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Original Research Article

EUROPEAN CLIMATE SIGNALS IN WATER BUDGET DYNAMICS

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A b s t r a c t

Monitoring the water budget helps us understand and manage the available water in a specific area, as well as track its use. Knowing the water budget (i.e., the difference between water inflow and outflow) allows us to predict water shortages or surpluses. In these times of climate change, the risk of extreme events such as droughts and floods is rising. The study considered the area of the European continent, classified according to the Koppen-Geiger climate zones, as it features a highly diverse climate. This research aims to evaluate the water budget across Europe and perform further analysis using indices: the Relative Retention Index (RRI), Storage Change Index (SCI), Water Stress Proxy (WSP), and Modified Runoff Ratio with EV correction (MRR). The research shows that area 4 (Scandinavia, with the coldest climate) exhibits the best water retention and balance. Monthly MERRA-2 data for precipitation, evapotranspiration and surface runoff were analysed for the period [2002-2025] across six European climatic regions. The results revealed a strong and coherent seasonal water budget cycle across all regions, while the magnitude of seasonal and interannual variability differed substantially among them. Correlations between regional water budget series and the European mean ranged from 0.834 to 0.912, indicating strong temporal coherence but also regional differences in the magnitude of water budget variability. Long-term trends in the annual water budget were weak and spatially heterogeneous, with values ranging from -3×10^{-9} to 5×10^{-9} yr^{-1}, and no statistically significant monotonic trend was detected across the six regions. The four derived indices complemented the aggregate water budget by characterising different aspects of water partitioning and hydroclimatic variability, including relative runoff response, storage-related changes and seasonal water stress. Their combined use revealed regional contrasts that were not apparent from the aggregate water-budget signal alone, particularly the stronger warm-season water-stress signal in southern regions and the distinct seasonal runoff response in the northern region.

Keywords: water budget, precipitation, evapotranspiration, surface runoff, indices

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1. INTRODUCTION

Climate change, which may indicate extreme phenomena such as droughts, requires monitoring. This is due to global warming disrupting the water cycle. There is a significant need to implement large scale measurements and observations, and remote sensing observations are ideal for such situations. To better understand and respond to phenomena in a disrupted water cycle, it is essential to study the water budget and develop coefficients to aid its interpretation.

Issues related to broadly understood water management were addressed already in ancient times, as water is the essence of life. It is important to determine water resources, which are the amounts of water available for abstraction. The water budget is the difference between supply (through precipitation and river inflow) and expenditure (direct surface runoff from rivers to the sea, indirect surface runoff, plus evaporation and transpiration). The values of water budget components are random events and change from year to year depending on climatic and hydrological conditions. In extreme years (dry or wet), the values of water budget components deviate from the multi-year average values [Akl and Thomas, 2024; Chen et al., 2024; Unnisa et al., 2023].

The value of the water budget is influenced by climate, terrain, distance from seas and oceans, ocean currents, and vegetation. The proposed study considered the European continent, which is highly diverse in each of these aspects, so each factor has a varying degree of influence on individual changes in the water budget [Healy et al., 2007; Baffaut et al., 2020; Martínez-Retureta, 2022].

Water budget assessments have increasingly benefited from the availability of satellite observations, reanalysis products and data driven approaches. Recent reviews show that complete water budget estimation has been conducted across a wide range of spatial and temporal scales, from individual basins to continental and global domains. However, the choice of datasets and spatial scale strongly affects the formulation and interpretation of the resulting water budget. Moyers et al. [2023] reviewed data-driven water budget studies published during 2012-2022 and showed that large-scale assessments increasingly rely on satellite remote sensing and reanalysis products, whereas ground-based observations remain more important at smaller spatial scales. The authors also highlighted the need for more explicit reporting of simplifying assumptions, uncertainties and the consistency of data sources when complete water budgets are constructed. These findings indicate that continental water budget assessments are feasible, but their interpretation requires particular attention to the spatial scale and to the representation of individual water cycle components.

Satellite gravimetry, particularly the Gravity Recovery and Climate Experiment (GRACE) mission, has provided an independent perspective on terrestrial water storage (TWS) changes. GRACE is particularly valuable because it integrates water storage changes across the soil, surface-water and groundwater compartments that are difficult to observe consistently at continental scales. GRACE-based studies have been used to investigate drought development, groundwater depletion and terrestrial water storage variability in Europe and globally. For example, Houborg et al. [2012] demonstrated the value of GRACE derived terrestrial water-storage information for drought monitoring, while Li et al. [2019] showed that assimilating GRACE observations can improve groundwater estimates at regional and global scales. In western and central Europe, GRACE observations have also been assimilated into land-surface models to improve simulated runoff and terrestrial water storage. Nevertheless, GRACE provides an integrated storage signal rather than a direct decomposition of precipitation, evapotranspiration and runoff, and its relatively coarse effective spatial resolution limits its ability to resolve detailed regional hydrological contrasts. Consequently, GRACE and water budget approaches provide complementary rather than interchangeable information on the terrestrial water cycle.

Reanalysis products have become another major source for large scale hydrological assessments because they provide spatially and temporally consistent estimates of precipitation, evapotranspiration, runoff and other land surface variables. MERRA-2, provides a longer-established global reanalysis framework with internally consistent atmospheric and land-surface variables and has been widely used for hydroclimatic analyses. However, reanalysis products are not interchangeable: differences in forcing data, land-surface parameterisations, spatial resolution and treatment of evapotranspiration and runoff can lead to differences in estimated water-cycle components. Recent intercomparison of terrestrial evapotranspiration products, for example, demonstrated systematic differences among ERA5-Land, MERRA, GLDAS and satellite-based products, indicating that the choice of reanalysis can influence water-balance estimates. Therefore, a consistent single reanalysis framework can be advantageous when the primary objective is to compare relative temporal and spatial behaviour across climatic regions rather than to combine heterogeneous estimates from multiple products.

