peters, D., 2006. Partitioning impacts of climate and regulation on water level variability in Great Slave Lake. J. Hydrol 329, 196–206. https://doi.org/10.1016/j.jhydrol.2006.02.011.

Gleick, P.H., 1993. Water in Crisis. Pacific Institute for Studies in Dev., Environment & Security. Stockholm Env. Institute, Oxford Univ. Press, 473p.p. 9.

Gleick, P.H., 2003. Global freshwater resources: soft-path solutions for the 21st century. Science 302, 1524–1528. https://doi.org/10.1126/science.1089967.

Guo, M., Wu, W., Zhou, X., Chen, Y., Li, J., 2015. Investigation of the dramatic changes in lake level of the Bosten Lake in northwestern China. Theor. Appl. Climatol. 119, 341–351. https://doi.org/10.1007/s00704-014-1126-y.

Haghighi, A.T., Kløve, B., 2017. Design of environmental flow regimes to maintain lakes and wetlands in regions with high seasonal irrigation demand. Ecol. Eng. 100, 120–129. https://doi.org/10.1016/j.ecoleng.2016.12.015.

Hamed, K.H., Rao, A.R., 1998. A modified Mann-Kendall trend test for autocorrelated data. J. Hydrol. 204, 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X.

Hammerl, M., Gattenhoehner, U., 2003. Lake Constance/Bodensee. Bodensee Stiftung, Konstanz. http://www.worldlakes.org/uploads/constance_30sep04.pdf.

Han, Q., Zhang, S., Huang, G., Zhang, R., 2016. Analysis of long-term water level variation in Dongting Lake, China. Water 8, 306. https://doi.org/10.3390/w8070306.

Hejazi, M.I., Cai, X., Ruddell, B.L., 2008. The role of hydrologic information in reservoir operation–learning from historical releases. Adv. Water Resour. 31, 1636–1650. https://doi.org/10.1016/j.advwatres.2008.07.013.

Horne, A., Szemis, J.M., Kaur, S., Webb, J.A., Stewardson, M.J., Costa, A., Boland, N., 2016. Optimization tools for environmental water decisions: a review of strengths, weaknesses, and opportunities to improve adoption. Environ. Model. Software 84, 326–338.

Kendall, M.G., 1948. Rank Correlation Methods.

Khazaei, B., Khatami, S., Alemohammad, S.H., Rashidi, L., Wu, C., Madani, K., Kalantari, Z., Destouni, G., Aghakouchak, A., 2019. Climatic or regionally induced by humans? tracing hydro-climatic and land-use changes to better understand the Lake Urmia tragedy. J. Hydrol. 569, 203–217. https://doi.org/10.1016/j.jhydrol.2018.12.004.

Loizeau, J.L., Dominik, J., 2000. Evolution of the Upper Rhone River discharge and suspended sediment load during the last 80 years and some implications for Lake Geneva. Aquat. Sci. 62, 54–67. https://doi.org/10.1007/s000270050075.

Lombardini, E., 1833. Della sistemazione dei laghi di Mantova per liberare la città dalle inondazioni e per migliorarne l'aria e la navigazione. In: Giornale dell'IR Istituto Lombardo di Scienze, Lettere ed Arti e biblioteca italiana. Imperiale Reale Istituto Lombardo di Scienze and Lettere ed Arti (Milano), vol. 5, pp. 415–437 (This document is written in Italian).

Longinelli, A., Stenni, B., Genoni, L., Flora, O., Defrancesco, C., Pellegrini, G., 2008. A stable isotope study of the Garda lake, northern Italy: its hydrological balance. J. Hydrol. 360, 103–116. https://doi.org/10.1016/j.jhydrol.2008.07.020.

Lovato, T., Pecenik, G., 2012. Three-dimensional modeling of pollutant dispersion in Lake Garda (north Italy). In: Developments in Environmental Modelling, vol. 25. Elsevier, pp. 319–330. https://doi.org/10.1016/B978-0-444-59396-2.00019-5.

