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Original paper

Drought characteristics of European river basins derived from GRACE and GRACE Follow-On total water storage (2002–2026)

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Abstract: Hydrological drought, i.e. a persistent deficit of water stored on and below the land surface, is poorly represented by traditional climate indices based on individual meteorological data. Now, well-established geodetic techniques provide a reliable insight into total water storage (TWS) anomalies. We analyze drought characteristics of 24 major river basins of Europe and its south-eastern margins using TWS from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions, computed from the recent JPL mascon solution for April 2002 to February 2026. For each basin, we compute the GRACE-based Drought Severity Index (GRACE-DSI) based on detrended TWS series, and further classify monthly conditions into wet and dry categories, and identify drought episodes. We show that 23 of 24 basins lose water, with trends from –0.06 cm/yr (Vuoksi–Neva) to –1.52 cm/yr (Kura–Ozero Sevan); only the Western Dvina basin shows no long-term change (+0.02 cm/yr). The greatest declines, below –0.75 cm/yr, occur in southern and south-eastern basins, i.e. the Po, Danube, Dniester, Don, Dnieper, Sakarya, Tigris–Euphrates and Kura–Ozero Sevan. We find that dry months exceeds wet months in 13 basins. We note that drought episodes last 3–19 months, on average 5.3 months, and the largest spatial extent of drought, with 16 of 24 basins in drought, occurred in July 2006 and November 2022. We find that the share of drought months increased in 19 basins, from 19.0% to 25.1% on average between GRACE and GRACE-FO periods, and the mean episode duration increased from 4.6 to 6.9 months, with the largest increase in the western and central basins. A detailed analysis of the Po, Vistula and Kura–Ozero Sevan basins shows that GRACE-DSI captures documented events, i.e. the 2022 Po drought, the 2024–2026 deficit in the Vistula basin, and the progressive water loss in the South Caucasus.

Keywords: GRACE/GRACE-FO, total water storage, drought severity index, warning conditions, European river basins

1. Introduction

Europe is the fastest-warming continent, with temperatures rising at about twice the global mean rate (WMO, 2024). It intensifies the hydrological cycle through higher evapotranspiration, shifts in the seasonality of precipitation and earlier snowmelt (Stagl et al., 2014), as well as more dry



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periods. In the last decade, Europe experienced a sequence of exceptional droughts; the 2015 drought affected central and eastern Europe (Ionita et al., 2017), the 2018–2020 multi-year drought set a new benchmark in central Europe (Rakovec et al., 2022), whereas the 2022 drought affected most of the continent (Bevacqua et al., 2024; Garrido-Perez et al., 2024). These events reduced crop yields, hydropower generation and inland navigation, and triggered ecological disasters such as the 2022 mass fish die-off in the Oder river (Slugocki and Czerniawski, 2023).

Drought is commonly divided into meteorological, agricultural, hydrological and socio-economic types (Mishra and Singh, 2010). Widely used indices, e.g. the Standardized Precipitation Index (SPI, McKee et al., 1993) or the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010), describe the atmospheric forcing of drought, but not its consequence for water stored in soils, aquifers, lakes, reservoirs, snow and more. In situ observations of these components are sparse, heterogeneous and rarely available in a consistent form for transboundary river basins (Sarfaraz et al., 2022). However, satellite gravimetry fills this gap. Since April 2002, the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004) and, since May 2018, its successor GRACE Follow-On (GRACE-FO) (Landerer et al., 2020) have provided monthly estimates of total water storage (TWS) at spatial scales of a few hundred kilometers by observing gravity field variations (Tapley et al., 2019). To date, GRACE-based TWS anomalies have been used to quantify e.g., groundwater depletion (Famiglietti et al., 2011; Voss et al., 2013), flood potential (Reager and Famiglietti, 2009) or global freshwater trends (Rodell et al., 2018) that enable the successful monitoring of changes in hydrology. Thus, GRACE have further been utilized to study climate change indirectly through the assimilation of data on groundwater and soil moisture percentiles (Houborg et al., 2012), the water storage deficit approach (Thomas et al., 2014) or directly by calculating the Drought Severity Index (DSI) (Zhao et al., 2017), but which depend on the treatment of trends and of the reference period (Gerdener et al., 2020). However, they may be successfully used to indicate drought characteristics on a regional (Lenczuk et al., 2024a) and global (Lenczuk et al., 2024b) scale.

In recent years, Europe has been subjected to more intense and more frequent local flash droughts (Walker et al. 2023) leading to its becoming the fastest-warming continent; i.e. warming twice as fast as other continent (Copernicus Climate Change Service, 2026). Rakovec et al. (2022) found that, since 2018, the average area affected by drought has been twice as large as it was ten to twenty years ago, and droughts last twice as long as in previous years. For example, Boergens et al. (2020) quantified the 2018–2019 central European drought with GRACE-FO, showing that the storage deficit of 2018 was not replenished before the drought of 2019. Moreover, the intensity of droughts is also increasing; droughts in recent years were over twice stronger than 10 years ago (Rakovec et al., 2022). In consequence, European river basins are facing warning conditions (Lenczuk, 2025), and identifying and monitoring drought characteristics is essential in this region

In our study, we analyze drought characteristics for the 24 major river basins based on GRACE/GRACE-FO-data. The contribution of this paper is fourfold: (i) we estimate long-term TWS trends for April 2002 – February 2026, including the record 2022–2025 dry years; (ii) we quantify the frequency of drought categories, the duration and severity of drought episodes based on GRACE-DSI computed from detrended TWS, and the spatial extent of droughts occurring simultaneously in many basins; (iii) we compare drought statistics for GRACE and GRACE-FO periods to assess nature of variations in droughts frequency and duration in Europe; as well as (iv) we discuss in detail three basins with contrasting climatic regimes, i.e. the Po, Vistula and Kura–Ozero Sevan, and show how long-term trends, non-linear water loss, and human water management affect DSI-based drought statistics.

The paper is organized as follows. Section 2 describes the GRACE/GRACE-FO mascon data. Section 3 presents the study area. Section 4 introduces the methodology. Results and discussion are given in Section 5, and the paper is completed with conclusions in Section 6.

2. GRACE/GRACE-FO mascon data

GRACE consisted of two identical satellites in a near-polar orbit (inclination 89°) at an initial altitude of about 500 km, separated by about 220 km along track (Tapley et al., 2004). Temporal changes of the Earth's gravity field were derived from inter-satellite range-rate variations measured with the K-band ranging (KBR) system, supported by GPS receivers and on-board accelerometers. GRACE operated from March 2002 and provided 163 monthly gravity field solutions; several months within the late GRACE period are missing due to battery management. After 11-month gap, GRACE-FO, launched on 22 May 2018, continues the record with the same orbit design and a microwave ranging system, complemented by the Laser Ranging Interferometer (LRI) as a technology demonstrator (Landerer et al., 2020). In contrast to the commonly used Level-2 spherical harmonic coefficients, we use the mass concentration (mascon) solution. The concept of mascons was introduced by Muller and Sjogren (1968) for the lunar gravity field. For GRACE, the surface mass change is parameterised directly as a set of spherical caps, each with a uniform surface mass density (Watkins et al., 2015). Because the mascons are estimated directly from the KBR observations with geophysical constraints applied during the inversion, the solution does not require empirical destriping or Gaussian smoothing, and it is less affected by leakage than filtered spherical harmonics (Watkins et al., 2015).

