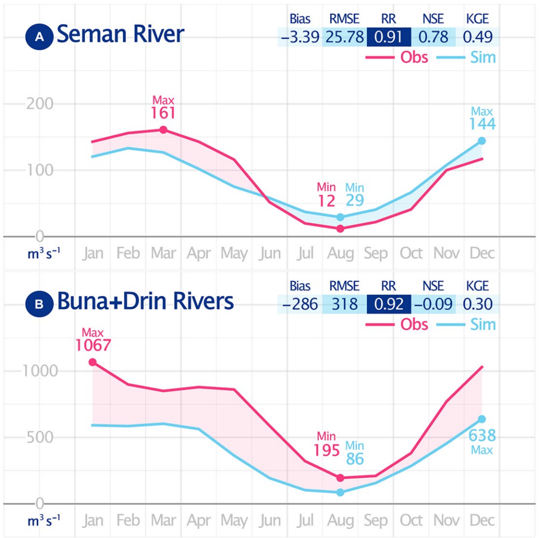

FIGURE 5
River discharge monthly climatology (m^3s^{-1}) of the Albanian rivers considering the observation data updated by Vodopivec et al. (2022).

The CAd's catchment area doubles the NAd subregion, but its freshwater discharge potential into the Adriatic Sea is three times higher than NAd and SAd subregions. Much of this potential comes from the Neretva River (Croatia), which alone adds 58% of the river discharges from the CAd. Other Croatian rivers, such as Cetina and Krka, add a further 27% due to the larger catchment area on the east coast. Almost all rivers in this subregion have river discharge values available in the literature, which allows for classifying the EFAS estimates as consistent for the entire CAd. The only exceptions were the Biferno (Italy) and Jadro (Croatia) Rivers, whose observations were underestimated by 50%.

SAd has a larger catchment area than NAd and CAd combined (Figure 3), and its contribution to the freshwater input into the Adriatic Sea follows this proportion (Table 2). However, as already discussed, this contribution could be more significant if discrepancies between literature data and EFAS estimates on discharges from Buna and Drin Rivers were overcome. On the other hand, considering the other subregion rivers, EFAS provided estimations in line with the referenced values again, especially when assessing the Albanian rivers that govern river discharges in SAd.

3.2 Second-level assessment

In this subsequent assessment phase, time series of daily averaged river discharges obtained from the hydrological monitoring networks along the Adriatic Sea basin are compared with EFAS reconstructions to assess the model skill to represent seasonal cycles, interannual and decadal trends, and the distribution parameters to classify extreme events. Unfortunately, the absence of daily discharge data reduced the number of rivers considered in this second-level assessment to 19, all located at SNAd and the western NAd from Isonzo River up to Tronto River (Figure 3).

The statistical indices obtained by comparing the observational data with the EFAS-modelled data are summarised in Table 3. The monitoring stations are 1.7 to 61.6 km from their respective river mouths (EFAS gridpoints), but only one-third are positioned up to 10 km. On the other hand, the availability of the observation time series ranges from 1 to 20 years (366 to 7,494 days), of which two-thirds have about 10 years or more. However, only the Po River at Pontelagoscuro station has data covering the 32 years (11,545 days) evaluated in the present study.

Generally, the integrated analysis of statistical indices is quite complex and often points in different directions. Not all reconstructions well correlated with observed data present low bias and RMSE, or NSE and KGE close to ideal (1). For example, the Cesano River reaches RR = 0.75, but the bias overestimates by almost 5x and explains the strongly negative NSE and KGE (Table 3). It is true that high correlations and small bias result in high NSE and KGE (see the indices for Isonzo, Tagliamento, Adige, and Po Rivers). None of the small rivers showed high NSE and KGE. Most presented values close to zero, indicating a good representation of average river discharges but not their seasonal variations (Knoben et al., 2019). The other part showed strongly negative NSE and KGE, meaning neither the average is well represented in these reconstructions.

To explore the relationship between observed and reconstruction data, Figure 6 shows the daily average river discharges of three particular rivers presented in Table 3: the Isonzo, Po and Potenza Rivers. The Isonzo, also known as Soča, has the 7th and 5th largest freshwater discharge in the Adriatic Sea and SNAd, respectively (Table 2), and was selected to represent rivers with discharge observations near the river mouth. The 5 km separating the monitoring station (Grado) and the river mouth is amongst the shortest analysed in Table 3 (about 8 km following the river course) and presents discharge data since September 2015.[2] In these 5 years of observed data (Figure 6), two annual river discharge peaks can be noticed, with the highest daily values reported during the winter (>600 m^3s^{-1}). The same applies to EFAS estimates, which correctly simulated the seasonal discharge cycle with a positive bias of 8.1% regarding the average discharge and good correlation, NSE and KGE (0.90, 0.81, and 0.86, respectively). An overestimation of autumnal discharges explains the positive bias. For example, the observed discharges were lower than expected in 2016 and 2019. However, as shown by the distribution parameters, EFAS was consistent with river discharges measured in Grado station, also providing realistic thresholds for extreme events of drought (P05) and flooding (P95). These suitable estimates result from a fair comparison where the short distance between Grado station and the river mouth (EFAS) minimises changes related to evaporation and human activities.

The second time series in Figure 6 assesses the daily average discharges of Po River at Pontelagoscuro, chosen for its extended set of observed data. It is the only river in which the EFAS estimates were extracted from a gridpoint far from the Adriatic coast (~70 km) due to the model concept that makes the representation of deltas unfeasible. It is also worth remembering that Po River discharges are

---

[2] www.arpa.fvg.it

TABLE 3 Statistical Indices computed for 19 Adriatic rivers with observational river discharges available daily.

ID	River	Station	Station Coordinates Lat(°N)	Lon(°E)	[a]Dist (km)	[b]Ovl (days)	Bias (%)	RMSE	RR	NSE	KGE
22	Isonzo	Grado	45.7294	13.5373	5.08	1929	14.17 (9)	90.25	0.90	0.81	0.86
29	Tagliamento	Lignano Sabbiadoro	45.6595	13.0747	3.12	1910	−26.82 (−22)	72.64	0.77	0.53	0.53
32	Livenza	Meduna di Livenza	45.8051	12.6106	29.01	1809	−0.98 (−1)	59.57	0.83	−1.82	−3.81
33	Piave	Ponte di Piave	45.7113	12.4547	29.57	5826	52.02 (96)	88.35	0.69	0.17	−0.07
41	Adige	Boara Pisani	45.1055	11.7842	41.40	5832	20.51 (11)	80.54	0.80	0.48	0.60
45	Po	Pontelagoscuro	44.8883	11.6081	1.67	11 545	−37.49 (−3)	470.51	0.90	0.79	0.89
53	Reno	Ponte Bastia	44.5774	11.8752	32.23	4047	50.13 (198)	78.23	0.77	−2.40	−2.74
54	Lamone	Mezzano	44.4696	12.0829	15.55	1816	−0.85 (−7)	16.97	0.39	0.10	0.14
60	Marecchia	Rimini SS16	44.0614	12.5420	2.65	1980	−0.64 (−5)	27.38	0.40	0.15	0.05
80	Trigno	Ponte Caprafica	41.8980	14.6399	20.14	7494	1.20 (18)	11.35	0.20	−0.25	0.05
63	Foglia	Pesaro	43.9076	12.8977	2.75	3564	1.12 (14)	19.00	0.50	0.25	0.06
64	Metauro	Acqualagna	43.6283	12.6845	37.65	4486	16.51 (199)	24.44	0.66	−1.30	−1.35
65	Cesano	Mondavio	43.6650	13.0146	15.41	366	6.54 (388)	8.84	0.75	−7.26	−5.79
66	Misa	Senigallia	43.6627	13.1650	6.57	3571	1.54 (48)	6.44	0.57	0.26	0.17
67	Esino	Genga	43.4064	12.9803	40.18	4659	3.62 (43)	11.69	0.61	0.08	0.40
68	Musone	Castelfidardo	43.4940	13.5667	7.39	4599	5.64 (537)	9.53	0.38	−17.44	−12.90
69	Potenza	San Severino	43.2295	13.1885	42.42	3764	2.63 (37)	8.00	0.60	−1.56	−1.62
70	Chienti	Camerino	43.0787	13.0807	61.66	864	11.48 (764)	15.30	0.36	−136.41	−63.29
73	Tronto	Ascoli Piceno	42.8522	13.6515	23.06	5201	−1.36 (−11)	14.54	0.48	0.20	0.22