Magilligan, F.J., Nislow, K.H., 2005. Changes in hydrologic regime by dams. Geomorphology 71, 61–78. https://doi.org/10.1016/j. geomorph.2004.08.017.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica. J. Econ. Soc. 245–259. https://doi.org/10.2307/1907187.

Matzinger, A., Pieters, R., Ashley, K.I., Lawrence, G.A., Wüest, A., 2007. Effects of impoundment on nutrient availability and productivity in lakes. Limnol. Oceanogr. 52, 2629–2640. https://doi.org/10.2307/4502408.

Mei, X., Dai, Z., Du, J., Chen, J., 2015. Linkage between Three Gorges Dam impacts and the dramatic recessions in China's largest freshwater lake, Poyang Lake. Sci. Rep. 5, 1–9. https://doi.org/10.1038/srep18197.

Micotti, M., Weber, E., Sessa, R.S., 2010. Il Progetto Interreg STRADA. D1-La Ricognizione. http://www.progettostrada.net/media/report_conclusivi/Report_Tecnici_Azione_2/d1.pdf (This document is written in Italian).

Ministero dei Lavori Pubblici - Servizio Idrografico, 1917. Annali idrologici - parte prima e seconda. This document is written in Italian.

Moisello, U., Todeschini, S., Vullo, F., 2013. The effects of water management on annual maximum floods of Lake Como and River Adda at Lecco (Italy). Civ. Eng. Environ. Syst. 30, 56–71. https://doi.org/10.1080/10286608.2012.710606.

Moore, D., Dore, J., Gyawali, D., 2010. The world commission on Dams+ 10: revisiting the large dam controversy. Water Altern. (WaA) 3.

Nicklow, J., Reed, P., Savic, D., Dessalegne, T., Harrell, L., Chan-Hilton, A., Karamouz, M., Minsker, B., Ostfeld, A., Singh, A., et al., 2010. State of the art for genetic algorithms and beyond in water resources planning and management. J. Water Resour. Protect. 136, 412–432. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000053.

Nilsson, C., Jansson, R., Zinko, U., 1997. Long-term responses of river-margin vegetation to water-level regulation. Science 276, 798–800. https://doi.org/10.1126/science.276.5313.798.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308, 405–408. https://doi.org/10.1126/science.1107887.

Oki, T., Kanae, S., 2006. Global hydrological cycles and world water resources. Science 313, 1068–1072. https://doi.org/10.1126/science.1128845.

Partal, T., Kahya, E., 2006. Trend analysis in Turkish precipitation data. Hydrol. Process. 20, 2011–2026. https://doi.org/10.1002/hyp.5993.

Piccolroaz, S., Amadori, M., Toffolon, M., Dijkstra, H.A., 2019. Importance of planetary rotation for ventilation processes in deep elongated lakes: evidence from Lake Garda (Italy). Sci. Rep. 9, 8290. https://doi.org/10.1038/s41598-019-44730-1.

Poff, N.L., 2018. Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world. Freshw. Biol. 63, 1011–1021. https://doi.org/10.1111/fwb.13038.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. Bioscience 47, 769–784. https://doi.org/10.2307/1313099.

Poikane, S., Zohary, T., Cantonati, M., 2020. Assessing the ecological effects of hydromorphological pressures on european lakes. Inland Waters 10, 241–255. https://doi.org/10.1080/20442041.2019.1654800.

Ruiz-Villanueva, V., Stoffel, M., Bussi, G., Francés, F., Bréthaut, C., 2015. Climate change impacts on discharges of the Rhone River in Lyon by the end of the twenty-first century: model results and implications. Reg. Environ. Change 15, 505–515. https://doi.org/10.1007/s10113-014-0707-8.

Salmaso, N., 2005. Effects of climatic fluctuations and vertical mixing on the interannual trophic variability of Lake Garda. Italy. Limnol. Oceanogr. 50, 553–565. https://doi.org/10.4319/lo.2005.50.2.0553.

