frontiers | Frontiers in Climate

TYPE Original Research
PUBLISHED 23 April 2024
DOI 10.3389/fclim.2024.1368456

The freshwater discharge into the Adriatic Sea revisited

Leonardo Aragão[1,2]*, Lorenzo Mentaschi[1], Nadia Pinardi[1,2], Giorgia Verri[3], Alfonso Senatore[4] and Silvana Di Sabatino[1]

[1]Department of Physics and Astronomy "Augusto Righi", University of Bologna, Bologna, Italy, [2]Earth System modeling and Data Assimilation (ESYDA) Division, Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy, [3]Global Coastal Ocean (GOCO) Division, Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Lecce, Italy, [4]Department of Environmental Engineering, University of Calabria, Arcavacata, Italy

Check for updates

OPEN ACCESS

EDITED BY
Francesco Marcello Falcieri,
National Research Council (CNR), Italy

REVIEWED BY
Giovanna Pisacane,
Energy and Sustainable Economic Development (ENEA), Italy
Robert V. Rohli,
Louisiana State University, United States

*CORRESPONDENCE
Leonardo Aragão
leonardo.aragao@unibo.it

RECEIVED 10 January 2024
ACCEPTED 18 March 2024
PUBLISHED 23 April 2024

CITATION
Aragão L, Mentaschi L, Pinardi N, Verri G, Senatore A and Di Sabatino S (2024) The freshwater discharge into the Adriatic Sea revisited.
Front. Clim. 6:1368456.
doi: 10.3389/fclim.2024.1368456

The present study reconstructs the river discharge climatology and its respective historical series for all rivers of the Adriatic Sea with averaged climatological daily river discharge above 1 m^3s^{-1}, to reach a better representation of the Adriatic rivers in hydrodynamic models and, consequently, to develop a more realistic freshwater balance in the different regions of the hydrographic basin. Based on the European Flood Awareness System (EFAS) data set, a careful method of identification and selection of the Adriatic rivers, followed by a rigorous assessment against observational data, was developed to evaluate the current state of the Adriatic river discharges and their respective trends throughout several climate indicators from 1991 to 2022. Observational data are limited to 85% of the identified rivers, totaling 98% of the overall freshwater input into the Adriatic Sea. The results confirm that the Shallow Northern Adriatic receives the largest freshwater inputs with a daily average exceeding 2,400 m^3s^{-1}, which amounts to 61% of the overall Adriatic discharges. Consequently, this region guides the freshwater seasonal cycle of the Adriatic Sea, which presents a well-defined pattern of two flood peaks in late autumn and late spring, separated by a minimum discharge period at mid-summer. From the Central to the Southern Adriatic subregions, the absence of snow-melting effects prevents the secondary flood peak during the spring, shaping the seasonal cycle of river discharges from a single flood peak in late autumn to a drought period in August. The 32 years of continuous river discharge data reveal a negligible trend in the overall Adriatic Sea but a negative trend for the last decade (2013–2022). This decadal decrease is driven by the extreme drought that drastically pounded the northern Adriatic in 2022.

KEYWORDS

river discharge, Adriatic Sea, EFAS, climatology, climate indicators, seasonal cycle

1 Introduction

The Mediterranean Sea is a semi-enclosed hydrological basin connected to the Atlantic Ocean through the relatively shallow Strait of Gibraltar and to the Black Sea through the Bosphorus and Dardanelles straits (Tanhua et al., 2013), making it a predominantly evaporative region whose surface water balance strongly depends on the precipitation regime and river discharges (Peixoto et al., 1982). Although the Mediterranean Sea's watershed comprises other smaller seas, bays, deltas, and countless rivers, 62% of freshwater inputs originate in the Adriatic Sea, the Gulf of Lion, and the Aegean Sea. At the river level, according to Struglia et al. (2004), the primary contributions to Mediterranean discharge are from the Rhone, Po, and

Nile Rivers (about 1700, 1,500, and 1,200 m^3s^{-1}, respectively). The Po River is the largest in the Adriatic basin and alone is responsible for 2/3 of the daily river discharges, which in extreme cases can exceed 10,000 m^3s^{-1} as observed in 1951 in Pontelagoscuro, a hydrological station about 70 km from the Adriatic coast (Provini et al., 1992; Montanari, 2012).

Located in the central Mediterranean Sea, the Adriatic is also a semi-enclosed sea that experiences complex water circulation patterns, exchanging waters at the Strait of Otranto by horizontally separated two-layer flows (Cessi et al., 2014). The exchange is characterised by high salinity waters inflowing at the Otranto Strait eastern side and a surface fresher water outflow at the western Strait side (Verri et al., 2018; Vodopivec et al., 2022). These circulation patterns are both wind and thermohaline-driven, placing the unique hydrodynamics of the Adriatic Sea as the mainframe in shaping its diverse marine ecosystem, which makes it one of the three primary regions in dense water formation within the Mediterranean Sea and the one with the densest water (Artegiani et al., 1997; Vested et al., 1998; Vilibić and Supić, 2005; Querin et al., 2013). During the winter, the air-sea interactions produce different types of dense waters, some reaching even the deep waters of the Eastern Mediterranean Sea (Pinardi et al., 2023).

The positive water budget frames the Adriatic Sea as an estuarine basin, meaning precipitation and river runoffs exceed evaporation. However, in exceptional situations of large freshwater discharges from Po River, the dense water formation processes change the dynamics of the Adriatic Sea conveyor belt, decreasing the induced vertical circulation in amplitude (Verri et al., 2018). Therefore, the first step toward understanding the impacts of climate change on the Adriatic basin involves a reasonable estimate of river discharges and how much the freshwater supply has already changed in the last climatological period.

Since the 1970s, the hydrological balance of the Adriatic Sea has been the subject of several modelling studies regarding the thermohaline circulation (Sanchez-Gomez et al., 2011; Verri et al., 2018; Vodopivec et al., 2022), the formation of dense waters (Vested et al., 1998; Querin et al., 2013; Carniel et al., 2016; Vilibić et al., 2016), the basin biogeochemistry (Polimene et al., 2006; Lazzari et al., 2012; Mussap et al., 2016), the sea level extremes (Terrado et al., 2014; Ferrarin et al., 2019, 2023), and climate change trends (Gualdi et al., 2013; Coppola et al., 2014; Vezzoli et al., 2015; Vilibić et al., 2019; Denamiel et al., 2020; Dunić et al., 2023). Most of these studies use river discharges as climatological estimates based on time series data from Raicich (1996) and Ludwig et al. (2009) without considering exceptional periods of flooding and drought. Given its importance not only for hydrology but also for local society and economy, the Po River Basin's vulnerability to climate change has been the target of several studies that explored the IPCC's variety of future scenarios. According to Coppola et al. (2014), by the end of 2050, the seasonal cycle of river discharge in the Northern Adriatic Sea is expected to present the spring flood peak 1 month in advance due to earlier snow-melting in the Alpine and Apennine chains. Furthermore, the autumn discharge peak is expected to occur later, during the winter months, due to increasingly extended hydrological summer drought periods. In 2100, the Po River is projected to experience a severe reduction in discharge from May to November, whilst the rest of the year will see an increase of up to 60% due to changes in precipitation patterns and increasing heavy precipitation events. On the other hand, during summer, extreme drought levels will become more common and result in a significant water deficit (Vezzoli et al., 2015). Recent projections confirm these seasonal cycle trends to the end of the century and extend them to the other north Adriatic rivers, mainly those in the shallow north Adriatic Sea, which is currently experiencing substantial warming as indicated by observed temperature trends and is more sensitive to radiational increase expected in future climate (Vilibić et al., 2019; Dunić et al., 2023).