[a] Distance from the Station to the River Mouth (EFAS). [b] Overlap days available throughout Station and EFAS data.

partitioned into nine branches based on the estimated value in Pontelagoscuro (about 1.67 km from the monitoring station, Figure 6). The discharge measurements in Pontelagoscuro date back to the 1920s and allow EFAS to be assessed over the whole analysis window.[3] The Po is the main river in the Adriatic basin and is responsible for 35% of freshwater discharge. Like the Isonzo River, its seasonal cycle has two annual peaks with exceptional discharges (P95) that exceed twice the average. Again, EFAS estimates showed exemplary skill in representing these features during the 32 years evaluated. Notably, the historical measurements at Pontelagoscuro were used on EFAS calibration and partially explained the low bias and RMSE (about 2.6 and 33.4% regarding the average discharge, respectively) and the high correlation, NSE and KGE highlighted in Figure 6.

Finally, Figure 6 compares the daily average discharges of the Potenza River estimated by EFAS and measured in San Severino Station, 42 km from the river mouth.[4] The river dimension justifies this selection. Although amongst the lowest river discharge in the Adriatic, this river represents an essential group of small rivers on the western coast, which collect 8% of the freshwater delivered in the Adriatic Sea. With small catchments along the Apennines, these rivers usually exhibit a seasonal cycle with a single maximum discharge during the winter and a minimum in the summer. Since snow accumulation appears at low altitudes, its melting occurs in late winter, and the spring's secondary maximum discharge is less evident than in Alpine rivers (Ricci et al., 2022). That is precisely what is observed at the San Severino station and estimated by EFAS for Potenza River over the 10+ years of available river discharge data. During this period, EFAS estimates satisfactory represented observational discharges, especially during droughts, so critical for rivers of these characteristics. On the other hand, as indicated by the RR and RMSE, the flash flood cases (typical of Apennine rivers) were often overestimated and notably increased the average river discharge, Q3 and P95. Additionally, the negative values of NSE and KGE indicate that EFAS is a good predictor only for the mean discharge of Potenza River and not for its variations.

4 River discharge climatology

Every day from 1991 to 2022, the Adriatic Sea received about 3,995 m^3s^{-1} of freshwater discharges from hundreds of rivers and streams, besides the various water exchange channels along the Po River delta and the lagoon systems of Venice and Marano (Figure 7A). Throughout the year, two wet periods are observed in late autumn (Nov, 5,620 m^3s^{-1}) and in mid-spring (May, 4,545 m^3s^{-1}), mainly governed by the SNAd seasonal cycle, and interrupted by a dry period with minimum river discharges during the summer months (Aug, 2,257 m^3s^{-1}). This pattern had already been reported previously by Struglia et al. (2004) but with different peak values (3,500, 1,600 and 3,000 m^3s^{-1} in May, August and November, respectively). We argue the difference is because their study evaluated only 78% of river discharges in the Adriatic Sea.

In November, the daily river discharge overcomes the annual average by 41%, often reaching 6,672 m^3s^{-1} (Q3) and exceeding 9,368 m^3s^{-1} in extreme cases (P95, Figure 7A). This increase, in large part, arises from the higher frequency of extratropical cyclones crossing the Adriatic Sea in late autumn (Aragão and Porcù, 2022), which, consequently, increases the precipitation collected by Alpine and Apennine rivers distributed along SNAd (Figure 7B) and NAd

---

[3] www.arpae.it

[4] www.arpa.marche.it

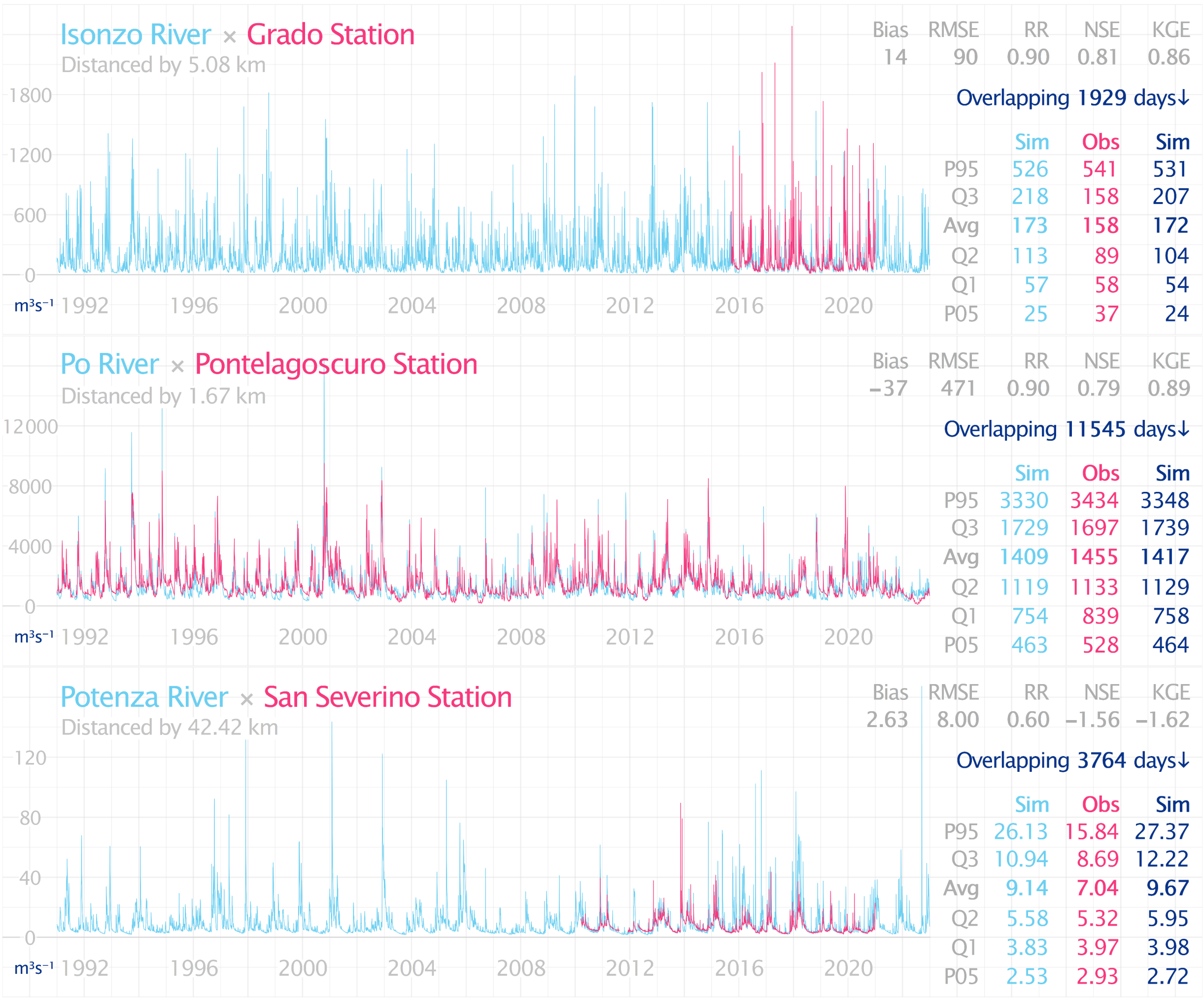

FIGURE 6
Daily averaged river discharge (m^{3}s^{-1}) of Isonzo, Po, and Potenza Rivers at the river mouth (EFAS gridpoint) and the monitoring station. EFAS reconstructions cover 1991–2022 (blue lines), whilst observations (magenta lines) include only the available period on each station. The embedded table shows the statistical indexes (grey) and the distribution parameters for the available period on EFAS (Sim, blue) and observations (Obs, magenta) and on EFAS but for the overlapping period with observations (Sim, dark blue).