The relevance of these large scale assessments has increased because climate change is altering both the amount and seasonal distribution of water availability across Europe. Changes in precipitation alone do not fully describe these impacts, because increasing atmospheric demand and evapotranspiration can amplify water deficits even where precipitation changes are relatively small. Observational and modelling studies have demonstrated that evapotranspiration can intensify European summer droughts and contribute substantially to the development of terrestrial water storage deficits. Teuling et al. [2013], for example, showed that increased evapotranspiration can amplify drought-related storage anomalies in central and western Europe, highlighting the importance of considering evapotranspiration together with precipitation and runoff. More recent European assessments indicate substantial spatial contrasts in future drought impacts, with southern and western Europe expected to experience particularly strong increases in drought related impacts under continued warming, while northern regions may experience different hydrological responses. These findings emphasise that changes in European water availability are spatially heterogeneous and cannot be adequately represented by a single continental average.

Several studies have also used normalised ratios and indices to describe how precipitation is partitioned among evapotranspiration, runoff and storage-related components. The runoff ratio is one of the most established examples and is commonly defined as the ratio of runoff to precipitation. It provides information on the long term partitioning of precipitation between runoff and evapotranspiration and is widely used to characterise hydrological response and constrain hydrological models. More generally, Budyko-type approaches use ratios between precipitation, evaporation and runoff to describe water-energy partitioning across contrasting climatic environments [Milly, 1994; Olden and Poff, 2003]. Recent global studies have further demonstrated that precipitation partitioning, and runoff response depend not only on mean climate but also on climate seasonality, soils, vegetation and other basin characteristics. These approaches demonstrate the value of dimensionless or normalised indicators for interpreting water budget components, but they generally focus on one partitioning relationship rather than combining several complementary indicators within a common continental scale framework.

Taken together, the existing literature demonstrates that European water availability has been investigated from several complementary perspectives: continental water-budget assessments describe the balance between major fluxes; GRACE provides an integrated observation of terrestrial water storage changes; reanalysis products provide spatially and temporally continuous estimates of water cycle components; and runoff ratios and related indices describe individual aspects of precipitation partitioning. However, these approaches are most often applied separately, at different spatial scales, or within individual catchments or specific hydrological processes. Consequently, there remains a need for a consistent framework that uses the same underlying climatic variables to examine several complementary characteristics of the water budget across contrasting European climate settings.

The present study addresses this gap by combining the climatic water budget with four complementary indicators - Relative Retention Index (RRI), Storage Change Index (SCI), Water Stress

Proxy (WSP), and Modified Runoff Ratio with evapotranspiration correction (MRR) - within a common MERRA-2 framework. The indicators are not assumed to provide statistically independent information; instead, they are used to emphasise different interpretations of the same underlying water budget components. The analysis is conducted for six climatic regions representing contrasting European climate conditions, allowing regional differences in water retention, water availability, water stress and runoff response to be examined without imposing political boundaries or restricting the analysis to individual drainage basins. This framework is intended to bridge the gap between continental scale water budget assessments and process specific regional hydrological studies.

The research aims to assess water budget parameters and analyse the dynamics of signals in the climatic regions of Europe. An innovative approach is an analysis of the water budget of the entire continent, a comparison of indicators and their modification. A regional framework is particularly useful for this purpose because the objective is not to resolve local basin scale hydrological processes, but to compare the temporal behaviour of climatic water budget signals across contrasting European climate settings.

Despite the extensive literature on European water budget variability, previous studies have predominantly focused on individual components of the water cycle, comparisons between different datasets or models, or specific hydrological processes and basins. The use of water budget information to simultaneously characterise retention, relative water availability, water stress and runoff response across contrasting climatic environments remains insufficiently explored. In particular, it has not been sufficiently addressed how the interpretation of a continental-scale water-budget signal changes when the same precipitation, evapotranspiration and surface runoff information is examined through several complementary indicators within a common spatial and temporal framework.

The scientific question addressed in this study is therefore: Can a set of complementary water budget indicators reveal spatially differentiated characteristics of water retention, water availability, water stress and runoff response across European climate regions that cannot be distinguished from the aggregate water budget signal alone? The four indicators considered - RRI, SCI, WSP, and MRR - are not treated as statistically independent variables. Rather, they provide different process oriented representations of the same underlying climatic water budget components. While the water budget expresses the net relationship between precipitation, evapotranspiration and surface runoff, RRI emphasises the fraction of precipitation not immediately represented as surface runoff, SCI provides a normalised indication of net water availability, WSP highlights conditions associated with potential water stress, and MRR characterises the runoff response relative to water remaining after evapotranspiration. Their combined use therefore enables the temporal behaviour of the water budget to be interpreted from several complementary hydrological perspectives.

A further element of the proposed framework is the use of climatic rather than political or basin boundaries. The six climatic regions were selected to represent contrasting European climate settings and the major climatic gradients across the continent. This regionalisation allows areas exposed to comparable climatic forcing to be evaluated within a consistent framework, irrespective of national borders or individual basin boundaries. In contrast to country scale analysis, which may combine several distinct climate regimes within one administrative unit, and basin scale analysis, which is primarily suited to closed hydrological systems, climate-region analysis is appropriate for the objective of this study: identifying common and contrasting climatic controls on water budget behaviour across Europe. The six region framework therefore provides a spatial scale intermediate between local/basin studies and continent wide aggregation, allowing regional differences to remain visible while avoiding an excessive fragmentation of the analysis.