We use the recent JPL GRACE/GRACE-FO mascon solution (Wiese et al., 2023). It consists of 4,551 equal-area 3° spherical cap mascons, provided as monthly TWS anomalies on a $0.5° \times 0.5°$ grid, for which a Coastline Resolution Improvement (CRI) filter separates land and ocean mass within mixed mascons (Wiese et al., 2016). The solution includes the replacement of degree-1 coefficients (Sun et al., 2016), of the C20 and C30 coefficients by satellite laser ranging (SLR) estimates (Loomis et al., 2020) and the correction for glacial isostatic adjustment based on the ICE6G-D model (Peltier et al., 2018). TWS anomalies are expressed as equivalent water height (EWH) relative to the 2004.0–2009.999 mean. In this study, for each of the 24 basins, we select the $0.5° \times 0.5°$ grid cells of the JPL mascon solution that cover the basin area and average their TWS values to obtain the monthly basin-average TWS series. We use 254 monthly solutions from April 2002 to February 2026. Min the case of the missing months, including the GRACE/GRACE-FO gap, are not interpolated.

3. Study area

We analyze the 24 major river basins defined by the United Nations (UN) Global Compact initiative. Following Lenczuk et al. (2025), we select basins larger than 50,000 km^2 that experienced extreme hydrometeorological events in recent years. The basins extend between about 30°N and 65°N. They range in size from 56,200 km^2 (Narva) to 1,360,000 km^2 (Volga), and they represent five climate zones of the Köppen classification (Cui et al., 2021). It worth to noted that eleven basins are smaller than 100,000 km^2, i.e. close to the effective resolution of GRACE (about 300 km); for these basins, signal leakage from neighbouring basins and seas is larger than for the large eastern basins (Lenczuk, 2025), which we consider in interpreting the results. Finally, we group the basins into six regions. (1) The Iberian and Mediterranean basins (Douro, Ebro, Rhone, Po), i.e. a region dominated by winter precipitation and dry, hot summers, and the Rhone and Po additionally depended on snow and glacier melt from the Alps. (2) The Atlantic basins (Loire, Seine, Rhine), characterized by a pluvial regime with a summer low flow driven by evapotranspiration. (3) The central European basins (Elbe, Oder, Vistula, Danube), exhibiting a mixed pluvio-nival regime with spring snowmelt from the Sudetes, the Carpathians and the Alps. (4) The Baltic and northern basins (Neman, Western Dvina, Narva, Vuoksi–Neva, Northern Dvina) which are dominated by snowmelt, and the Narva and Vuoksi–Neva regions, whose water management is regulated by

the Peipus, Saimaa and Ladoga lakes. (5) The Black Sea and Caspian lowland basins (Dniester, Dnieper, Don, Volga), where snowmelt supplies water in the spring, and the Dnieper and Volga, are regulated by reservoir cascades. (6) The Caucasian, Anatolian and Mesopotamian basins (Kura–Ozero Sevan, Kızılırmak, Sakarya, Tigris–Euphrates) that are characterized by semi-arid to arid climates, snowmelt-fed headwaters, large dams and intensive irrigation.

Table 1. Characteristics of the analysed river basins. Areas and climate zones as defined by Lenczuk (2025) and Cui et al. (2021); the dominant supply regime is denotes as follows: P – pluvial (rainfall), N – nival (snowmelt), G – glacial, L – lake-regulated, R – reservoir-regulated.

No.	River basin	Area (10^3 km^2)	Main countries	Climate zone	Supply regime	Outlet
1	Douro	97.3	ES, PT	cold semi-arid	P, N	Atlantic Ocean
2	Ebro	88.5	ES	cold semi-arid	P, N, R	Mediterranean Sea
3	Rhone	98.5	FR, CH	temperate oceanic	G, N, P	Mediterranean Sea
4	Po	74.0	IT, CH	temperate oceanic	G, N, P	Adriatic Sea
5	Loire	117.0	FR	temperate oceanic	P	Atlantic Ocean
6	Seine	78.6	FR	temperate oceanic	P	English Channel
7	Rhine	185.0	CH, DE, FR, NL	temperate oceanic	G, N, P	North Sea
8	Elbe	148.3	CZ, DE	warm-summer humid continental	P, N	North Sea
9	Oder	118.8	PL, CZ, DE	warm-summer humid continental	P, N	Baltic Sea
10	Vistula	169.0	PL	warm-summer humid continental	P, N	Baltic Sea
11	Danube	817.0	19 countries	warm-summer humid continental	P, N, G	Black Sea
12	Dniester	72.1	UA, MD	warm-summer humid continental	P, N	Black Sea
13	Neman	90.0	BY, LT, RU	warm-summer humid continental	N, P	Baltic Sea
14	Western Dvina	88.0	RU, BY, LV	warm-summer humid continental	N, P	Baltic Sea
15	Narva	56.2	EE, RU	warm-summer humid continental	N, L	Baltic Sea
16	Vuoksi–Neva	345.0	FI, RU	subarctic	N, L	Baltic Sea
17	Northern Dvina	357.0	RU	subarctic	N	White Sea

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Table 1 – *Continued from previous page*

No.	River basin	Area (10^3 km^2)	Main countries	Climate zone	Supply regime	Outlet
18	Volga	1,360.0	RU	warm-summer humid continental	N, R	Caspian Sea
19	Don	425.6	RU, UA	warm-summer humid continental	N, P, R	Sea of Azov
20	Kura–Ozero Sevan	188.0	GE, AZ, AM, TR	humid continental/ cold semi-arid	N, P, L	Caspian Sea
21	Tigris–Euphrates	875.0	TR, SY, IQ, IR	hot desert	N, P, R	Persian Gulf
22	Kızılırmak	78.0	TR	cold semi-arid	N, P, R	Black Sea
23	Sakarya	85.0	TR	cold semi-arid	P, N, R	Black Sea
24	Dnieper	516.3	RU, BY, UA	warm-summer humid continental	N, P, R	Black Sea

4. Methodology

For each basin, we first estimate the linear trend of the monthly basin-average TWS series using least-squares estimation (LSE) approach. The trend describes the mean rate of water gain or loss over analyzed period. The estimated trend is then removed from the TWS series, and the detrended series is applied to compute the DSI. In this way, the drought statistics describe deviations from the long-term tendency of each basin, while the tendency itself is described by the trend.

4.1. GRACE-based Drought Severity Index

Following Zhao et al. (2017), GRACE-DSI is the standardised anomaly of TWS computed separately for each calendar month. Standardizing each calendar month individually eliminates the impact of seasonal cycles, so that DSI expresses whether a given month was drier or wetter than usual for that time of the year. DSI is unitless and comparable between basins of different size and climate.

To identify the direction of persistent changes, we also compute the cumulative DSI, i.e. the running sum of DSI from the first month of the series. A rising cumulative DSI indicates a period dominated by positive (wet) anomalies, and a falling cumulative DSI indicates a period dominated by negative (dry) anomalies. However, the turning point of the cumulative DSI marks the transition between the two regimes.

4.2. Drought categories and drought episodes

Each monthly DSI value is assigned to one of eleven wet and dry categories, from exceptional drought (D4) to exceptionally wet conditions (W4), according to the classification of Zhao et al. (2017). In the following analysis, we count months in categories D1–D4 (DSI ≤ -0.8) as drought months and in categories W1–W4 (DSI ≥ 0.8) as wet months. Categories D0 and W0 describe slight anomalies, and WD describes near-normal conditions.

We then identify drought episodes using run theory (Yevjevich, 1967). An episode is a run of at least three consecutive months with DSI ⩽ –0.8, i.e. in categories D1–D4; a missing month, including the GRACE/GRACE-FO gap, ends an episode. The minimum duration of three months limits the effect of short-term fluctuations and monthly noise in the GRACE data (Lenczuk et al., 2024b). For each basin, we report the number of episodes, the duration and timing of the longest episode, and the mean duration, computed as the arithmetic mean of the durations of all episodes in the analysed period.