River discharge not only provides freshwater access to coastal ecosystems but also delivers an essential supply of nutrients that play a crucial role in regulating their hydrology, biogeochemistry, and productivity. The amount and timing of fresh water and nutrients provided by rivers can significantly influence the physical, chemical, and biological conditions of coastal ecosystems, affecting the growth and survival of species, the cycling of nutrients, and the ecosystem's overall health (Ludwig et al., 2009; Cozzi et al., 2012). The northern Adriatic region experiences significant nutrient loads from various rivers, not only the Po, where this nutrient-rich environment leads to the development of a thriving phytoplankton community during the autumn and winter seasons (Zavatarelli et al., 1998). The high levels of nutrients in the water provide an ideal environment for these microscopic organisms to grow and thrive, which plays a crucial role in the overall health and productivity of the region's aquatic ecosystem. Another relevant aspect of the river discharge in the Adriatic Sea regards its dilution basin characteristics, where rivers contribute to an average freshwater input gain of about 1 m $year^{-1}$ (Artegiani et al., 1997). This balance is achieved since evaporation and precipitation almost offset each other, allowing the basin to maintain equilibrium (Raicich, 1996; Zavatarelli et al., 1998; Verri et al., 2018).

Inaccurate estimates of river discharges in a hydrological system as complex as the Adriatic Sea can lead to entirely different perceptions in all aspects discussed above. As demonstrated by Verri et al. (2018), a complete cessation of riverine freshwater loads has the potential to abruptly strengthen the Adriatic-Ionian anti-estuarine Thermohaline Cell (AITHC, Orlić et al., 2006). Otherwise, if the river discharge doubles, it may produce a positive buoyancy flow, sinking the net energy and, consequently, weakening the anti-estuarine circulation. According to Vilibić et al. (2016), the low quality of runoff climatologies limits the capability to represent the Adriatic Sea dynamics, where an overestimation of the riverine freshwater input may unreasonably reduce or prevent the local dense water formation.

Considering the lack of recent estimates of the Adriatic Sea river discharges, the main objective of the present study is to reconstruct the river discharge climatology and its respective historical series, not only for the principal rivers of the Adriatic Sea basin but for all rivers with average climatological discharges above 1 m^3s^{-1}. The analysis will be based on the European Flood Awareness System (EFAS) reconstructions from 1991 to 2022 and a careful method of identifying and selecting the Adriatic rivers, followed by a rigorous assessment against observational hydrological station data. Thus, it is expected that the new climatology of river discharge into the Adriatic Sea can contribute to a better representation of rivers in general circulation models and their biogeochemical counterparts and, consequently, construct a more realistic freshwater balance in the different regions of the hydrographic basin.

2 Data and methods

This section presents the study region and proposes its division into four subregions based on the geomorphology of the Adriatic basin. Then, the hydrological model used to estimate river discharges in the Adriatic Sea (EFAS) is described in detail, as well as the method of river identification and data extraction and assessment for each river considered. Finally, the climate indicators are defined to construct the climatology of river discharges at different spatial and temporal scales.

2.1 Adriatic Sea subregions

According to Artegiani et al. (1997), the Adriatic Sea can be divided into three subregions based on bathymetry measurements. The first, Southern Adriatic (SAd), starts in the Strait of Otranto (Figure 1), where the Adriatic Sea exchanges waters with the Mediterranean Sea through the Otranto Channel, extending ~350 km north up to Vieste, in the Gargano Peninsula. The SAd is the deepest subregion of the Adriatic, where the largest portion presents depths greater than 800 m, and the deepest point reaches 1,200 m.

The second subregion, Central Adriatic (CAd), comprises the northern coast of the Gargano Peninsula and the Pomo Depressions, presenting an extension of approximately 210 km. In this transition region between deep and shallow Adriatic areas, the depths are heterogeneous but limited to 100 down to 200 m, except for the areas related to the Pomo Depressions that reach 260 m.

The last subregion extends 300 km north until the Gulf of Venice, distributed over a very shallow and gently sloping area, with an average bottom depth of around 35 m but no deeper than 100 m. This region is well-known for the high density of its waters, the densest in the entire Mediterranean Sea (Robinson et al., 1992), resulting from a constant transport of sediments from the Delta of Po and the Lagoons of Venice (Zavatarelli et al., 1998; Struglia et al., 2004). For this reason, this subregion will be split into two subregions following Vilibić and Supić (2005) and Denamiel et al. (2021): (i) the Northern Adriatic (NAd), comprising areas with depths between 50 and 100 m and extending for 170 km north from the Central Adriatic subregion; and (ii) the Shallow Northern Adriatic (SNAd) referring to areas with