Accordingly, the novelty of this study lies in the integration of four complementary water-budget indicators with a common MERRA-2-based water budget framework across six contrasting European climate regions. This approach enables the study to distinguish between the aggregate water budget response and changes in retention, relative water availability, water stress and runoff response, while maintaining a consistent climatic basis for comparison across the continent.

2. MATERIALS AND METHODS

2.1. Used data and models

The study was conducted in Europe, divided according to the Köppen-Geiger climate classification (Figure 1). The division is consistent with the previous author's research on the area [Birylo, 2026a; Birylo, 2026b; Birylo, 2026c]. The six regions used in this study were defined to provide spatially coherent climatic units representing the major climatic conditions occurring across Europe while maintaining a sufficient spatial extent for robust aggregation of the MERRA-2 data. The division was based on the spatial distribution of the Köppen-Geiger climate classification and was designed to distinguish the main climatic gradients across Europe, including oceanic, continental, Mediterranean, and cold/northern conditions. The six region configuration was retained to ensure consistency with the spatial framework used in our previous research and to allow direct comparison of the climatic water budget characteristics between regions. Thus, the six regions should be regarded as analytical climatic domains rather than as independent hydrological basins or as the only possible subdivision of the European continent.

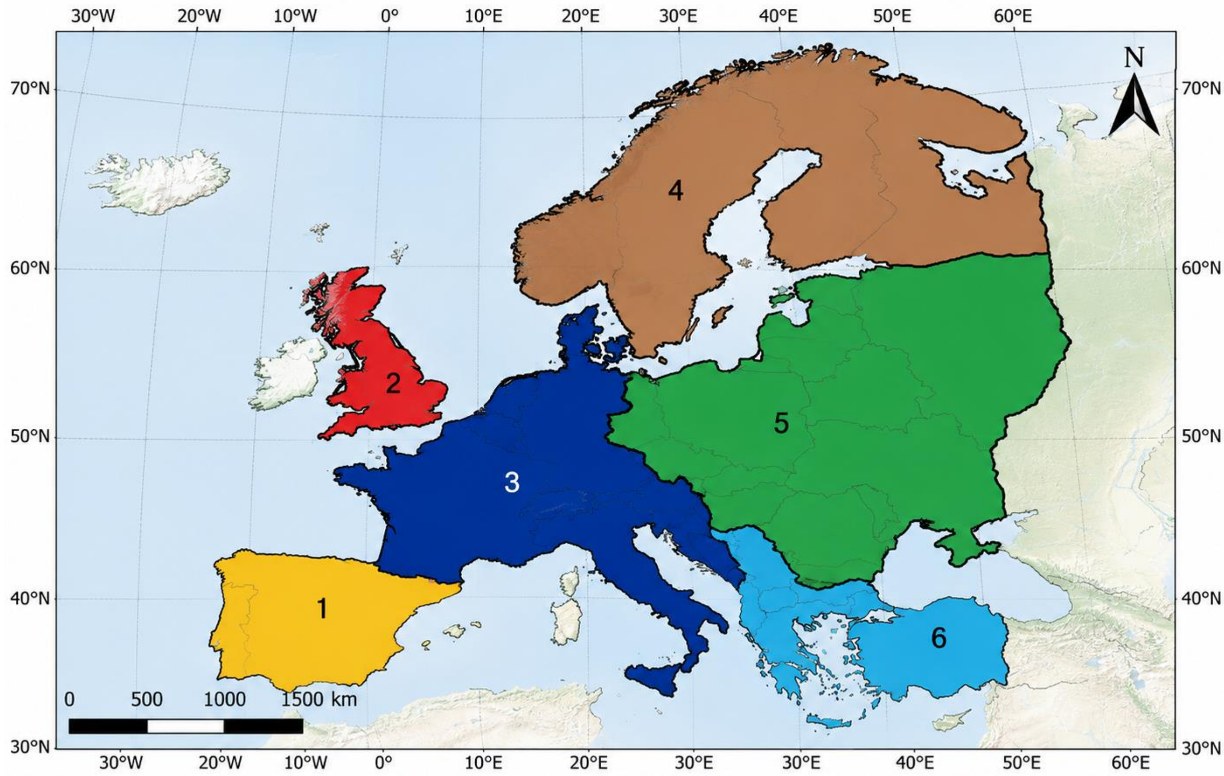


Fig. 1. Division of Europe into climatic zones according to the Köppen-Geiger division. The areas were assigned numbers, which were then used in the presented work

MERRA 2 (Modern-Era Retrospective Analysis for Research and Applications) observations were used for the analyses. This is a climate data reanalysis model that spans the period from 1980 to the present. The model is based on GEOS (Goddard Earth Observing System). Observations are published at 72 levels at a monthly time resolution on a grid of 0.5° latitude and 0.625° longitude. The MERRA model aims to use advanced numerical models to combine observations from multiple sources (in situ atmospheric observations, remote sensing data, observations from microwave sonars, and hyperspectral infrared instruments). Model creation is based on grid-point statistical interpolation [Rienecker et al., 2011; Reichle et al., 2017; Hamal et al., 2020].

For further analysis, publicly available data were collected: precipitation, evapotranspiration, and surface runoff from https://gmao.gsfc.nasa.gov/gmao-products/merra-2/data-access_merra-2/ (accessed on 23.10.2025). Each parameter was analysed separately for each of the six selected European regions, as shown in Figure 1.