5. Results and discussion

5.1. Long-term changes of TWS

We show that 23 of 24 basins lost water between April 2002 and February 2026 (Fig. 1). The only exception is the Western Dvina basin, with a practically zero trend of +0.02 cm/yr. We distinguish three groups of basins. The first group, with trends between –0.10 and +0.02 cm/yr, comprises the northern and northeastern basins (Western Dvina, Vuoksi–Neva, Narva, Northern Dvina) and the Douro. The second group, with trends between –0.22 and –0.49 cm/yr, comprises the Loire, Ebro, Neman, Seine, Volga, Rhone and Elbe. The third group, with trends below –0.5 cm/yr, comprises twelve basins located mainly in the central, southern and southeastern parts of Europe. The largest declines are found for the Kura–Ozero Sevan (–1.52 cm/yr) and Dniester (–1.35 cm/yr) basins, followed by the Dnieper (–0.90 cm/yr), Po (–0.87 cm/yr), Sakarya (–0.86 cm/yr) and Danube (–0.81 cm/yr). Over the 24 years, these trends correspond to a water loss of 19–36 cm of EWH.

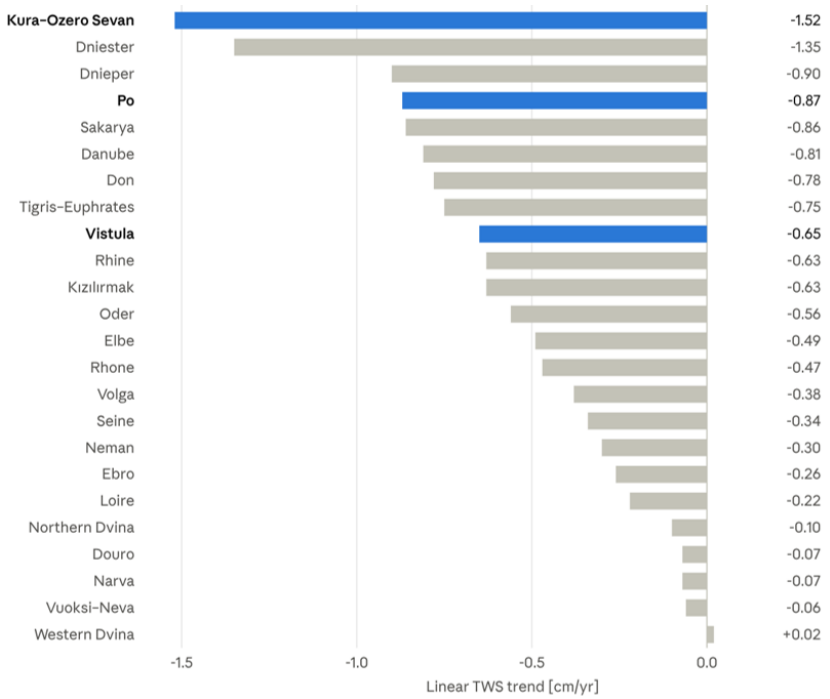


Fig. 1. Linear trends of TWS estimated for the 24 river basins from the JPL mascon solution for April 2002 – February 2026 period. Basins analyzed in detail in Section 5.3 are shown in blue. The values are in cm/yr.

The north-to-south-east gradient of TWS trends agrees with the global pattern of emerging freshwater changes, i.e. wetting of high latitudes and drying of mid-latitudes (Rodell et al., 2018), and with the decline of groundwater resources in the Euro-Mediterranean region reported by Xanke and Liesch (2022). The magnitude of the trends differs from the values obtained for the GRACE-FO period only (Lenczuk, 2025). For June 2018 – February 2024, the JPL mascon trends reached +3.2 cm/yr for the Narva and +2.7 cm/yr for the Vuoksi–Neva, and –2.5 to –3.6 cm/yr for the Rhone, Po, Tigris–Euphrates and Kura–Ozero Sevan. Here, the trends are two to four times smaller in magnitude, and the northern basins show no long-term change. This highlights that trends estimated over a few years are dominated by interannual variability, e.g. a drought at the beginning and a wet period at the end of the series, and should not be interpreted as climate-driven changes.

The strongest negative trends require careful interpretation, as they may contain non-climatic contributions. For the Kura–Ozero Sevan basin, signal leakage from the shrinking Caspian Sea is likely (Section 5.3). The Dniester is the second smallest basin in this study (72,100 km^2); in Lenczuk (2025) it showed one of the largest leakage contributions to the total signal, so its trend may be partly inherited from the neighbouring Dnieper and Danube basins. For the Dnieper, the drainage of the Kakhovka reservoir after the destruction of the dam on June 2023 removed about 18 km^3 of water (Vyshnevskyi and Shevchuk, 2024), i.e. about 3.5 cm of EWH averaged over the basin. This is equivalent to about four years of the mean trend, however it is small compared with the interannual variability of TWS in this basin (Lenczuk, 2025).

5.2. Frequency of drought categories and drought duration

Near-normal and slightly anomalous conditions (D0–W0) cover 124–161 of 254 months, i.e. 49–63% of the record (Table 2). Drought months (D1–D4) account for 45–68 months (18–27%), and wet months (W1–W4) for 44–65 months. It should be noted that DSI is standardised separately for each calendar month, so for normally distributed anomalies about 21% of months fall below –0.8 and the same share above 0.8. The differences between basins therefore reflect the asymmetry and persistence of TWS anomalies rather than the overall frequency of dry conditions. Drought months outnumber wet months in nine basins (Douro, Ebro, Rhine, Oder, Vistula, Kızılırmak, Dnieper, Vuoksi–Neva and Northern Dvina), both counts are equal for the Po, and wet months prevail in the remaining 14 basins. The largest numbers of drought months are found for the Douro (68), Rhine and Elbe (60 each), and Tigris–Euphrates and Volga (59 each) basins, and the smallest for the Kura–Ozero Sevan (45), Rhone (46) and Narva (47) basins. Exceptional drought (D4) is most frequent in the Narva and Kura–Ozero Sevan basins (11 months each), followed by the Western Dvina and Vuoksi–Neva basins (9 months each), whereas the Rhine, Elbe, Oder and Northern Dvina basins have no D4 month. The Vistula (13 months) and Oder (12 months) basins have the largest number of exceptionally wet months (W4), which reflects the wet period of 2010–2011 in central Europe.

Table 2. Number of months in GRACE-DSI categories for the 24 European river basins during April 2002 to February 2026. Basins are ordered from south-west to north-east. The columns D and W mean dry and wet categories defined by Zhao et al. (2017) and D0–W0 sums categories D0, WD (i.e., normal) and W0.