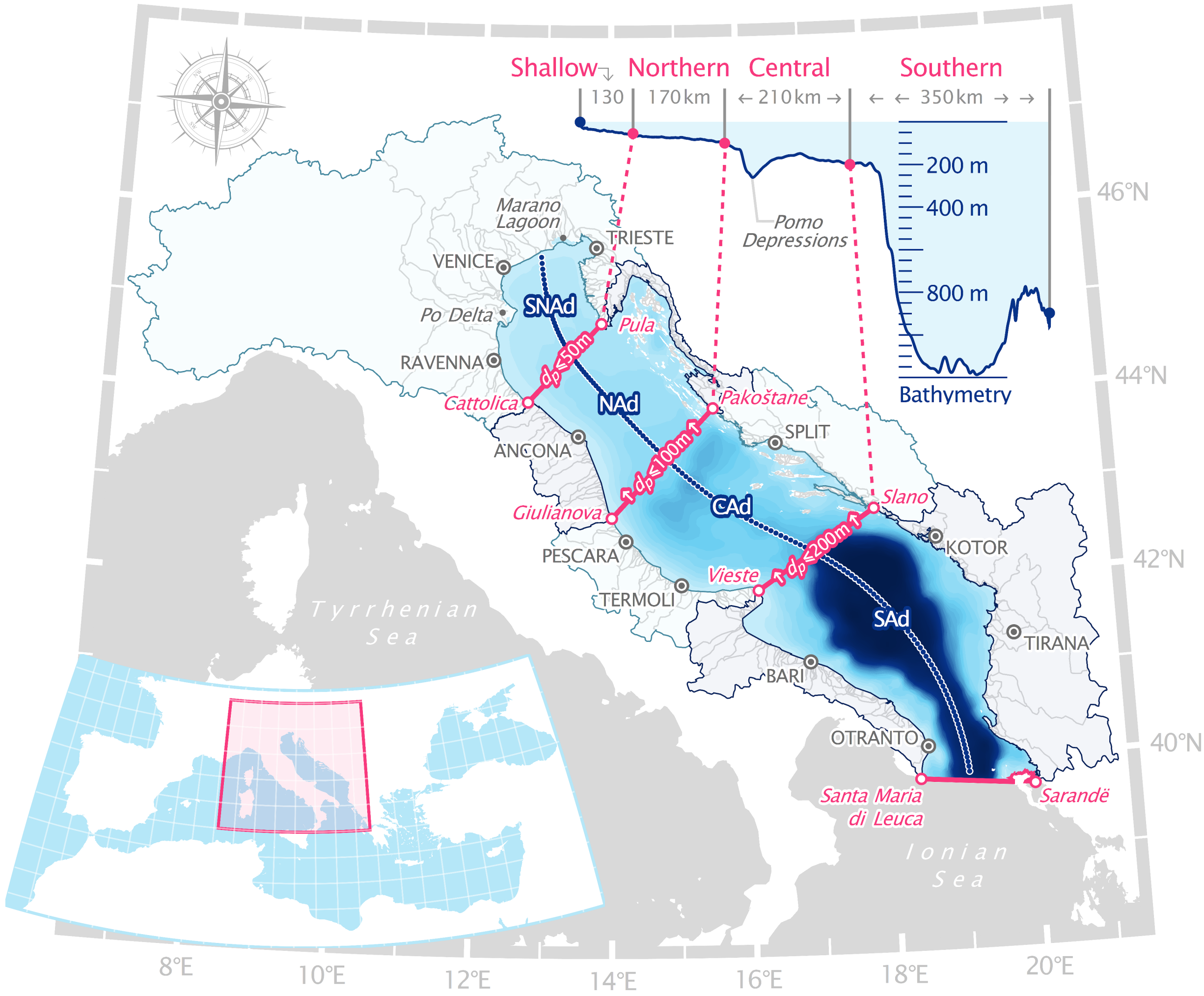

FIGURE 1
Adriatic Sea subregions defined by bathymetry: Shallow Northern Adriatic Sea (SNAd), Northern Adriatic Sea (NAd), Central Adriatic Sea (CAd), and Southern Adriatic Sea (SAd). The shaded areas represent the hydrological catchments of each subregion, whilst the embedded graphics show the bathymetry along the blue circles' path (top) and the domain position within the Mediterranean Region (bottom).

depths under 50 m, which extends for another 130 km north up to the Venetian coastline. A summary of the four Adriatic Sea subregions and their respective hydrological catchments is presented in Figure 1, whilst Table 1 shows the coordinates regarding the Adriatic Sea subregion divisions.

TABLE 1 Adriatic Sea subregions coordinates in Figure 1.

	Western Adriatic Coast			Eastern Adriatic Coast		
	Lat (°N)	Lon (°E)	near to	Lat (°N)	Lon (°E)	near to
SNAd	43.97	12.74	Cattolica (IT)	44.82	13.85	Pula (HR)
NAd	42.71	14.00	Giulianova (IT)	43.90	15.52	Pakoštane (HR)
CAd	41.91	16.15	Vieste (IT)	42.76	17.88	Slano (HR)
SAd	39.80	18.38	SM di Leuca (IT)	39.69	19.98	Sarandë (AL)

2.2 Discharge data set

In this study, the analysis of the river discharge into the Adriatic Sea was based on EFAS, the European Flood Awareness System (Bartholmes et al., 2009; Thielen et al., 2009), an operational early-warning system part of the COPERNICUS Emergency Management Service (CEMS) that provides gridded modelled sub-daily and daily hydrological time series forced with meteorological reanalysis, analysis and forecasts. Available from January 1991 to the present (6 days delayed), the primary data set describes the hydrological processes in terms of river discharge, moisture for three soil layers, and snow water equivalent into a domain that covers most of the European continent on a 5 × 5 km equal-area grid. Additionally, an auxiliary data set completes this list with other static variables such as the upstream area, elevation, soil depth, wilting capacity and field capacity.

EFAS is driven by LISFLOOD (DeRoo et al., 2000; Van Der Knijff et al., 2010), a GIS-based hydrological rainfall-runoff-routing model which simulates the hydrological processes within a catchment using as initial conditions information on soils, land cover, topography, hydrology and meteorology. Its operational implementation in EFAS is continuously calibrated by recent observed meteorological fields such as precipitation, temperature, wind speed, solar radiation and vapour pressure, and land surface data, including land surface information and model parameters. The EFAS forecasts are forced by high-resolution ensemble forecasts from the European Centre of Medium-range Weather Forecasts (ECMWF) with 51 ensemble members, high-resolution forecasts from the Deutsches Wetter Dienst (DWD) and the ensemble forecasts from the COSMO Local Ensemble Prediction System (COSMO-LEPS) with 20 ensemble members. In this case, the delivered forecast reaches 5–15 days, depending on the forcing numerical weather prediction model, but its real-time data are only available to EFAS partners. For historical periods, the EFAS simulations are forced by hydro-meteorological observations taking advantage of the Meteorological Archival and Retrieval System (MARS), the main repository of hydro-meteorological data at ECMWF. According to Wetterhall and Di Giuseppe (2018), seamless forecasts such as EFAS show better overall skill and a lower bias over most areas in Europe.

For our purposes, the EFAS river discharge data were collected at the maximum temporal and horizontal resolution using the historical simulations (hereafter, reconstructions), version 4.0 (6-hourly and 5 × 5 km, respectively). It is worth mentioning that, after the development of the present study, the EFAS operational version 5.0 was released on 20/09/2023 with an increased horizontal resolution (~1.5 × 1.5 km). The data set was initially obtained for the entire domain from the Copernicus Climate Change Service (C3S) and then reduced to allow a faster semi-automatic river mouth detection along the Adriatic Sea coastline (described in the next section). The analysis covers the last 32-year period (1991–2022) and comprises all entire-year data available at C3S.

2.3 River mouth positions

Identifying river streamflows through river discharge data is only possible because EFAS was designed as a one-dimensional channel routing model where the water exchange between grid cells occurs only in one direction (Van Der Knijff et al., 2010). Consequently, the watercourse is always channelled from one grid cell to another, highlighting the main streamflow, allowing channel unifications, and preventing bifurcations downstream. Following the terrain elevation, these rivers always flow until they reach another lower water body (flooding area, another river, lake, sea, or ocean), and at this position, we define the river mouth.