The MERRA-2 data used in this study were analysed at monthly temporal resolution. The monthly data were organised according to calendar year and month and subsequently matched across all water budget variables to provide a common temporal basis for the analysis. Before calculating the water budget and derived indices, the time series were checked for missing values, physically implausible values and temporal discontinuities. The completeness and temporal consistency of the resulting monthly series were verified before further analysis. Given the resolution of the collected data, values were averaged across entire areas using the arithmetic mean. The use of such data inherently necessitates the analysis of large areas rather than individual grid cells; therefore, this procedure does not affect the result.

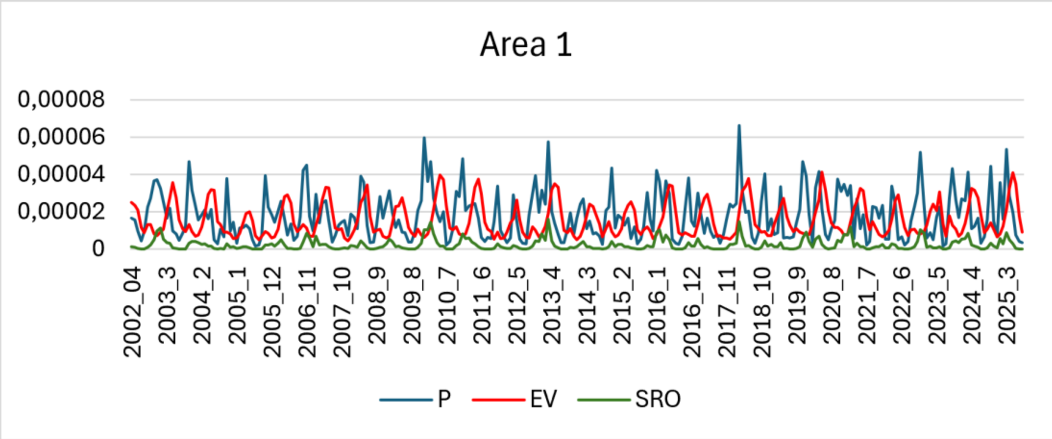
Precipitation is not a regular and cyclical phenomenon in Europe. In Area 1 (Figure 2a), evapotranspiration lags maximum precipitation by about 5 months and is approximately 0.00001-0.00002 kg m^{-2} s^{-1} lower. The highest precipitation falls in autumn. Typically, maximum precipitation values are around 0.00004 kg $m^{-2}s^{-1}$, but in 2009, 2013, 2018, and 2025, precipitation reached 0.00006 kg $m^{-2}s^{-1}$. In area 2 (Figure 2b), precipitation does not fall below 0.00001 kg $m^{-2}s^{-1}$. Maximum values reach 0.00004-0.00005 kg $m^{-2}s^{-1}$, but since 2018, they have consistently remained at 0.00005 kg $m^{-2}s^{-1}$, with maximums occurring twice a year, at the beginning of spring and autumn. For most of the time, the precipitation and evapotranspiration time series have maxima at similar levels. Interestingly, evapotranspiration values in area 3 (Figure 2c) slightly exceed or are equal to precipitation values (except for the years 2002, 2014, and 2024). The maximum values of both series reach approximately 0.00005 kg $m^{-2}s^{-1}$. Area 4 (Figure 2d) shows a significant difference between precipitation (with values ranging from 0.00006 to 0.00008 kg $m^{-2}s^{-1}$) and evapotranspiration. Compared to the other areas, this area shows a more pronounced cyclical nature of precipitation, with the highest values at the beginning of summer. In this area, the lowest precipitation values are at the level of 0.000015 kg $m^{-2}s^{-1}$. Area 5 (Figure 2e) is characterised by quite high cyclicality and convergence in epoch and amplitude with evapotranspiration. Precipitation has very constant values, with August 2008 and June 2020 standing out, when precipitation values are higher than usual (approx. 0.000055 kg $m^{-2}s^{-1}$), and spring 2019, when values are exceptionally low compared to the same periods in the entire time series (0.000022 kg $m^{-2}s^{-1}$ - twice the maximum than usual).

Area 6 (Figure 2f) is characterised by very irregular precipitation, with many peaks. Periods of very high precipitation values are noticeable (December 2002, October 20010, February 2018, January 2021, October 2021) - around 0.00007 kg $m^{-2}s^{-1}$.

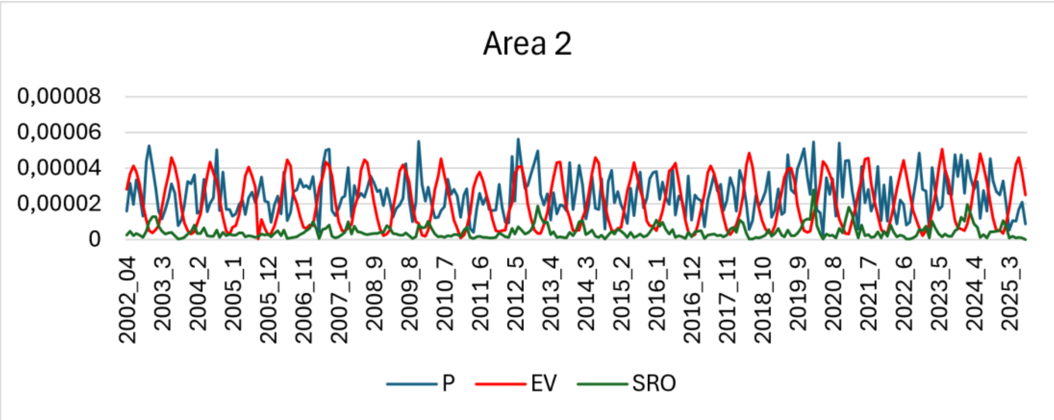
In every selected part of Europe, a pronounced seasonality of evapotranspiration is noticeable, with the highest values occurring in the summer months and the lowest in the winter months, consistent with the seasonal patterns in Europe. In each area, evapotranspiration values range between 0 and approximately 0.00004/0.00005 kg $m^{-2}s^{-1}$ (Figures 2a, 2b, 2c, 2d, 2e, 2f). The highest amplitudes were observed in areas 3 and 5 (the most continental climate), and the lowest in area 1 (ocean influence). A high degree of regularity in cyclical changes was observed for areas 2, 3, 4, and 5. In areas 1 and 6, variable amplitudes and regular double peaks of the highest values were observed.