River basin	D4	D3	D2	D1	D0–W0	W1	W2	W3	W4	D1–D4	W1–W4
Douro	2	9	16	41	124	40	11	9	2	68	62
Ebro	6	11	10	30	145	31	10	8	3	57	52
Loire	4	9	10	28	149	29	12	9	4	51	54

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Table 2 – *Continued from previous page*

River basin	D4	D3	D2	D1	D0–W0	W1	W2	W3	W4	D1–D4	W1–W4
Rhone	5	8	12	21	151	32	15	7	3	46	57
Seine	3	8	10	31	148	30	10	9	5	52	54
Po	4	7	16	25	150	23	13	8	8	52	52
Rhine	0	8	17	35	138	19	17	15	5	60	56
Elbe	0	6	11	43	132	35	10	11	6	60	62
Danube	7	6	6	32	148	30	9	11	5	51	55
Oder	0	4	7	44	155	14	8	10	12	55	44
Sakarya	4	13	14	18	143	42	9	8	3	49	62
Vistula	1	6	9	32	161	21	5	6	13	48	45
Kızılırmak	4	11	15	28	143	30	14	6	3	58	53
Dniester	5	9	16	25	143	36	8	10	2	55	56
Tigris–Euphrates	1	5	13	40	133	34	8	15	5	59	62
Neman	3	9	13	27	145	30	11	12	4	52	57
Dnieper	4	13	13	26	150	23	11	9	5	56	48
Western Dvina	9	12	4	24	146	41	10	7	1	49	59
Narva	11	6	7	23	150	38	12	6	1	47	57
Kura–Ozero Sevan	11	6	6	22	158	29	4	13	5	45	51
Don	1	3	12	36	145	28	10	13	6	52	57
Vuoksi–Neva	9	6	8	35	142	35	12	5	2	58	54
Volga	7	7	13	32	130	35	19	11	0	59	65
Northern Dvina	0	7	16	28	154	27	9	5	8	51	49

Figure 2 presents monthly GRACE-DSI for all basins in a single space–time diagram, with basins ordered from south-west to north-east, i.e. from the Douro to the Volga and Northern Dvina basins. The diagram shows that droughts frequently affect many basins at the same time. More than 10 of 24 basins are in drought (D1–D4) in 22 months, of which 20 belong to four periods, i.e. 2003, 2006, 2019–2020 and 2022–2023, and the remaining two are January 2016 and March 2025 (bottom panel of Fig. 3). The largest spatial extent of drought is reached in July 2006 and November 2022, with 16 basins in categories D1–D4, and in July 2019 and June 2023, with 15 basins. The 2002–2003 drought affected mainly the central, eastern and northeastern basins, i.e. from the Danube and Vistula to the Volga and Kura–Ozero Sevan basins (13 basins in May 2003). In July 2006, drought covered both the western basins, from the Douro to the Oder, and the Baltic and northeastern basins. The 2019 and 2022–2023 droughts were centred on the western and central basins, from the Iberian Peninsula to the Vistula, with D3–D4 conditions in the Rhone, Loire, Seine and Po basins in 2022, which agrees with the exceptional 2022 European drought (Bevacqua et al., 2024; Garrido-Perez et al., 2024). In 2025, drought shifted to the central, eastern and Anatolian basins, with 12 basins in drought in March 2025. In contrast, the years 2013 and 2024 were almost free of drought, with on average less than one basin per month in categories D1–D4, and 2024 was wet in most western and central basins.

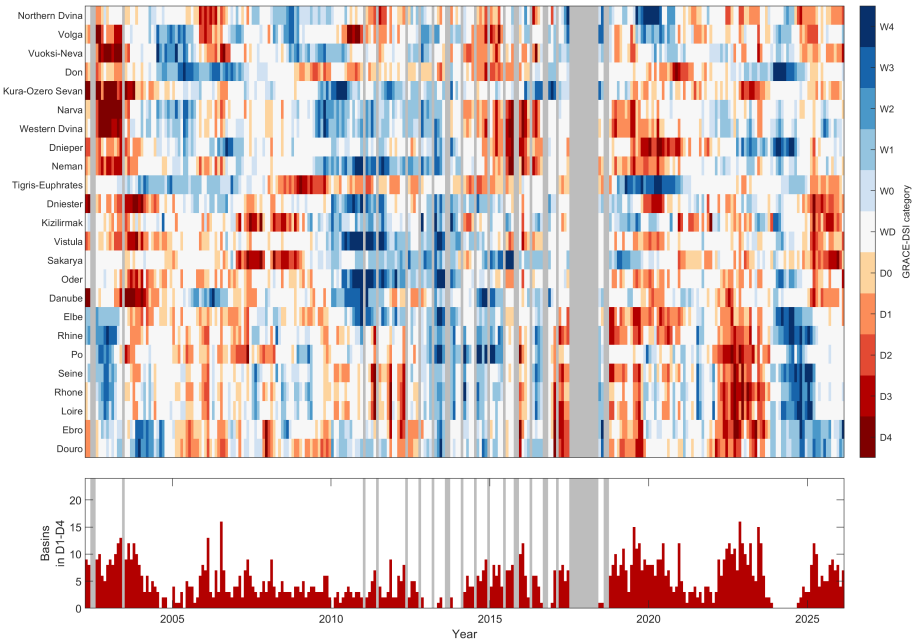


Fig. 2. Monthly GRACE-DSI for the 24 river basins for April 2002 – February 2026 period. Basins are ordered from south-west (bottom) to north-east (top). The colours denote DSI categories D4–W4 defined by Zhao et al. (2017); grey columns mark missing months, including the GRACE/GRACE-FO gap. The bottom panel shows the number of basins in drought (i.e., D1–D4 categories) in each month.

We also calculate the cumulative DSI which provides information on the timing of persistent dry and wet anomalies relative to the long-term tendency of each basin. As DSI is computed from detrended and standardized TWS, the cumulative DSI is close to zero at the end of the record, and its maximum marks the end of a period dominated by wetter-than-usual conditions. The maximum occurs in 2013–2016 for the Rhone, Rhine, Elbe, Oder, Vistula, Neman, Dnieper, Western Dvina, Narva and Vuoksi–Neva basins, which indicates that dry anomalies prevailed during the last decade. It occurs even later, in 2019–2021, for the Po, Danube, Sakarya, Kızılırmak, Dniester, Kura–Ozero Sevan, Volga and Northern Dvina basins, where dry anomalies are concentrated in the last five to six years. In the Douro, Ebro, Loire, Seine, Don and Tigris–Euphrates basins, the maximum occurs already in 2005–2009, i.e. dry anomalies prevailed during most of the record.

Further, in Table 3 we show the statistics of drought episodes. We identify 169 drought episodes in total, i.e. from 4 to 9 episodes per basin (Table 3). The mean duration of episodes ranges from 3.7 months for the Oder basin to 8.2 months for the Sakarya basin, with an average of 5.3 months. Most episodes last 3–5 months, i.e. one dry season. The longest episodes occurred in the Tigris–Euphrates (19 months, May 2008 – November 2009), Rhone (18 months, March 2022 – August 2023), Dnieper (17 months, September 2019 – January 2021) and Po (16 months, January 2022 – April 2023) basins. In 12 basins, mainly in the western, central and eastern parts of the study area, the longest episode occurred after 2018. In the northeastern basins (Western Dvina, Narva, Vuoksi–Neva) and in the Kura–Ozero Sevan basin, the longest and most severe episode is the drought of August 2002 – May 2003. This episode starts after two missing months at the beginning of the record, so its duration may be underestimated. Two episodes are still ongoing in February 2026, i.e. in the Northern Dvina (since October 2025) and Vuoksi–Neva (since December 2025) basins, so their durations are lower bounds.

Table 3. Statistics of drought episodes (DSI ⩽ –0.8 for at least three consecutive months) for April 2002 – February 2026 period. The severity is the sum of monthly DSI values within an episode. Dates are given as year/month.