In the present study, we developed a semi-automatic method to identify river mouths from the EFAS data set, which starts from a domain reduction to 38.0–47.5°N and 6.5–21.5°E (Figure 1). Then, using the flag-assigned grid cells, we delimited the Adriatic Sea and defined the coastline grid cells belt from Sarandë (Albania) to Santa Maria di Leuca (Italy), as presented in Table 1. To avoid subgrid and border issues, we created the coastline belt with six grid cells of thickness. For each grid cell surrounding this belt, we computed the climatological daily averaged river discharge from 1991 to 2022 and assigned every grid cell presenting quantities above 1 m^3s^{-1} as a river-mouth candidate.

A list containing the 67 main Adriatic Sea rivers gathering information from Ludwig et al. (2009) and Verri et al. (2018) was verified, and each actual river-mouth position was identified from satellite images. Then, these actual river-mouth positions were associated with four candidates along the Adriatic Sea coastline belt using the nearest neighbour method, where the candidate with the highest averaged river discharge was selected. The automatic identification was submitted to a subjective analysis when two or more different river mouths had mutual candidates. This procedure was to select the best grid cell for each river mouth and avoid the selection of bogus candidates.

Figure 2 shows an example where the method effectively defined the Adige River grid cell according to the average daily river discharges monitored at the CNR ISMAR stations (Verri et al., 2018). However, it failed for the Brenta River as its mouth is located only 3 km to the north of the Adige River mouth, a distance shorter than the EFAS resolution (5 km). In this case, the subjective analysis allowed the selection of another inland grid cell positioned along the river's course. The candidates not assigned to the 67 main rivers of the Adriatic Sea were analysed similarly and allowed us to add 19 other rivers to our list, whose names were assigned following OpenStreetMap information.[1]

1 www.openstreetmap.org

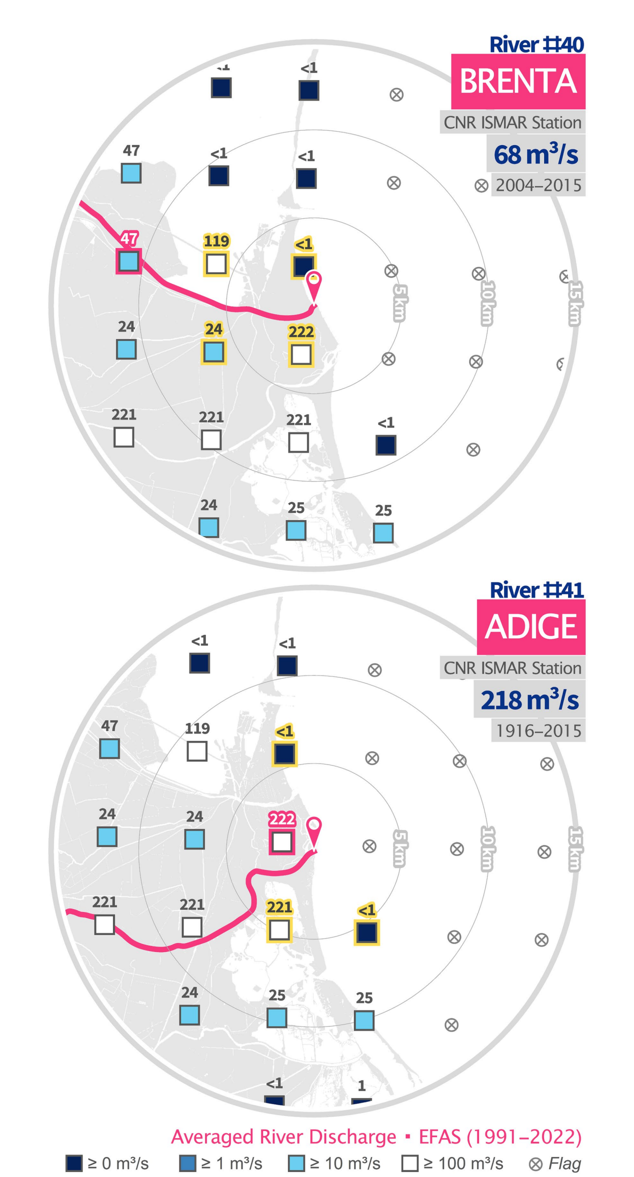

FIGURE 2
Examples of the EFAS grid cell selection method for Brenta (automatic + subjective) and Adige (automatic) Rivers. The magenta lines and the pins represent the rivers' actual course and mouths, respectively, whilst the coloured squares are the grid cells' centre. The cells highlighted in yellow are those four identified by the nearest neighbour method (automatic), whilst the one highlighted in magenta is the chosen grid cell to represent the river mouth.

Finally, all 86 rivers identified by the described method were submitted to another subjective analysis to confirm if the selected grid cell represents the river-mouth position and daily river discharge well. Excluding the nine branches of the Po River identified exclusively by the subjective analysis, the rivers that did not have their mouth position selected automatically were Zrnovnica (Croatia), Isonzo, Porto Buso, Canale dei Lovi, Porto di Chioggia, Brenta, Bevano, Uso, Misa, and Cervaro (Italy).

The spatial distribution of these river-mouths along the Adriatic Sea coastline is presented in Figure 3, highlighting the Po Delta and its nine branches between the Po di Levante and Po di Volano Rivers. Additionally, the embedded table shows the total of rivers by Adriatic Sea subregions and their respective catchment area. The SNAd sums up 50% of the considered rivers supported by more than 54% of the Adriatic Sea inland catchment area. It is also worth mentioning the small number of river mouths along the eastern coastline due to the complex topography within the Balkans that favours the water collection by the Danube River, which discharges on the Black Sea (Struglia et al., 2004). The SAd western coastline also presents a few rivers (Candelaro, Cervaro, Carapelle and Ofanto). According to Verri et al. (2017), this region has low hydraulic conductivity and high soil permeability, which tend to drain water into groundwater and restrict its surface transport through rivers and streams.

Given the channel routing concept that does not allow EFAS to represent river branches, discharges regarding the Po River were extracted from the nearest gridpoint to Pontelagoscuro Station (44.8883°N, 11.6081°E) and distributed along the nine tributaries of the Po River (from Maistra to Goro, Figure 3) as in Provini et al. (1992). Observation-based parameterisations prevent a river's entire freshwater volume from being discharged by only one branch and allow the use of EFAS appropriately for the spatial representation of river discharges along deltas.

2.4 Data consistency assessments

The EFAS river discharge data obtained at each river-mouth position in the Adriatic Sea were submitted to a detailed assessment process performed in two levels. The first compares directly the climatological daily river discharge available in the literature (Ludwig et al., 2009; Verri et al., 2018) to quantify the number of rivers monitored and identify the Adriatic regions with the highest uncertainties of the overall riverine discharges.