The surface runoff time series has the lowest amplitudes, constituting about 15% of the values of the other two parameters (Figures 2a, 2b, 2c, 2d, 2e, 2f).

a)



b)



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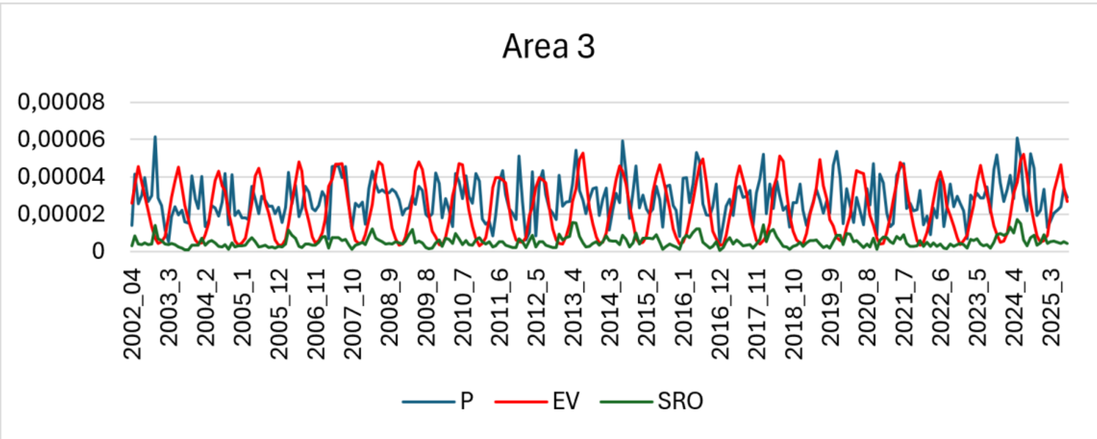
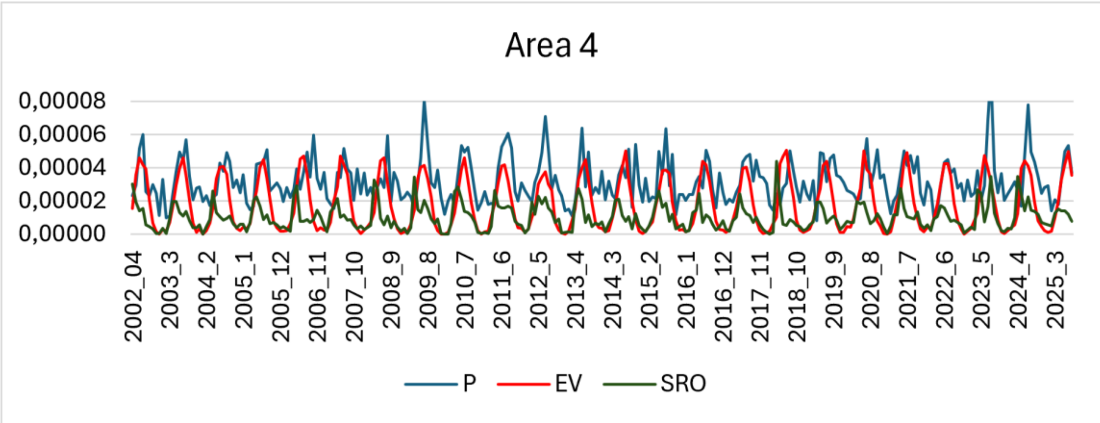
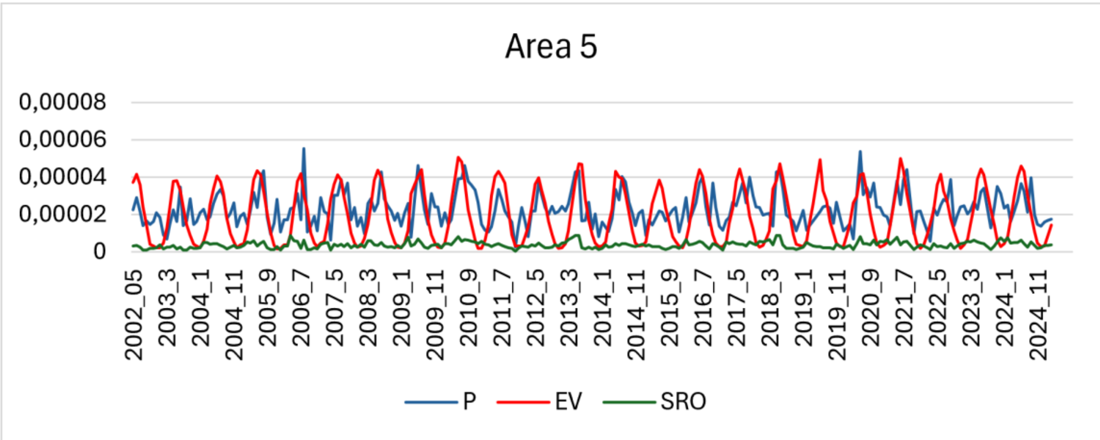


d)



e)