River basin	Number of episodes	Duration range (months)	Mean duration (months)	Longest episode	Most severe episode (sum of DSI)
Douro	9	3–10	5.2	2019/02–2019/11	2022/02–2022/11 (–14.1)
Ebro	9	3–11	4.9	2022/02–2022/12	2022/02–2022/12 (–16.7)
Loire	7	3–13	4.6	2022/03–2023/03	2022/03–2023/03 (–20.5)
Rhone	5	3–18	6.0	2022/03–2023/08	2022/03–2023/08 (–30.6)
Seine	9	3–11	4.4	2022/05–2023/03	2022/05–2023/03 (–16.3)
Po	6	3–16	6.5	2022/01–2023/04	2022/01–2023/04 (–25.7)
Rhine	7	3–11	5.6	2022/05–2023/03	2022/05–2023/03 (–14.3)
Elbe	7	3–10	5.3	2020/04–2021/01	2020/04–2021/01 (–12.2)
Danube	9	3–9	4.6	2003/07–2004/03	2003/07–2004/03 (–17.6)
Oder	6	3–6	3.7	2003/08–2004/01	2003/08–2004/01 (–9.2)
Sakarya	5	3–12	8.2	2008/02–2009/01	2007/01–2007/11 (–19.2)
Vistula	4	3–9	6.3	2003/07–2004/03	2003/07–2004/03 (–13.9)
Kızılırmak	6	3–8	5.5	2008/02–2008/09	2008/02–2008/09 (–11.8)
Dniester	6	3–12	6.3	2025/01–2025/12	2025/01–2025/12 (–17.1)
Tigris–Euphrates	9	3–19	5.1	2008/05–2009/11	2008/05–2009/11 (–27.9)
Neman	6	3–13	6.0	2019/06–2020/06	2019/06–2020/06 (–16.5)
Dnieper	7	3–17	5.1	2019/09–2021/01	2019/09–2021/01 (–29.1)
Western Dvina	7	3–10	5.3	2002/08–2003/05	2002/08–2003/05 (–19.7)
Narva	8	3–10	4.1	2002/08–2003/05	2002/08–2003/05 (–24.0)
Kura–Ozero Sevan	5	3–10	6.0	2002/08–2003/05	2002/08–2003/05 (–20.1)
Don	9	3–9	4.3	2020/09–2021/05	2020/09–2021/05 (–13.0)
Vuoksi–Neva	8	3–10	4.4	2002/08–2003/05	2002/08–2003/05 (–21.8)
Volga	9	3–8	4.7	2010/05–2010/12	2010/05–2010/12 (–13.3)
Northern Dvina	6	3–7	4.8	2005/11–2006/05	2005/11–2006/05 (–11.4)

To assess whether droughts became more frequent and longer, we compare drought statistics for the GRACE (April 2002 – June 2017, 163 months) and GRACE-FO (June 2018 – February 2026, 91 months) periods (Table 4). DSI is computed once for the whole detrended record, and the statistics are only split at the gap between the missions, so that both periods share the same monthly reference. Because both periods differ in length, the number of drought months is expressed as a percentage of the available months in each period. The share of drought months increased in 19 of 24 basins, from 19.0% to 25.1% on average, and the mean duration of episodes increased in 17 of 24 basins, from 4.6 to 6.9 months on average. The increase is the largest in the western and central basins; the share of drought months doubled in the Loire (from 14.1% to 30.8%), Rhone (13.5% to 26.4%), Seine (14.7% to 30.8%), Rhine (16.6% to 36.3%) and Elbe (15.3% to 38.5%) basins. The longest episodes of the GRACE-FO period, lasting 12–18 months, occurred in the Rhone, Dnieper, Po, Neman, Loire, Dniester and Sakarya basins. Only five basins, located in the northeastern and southeastern parts of the study area, i.e. the Narva, Vuoksi–Neva, Volga, Don and Tigris–Euphrates, show fewer drought months in the GRACE-FO period. As DSI is computed from detrended TWS, this increase does not result from the long-term water loss, but from larger and more persistent storage deficits in recent years, i.e. during the 2018–2020 and 2022–2023 droughts (Rakovec et al., 2022; Bevacqua et al., 2024). It should be noted that the GRACE-FO period is shorter, so its mean durations are based on one to five episodes per basin.

Table 4. Drought statistics for the GRACE (April 2002 – June 2017) and GRACE-FO (June 2018 – February 2026) periods, i.e., share of drought months (D1–D4), number of drought episodes, and mean episode duration.

River basin	D1–D4 (%) GRACE	D1–D4 (%) GRACE-FO	Episodes GRACE	Episodes GRACE-FO	Mean duration (months) GRACE	Mean duration (months) GRACE-FO
Douro	24.5	30.8	6	3	4.0	7.7
Ebro	19.6	27.5	6	3	3.5	7.7
Loire	14.1	30.8	2	5	3.5	5.0
Rhone	13.5	26.4	3	2	3.0	10.5
Seine	14.7	30.8	5	4	3.2	6.0
Po	19.6	22.0	4	2	5.0	9.5
Rhine	16.6	36.3	3	4	3.7	7.0
Elbe	15.3	38.5	3	4	3.3	6.8
Danube	17.8	24.2	5	4	4.4	4.8
Oder	17.8	28.6	4	2	3.8	3.5
Sakarya	16.0	25.3	2	3	11.5	6.0
Vistula	16.6	23.1	2	2	6.0	6.5
Kızılırmak	20.2	27.5	3	3	6.0	5.0
Dniester	17.2	29.7	4	2	4.5	10.0
Tigris–Euphrates	28.2	14.3	7	2	5.6	3.5
Neman	19.6	22.0	5	1	4.6	13.0
Dnieper	19.6	26.4	6	1	3.2	17.0
Western Dvina	19.0	19.8	5	2	4.8	6.5
Narva	21.5	13.2	6	2	4.2	4.0
Kura–Ozero Sevan	13.5	25.3	3	2	5.7	6.5
Don	22.7	16.5	7	2	3.9	6.0
Vuoksi–Neva	23.9	20.9	6	2	4.8	3.0
Volga	26.4	17.6	7	2	4.9	4.0
Northern Dvina	17.8	24.2	3	3	4.3	5.3

5.3. Regional analysis

We select three basins for a detailed analysis. Each represents a different climatic regime and illustrates a different aspect of GRACE-based drought characterization.

5.3.1. Po river basin

The Po basin represents the southern, snow- and glacier-dependent basins. It shows the steepest TWS decline among the western and southern European basins (–0.87 cm/yr) and hosts one of the longest and most severe drought episodes of the GRACE-FO period (16 months, sum of DSI –25.7). This episode corresponds to the 2022 drought, the most severe in at least two centuries (Montanari et al., 2023), which provides a benchmark for GRACE-DSI. The Po basin also covers about one quarter of Italy and supports intensive irrigation and hydropower, so its water deficit has large economic consequences. TWS in the Po basin was highest at the beginning of the record, reaching +17 cm in January 2003, and lowest in August 2022, at about –30 cm (Fig. 3). GRACE-DSI shows a dry period in 2006–2008, with two episodes of 6–7 months, and a wet period in 2013–2014, with the maximum DSI of 2.83 in August 2014. In 2022, DSI was negative in all months (annual mean –1.6) and reached its minimum of –2.06 in August 2022. The longest episode lasted 16 months, from January 2022 to April 2023, and was followed by a further 3-month episode in August–October 2023. In total, the Po basin has 52 dry and 52 wet months, and six episodes with a mean duration of 6.5 months. The cumulative DSI decreases until 2008, increases until September 2021 and drops sharply afterwards. The share of drought months is similar in both periods (19.6% for GRACE and 22.0% for GRACE-FO), but the mean duration of episodes nearly doubled, from 5.0 to 9.5 months. The most significant episode was the 2022 drought.