The second-level assessment evaluates daily river discharge through time-series analysis and statistical indices to verify the EFAS skill in representing seasonal cycles, statistical distributions, and extreme events thresholds. The statistical indexes include bias, root-mean-square error (RMSE), Pearson correlation (RR), Nash–Sutcliffe efficiency coefficient (NSE) and Kling-Gupta efficiency (KGE). At the same time, the distribution parameters consider the average (Avg), the first quartile (Q1, or lower quartile), the second quartile (Q2, or median), the third quartile (Q3, or upper quartile), and the 95th lower and upper percentiles (P05 and P95).

Unfortunately, the lack of open-source monitoring data limited the analysis for a small number of rivers evaluated for different periods. As discharge measurements at the river mouth are rare and sometimes distanced by more than 100 km, additional EFAS data were considered (exclusively for this analysis) using the nearest neighbour gridpoints to the hydrological station positions.

2.5 Climate indicators

To understand and quantify the Adriatic Sea climate freshwater balance, the river discharges were analysed through monthly climatology, monthly trends, and long-term climate indicators, where single river contributions were aggregated by the overall Adriatic Sea and its subregions. The current climatology presents the monthly means of the daily averaged river discharge from 1991 to 2022, whilst

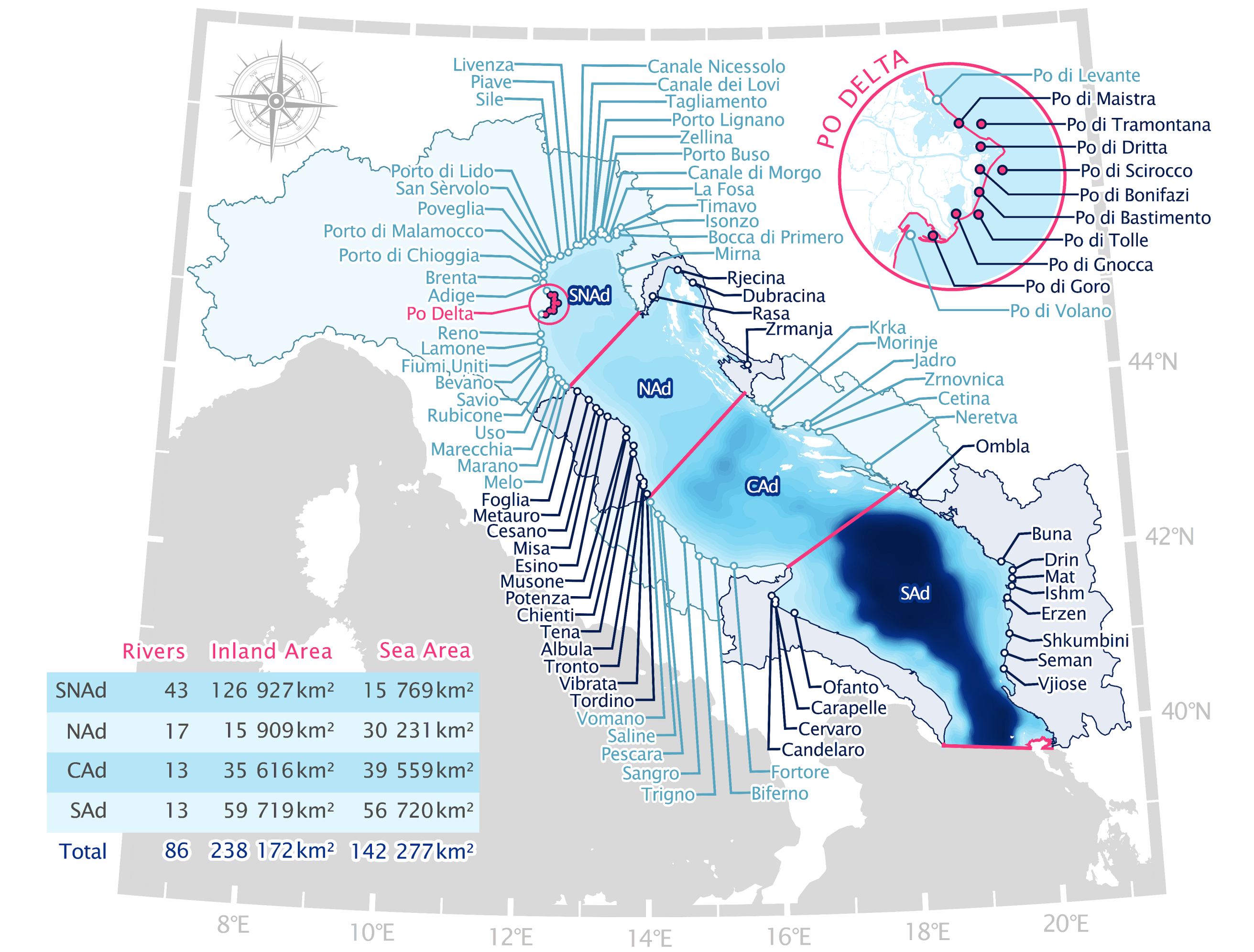

FIGURE 3
Distribution of the 86 river mouths (circles) considered in this study within the four Adriatic Sea subregions. The main river (Po) is represented by nine branches (magenta points) between the Po di Volano and Po di Levante Rivers.

the river discharge trends present the monthly averaged time series for the same period.

The long-term climate indicator is calculated as the Standardised Flow Index (SFI, Shukla and Wood, 2008), estimated using river discharge applied into a set of moving average periods (1, 3, 6, 12, 24 and 48 months) normalised by the standard deviation obtained from its gamma distribution. The SFI is computed as the Standardised Precipitation Index (SPI) described in McKee et al. (2013), replacing the monthly accumulated precipitation with the monthly averaged river discharge. The results can be framed into several drought categories ranging from extremely wet to extremely dry conditions, providing extreme event severity and return period (see Svoboda et al., 2012 for more details).

3 River discharge consistency

3.1 First-level assessment

Considering the set of 67 rivers extracted from Ludwig et al. (2009) and Verri et al. (2018), and reducing the nine Po Delta rivers to Po River at Pontelagoscuro due to the absence of long-term observational data, Figure 4 shows the comparison between the average daily river discharge (m^3s^{-1}) obtained in the literature (observations) and those proposed in the present study based on EFAS (also presented in Table 2). Although the observed data refer to different periods (many of them before 1991), these river discharge data are often used as initial and boundary conditions in several modelling studies (Lazzari et al., 2012; Gualdi et al., 2013; Terrado et al., 2014; Rodellas et al., 2015), underlining the importance of reviewing the freshwater supply to the Adriatic Sea.