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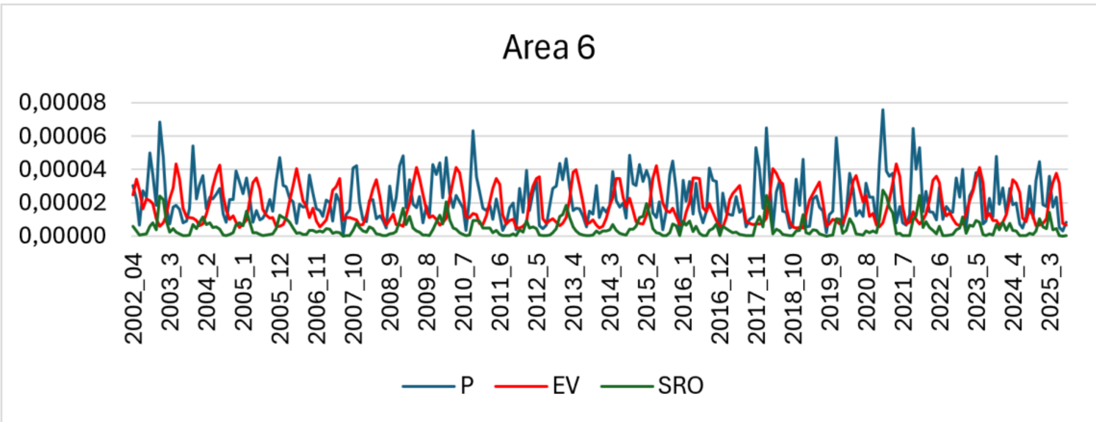

Fig. 2. Precipitation, evapotranspiration and surface run-off time series for regions 1 (a), 2 (b), 3 (c), 4 (d), 5 (e), and 6(f). All values in kg $m^{-2}s^{-1}$

Basic statistical characteristics were analysed for each element. The highest precipitation values were observed for area 4 (Figure 3a). 0.000025 kg $m^{-2}s^{-1}$lower precipitation values were observed in area 6, and the remaining areas had maximum values at a similar level, approximately 0.00005 kg $m^{-2}s^{-1}$(approximately $\frac{1}{3}$ lower than in area 4). Maximum evapotranspiration values are quite similar across Europe (around 0.000045 kg $m^{-2}s^{-1}$), with slightly lower maximum values in areas 1 and 6 (0.00004 kg $m^{-2}s^{-1}$). Among the three time series studied, the maximum values are most diverse for surface runoff. The highest maximum values are found in area 4 (reaching approximately 0.000045 kg $m^{-2}s^{-1}$), while in area 5, the maximum runoff values are one-quarter of those in area 4.

When it comes to minimum precipitation values, there are large variations (Figure 3b). Area 4 has a minimum value of 0.000008 kg$m^{-2}s^{-1}$, while areas 1 and 6 have dry periods, with very slight precipitation values. The minimum evapotranspiration in area 4 reaches zero values - this is an area with a polar climate and therefore little sunlight and heat for a large part of the year. Area 1 and Area 6 have significantly higher evapotranspiration minimum compared to the others; these are the areas located most southerly in Europe. Surface runoff is almost zero in terms of minimum values, especially in areas 1, 4, and 6

Mean precipitation values (Figure 3c) are highest in area 4 - in addition to regular precipitation, this area experiences the heaviest snowfall. Interestingly, areas 5 and 6 have similar mean precipitation values, 0.000025 kg $m^{-2}s^{-1}$. The lowest mean precipitation was recorded in area 1 (approximately 0.000018 kg $m^{-2}s^{-1}$). The highest average evapotranspiration values were observed in area 3 (0.000025 kg $m^{-2}s^{-1}$) - a climate with maritime and continental influences. The lowest average evapotranspiration was observed in area 1 (0.000015 kg $m^{-2}s^{-1}$). It is worth noting that the average values of precipitation and evapotranspiration are similar in area 1.

Figure 3d shows the standard deviation of all the parameters tested. The lowest precipitation values are for area 5 (0.0000085 kg $m^{-2}s^{-1}$), which indicates the smallest variation in the variable time series. The highest values were recorded for areas 4 and 6 (approx. 0.000014 kg $m^{-2}s^{-1}$), meaning these are the areas where the values deviate the most from the mean. The standard deviation of evapotranspiration is mostly high and higher than that of precipitation, because in most areas it drops to almost zero in winter.

A relatively low value, especially compared to the other areas, is found in Area 1 (0.000009 kg $m^{-2}s^{-1}$); the remaining areas have values above 0.00001 kg $m^{-2}s^{-1}$. In the case of surface runoff, the standard deviation in Area 4 is clearly distinguished, being twice as high as the standard deviations of the other areas, reaching 0.000008 kg$m^{-2}s^{-1}$.