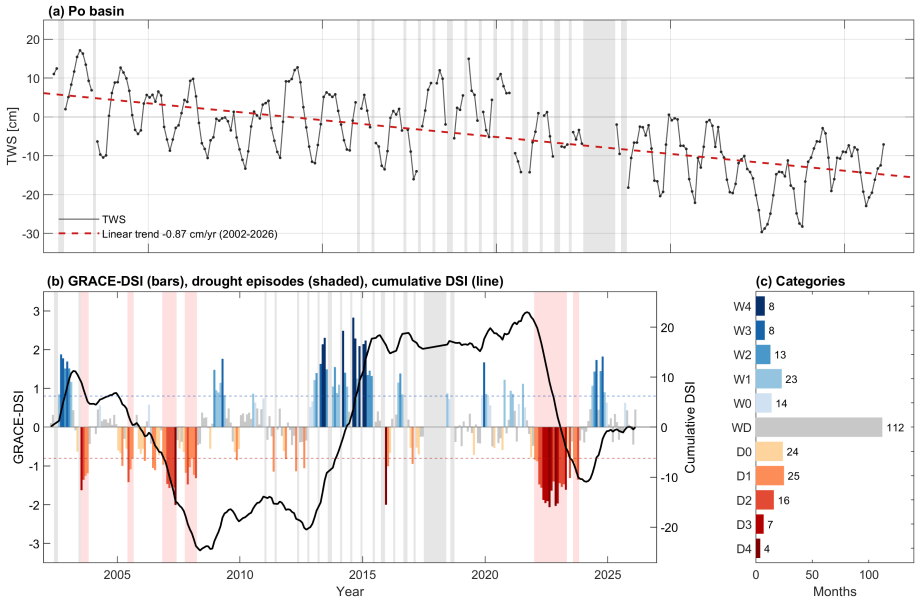


Fig. 3. Po basin: (a) monthly TWS with the linear trend for April 2002 – February 2026; (b) GRACE-DSI computed from detrended TWS (bars colored by category), drought episodes (shaded) and cumulative DSI (line, right axis); (c) number of months in DSI categories. Noted that grey bands mark missing months.

It was resulted from a long precipitation deficit combined with high temperatures and an exceptionally low Alpine snowpack, which led to record-low discharge of the Po river (Montanari et al., 2023). GRACE-DSI captures this event as the longest and most severe episode in the whole record. Moreover, GRACE shows that the storage deficit did not end with the summer of 2022 but persisted until spring 2023. This probably reflects the slow recovery of groundwater and the lack of snow recharge in two consecutive winters, which cannot be inferred from precipitation-based indices. A similar episode of 18 months (March 2022 – August 2023) occurs in the neighbouring Rhone basin, with the largest severity of all episodes in this study (sum of DSI –30.6), which confirms the Alpine-wide character of the 2022 drought (Bevacqua et al., 2024). The long-term decline of TWS in the Po basin also contains the loss of Alpine glacier ice, which GRACE cannot separate from other storage components. For the GRACE-FO period, Lenczuk (2025) obtained a three times steeper trend (–2.7 cm/yr) for the same basin, which shows how strongly the 2022–2023 drought dominates short records. The Po basin is also one of the smallest basins analysed (74,000 km^2), so leakage from the Adriatic Sea and the Alpine parts of the Rhone and Danube basins may affect the magnitude, but not the timing, of the detected events.

5.3.2. Vistula river basin

The Vistula basin represents the central European lowlands with a pluvio-nival regime and covers about 54% of Poland. This basin shows that a substantial long-term water loss may occur without frequent droughts. The TWS trend is –0.65 cm/yr, i.e. a loss of about 15 cm over 24 years, but the basin has one of the smallest numbers of dry months (48) and the largest number of exceptionally wet months (13 months in W4). Moreover, the TWS tendency changed sign during the study period (Fig. 4). TWS in the Vistula basin increased until 2010–2011, reaching +13 cm in December 2010, and decreased afterwards to about –21 cm in October 2025. The trend is +0.65 cm/yr

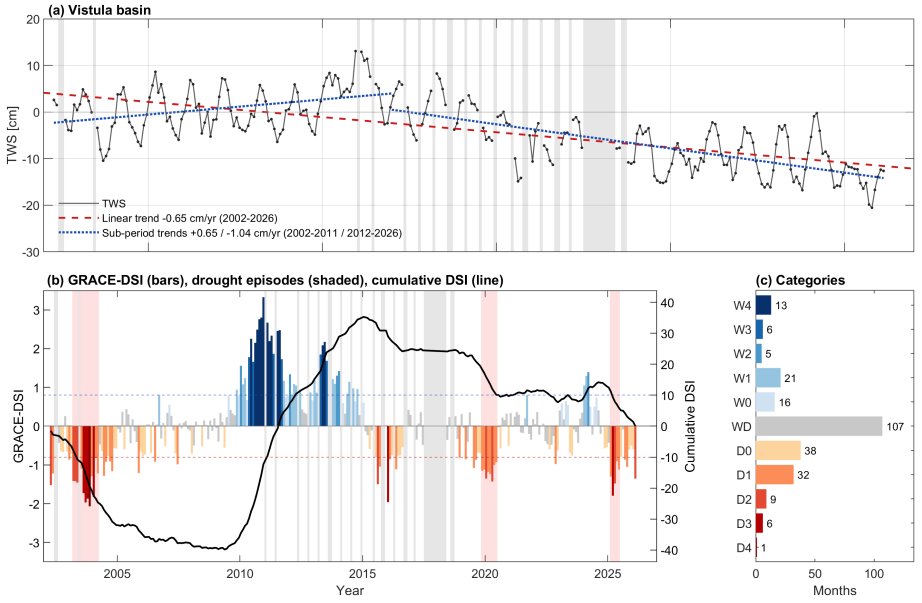


Fig. 4. Vistula basin: (a) monthly TWS with the linear trend for April 2002 – February 2026; (b) GRACE-DSI computed from detrended TWS (bars colored by category), drought episodes (shaded) and cumulative DSI (line, right axis); (c) number of months in DSI categories. Noted that grey bands mark missing months.

for 2002–2011 and –1.04 cm/yr for 2012–2026, i.e. the water loss started after the wet years 2010–2011. GRACE-DSI is negative in 2002–2004, with the minimum of –2.07 in November 2003, and strongly positive in 2010–2013, with the maximum of 3.33 in December 2010, which corresponds to the floods of May–June 2010 and the wet years that followed. After 2015, DSI varies mostly between –1.5 and +0.5. We identify only four drought episodes, lasting 3–9 months: March–May 2003, July 2003 – March 2004, November 2019 – June 2020 and February–June 2025. The share of drought months increased from 16.6% in the GRACE period to 23.1% in the GRACE-FO period. The cumulative DSI decreases until May 2009, increases until January 2015 and decreases afterwards. The observed drought episodes correspond to documented events, i.e. the 2003 drought in central Europe and the 2018–2020 multi-year drought, during which the storage deficit was not replenished in winter (Boergens et al., 2020; Rakovec et al., 2022). The 2015 summer drought, with record-low river flows in central and eastern Europe (Ionita et al., 2017), appears as single months with DSI down to –2.0, but not as an episode of at least three months. Notably, the record-low water levels of the Vistula in 2024 (IMGW-PIB, 2024) are not classified as drought. TWS in September 2024, about –16 cm, was close to the declining long-term tendency, so the anomaly relative to the trend was small (DSI $\geqslant$ –0.6 in 2024). This shows that in basins with a negative trend, low water storage is increasingly the new normal rather than an anomaly, and DSI computed from detrended TWS must be interpreted together with the trend. The Vistula basin also illustrates the dependence of trends on the analysed period, e.g., for June 2018 – February 2024, Lenczuk (2025) obtained a trend of –0.4 cm/yr from the JPL mascon solution and positive trends of up to +1.2 cm/yr from spherical harmonic solutions. The basin (169,000 km^2) is large compared with the resolution of GRACE and surrounded by land basins with similar hydrological behavior, so leakage is a minor issue, as Lenczuk (2025) has shown.