Figure 4 includes 58 rivers plus the Po River at Pontelagoscuro (split into nine rivers), amounting to 67 of the 86 rivers analysed in this study (78%). However, their participation in freshwater discharges into the Adriatic Sea easily overcomes 96% (3,846 of 3,995 m^3s^{-1}, Table 2). The linear regression shows a slight EFAS underestimation concerning observations, whilst the statistical indices show a correlation of 0.91 and relatively small errors regarding the overall Adriatic river discharge. The EFAS estimates were consistent for rivers with observed discharges above 200 m^3s^{-1}, except for the Albanian rivers. The courses and discharges of the Buna and Drin Rivers were modified by constructing three dams around the Shkoder Lake for

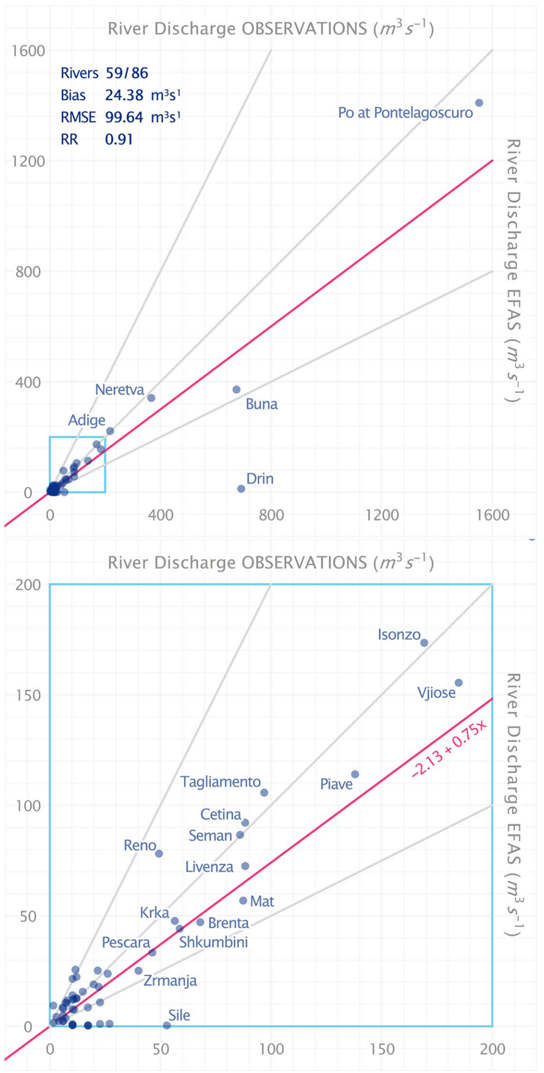

FIGURE 4
Comparison between averaged daily river discharge (m^3s^{-1}) from observations and EFAS reconstructions. The upper panel presents all evaluated discharges, whilst the lower panel presents only those smalle.

hydropower production (Vau Dejës in 1975, Fierzë in 1978, and Kaman in 1985), and a large part of Drin discharges was shifted to the Buna River (Vodopivec et al., 2022). Since 100% of the energy consumed in Albania comes from hydropower and a 20% reduction in runoff implies a 60% reduction in energy production, the water uses and the current discharges in these rivers diverge a lot in the literature (Knez et al., 2022).

For discharges under 200 m^3s^{-1} (Figure 4, lower panel), EFAS agrees with observations within a factor of two, which justifies the satisfactory statistical parameters. There are a few cases where EFAS underestimated the river discharge, all of them located in the Venice Lagoon and the Marano Lagoon: Bocca di Primero, La Fosa, Canale di Morgo, Porto Buso, Canale dei Lovi, Sile, Porto di Lido, Porto di Malamocco, Porto di Chioggia. In this case, the difference is explained by the station's position inland, far from its lagoon outlets. Moreover, the present study analyses only river mouths distributed along the Adriatic Sea coastline, not those with discharges toward lagoons. As a reference, excluding the above mentioned rivers, the linear regression adjusts to 1.57 + 0.91x, and bias, RMSE and RR improve to 5.56, 23.82 and 1.00, respectively. This result portrays how EFAS estimates are confident and similar to the observational river discharges in the Adriatic Sea. On the other hand, it is not yet possible to validate or make a fair comparison of river discharge estimates in regions of the Adriatic Sea deltas and lagoons due to the lack of monitoring data near the river mouths (Cozzi and Giani, 2011) and the lagoons outlets where actual freshwater releases occur.

Regarding the Albanian rivers, a recent publication updated the discharges of the Seman, Buna, and Drin Rivers, providing their monthly climatological runoff (Vodopivec et al., 2022). However, as the monitoring station measures the Shkoder Lake outflow, the individual discharges of Buna and Drin are unavailable, explaining the label Buna+Drin addressed to these data. Figure 5 compares these data with the EFAS estimates, exploring the statistical indices computed using the monthly averaged river discharges. A strong correlation was found between the observed and the reconstructed discharge's seasonal cycle for the Seman River (Figure 5A). The high NSE (0.78) indicates that the reconstructed data, not only represent the observed mean river discharge well, but also can adequately describe its seasonal variations. The updated mean discharge of Seman River is remarkably close to Verri et al. (2018), Table 2, and does not change the first-level assessment result, but expands its validity to the seasonal cycle. On the other hand, the sum of the average discharges of the Buna and the Drin Rivers in Table 2 (1,367 m^3s^{-1}) exceeds twice that updated by Vodopivec et al. (2022), 671 m^3s^{-1}, which doubles the EFAS reconstructions (384 m^3s^{-1}, where 372 m^3s^{-1} is discharged only by Buna). Despite this, the seasonal cycle estimated by EFAS proved quite satisfactory compared to the updated observed data (Figure 5B; RR = 0.92), even with the disparity in its average values, which explains the negative NSE. This only confirms that divergences concerning the Albanian river discharges persist, and its monitoring station is still not integrated and assimilated on EFAS.

Table 2 shows each river and subregion's contributions to freshwater discharges into the Adriatic Sea. In a certain way, the contribution of each subregion is relatively proportional to the catchment area, where the SNAd appears in the first place, with 61% of river discharge into the Adriatic Sea collected by 53% of its hydrological basin. The Po River (at Pontelagoscuro) alone is responsible for 58% of the SNAd discharges, with about 1,410 of 2,432 m^3s^{-1}. These EFAS estimates agree with other reference studies (Raicich, 1996; Struglia et al., 2004; Ludwig et al., 2009; Montanari, 2012) and the observational data measured at Pontelagoscuro station about 70 km from the river mouth, highlighting the importance of long and continuous time series for runoff modelling.

Other significant Alpine rivers in the SNAd with discharges above 100 m^3s^{-1} are Adige, Isonzo, Piave and Tagliamento. Despite the disparity regarding the Po River discharges, these four rivers have proper estimates by EFAS and tally about 16% of the Adriatic Sea discharge, exceeding those reported for NAd and CAd. Six of the nine branches of Po River complete the top 10 discharges within SNAd, showing the Po River's importance not only for the SNAd but the entire Adriatic Sea. As Vilibić and Supić (2005) argue, the reliable representation of these river discharges is fundamental in sediment modelling, especially under the recent and worrying decreases in river discharges, which increasingly

TABLE 2 Adriatic Sea rivers considered in the present study ranked by averaged daily river discharge from EFAS reconstructions and Adriatic Sea subregions. The rank-related percentages report the participation in the overall river discharge into the domain and each subregion of the Adriatic Sea. Po River discharges at Pontelagoscuro are presented only as a reference and have not been accounted for in the SNAd and Adriatic Sea totals. The reference literature are (a) Ludwig et al. (2009) and (b) Verri et al. (2018, Table 2).