(Figure 7C) basins. The slight detachment of the average (Avg) and median (Q2) curves in the previous months (quite evident in October, Figure 7B) is an indication of brief but intense rainfalls typically associated with cyclones, which are intense enough to increase the averaged river discharge but not often to modify its median.

In the following months (Jan-Mar), the freshwater input into the Adriatic Sea gradually decreases to its annual levels, mainly sustained by the CAd and SAd rivers (Figures 7D,E). Unlike the SNAd and NAd rivers, which experienced a significant decrease in this period (Figures 7B,C), the Central and Southern Adriatic rivers preserve their discharges about 50% above their annual averages throughout the winter, also supported by small rivers (annual discharges <1% of Adriatic Sea discharges), which present their highest participation within the overall discharge during these months. This winter behaviour, added by the low influence of snowmelt during spring (Ricci et al., 2022), defines the annual cycle of discharges within CAd and SAd catchments, i.e., a long and continuous period of 8 months (Oct–May) in which daily average river discharges range about 30–50% above average, interrupted by intense dry spells peaking in August when discharges often drop to a meagre 25–30% of annual levels.

Before facing the dry summer months, the SNAd rivers receive an essential contribution of freshwater accumulated throughout the winter in the form of snow, which produces a secondary high-discharge peak during spring due to snow melting stored in catchment areas along the Alps and Apennines (Raicich, 1996; Struglia et al., 2004; Vilibić and Supić, 2005). Although the distribution parameters Q1 and Q3 (Figure 7B) present values close to the average discharge for May, the recent years have been marked by a significant reduction in snow accumulation during the winter in the Eastern Alps due to climate warming, suggesting that the current seasonal cycle may change in the coming years (Cozzi et al., 2012).

The dry period is the common feature amongst the seasonal cycles of river discharges in the four subregions of the Adriatic Sea. During the summer, the precipitation regime in the Central Mediterranean tends to be governed by thermal lows, which produce

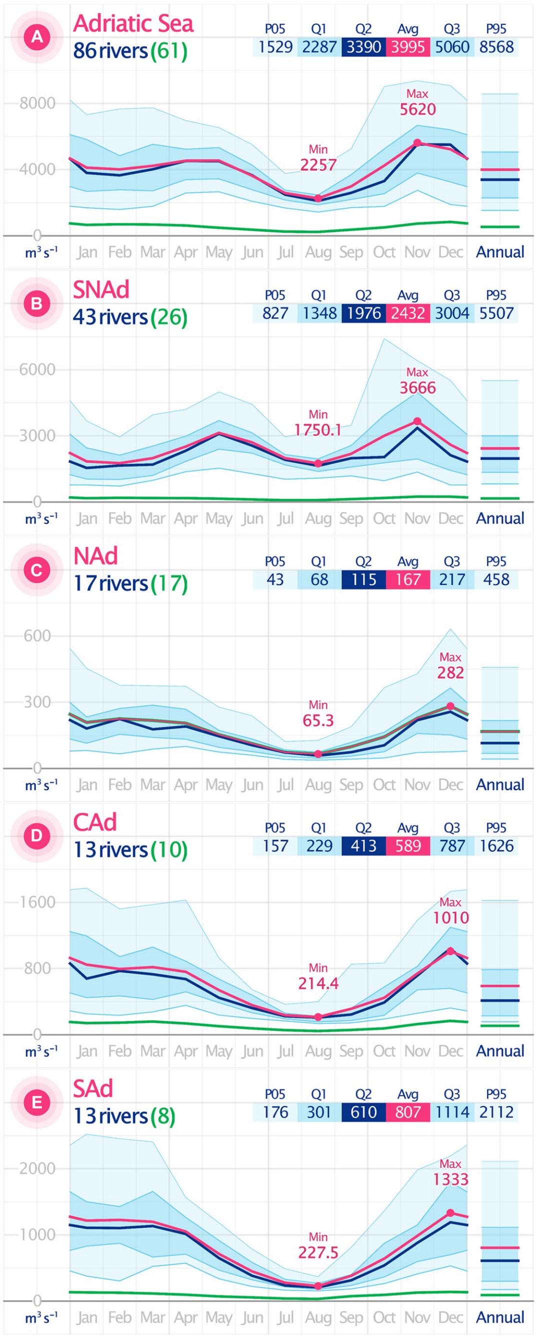

FIGURE 7
Monthly climatology of the overall river discharge (m^{3}s^{-1}) into **(A)** the Adriatic Sea, **(B)** SNAd, **(C)** NAd, **(D)** CAd, and **(E)** SAd during 1991–2022, shown by average (Avg, magenta line), median (Q2, blue line), 1st (Q1) and 3rd (Q3) quantiles (blue area), and bottom (P05) and top (P95) 95th percentiles (light blue area). Additionally, the overall river discharge considering only small rivers (annual discharges <1% of Adriatic Sea discharges) is presented (green line). The respective annual averaged river discharges are presented in the last column and the embedded table.

isolated rains inland (Aragão and Porcù, 2022) but are insufficient to supply the water demand. Only a tiny part of these waters reaches the riverbeds since the major part evaporates, is absorbed by soil and vegetation, or is withdrawn for irrigation (Provini et al., 1992; Montanari, 2012). Consequently, all rivers flowing to the Adriatic Sea present significant reductions in their discharges with a minimum in August when the statistical parameters show a discharge distribution with the slightest deviation in the 32 years evaluated. In this critical month, the Adriatic Sea experiences a 44% reduction in the freshwater input, mainly due to a significant reduction at the SNAd rivers (28%), which are responsible for 61% of the overall discharges. A 44% reduction is reasonable compared to the 36% reported by Struglia et al. (2004), valid for 78% of the overall discharges into the Adriatic Sea. In the other subregions, the discharge reductions are much more pronounced, CAd (61%), SAd (71%), and NAd (72%), since these regions are characterised by few rivers loaded by small catchment areas.

Amongst the 86 rivers evaluated, 61 were classified as minor. These rivers are highly susceptible to long periods of drought and may even experience zero flows in some months. As drought impacts are numerous and cumulative, Section 6 delves deeper into this topic and provides additional insights and trends with the help of a long-term climate indicator.

5 River discharge trends

Since the EFAS reconstructions date back to the early 1990s, assessing how much river discharges have changed in the past three decades and which subregions were most influenced is essential to understanding the current freshwater dynamics in the Adriatic Sea. Figure 8 presents the monthly averages of river discharges into 1991–2022 for the Adriatic Sea and its subregions, as well as the statistical distribution parameters and the respective trends expressed by linear regression for the entire analysis period (32 years) and the last decade.