5.3.3. Kura–Ozero Sevan river basin

The Kura–Ozero Sevan basin in the South Caucasus represents the semi-arid basins with strong human water use. It shows the most significant TWS decline of all basins (–1.52 cm/yr), but at the same time the smallest number of dry months (45) and, together with the Narva basin, the largest number of D4 months (11). This apparent contradiction makes it a test case for the interpretation of DSI computed from detrended TWS, as climatic, anthropogenic and leakage-related factors overlap. TWS in the Kura–Ozero Sevan basin remained nearly stable until about 2010, with a trend of –0.34 cm/yr for 2002–2011, and decreased rapidly afterwards, with a trend of –2.05 cm/yr for 2012–2026, reaching about –38 cm in October 2025 (Fig. 5). The seasonal amplitude is small compared with the long-term change. GRACE-DSI is strongly negative in 2002–2003, with the minimum of –2.52 in October 2003, positive in 2009–2013 and 2016–2018, with the maximum of 2.31 in May 2010, and negative again in 2019–2023 and 2025. The two longest episodes, each lasting 10 months, occurred in August 2002 – May 2003 and November 2022 – August 2023. The percentage of months with dry conditions increased from 13.5% in the GRACE period to 25.3% in the GRACE-FO period. In 2024–2025, Armenia reported below-normal precipitation, a reduced snow cover and a further decline of the level of Lake Sevan (Arminfo, 2025), which agrees with negative DSI in 2025. The DSI series of the Kura–Ozero Sevan basin reflects the change in the rate of water loss during the study period. In 2002–2003, DSI was strongly negative, and all 11 months in category D4 occurred in this period, as TWS was below its long-term tendency. In 2009–2013 and 2016–2018, positive anomalies prevailed, with W3–W4 conditions in 2010 and 2016–2017, when TWS remained above the long-term tendency. After 2019, when TWS declined at about –2 cm/yr, negative anomalies dominated again, with the 10-month episode of November 2022 – August 2023 and further dry months in 2025. Consequently, the cumulative DSI decreases until January 2005, increases until May 2019 and decreases afterwards. A similar sequence of negative,

positive and again negative anomalies occurs in the Dniester basin, where the trend changed from –0.32 cm/yr in 2002–2011 to –1.80 cm/yr in 2012–2026. It is also important to consider the physical causes of this phenomenon. Part of the decline is caused by water use, i.e. irrigation from the Kura and Araks rivers, reservoir operation and the regulation of Lake Sevan. Another part may be leakage from the Caspian Sea, which borders the lower Kura plain and whose level has been falling by several centimeters per year (Prange et al., 2020). The basin width is comparable with the size of a single 3° mascon, so the mass loss of the Caspian Sea can be partly assigned to the adjacent land mascons. This interpretation is supported by Lenczuk (2025), who found that the JPL mascon trend for this basin was –3.6 cm/year, while the GLDAS model – which does not account for groundwater or human water use – showed a trend of +1.4 cm/year between 2018 and 2024. It is worth noting that, in such cases, separating these components requires predictive modeling of the signal from neighboring areas or the acquisition of independent in situ data.

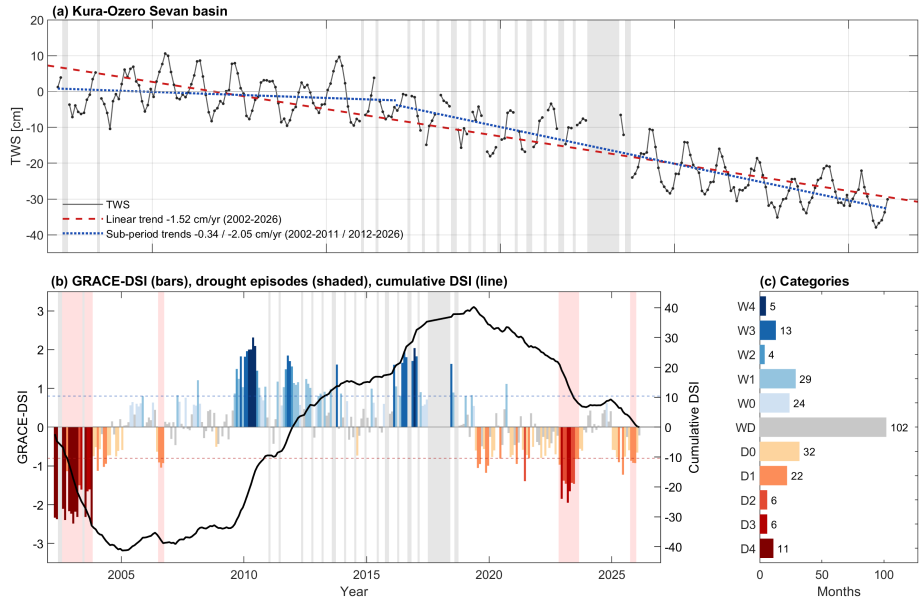


Fig. 5. Po basin: (a) monthly TWS with the linear trend for April 2002 – February 2026; (b) GRACE-DSI computed from detrended TWS (bars colored by category), drought episodes (shaded) and cumulative DSI (line, right axis); (c) number of months in DSI categories. Noted that grey bands mark missing months.

5.4. Remaining basins

The remaining 21 basins follow the regional patterns visible in Figure 2, but they differ in the timing, persistence and recent change of droughts.

Iberian basins (Douro, Ebro). Both basins show small TWS trends (–0.07 and –0.26 cm/yr), but frequent droughts: nine episodes each, with mean durations of 5.2 and 4.9 months. The Douro basin has the largest number of drought months of all basins (68). The lowest DSI values (–2.64 and –2.80) occurred in January 2017, during the dry year that preceded the devastating fires in Portugal (Turco et al., 2019). The most severe episodes occurred in 2022 and were followed by a further deficit in 2023, which led to restrictions of irrigation supply in the Ebro basin (Altés et al., 2024). The cumulative DSI peaks as early as 2005, and the share of drought months increased from 24.5% to 30.8% (Douro) and from 19.6% to 27.5% (Ebro) between the GRACE and GRACE-FO periods.

Atlantic and Alpine basins (Loire, Seine, Rhone, Rhine). All four basins lose water (–0.22 to –0.63 cm/yr). The lowest DSI values of the Loire (–3.09, the minimum of all basins), Seine (–2.92) and Rhone (–2.74) basins occurred in May 2011, i.e. during the exceptionally dry spring of 2011 in France. The longest and most severe episodes of all four basins occurred in 2022–2023 and lasted 11–18 months. In the Rhine basin, the minimum DSI (–1.96) occurred in November 2018, during one of the most severe droughts in west-central Europe in recent decades (Aalbers et al., 2023), and the Rhine has no D4 month but, together with the Douro, the largest number of D2–D3 months among the western basins (25). In all four basins, the share of drought months approximately doubled in the GRACE-FO period.

Central European basins (Elbe, Oder, Danube). The Elbe basin shows the largest increase in the share of drought months, from 15.3% to 38.5%. Its two longest episodes, June 2019 – February 2020 (9 months) and April 2020 – January 2021 (10 months), were separated by a single month and correspond to the 2018–2020 multi-year drought, described as one of the most extreme droughts since the 16th century in the German part of the basin (Rakovec et al., 2022). The Oder basin has the shortest droughts of all basins (mean 3.7 months, maximum 6 months) and 12 months of exceptionally wet conditions. In the Danube basin, the longest and most severe episode occurred in July 2003 – March 2004, and two further episodes in 2025 (3 and 7 months) mark the onset of a new deficit. The very low water levels of the Danube in September 2024, are not classified as drought, because TWS was close to its declining long-term tendency (DSI ≥ -0.4 in 2024), similarly to the Vistula basin.