SubReg Rank(%)	Domain Rank(%)	ID	River	Country	SubReg	EFAS Coordinates Lat (°N)	Lon (°E)	Area (km^2)	River Discharge (m^3s^{-1}) Literature	EFAS
-- --	-- --	87	Adriatic Sea	Domain	--	43.3146	16.0550	238 172	--	3 994.98
-- --	1 (61)	88	Shallow Northern Adriatic Sea	SubReg	SNAd	45.1570	12.9807	126 927	--	2 431.95
-- (58)	-- (35)	92	Po at Pontelagoscuro	Italy	SNAd	44.9019	11.5989	71 337	[a]1 552.50	1 409.46
1 (17)	1 (11)	45	Po di Dritta	Italy	SNAd	44.9747	12.4873	--	--	424.25
2 (9)	4 (6)	50	Po di Gnocca	Italy	SNAd	44.8411	12.4182	--	--	224.10
3 (9)	5 (6)	41	Adige	Italy	SNAd	45.1592	12.3049	14 128	[b]218.00	221.56
4 (9)	6 (5)	49	Po di Tolle	Italy	SNAd	44.8396	12.4813	--	--	215.65
5 (7)	7 (4)	22	Isonzo	Italy	SNAd	45.7580	13.4864	3 341	[a]169.25	173.50
6 (6)	9 (4)	44	Po di Tramontana	Italy	SNAd	45.0198	12.4893	--	--	150.81
7 (6)	10 (4)	51	Po di Goro	Italy	SNAd	44.7975	12.3532	944	--	140.95
8 (5)	11 (3)	33	Piave	Italy	SNAd	45.5104	12.7032	4 445	[a]137.99	114.04
9 (4)	12 (3)	29	Tagliamento	Italy	SNAd	45.6349	13.0939	2 608	[b]96.92	105.73
10 (4)	14 (2)	47	Po di Bonifazi	Italy	SNAd	44.9297	12.4853	--	--	87.39
11 (3)	16 (2)	53	Reno	Italy	SNAd	44.5736	12.2810	5 942	[b]49.33	78.15
12 (3)	17 (2)	32	Livenza	Italy	SNAd	45.5971	12.8356	2 502	[b]88.33	72.51
13 (3)	18 (2)	43	Po di Maistra	Italy	SNAd	45.0212	12.4260	--	--	63.43
14 (2)	19 (1)	48	Po di Bastimento	Italy	SNAd	44.8846	12.4833	--	--	59.20
15 (2)	22 (1)	40	Brenta	Italy	SNAd	45.2070	12.1798	4 268	[b]68.00	47.11
16 (2)	23 (1)	21	Timavo	Italy	SNAd	45.8008	13.5534	--	--	44.28
17 (2)	25 (1)	46	Po di Scirocco	Italy	SNAd	44.9282	12.5484	--	--	43.69
18 (1)	28 (<1)	42	Po di Levante	Italy	SNAd	45.0677	12.3646	2 345	[b]21.67	25.22
19 (<1)	31 (<1)	55	Fiumi Uniti	Italy	SNAd	44.3919	12.3363	1 261	[b]12.06	22.35
20 (<1)	32 (<1)	28	Porto Lignano	Italy	SNAd	45.7249	13.0990	--	[b]10.28	21.47
21 (<1)	37 (<1)	54	Lamone	Italy	SNAd	44.4834	12.2773	878	[b]12.06	12.82
22 (<1)	39 (<1)	57	Savio	Italy	SNAd	44.3018	12.3326	649	[b]12.06	12.51
23 (<1)	41 (<1)	60	Marecchia	Italy	SNAd	44.0706	12.5725	520	--	12.12
24 (<1)	43 (<1)	20	Mirna	Croatia	SNAd	45.3038	13.5851	583	[b]7.91	11.74
25 (<1)	45 (<1)	31	Canale Nicessolo	Italy	SNAd	45.5953	12.8995	718	[b]22.70	10.86
26 (<1)	55 (<1)	52	Po di Volano	Italy	SNAd	44.7989	12.2901	541	[b]6.00	8.01
27 (<1)	58 (<1)	27	Zellina	Italy	SNAd	45.7661	13.2299	--	[b]10.28	7.58
28 (<1)	62 (<1)	58	Rubicone	Italy	SNAd	44.1637	12.4518	217	[b]6.00	4.98
29 (<1)	67 (<1)	62	Melo	Italy	SNAd	43.9772	12.6927	53	--	3.61
30 (<1)	68 (<1)	59	Uso	Italy	SNAd	44.1186	12.4499	149	[b]6.00	2.39
31 (<1)	70 (<1)	56	Bevano	Italy	SNAd	44.3469	12.3345	320	[b]6.00	2.29
32 (<1)	72 (<1)	61	Marano	Italy	SNAd	44.0239	12.6326	66	--	1.54
33 (<1)	74 (<1)	30	Canale dei Lovi	Italy	SNAd	45.6386	12.9659	61	[b]22.70	1.06
34 (<1)	75 (<1)	23	Bocca di Primero	Italy	SNAd	45.7130	13.4835	--	[b]10.28	1.06
35 (<1)	77 (<1)	24	La Fosa	Italy	SNAd	45.6721	13.3526	--	[b]10.28	0.59
36 (<1)	78 (<1)	25	Canale di Morgo	Italy	SNAd	45.7191	13.2913	--	[b]10.28	0.54
37 (<1)	80 (<1)	26	Porto Buso	Italy	SNAd	45.7211	13.2272	--	[b]10.28	0.49
38 (<1)	81 (<1)	37	Poveglia	Italy	SNAd	45.3844	12.3143	--	--	0.44
39 (<1)	82 (<1)	36	San Sèrvolo	Italy	SNAd	45.4280	12.3800	--	--	0.43
40 (<1)	83 (<1)	39	Porto di Chioggia	Italy	SNAd	45.2493	12.3087	--	[b]17.27	0.42
41 (<1)	84 (<1)	34	Sile	Italy	SNAd	45.4686	12.5734	647	[b]52.92	0.39
42 (<1)	85 (<1)	38	Porto di Malamocco	Italy	SNAd	45.3394	12.3124	--	[b]17.27	0.38
43 (<1)	86 (<1)	35	Porto di Lido	Italy	SNAd	45.4266	12.4438	--	[b]17.27	0.34

(Continued)

TABLE 2 (Continued)