In general, the time series presented in Figure 8 aligns with the previously discussed seasonal climatology, where the SNAd tends to guide the overall river discharge in the Adriatic Sea with two yearly peaks. Moving south (Figures 8C–E), the number of yearly peaks decreases gradually, reaching a clear single annual peak in CAd and SAd. Although the river discharge into the Adriatic Sea during the 32 years evaluated indicates a non-statistically significant negative trend, different responses are observed between the northern and southern subregions supported by statistically significant trends (except CAd). In the northern region, both SNAd and NAd (Figures 8B,C) have exhibited a decreasing trend over time, in agreement with the results of Giani et al. (2012), Appiotti et al. (2014) and Djakovac et al. (2015). The negative trend in SNAd is more than three times that of the Adriatic Sea. According to Montanari (2012), who analysed almost 100 years of observational discharges of the main Adriatic river, Po River at Pontelagoscuro, the non-significant trend for the 32 years raises concerns as it results from a fragile balance between intense drought and flood periods. On the other hand, the southern subregions, CAd and SAd, recorded positive trends, especially for SAd rivers (Figure 8E), with continuously ascendent discharges from Buna, Vjiose and Seman. These positive trends derive from two particular dry periods in southern Italy during the early 90s and the early 00s (Mendicino et al., 2008).

Reducing the analysis period to the last 10 years (2013–2022), negative trends are observed in river discharges from all subregions of the Adriatic, including the overall trend that shows a 170 m^{3}s^{-1} drop by year (Figure 8A). In this case, all trends met the statistical significance criterion of 95% and had the lowest river discharges of the

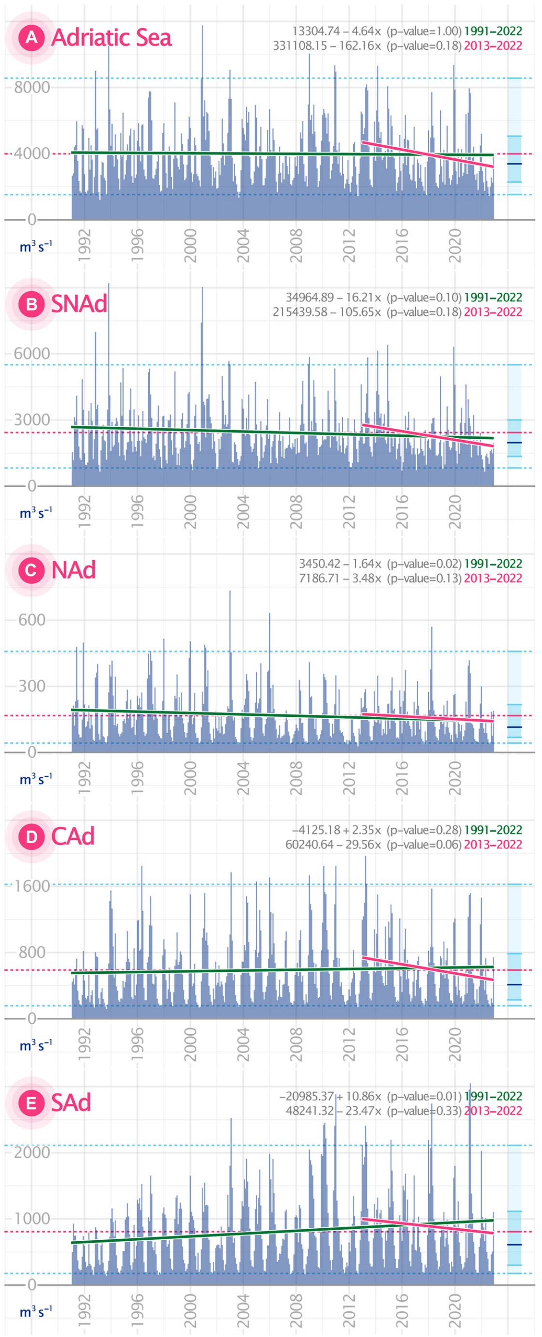

FIGURE 8
Monthly averaged river discharges ($m^3 s^{-1}$, dark blue bars) into **(A)** the Adriatic Sea, **(B)** SNAd, **(C)** NAd, **(D)** CAd, and **(E)** SAd during 1991–2022. The monthly river discharge trends are presented for the last 32 years (green line, the whole period) and only for the last 10 years (magenta line). As a reference, the distribution parameters are presented in the sidebar (as in Figure 7).

last 32 years in 2022, driving the strong negative trend. Proportionally, these trends point to a 10-year accumulated drop of 36, 24, 43 and 29% in SNAd, NAd, CAd and SAd (Figures 8B–E), resulting in a 35% reduction in river discharges from the Adriatic Sea since 2013. According to Pintori and Serpelloni (2023), only the Po River basin lost about 80 billion tons of freshwater during the 2021–2022 drought as a result not only of the lack of precipitation but also the water use in manifold activities of local economies deeply dependent of water resources (see Crovella et al., 2022; Mazzoni et al., 2022 and Pronti and Berbel, 2023).

Another noteworthy piece of information extracted from Figure 8 concerns extreme events. Taking the upper and lower 95th percentiles as a reference, it is possible to assess the frequency of flood and drought events over the 32 years evaluated. For example, comparing the SNAd river discharges of the first and the last 10 years analysed (Figure 8B), there are only three records under the P05 threshold in the first decade against five records in the last decade, showing that extreme drought event frequency almost doubled within the three decades analysed. Although these numbers suggest an increase in months with low discharges and follow the negative trend for the SNAd, this relationship appears somewhat unbalanced with the extreme flooding events. In the last 10 years (2013–2022), the SNAd experienced a double of months exceeding the P95 regarding the first decade evaluated (1991–2000), showing that the total number of extreme events is continually growing, regardless of whether it is a drought or flood event. This result reinforces the fragile balance highlighted by Montanari (2012), where average river discharges tend to increasingly compensate alternating extreme events of low and high discharges.

Conversely, Figure 8E shows five records under the P05 threshold in the first decade compared to only one recorded in the last decade, following Mendicino et al. (2008) results. Combining these numbers with seven records exceeding the P95 in the last decade and the absence of such records during the first decade, a compelling explanation can be established for the positive trend observed in the SAd. In this case, as SAd presents a seasonal cycle of river discharge with a single annual peak, months with high discharge are often consecutive by two to four consecutive months, which could be understood as exceptional seasons instead of exceptional months. This feature distinguishes the south Adriatic Sea subregions by its well-defined seasonal cycle of river discharges, whilst the north subregions tend to present isolated single months with exceptionally high discharges.

6 Long-term climate indicator

As discussed before, to understand the climate river discharge changes, the analysis must go further than identifing the number and frequency of months with discharges under a specific threshold. For this reason, Figure 9 shows the Standardised Flow Index considering a time window of 12 months (SFI12) computed using the monthly averaged river discharge presented in Figure 8. The time window could be easily modified to aggregate 3 or 6 months to assess short and medium-term moisture and precipitation conditions. Nevertheless, once the target here frames the climatological scale and the seasonal cycle was widely discussed in Section 4, the 12-month aggregation was applied to identify long-term precipitation patterns which could influence river discharges, reservoir levels and groundwater levels (Marcos-Garcia et al., 2017).