Baltic and northern basins (Neman, Western Dvina, Narva, Vuoksi–Neva, Northern Dvina). These basins show practically no long-term change (–0.30 to +0.02 cm/yr), but rare and intense droughts: the Narva, Western Dvina and Vuoksi–Neva basins have 9–11 months in D4. The longest and most severe episode of these three basins is the drought of August 2002 – May 2003. Shorter episodes in 2015–2016 agree with the 2015 European drought (Ionita et al., 2017), and the longest episode of the Neman basin, June 2019 – June 2020 (13 months), agrees with the critically low river levels in Lithuania in 2020 (LRT, 2020). The Northern Dvina basin was exceptionally wet in 2017–2020, with the maximum DSI of 3.16 in January 2020, but since 2023 droughts have recurred, and the episode that started in October 2025 is still ongoing. The Narva and Vuoksi–Neva basins are two of only five basins with fewer drought months in the GRACE-FO period.

Eastern lowland basins (Dniester, Dnieper, Don, Volga). The Dniester (–1.35 cm/yr), Dnieper (–0.90 cm/yr) and Don (–0.78 cm/yr) basins belong to the group with the steepest water loss. In the Dniester basin, the longest and most severe episode lasted for the whole of 2025 (12 months), whereas in the Dnieper basin it lasted 17 months, from September 2019 to January 2021, and is the second most severe episode of all basins (sum of DSI –29.1). In 2023–2024, DSI in the Dnieper basin was positive (annual means +1.2 and +1.4), so the drainage of the Kakhovka reservoir in June 2023, which removed about 18 km^3 of water (Vyshnevskyi and Shevchuk, 2024), i.e. about 3.5 cm of EWH averaged over the basin, is not visible as a drought at the basin scale. The Don basin has frequent and short droughts (nine episodes, mean duration 4.3 months), and 2024 was wet there (DSI above +0.8 in all months). In the Volga basin, the minimum DSI (–2.32) and the longest episode (May–December 2010) correspond to the record-breaking heatwave and drought of summer 2010 in European Russia (Barriopedro et al., 2011). The Don and Volga basins show fewer drought months in the GRACE-FO period than in the GRACE period.

Anatolian and Mesopotamian basins (Kızılırmak, Sakarya, Tigris–Euphrates). All three basins lose water (–0.63 to –0.86 cm/yr). The Sakarya basin has the longest droughts on average (8.2 months), with episodes of 11 and 12 months in 2007 and 2008–2009, and another 12-month episode from February 2025 to January 2026, when precipitation in the Marmara region was far below normal (Reuters, 2025). In the Kızılırmak basin, the longest episode (February–September 2008) and two episodes in 2025 agree with the meteorological droughts analyzed by Aktürk et al. (2024).

The Tigris–Euphrates basin hosts the longest episode of all basins, May 2008 – November 2009 (19 months, sum of DSI –27.9), which corresponds to the 2007–2009 drought and the groundwater depletion detected by GRACE in this region (Voss et al., 2013). After a wet period in 2019–2020, with the maximum DSI of 2.18 in March 2020, DSI remains near normal during the 2021–2022 meteorological drought (Darvishi Boloorani et al., 2024) and becomes negative again in 2025. The Tigris–Euphrates basin shows the largest decrease in the share of drought months, from 28.2% to 14.3%, because its most severe drought occurred in the GRACE period. Upstream dams and groundwater abstraction amplify the climatic deficit in all three basins (Xanke and Liesch, 2022).

5.5. Limitations

The drought statistics presented here are subject to several limitations. First, the effective spatial resolution of GRACE (about 300 km) is close to the size of eleven of the analysed basins. Even for the mascon solution, part of the signal of small coastal and neighbouring basins is mixed, which affects the magnitude of TWS and DSI in the Narva, Dniester, Po, Seine, Kızılırmak and Sakarya basins (Lenczuk, 2025). Second, the 11-month gap between GRACE and GRACE-FO and the missing months of the late GRACE period interrupt the time series and may split or shorten drought episodes, e.g. around 2017–2018. Third, the episodes that are still ongoing in February 2026, i.e. in the Northern Dvina and Vuoksi–Neva basins, are censored at the end of the analyzed period, whereas episodes from August 2002 to May 2003 in the northeastern basins may be censored from the beginning of the period because data for June and July 2002 are missing; their durations are lower bounds. Finally, TWS includes human-managed storage, i.e. reservoirs and groundwater abstraction. GRACE-DSI therefore describes the total storage deficit, regardless of whether it is caused by climate, water use or, as in the Dnieper basin in 2023, by the destruction of infrastructure.

6. Summary and conclusions

In this study, we analyzed drought characteristics of 24 major European river basins using GRACE/GRACE-FO mascon TWS for April 2002 – February 2026. We estimated linear TWS trends, computed GRACE-DSI and its cumulative sum, classified monthly drought and wet conditions, and identified drought episodes. Our main conclusions are as follows:

1. Water storage decreases in 23 of 24 basins. The trends range from –0.06 cm/yr (Vuoksi–Neva) to –1.52 cm/yr (Kura–Ozero Sevan), and only the Western Dvina basin shows no long-term change. The most significant declines, of –0.75 cm/yr or less, occur in eight central, southern and southeastern basins, which lost 18–36 cm of EWH over 24 years.
2. Trends estimated for the GRACE-FO period only are two to four times larger in magnitude and partly differ in sign from the long-term trends. Short records are dominated by interannual variability, so trends from both missions should be preferred in climate-related studies.
3. Droughts frequently affect many basins at the same time. More than 10 of 24 basins were in drought mainly in 2003, 2006, 2019–2020 and 2022–2023, with a maximum of 16 basins in July 2006 and November 2022, whereas 2013 and 2024 were almost free of drought.
4. Drought episodes last 3–19 months, on average 5.3 months. The longest episodes occurred in the Tigris–Euphrates (2008–2009, 19 months), Rhone (2022–2023, 18 months), Dnieper (2019–2021, 17 months) and Po (2022–2023, 16 months) basins, and in 12 basins the longest episode occurred after 2018.
5. Between the GRACE (2002–2017) and GRACE-FO (2018–2026) periods, the share of drought months increased in 19 of 24 basins, from 19.0% to 25.1% on average, and the mean episode duration increased in 17 basins, from 4.6 to 6.9 months. The share of drought months doubled in the Loire, Rhone, Seine, Rhine and Elbe basins and decreased only in five northeastern and southeastern basins.

The results we obtained highlight that in basins with a negative trend, low storage becomes the new normal, and that linear detrending may produce spurious early droughts where water loss accelerates. Moreover, we show a potential of satellite gravimetry for monitoring hydrological drought in large and transboundary river basins, where consistent in situ data are lacking.

Author contributions

Conceptualization: A.L.; data collection and curation: A.L., L.D.; methodology: A.L., L.D.; formal analysis: A.L., L.D.; visualization: A.L., L.D.; writing – original draft: A.L., L.D.; writing – review & editing: A.L.; supervision: A.L.

Data availability statement

The JPL GRACE/GRACE-FO mascon solution RL06.3Mv04 is available at https://grace.jpl.nasa.gov. Basin-average TWS series and GRACE-DSI values computed in this study are available from the corresponding author upon request.

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