-- --	4 (4)	89	Northern Adriatic Sea	SubReg	NAd	44.5850	14.6042	15 909	--	167.30
1 (15)	27 (<1)	64	Metauro	Italy	NAd	43.8317	13.0583	1 401	[a]11.59	25.63
2 (15)	29 (<1)	16	Zrmanja	Croatia	NAd	44.2229	15.5817	856	[b]40.10	25.15
3 (8)	36 (<1)	70	Chienti	Italy	NAd	43.3113	13.7695	1 336	[a]10.25	14.04
4 (7)	40 (<1)	73	Tronto	Italy	NAd	42.8988	13.9266	1 243	[a]10.77	12.38
5 (7)	42 (<1)	67	Esino	Italy	NAd	43.6418	13.3577	962	[a]10.53	12.10
6 (7)	44 (<1)	65	Cesano	Italy	NAd	43.7378	13.1773	636	--	11.47
7 (6)	46 (<1)	18	Rjecina	Croatia	NAd	45.3147	14.4786	189	[b]7.22	10.77
8 (6)	49 (<1)	63	Foglia	Italy	NAd	43.9272	12.8769	707	--	9.48
9 (6)	50 (<1)	19	Rasa	Croatia	NAd	45.0153	14.0739	496	[b]1.58	9.40
10 (5)	51 (<1)	69	Potenza	Italy	NAd	43.4059	13.6523	772	--	9.14
11 (4)	59 (<1)	75	Tordino	Italy	NAd	42.7612	13.9786	444	--	7.16
12 (4)	60 (<1)	68	Musone	Italy	NAd	43.4960	13.6580	639	--	7.08
13 (3)	61 (<1)	71	Tena	Italy	NAd	43.2212	13.7638	490	--	5.59
14 (3)	64 (<1)	66	Misa	Italy	NAd	43.6908	13.2367	391	--	4.30
15 (1)	69 (<1)	17	Dubracina	Croatia	NAd	45.1687	14.7214	215	[b]4.14	2.33
16 (<1)	76 (<1)	74	Vibrata	Italy	NAd	42.8537	13.9237	110	--	0.77
17 (<1)	79 (<1)	72	Albula	Italy	NAd	42.9462	13.8686	272	--	0.49
-- --	3 (15)	90	Central Adriatic Sea	SubReg	CAd	43.1965	16.5824	35 616	--	589.03
1 (58)	3 (9)	10	Neretva	Croatia	CAd	43.0196	17.4325	13 127	[b]366.86	341.27
2 (16)	13 (2)	11	Cetina	Croatia	CAd	43.4339	16.6805	3 860	[b]88.28	92.13
3 (8)	21 (1)	15	Krka	Croatia	CAd	43.7112	15.8426	2 519	[b]56.51	47.69
4 (6)	26 (<1)	78	Pescara	Italy	CAd	42.4809	14.2028	3 158	[a]46.35	33.41
5 (3)	34 (<1)	79	Sangro	Italy	CAd	42.2398	14.5489	1 745	[a]22.09	17.85
6 (2)	48 (<1)	14	Morinje	Croatia	CAd	43.6628	15.8998	567	--	10.24
7 (1)	52 (<1)	81	Biferno	Italy	CAd	41.9916	15.0124	1 319	[a]17.19	8.57
8 (1)	53 (<1)	76	Vomano	Italy	CAd	42.6686	14.0333	789	--	8.56
9 (1)	54 (<1)	82	Fortore	Italy	CAd	41.9311	15.3086	1 605	[a]5.87	8.54
10 (1)	56 (<1)	77	Saline	Italy	CAd	42.5285	14.1454	612	--	7.84
11 (1)	57 (<1)	80	Trigno	Italy	CAd	42.0483	14.7758	1 208	[a]11.01	7.62
12 (<1)	66 (<1)	13	Jadro	Croatia	CAd	43.5356	16.5063	202	[b]7.18	3.65
13 (<1)	71 (<1)	12	Zrnovnica	Croatia	CAd	43.4907	16.5013	61	[b]1.76	1.66
-- --	2 (20)	91	Southern Adriatic Sea	SubReg	SAd	41.2394	19.1028	59 719	--	806.71
1 (46)	2 (9)	08	Buna	Albania	SAd	41.8567	19.4040	6 044	[b]675.00	371.69
2 (19)	8 (4)	01	Vjiose	Albania	SAd	40.6354	19.3388	6 651	[a]184.82	155.45
3 (11)	15 (2)	02	Seman	Albania	SAd	40.8148	19.3655	8 382	[b]86.00	86.62
4 (7)	20 (1)	06	Mat	Albania	SAd	41.6606	19.5548	2 624	[b]87.40	56.88
5 (5)	24 (1)	03	Shkumbini	Albania	SAd	41.0333	19.4581	--	[b]58.70	44.14
6 (3)	30 (<1)	04	Erzen	Albania	SAd	41.4423	19.4607	1 007	[a]26.16	23.82
7 (2)	33 (<1)	05	Ishm	Albania	SAd	41.5710	19.5408	768	[b]19.80	18.96
8 (2)	35 (<1)	86	Ofanto	Italy	SAd	41.3805	16.2168	2 777	[b]14.92	15.67
9 (2)	38 (<1)	07	Drin	Albania	SAd	41.7501	19.5689	13 060	[a]692.28	12.62
10 (1)	47 (<1)	83	Candelaro	Italy	SAd	41.5823	15.8775	2 135	[a]7.63	10.46
11 (<1)	63 (<1)	85	Carapelle	Italy	SAd	41.4887	15.9284	1 035	--	4.98
12 (<1)	65 (<1)	84	Cervaro	Italy	SAd	41.5337	15.9327	676	[b]2.92	4.27
13 (<1)	73 (<1)	09	Ombla	Croatia	SAd	42.6944	18.1262	37	[b]27.00	1.16

require continuous monitoring and modelling efforts to trace the exact location of dense water generation in the SNAd.

Due to its small catchment area, NAd is responsible for only 4% of discharges into the Adriatic Sea (Table 2). Assuming 1% of the overall discharge of the Adriatic Sea as a threshold to classify a river as small, all 17 NAd rivers would be classified as minor. Its principal rivers are the Metauro (Italy) and the Zrmanja (Croatia), accounting for 30% of the freshwater input collected in the basin. The EFAS estimates proved quite realistic for the western coast rivers compared to the literature (Ludwig et al., 2009; Verri et al., 2018). However, the same cannot be said about the Croatian coast discharges, where the EFAS underestimated by 37 and 44% the observed values in the Zrmanja and Dubracina Rivers, respectively, and overestimated by 5x discharges from the Rasa River. All these rivers present measurements referring to 1947–2000 (Verri et al., 2018), allowing an overlap for only 10 years with the present study period (1991–2022). Despite the outdated literature values, another river with data from the same source (Rjecina) presented satisfactory estimates with EFAS.