As expected for a large river basin such as the Adriatic Sea, the last 32 years of river discharges showed a balanced SFI12 alternating between wet and dry periods. However, the SFI12 trend indicates an increasing intensification and extension of wet and dry periods, i.e., presenting shorter and near-normal intensities in the first decade

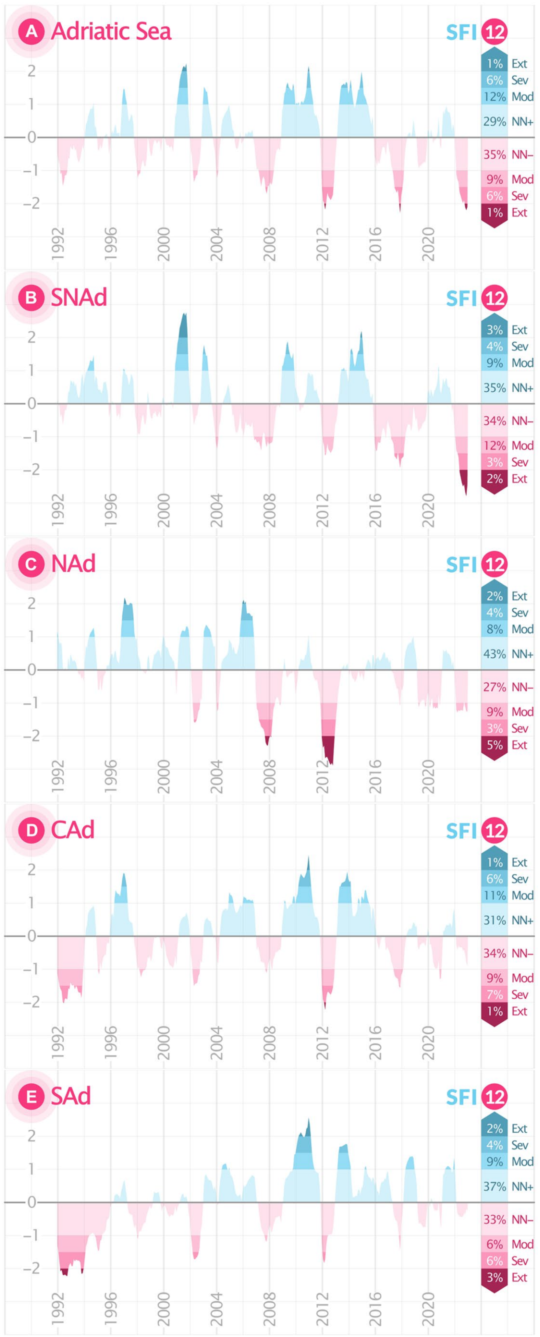

FIGURE 9
Standardised Flow Index (SFI) for **(A)** the Adriatic Sea, **(B)** SNAd, **(C)** NAd, **(D)** CAd, and **(E)** SAd from 1991 to 2022 with a 12-month timescale. Positive values represent wet months (blue areas), whilst negative values represent dry months (magenta areas). The intensity scale ranges from Near Normal (NN+ and NN-) to Moderate (Mod ±1.0), Severe (Sev ± 1.5) and Extreme (Ext ± 2.0), and their respective frequencies are presented in the sidebar.

analysed and more extended and intense periods in the last 10 years (Figure 9A). Although the SFI12 distribution shows about 18% of months under moderate to extreme wet conditions against 16% under dry conditions, the last presents a constantly increasing intensity since 2008 with a cyclic frequency of about 4–5 years. It is worth mentioning that the balanced SFI12 found for the Adriatic Sea is a result of its hydrological basin dimensions, which comprise river discharge deficits of some sub-basins constantly neutralised for high discharges in others, and *vice-versa*. As the analysed catchment area decreases, the range of variability on sub-basin discharges increases, triggering accumulated effects of wet and dry periods on the hydrological basin.

The long and dry period identified between 2008 and 2022 in the Adriatic Sea primarily responds to continuous reductions in the SNAd river discharges. As indicated in Figure 9B, the period was the longest and the only one with negative SFI12 reaching extreme values in 2022. According to Bonaldo et al. (2022), as drought periods are increasing in frequency, events like the one of 2022 will become ordinary in the relatively near future. This result supports Pintori and Serpelloni (2023), who also pointed out the period as the most extreme drought in recent decades, but based on observational data through the Standardised Precipitation and Evapotranspiration Index (SPEI) also for 12 months, proving once again the accuracy of the EFAS model in identifying the most relevant extreme events. In 2020, the SNAd's SFI12 shifted, whilst the Adriatic Sea oscillated through positive and negative values in response to the low discharges still registered along other Adriatic subregions (Figures 9C–E), following their river discharge trends (Figure 8).

As discussed in Section 5, the vulnerability of NAd rivers to drought events is even more prominent in Figure 9C (2007–2013), when two periods of intense drought caused more than 18 months with SFI12 at extremely negative levels. This result postulates the NAd rivers as the most exposed to extreme drought events. According to Ricci et al. (2022), these systematic reductions in freshwater inputs in NAd derive from modifications in the seasonal precipitation cycle. Additionally, this vulnerability is amplified given the characteristics of most of NAd rivers (western coast), which naturally reduce their levels during the summer months (some of them dry completely), exposing the entire coastal region to deficits of biomass loads, increases of salinity in surface waters and, consequently, significant changes in the vertical distribution of nutrients (Zavatarelli et al., 1998; Cozzi and Giani, 2011).

Whilst 2008–2022 was marked by extreme drought events in the northern subregions of the Adriatic Sea (SNAd and NAd), the CAd and SAd subregions experienced exceptionally wet periods, with some months classified as extremely wet in both subregions during 2010 (Figures 9D,E). In 2012, the SFI12 accumulated in CAd and SAd also presented negative values but not as intense as in SNAd and NAd and then shifted to positive for 3–4 years. Despite the substantial difference between the total volume of freshwater delivered at each Adriatic Sea subregion, several pieces of evidence suggest that the whole Adriatic Sea discharge is governed by a balanced relationship between discharges from the northern (SNAd and NAd) and southern (CAd and SAd) regions, triggered by changes in the seasonal cycle of precipitation which rarely presents the same trend simultaneously in both areas. Many studies in the literature show the Mediterranean precipitation variability intensely correlated with several atmospheric teleconnections, such as El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), East Atlantic Pattern (EAP), Scandinavian (SCA) and others (Quadrelli et al., 2001; Philandras et al., 2011; Krichak et al., 2014; Sánchez and Aragão, 2021). According to Kalimeris et al. (2017), along the Adriatic coast, most of the variability in local precipitation occurs at bi-decadal scales, when the SCA effects weaken due to the dominant Bora circulation, but the EA can temporarily affect the decadal variability during winter. On the other hand, at short time scales (months), precipitation strongly correlates with NAO and other Atlantic patterns rather than Arctic patterns (Romano et al., 2022). Nevertheless, it is essential to highlight the lack of studies dedicated to the Adriatic Sea that provide a detailed evaluation of the interaction of these teleconnection components through different temporal scales.

7 Discussion and final remarks

This study revisited the freshwater inputs into the Adriatic Sea via river discharges over the last climatological period (1991–2022) obtained from the EFAS reconstructions and a careful and accurate method for identifying rivers, allowing accounting discharges of all rivers with average daily runoff exceeding 1 m^3s^{-1}. In total, 86 rivers compose the freshwater balance in the Adriatic Sea, evaluated individually and by each Adriatic subregion, and taking advantage of dedicated climate indicators computed daily, monthly and annually to quantify river discharge's extreme levels (wet and dry) and classify seasonal cycles within a climatological scale.