Salmaso, N., 2010. Long-term phytoplankton community changes in a deep subalpine lake: responses to nutrient availability and climatic fluctuations. Freshw. Biol. 55, 825–846. https://doi.org/10.1111/j.1365-2427.2009.02325.x.

Salmaso, N., Mosello, R., 2010. Limnological research in the deep southern subalpine lakes: synthesis, directions and perspectives. Adv. Oceanogr. Limnol. 1, 29–66. https://doi.org/10.4081/aiol.2010.5294.

Salmaso, N., Anneville, O., Straile, D., Viaroli, P., 2018a. European large perialpine lakes under anthropogenic pressures and climate change: present status, research gaps and future challenges. Hydrobiologia 824, 1–32. https://doi.org/10.1007/s10750-018-3758-x.

Salmaso, N., Boscaini, A., Capelli, C., Cerasino, L., 2018b. Ongoing ecological shifts in a large lake are driven by climate change and eutrophication: evidences from a three-decade study in Lake Garda. Hydrobiologia 824, 177–195. https://doi.org/10.1007/s10750-017-3402-1.

Schulz, S., Darehshouri, S., Hassanzadeh, E., Tajrishy, M., Schüth, C., 2020. Climate change or irrigated agriculture–what drives the water level decline of Lake Urmia. Sci. Rep. 10, 1–10. https://doi.org/10.1038/s41598-019-57150-y.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Simeoni, F., Cassia, F., Ugolini, M.M., 2019. Understanding the weak signals of demand in a mature tourist destination: the contribution of a sustainable approach. J. Clean. Prod. 219, 775–785. https://doi.org/10.1016/j.jclepro.2019.02.072.

Sneyers, R., 1990. WMO Technical Note. On the Statistical Analysis of Series of Observations, vol. 143. World Meteorological Organization.

Spearman, C., 1987. The proof and measurement of association between two things. Am. J. Psychol. 100, 441–471. https://doi.org/10.2307/1422689.

Theil, H., 1950. A rank-invariant method of linear and polynomial regression analysis. Indagat. Math. 1, 467–482. https://doi.org/10.1007/978-94-011-2546-8_20.

Tolotti, M., Dubois, N., Milan, M., Perga, M.E., Straile, D., Lami, A., 2018. Large and deep perialpine lakes: a palaeolimnological perspective for the advance of ecosystem science. Hydrobiologia 824, 291–321. https://doi.org/10.1007/s10750-018-3677-x.

Valerio, C., 2018. Uso della risorsa idrica e gestione dei manufatti idraulici nel bilancio idrico del fiume Mincio. Master's Thesis. University of Trento, Italy (This document is written in Italian).

Vinson, M.R., 2001. Long-term dynamics of an invertebrate assemblage downstream from a large dam. Ecol. Appl. 11, 711–730. https://doi.org/10.2307/3061112.

Ward, J., Stanford, J., Fontaine, T., Bartell, S., 1983. The serial discontinuity concept of lotic ecosystems. In: Dynamics of Lotic Ecosystems, pp. 29–42.

Wei, G., Yang, Z., Cui, B., Li, B., Chen, H., Bai, J., Dong, S., 2009. Impact of dam construction on water quality and water self-purification capacity of the Lancang River, China. Water Resour. Manag. 23, 1763–1780. https://doi.org/10.1007/s11269-008-9351-8.

World Commission on Dams, 2000. Dams and development: a new framework for decision-making: the report of the world commission on dams. Earthscan Publications, London. https://doi.org/10.4324/9781315541518.

Yagbasan, O., Demir, V., Yazicigil, H., 2020. Trend analyses of meteorological variables and lake levels for two shallow lakes in Central Turkey. Water 12, 414. https://doi.org/10.3390/w12020414.

Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann–Kendall and spearman's rho tests for detecting monotonic trends in hydrological series. J. Hydrol. 259, 254–271. https://doi.org/10.1016/S0022-1694(01)00594-7.

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. Aquat. Sci. 77, 161–170. https://doi.org/10.1007/s00027-014-0377-0.