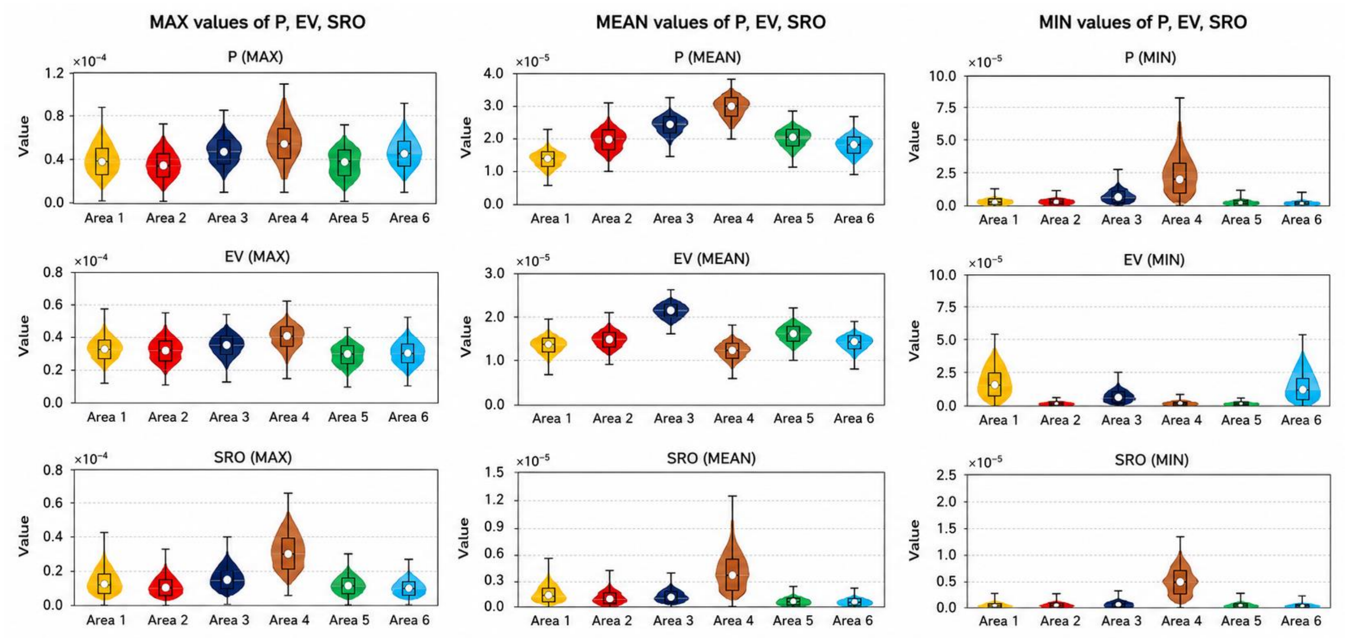

Fig. 3. Maximum, minimum, and mean) values of precipitation, evapotranspiration, and surface runoff for 6 selected areas

2.2. Methods

Figure 4 illustrates the study's design.

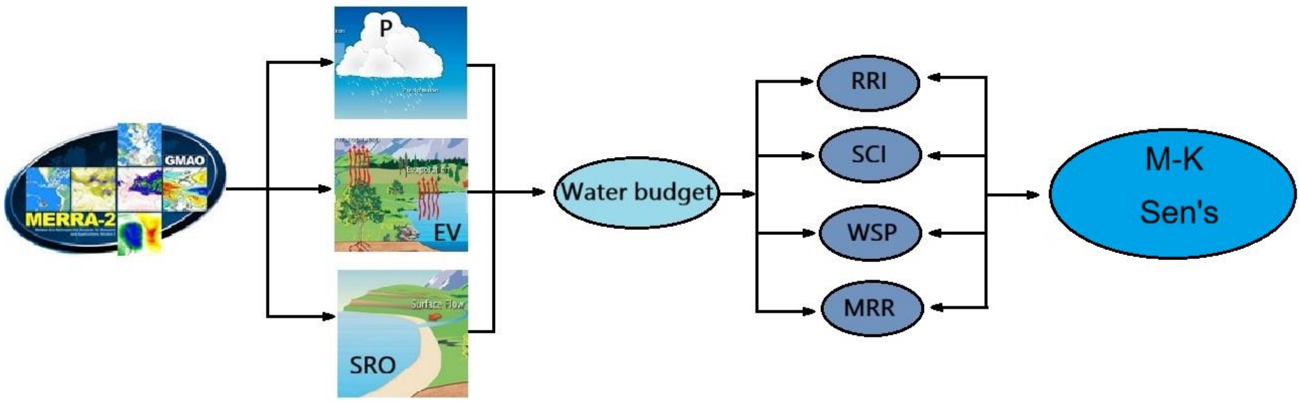

Fig. 4. Flowchart presenting the flow of data and models in the research

The study used a dataset from the MERRA 2 Reanalysis model: precipitation (P), evapotranspiration (EV), and surface runoff (SRO). Observations were collected for the period from April 2002 to August 2025 for all six identified areas. The prepared data were used to calculate time series of water budgets in each area. In the next step, based on the previously prepared parameters, 4 parameters were assessed for additional analysis: RRI, SCI, WSP, and MRR.

A simplified water budget considers all water that flows into and out of a basin area or specific area [Birylo et al., 2018; Blaszczak Bak et al., 2025]. It includes precipitation as input and evaporation, transpiration, and runoff as output [Kansoh et al., 2020; Shao et al., 2021; Avanzi et al., 2020; Weatherl et al., 2021]. It can be computed according to the formula:

$$\boldsymbol{WB = P - EV - SRO} \tag{2.1}$$

The water budget formulation adopted in this study represents a simplified climatic water budget approach. Because the analysed units are large Köppen-Geiger climatic regions rather than closed hydrological basins, the formulation includes only the dominant atmospheric water fluxes (P, EV, SRO). Other components such as groundwater inflow/outflow, snow and glacier storage changes, anthropogenic water use and lateral water transfer are not explicitly represented. Consequently, the calculated simplified water budget should be interpreted as a climatic indicator describing the balance between the principal atmospheric inputs and outputs rather than a complete hydrological mass balance.

Water budgets are interpreted as positive or negative. Areas where precipitation exceeds evapotranspiration in the water system have a positive water budget [Tardif et al., 2015; Blaszczak-Bąk et al., 2025]. It's worth noting that the greater the excess precipitation, the denser the surface water network. In the opposite situation, i.e., when evapotranspiration predominates over precipitation, they have a negative water budget. Studying and assessing the water budget in land areas is particularly important, as the water budget of individual land areas determines their freshwater resources.