The data extraction method proved to be a necessary step for a suitable representation of river discharges in all subregions of the Adriatic Sea and the most diverse classes of river basins. The assessment against observational data was possible for 67 of 86 identified rivers, which account for more than 96% of freshwater inputs into the Adriatic Sea. The EFAS estimates proved reliable even for small rivers, supported by relatively small errors and a correlation of 0.91. EFAS strongly underestimated the river discharges in the Venice and the Marano Lagoons, showing that the representation of lake and lagoon outflows is still imprecise due to the lack of observational measurements *in situ*, i.e., along the coast (outlets) and river mouths. Concerning the most significant rivers (those with average river discharges over 5% of the Adriatic overall or 200 m^3s^{-1}), only the Albanian rivers (Buna and Drin) presented discharge estimates conflicting with observational data, justified by several river course modifications for hydroelectric plant purposes after the free available data on literature. Although Vodopivec et al. (2022) have recently updated the monthly climatology of discharges from the Buna+Drin and Seman Rivers, these data have not yet been assimilated by EFAS. Furthermore, they are still insufficient to quantify River Drin discharges individually, resulting in the most significant bias between observed (692 m^3s^{-1}, Ludwig et al., 2009) and reconstructed (13 m^3s^{-1}, EFAS) mean river discharges found throughout the Adriatic Sea. Given the relevance of these rivers to the Adriatic hydrographic basin, the free availability of continuous and updated measurements of river discharges is exceptionally urgent for a better representation of these rivers in hydrological models.

The seasonal cycle analysis allowed the identification of two river discharge regimes in the Adriatic Sea. The first is characterised by two annual flood peaks in November and May, separated by a dry peak in August, whilst the second presents only one flood peak in December and a dry peak in August. The regime with two annual floods is exclusively found in the 43 rivers of the SNAd, which, given their dimensions, govern 61% of the overall discharges in the Adriatic Sea and lead the entire basin to this regime. However, due to the successive reduction in snow accumulation over the Alpine and Apennine areas during the winter months, there is a high risk of the secondary flood peak disappearing in May.

Over the past 32 years, river discharges have shown different trends along the Adriatic Sea subregions, where a delicate balance between dry seasons in some subregions has been slightly balanced by flood seasons in others and vice versa. This delicate balance, combined with the diversity of its river basins, prevents us from estimating a trend with statistical significance for the Adriatic Sea. However, the river discharge trends are forthright when computed individually for each subregion, balancing slightly negative trends in the northern subregions (−0.6% and − 1.0% per year in SNAd and NAd) with intriguingly positive trends in the southern subregions (+0.4% and + 1.3% per year in CAd and SAd). When the analysis window narrows to the last decade (2013–2022), the balance breaks down, and a strong negative trend emerges across the entire Adriatic Sea, without exception, indicating reductions of −4.2% per year in freshwater input throughout the river basin. According to the SFI results, a climate indicator used to estimate the long-term impact of drought and flood periods on river discharges, 2022 was crucial for the last negative decadal trend. During this year, the northern Adriatic experienced the driest period in the last 32 years, whilst the southern Adriatic experienced river discharge reductions during flood months. Nevertheless, the most worrying element about the extreme drought of 2022 is that this year is part of a drought cycle that has continuously reduced freshwater availability in the Adriatic Sea every 4–5 years since 2008.

Finally, it is noteworthy that the study comprises data on the daily river discharges of 86 rivers, including the corresponding discharges per subregion (SNAd, NAd, CAd, and SAd) and the entire Adriatic Sea, defining the framework for monitoring the hydrological cycle trends and the indicators that might allow reveal sudden changes. Furthermore, the data set provides the geographical coordinates of each river mouth and the Adriatic subregion to which it pertains. The data span from January 1, 1991, to December 31, 2022, with daily frequency and are expected to improve the representation of riverine freshwater inputs in hydrodynamic, biogeochemical, and oceanographic simulations dedicated to the Adriatic Sea. It will be interesting to continue this work for years to come and connect with the ocean circulation-induced changes, as shown by Verri et al. (2024).

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://erddap.cmcc-opa.eu/erddap/search/index.html?page=1&itemsPerPage=1000&searchFor=AdriaClim+Indicators+%7C+RD+and+MH.

Author contributions

LA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LM: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. NP: Conceptualization, Funding acquisition, Investigation,

Methodology, Project administration, Supervision, Writing – review & editing. GV: Formal analysis, Resources, Writing – review & editing, Methodology. AS: Formal analysis, Writing – review & editing, Methodology. SS: Project administration.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work is carried out under the AdriaCLIM project (ID 10252001) funded by the Italy-Croatia Interreg Cooperation Programme through the European Regional Development Fund.

Acknowledgments

The authors would like to thank ECMWF and Copernicus for making the EFAS data set available. We also thank the two reviewers of this paper for their comments, which helped us to improve the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Appiotti, F., Krželj, M., Russo, A., Ferretti, M., Bastianini, M., and Marincioni, F. (2014). A multidisciplinary study on the effects of climate change in the northern Adriatic Sea and the Marche region (Central Italy). *Reg. Environ. Chang.* 14, 2007–2024. doi: 10.1007/s10113-013-0451-5

Aragão, L., and Porcù, F. (2022). Cyclonic activity in the Mediterranean region from a high-resolution perspective using ECMWF ERA5 dataset. *Clim. Dyn.* 58, 1293–1310. doi: 10.1007/s00382-021-05963-x

Artegiani, A., Paschini, E., Russo, A., Bregant, D., Raicich, F., and Pinardi, N. (1997). The Adriatic Sea general circulation. Part I: Air–Sea interactions and water mass structure. *J. Phys. Oceanogr.* 27, 1492–1514. doi: 10.1175/1520-0485(1997)027<1492:TASGCP>2.0.CO;2

Bartholmes, J., Thielen, J., Ramos, M., and Gentilini, S. (2009). The European flood alert system EFAS – part 2: statistical skill assessment of probabilistic and deterministic operational forecasts. *Hydrol. Earth Syst. Sci.* 13, 141–153. doi: 10.5194/hess-13-141-2009

Bonaldo, D., Bellafiore, D., Ferrarin, C., Ferretti, R., Ricchi, A., Sangelantoni, L., et al. (2022). The summer 2022 drought: a taste of future climate for the Po valley (Italy)? *Reg. Environ. Chang.* 23, 1–6. doi: 10.1007/s10113-022-02004-z

Carniel, S., Benetazzo, A., Bonaldo, D., Falcieri, F., Miglietta, M., Ricchi, A., et al. (2016). Scratching beneath the surface while coupling atmosphere, ocean and waves: analysis of a dense water formation event. *Ocean Model.* 101, 101–112. doi: 10.1016/j.ocemod.2016.03.007

Cessi, P., Pinardi, N., and Lyubartsev, V. (2014). Energetics of semienclosed basins with two-layer flows at the strait. *J. Phys. Oceanogr.* 44, 967–979. doi: 10.1175/JPO-D-13-0129.1

Coppola, E., Verdecchia, M., Giorgi, F., Colaiuda, V., Tomassetti, B., and Lombardi, A. (2014). Changing hydrological conditions in the Po basin under global warming. *Sci. Total Environ.* 493, 1183–1196. doi: 10.1016/j.scitotenv.2014.03.003

Cozzi, S., Falconi, C., Comici, C., Čermelj, B., Kovac, N., Turk, V., et al. (2012). Recent evolution of river discharges in the Gulf of Trieste and their potential response to climate changes and anthropogenic pressure. *Estuar. Coast. Shelf Sci.* 115, 14–24. doi: 10.1016/j.ecss.2012.03.005

Cozzi, S., and Giani, M. (2011). River water and nutrient discharges in the northern Adriatic Sea: current importance and long term changes. *Cont. Shelf Res.* 31, 1881–1893. doi: 10.1016/j.csr.2011.08.010

Crovella, T., Paiano, A., and Lagioia, G. (2022). A meso-level water use assessment in the Mediterranean agriculture. Multiple applications of water footprint for some traditional crops. *J. Clean. Prod.* 330:129886. doi: 10.1016/j.jclepro.2021.129886

Denamiel, C., Tojčić, I., and Vilibić, I. (2020). Far future climate (2060–2100) of the northern Adriatic air–sea heat transfers associated with extreme bora events. *Clim. Dyn.* 55, 3043–3066. doi: 10.1007/s00382-020-05435-8

Denamiel, C., Tojčić, I., and Vilibić, I. (2021). Balancing accuracy and efficiency of atmospheric models in the northern Adriatic during severe bora events. *J. Geophys. Res. Atmos.* 126, 1–25. doi: 10.1029/2020JD033516

DeRoo, A., Wesseling, C., and Van Deursen, W. (2000). Physically based river basin modelling within a GIS: the LISFLOOD model. *Hydrol. Process.* 14, 1981–1992. doi: 10.1002/1099-1085(20000815/30)14:11/12<1981::AID-HYP49>3.0.CO;2-F

Djakovac, T., Supić, N., BernardiAubry, F., Degobbis, D., and Giani, M. (2015). Mechanisms of hypoxia frequency changes in the northern Adriatic Sea during the period 1972–2012. *J. Mar. Syst.* 141, 179–189. doi: 10.1016/j.jmarsys.2014.08.001

Dunić, N., Supić, N., Sevault, F., and Vilibić, I. (2023). The northern Adriatic circulation regimes in the future winter climate. *Clim. Dyn.* 60, 3471–3484. doi: 10.1007/s00382-022-06516-6

Ferrarin, C., Davolio, S., Bellafiore, D., Ghezzo, M., Maicu, F., Mc Kiver, W., et al. (2019). Cross-scale operational oceanography in the Adriatic Sea. *J. Oper. Oceanogr.* 12, 86–103. doi: 10.1080/1755876X.2019.1576275

Ferrarin, C., Orlić, M., Bajo, M., Davolio, S., Umgiesser, G., and Lionello, P. (2023). The contribution of a mesoscale cyclone and associated meteotsunami to the exceptional flood in Venice on November 12, 2019. *Q. J. R. Meteorol. Soc.* 149, 2929–2942. doi: 10.1002/qj.4539

Giani, M., Djakovac, T., Degobbis, D., Cozzi, S., Solidoro, C., and Umani, S. F. (2012). Recent changes in the marine ecosystems of the northern Adriatic Sea. *Estuar. Coast. Shelf Sci.* 115, 1–13. doi: 10.1016/j.ecss.2012.08.023

Gualdi, S., Somot, S., Li, L., Artale, V., Adani, M., Bellucci, A., et al. (2013). The CIRCE simulations: regional climate change projections with realistic representation of the Mediterranean Sea. *Bull. Am. Meteorol. Soc.* 94, 65–81. doi: 10.1175/BAMS-D-11-00136.1

Kalimeris, A., Ranieri, E., Founda, D., and Norrant, C. (2017). Variability modes of precipitation along a Central Mediterranean area and their relations with ENSO, NAO, and other climatic patterns. *Atmos. Res.* 198, 56–80. doi: 10.1016/j.atmosres.2017.07.031

Knez, S., Štrbac, S., and Podbregar, I. (2022). Climate change in the Western Balkans and EU green Deal: status, mitigation and challenges. *Energy Sustain. Soc.* 12, 1–14. doi: 10.1186/s13705-021-00328-y

Knoben, M. W. J., Freer, E. J., and Woods, A. R. (2019). Technical note: inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores. *Hydrol. Earth Syst. Sci.* 23, 4323–4331. doi: 10.5194/hess-23-4323-2019

Krichak, S. O., Breitgand, J. S., Gualdi, S., and Feldstein, S. B. (2014). Teleconnection–extreme precipitation relationships over the Mediterranean region. *Theor. Appl. Climatol.* 117, 679–692. doi: 10.1007/s00704-013-1036-4

Lazzari, P., Solidoro, C., Ibello, V., Salon, S., Teruzzi, A., Béranger, K., et al. (2012). Seasonal and inter-annual variability of plankton chlorophyll and primary production in the Mediterranean Sea: a modelling approach. *Biogeosciences* 9, 217–233. doi: 10.5194/bg-9-217-2012

Ludwig, W., Dumont, E., Meybeck, M., and Heussner, S. (2009). River discharges of water and nutrients to the Mediterranean and Black Sea: major drivers for ecosystem changes during past and future decades? *Prog. Oceanogr.* 80, 199–217. doi: 10.1016/j.pocean.2009.02.001

Marcos-Garcia, P., Lopez-Nicolas, A., and Pulido-Velazquez, M. (2017). Combined use of relative drought indices to analyse climate change impact on meteorological and hydrological droughts in a Mediterranean basin. *J. Hydrol.* 554, 292–305. doi: 10.1016/j.jhydrol.2017.09.028

Mazzoni, F., Marsili, V., Alvisi, S., and Franchini, M. (2022). Exploring the impacts of tourism and weather on water consumption at different spatiotemporal scales: evidence from a coastal area on the Adriatic Sea (northern Italy). *Environ. Res. Infrastruct. Sustain.* 2:025005. doi: 10.1088/2634-4505/ac611f

McKee, T., Doesken, N., and Kleist, J. (2013). The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology, 17 179–183, Anaheim

Mendicino, G., Senatore, A., and Versace, P. (2008). A groundwater resource index (GRI) for drought monitoring and forecasting in a Mediterranean climate. *J. Hydrol.* 357, 282–302. doi: 10.1016/j.jhydrol.2008.05.005

Montanari, A. (2012). Hydrology of the Po River: looking for changing patterns in river discharge. *Hydrol. Earth Syst. Sci.* 16, 3739–3747. doi: 10.5194/hess-16-3739-2012

Mussap, G., Zavatarelli, M., Pinardi, N., and Celio, M. (2016). A management oriented 1-D ecosystem model: implementation in the Gulf of Trieste (Adriatic Sea). *Reg. Stud. Mar. Sci.* 6, 109–123. doi: 10.1016/j.rsma.2016.03.015

Orlić, M., Dadić, V., Grbec, B., Leder, N., Marki, A., Matić, F., et al. (2006). Wintertime buoyancy forcing, changing seawater properties, and two different circulation systems produced in the Adriatic. *J. Geophys. Res. Oceans* 111, 1–21. doi: 10.1029/2005JC003271

Peixoto, J., DeAlmeida, M., Rosen, R., and Salstein, D. (1982). Atmospheric moisture transport and the water balance of the Mediterranean Sea. *Water Resour. Res.* 18, 83–90. doi: 10.1029/WR018i001p00083

Philandras, C. M., Nastos, P. T., Kapsomenakis, J., Douvis, K. C., Tselioudis, G., and Zerefos, C. S. (2011). Long term precipitation trends and variability within the Mediterranean region. *Nat. Hazards Earth Syst. Sci.* 11, 3235–3250. doi: 10.5194/nhess-11-3235-2011

Pinardi, N., Estournel, C., Cessi, P., Escudier, R., and Lyubartsev, V. (2023). "Dense and deep water formation processes and Mediterranean overturning circulation" in *Oceanography of the Mediterranean Sea* (Amsterdam, Netherlands: Elsevier), 209–261.

Pintori, F., and Serpelloni, E. (2023). Drought-induced vertical displacements and water loss in the Po river basin (northern Italy) from GNSS measurements. *ESS Open Archive* 1-23. doi: 10.22541/essoar.168606938.84604867/v1 [Pre-print].

Polimene, L., Pinardi, N., Zavatarelli, M., and Colella, S. (2006). The Adriatic Sea ecosystem seasonal cycle: validation of a three-dimensional numerical model. *J. Geophys. Res. Oceans* 112:C03S19. doi: 10.1029/2005JC003260

Pronti, A., and Berbel, J. (2023). The impact of volumetric water tariffs in irrigated agriculture in northern Italy. *Environ. Impact Assess. Rev.* 98:106922. doi: 10.1016/j.eiar.2022.106922

Provini, A., Crosa, G., Marchetti, R., Vollenweider, R., Marchetti, R., and Viviani, R. (1992). Nutrient export from the Po and Adige river basins over the last 20 years. *Sci. Total. Environ.* 1, 291–313. doi: 10.1016/B978-0-444-89990-3.50027-4

Quadrelli, R., Pavan, V., and Molteni, F. (2001). Wintertime variability of Mediterranean precipitation and its links with large-scale circulation anomalies. *Clim. Dyn.* 17, 457–466. doi: 10.1007/s003820000121

Querin, S., Cossarini, G., and Solidoro, C. (2013). Simulating the formation and fate of dense water in a midlatitude marginal sea during normal and warm winter conditions. *J. Geophys. Res. Oceans* 118, 885–900. doi: 10.1002/jgrc.20092

Raicich, F. (1996). On the fresh balance of the Adriatic Sea. *J. Mar. Syst.* 9, 305–319. doi: 10.1016/S0924-7963(96)00042-5

Ricci, F., Capellacci, S., Campanelli, A., Grilli, F., Marini, M., and Penna, A. (2022). Long-term dynamics of annual and seasonal physical and biogeochemical properties: role of minor river discharges in the north-western Adriatic coast. *Estuar. Coast. Shelf Sci.* 272:107902. doi: 10.1016/j.ecss.2022.107902

Robinson, A. R., Malanotte-Rizzoli, P., Hecht, A., Michelato, A., Roether, W., Theocharis, A., et al. (1992). General circulation of the eastern Mediterranean. *Earth Sci. Rev.* 32, 285–309. doi: 10.1016/0012-8252(92)90002-B

Rodellas, V., Garcia-Orellana, J., Masque, P., Feldman, M., and Weinstein, Y. (2015). Submarine groundwater discharge as a major source of nutrients to the Mediterranean Sea. *Proc. Natl. Acad. Sci.* 112, 3926–3930. doi: 10.1073/pnas.1419049112

Romano, E., Petrangeli, A. B., Salerno, F., and Guyennon, N. (2022). Do recent meteorological drought events in Central Italy result from long-term trend or increasing variability? *Int. J. Climatol.* 42, 4111–4128. doi: 10.1002/joc.7487

Sánchez, P.L., and Aragão, L. (2021). North Atlantic oscillation-related impacts on precipitation over the Italian peninsula during the 1979-2020 period. EGU General Assembly 2021, 9183. Vienna, Austria.

Sanchez-Gomez, E., Somot, S., Josey, S., Dubois, C., Elguindi, N., and Déqué, M. (2011). Evaluation of Mediterranean Sea water and heat budgets simulated by an ensemble of high resolution regional climate models. *Clim. Dyn.* 37, 2067–2086. doi: 10.1007/s00382-011-1012-6

Shukla, S., and Wood, A. (2008). Use of a standardised runoff index for characterising hydrologic drought. *Geophys. Res. Lett.* 35, 1–17. doi: 10.1029/2007GL032487

Struglia, M. V., Mariotti, A., and Filograsso, A. (2004). River discharge into the Mediterranean Sea: climatology and aspects of the observed variability. *J. Clim.* 17, 4740–4751. doi: 10.1175/JCLI-3225.1

Svoboda, M., Hayes, M., and Wood, D. (2012). *Standardised precipitation index user guide*. World Meteorological Organization, *1090*, 1–16. Geneva

Tanhua, T., Hainbucher, D., Schroeder, K., Cardin, V., Alvarez, M., and Civitarese, G. (2013). The Mediterranean Sea system: a review and an introduction to the special issue. *Ocean Sci.* 9, 789–803. doi: 10.5194/os-9-789-2013

Terrado, M., Acuna, V., Ennaanay, D., Tallis, H., and Sabater, S. (2014). Impact of climate extremes on hydrological ecosystem services in a heavily humanised Mediterranean basin. *Ecol. Indic.* 37, 199–209. doi: 10.1016/j.ecolind.2013.01.016

Thielen, J., Bartholmes, J., Ramos, M., and de Roo, A. (2009). The European flood alert system – part 1: concept and development. *Hydrol. Earth Syst. Sci.* 13, 125–140. doi: 10.5194/hess-13-125-2009

Van Der Knijff, J., Younis, J., and De Roo, A. (2010). LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. *Int. J. Geogr. Inf. Sci.* 24, 189–212. doi: 10.1080/13658810802549154

Verri, G., Furnari, L., Gunduz, M., Senatore, A., Santos da Costa, V., De Lorenzis, A., et al, (2024). Climate projections of the Adriatic Sea: the role of river release. *Front. Clim.*. Under review.

Verri, G., Pinardi, N., Gochis, D., Tribbia, J., Navarra, A., Coppini, G., et al. (2017). A meteo-hydrological modelling system for the reconstruction of river runoff: the case of the Ofanto river catchment. *Nat. Hazards Earth Syst. Sci.* 17, 1741–1761. doi: 10.5194/nhess-17-1741-2017

Verri, G., Pinardi, N., Oddo, P., Ciliberti, S., and Coppini, G. (2018). River runoff influences on the Central Mediterranean overturning. *Clim. Dyn.* 50, 1675–1703. doi: 10.1007/s00382-017-3715-9

Vested, H., Berg, P., and Uhrenholdt, T. (1998). Dense water formation in the northern Adriatic. *J. Mar. Syst.* 18, 135–160. doi: 10.1016/S0924-7963(98)00009-8

Vezzoli, R., Mercogliano, P., Pecora, S., Zollo, A., and Cacciamani, C. (2015). Hydrological simulation of Po River (North Italy) discharge under climate change scenarios using the RCM COSMO-CLM. *Sci. Total Environ.* 521-522, 346–358. doi: 10.1016/j.scitotenv.2015.03.096

Vilibić, I., Mihanović, H., Janeković, I., and Šepić, J. (2016). Modelling the formation of dense water in the northern Adriatic: sensitivity studies. *Ocean Model.* 101, 17–29. doi: 10.1016/j.ocemod.2016.03.001

Vilibić, I., and Supić, N. (2005). Dense water generation on a shelf: the case of the Adriatic Sea. *Ocean Dyn.* 55, 403–415. doi: 10.1007/s10236-005-0030-5

Vilibić, I., Zemunik, P., Šepić, J., Dunić, N., Marzouk, O., Mihanović, H., et al. (2019). Present-climate trends and variability in thermohaline properties of the northern Adriatic shelf. *Ocean Sci.* 15, 1351–1362. doi: 10.5194/os-15-1351-2019

Vodopivec, M., Zaimi, K., and Peliz, Á. (2022). The freshwater balance of the Adriatic Sea: a sensitivity study. *J. Geophys. Res. Oceans* 127:e2022JC018870. doi: 10.1029/2022JC018870

Wetterhall, F., and Di Giuseppe, F. (2018). The benefit of seamless forecasts for hydrological predictions over Europe. *Hydrol. Earth Syst. Sci.* 22, 3409–3420. doi: 10.5194/hess-22-3409-2018

Zavatarelli, M., Raicich, F., Bregant, D., Russo, A., and Artegiani, A. (1998). Climatological biogeochemical characteristics of the Adriatic Sea. *J. Mar. Syst.* 18, 227–263. doi: 10.1016/S0924-7963(98)00014-1