To analyse the water budget, indicators have been developed to expand its interpretation. These include the Relative Retention Index (RRI), Storage Change Index (SCI), Water Stress Proxy (WSP), and Modified Runoff Ratio with EV correction (MRR).

IRR aims at interpreting the portion of precipitation that does not immediately flow out as surface runoff (that is, it discharges in the form of infiltration or evapotranspiration or is stored). It can be computed following the formula [Pappalardo et al., 2017, Bertrand-Krajewski, et al., 2018]:

$$RRI = \frac{P - SRO}{P} = 1 - \frac{SRO}{P} \tag{2.2}$$

RRI values range from 0.1 to 1, where 1 means all precipitation was retained (no runoff) and 0 means all precipitation flowed as surface runoff (no retention). Typically, values range from 0.3 to 0.8, depending primarily on soil conditions and urbanisation [Pappalardo et al., 2017; Bertrand-Krajewski et al., 2018].

The Storage Change Index (SCI) is used in this study as a normalised water availability proxy derived from the climatic water budget rather than as a direct measurement of terrestrial water storage. The index relates the net water budget component (precipitation minus evapotranspiration and surface runoff) to precipitation, thereby expressing the proportion of precipitation remaining after the considered atmospheric and surface losses. Because groundwater storage, soil moisture, snow storage and other subsurface or lateral fluxes are not explicitly represented in the formulation, SCI should not be interpreted as a direct estimate of physical storage change. Instead, it provides a relative measure of the potential amount of water remaining within the analysed climatic system and allows comparison of temporal variability between regions and periods:

$$SCI = \frac{P - EV - SRO}{P} = \frac{WB}{P} \tag{2.3}$$

SCI is a proxy index, not a direct measurement of storage. Accordingly, positive SCI values indicate that the considered water inputs exceed the represented losses, whereas negative values indicate that evapotranspiration and surface runoff exceed precipitation within the simplified formulation. The

magnitude of SCI should therefore be interpreted comparatively rather than as an absolute volume of stored water.
From the calculated water budget, we obtain the net value of the amount of water that remains in the system (soil, resources, underground runoff, etc.) after deducting losses through evapotranspiration and surface runoff (this relationship follows directly from the water budget formula). Normalising the formula yields the fraction of precipitation that remains in the water budget. A value of 1 indicates that almost all precipitation remains (low losses) and water availability is high; conversely, a value of 0 indicates that almost all precipitation P has evaporated or run off. A value below 0 indicates water losses that exceed precipitation (e.g., local drought). The interpretation of the study was based on the following principles:

WSP is intended to determine the potential water deficit (i.e., if evapotranspiration exceeds precipitation, it will indicate drought). It is calculated as [Nagler et al., 2007]:

$$WSP = \frac{EV}{P} \tag{2.4}$$

WSP is an indicator describing the severity of water stress in each area. The higher the WSP value, the greater the water demand relative to its availability (which indicates greater water stress, i.e., moisture deficit in the system (e.g., in the soil or vegetation). The results are generally interpreted as:

The SCI and WSP were primarily interpreted as continuous indices, with higher SCI values indicating a relatively larger positive water budget signal and higher WSP values indicating a stronger relative water-stress signal.

MRR is an attempt to assess runoff coefficient corrected for evapotranspiration. It can be computed from the formula [Gokmen et al., 2013]:

$$MRR = \frac{SRO}{P - EV} \tag{2.5}$$

This coefficient depends on land cover, soil type, and topography. Since the denominator may approach zero during extremely dry periods, MRR values may become unstable. In the analysed dataset, such situations occurred only occasionally and were interpreted with caution.

Although all indices are derived from the same three hydrological variables, each index emphasises a different aspect of the water budget (retention, storage, water stress and runoff efficiency). Therefore, the indices should be interpreted as complementary descriptors rather than statistically independent metrics.

The uncertainty of the derived water budget indicators is primarily related to uncertainties in the underlying MERRA-2 estimates of precipitation, evapotranspiration and surface runoff and to the simplified representation of hydrological processes at the continental scale. Because the three variables originate from the same internally consistent reanalysis framework, their uncertainties are not statistically independent. Therefore, formal propagation of independent measurement errors was not applied. Instead, uncertainty was addressed through statistical significance testing, confidence intervals for trend estimates and sensitivity analysis of the derived indices. The limitations associated with the spatial aggregation of the MERRA-2 variables and the simplified water budget formulation are considered when interpreting the results.

2.3. Statistical trend analysis

To assess whether the observed temporal changes represent statistically significant long term trends rather than fluctuations associated with the pronounced seasonal variability, non parametric trend analysis was applied to the water-budget and index time series. The Mann-Kendall test was used to evaluate the statistical significance and direction of monotonic trends, while Sen's slope estimator was used to quantify the magnitude of the trend. The non-parametric approach was selected because the analysed hydrological time series are not necessarily normally distributed and may contain extreme values.

3. RESULTS

3.1. Water budget variability

According to Equation (1), the water budget time series show a pronounced and consistent seasonal cycle across all six climatic regions (Figure 5). Positive water budget values generally occur during the autumn-winter period, whereas negative values are most pronounced during spring and summer. This common seasonality indicates that the annual water budget signal is primarily controlled by the seasonal relationship between precipitation and evapotranspiration.

Despite this common seasonal structure, substantial differences occur in the amplitude and temporal variability among the regions. Area 5 exhibits the narrowest and most stable range, approximately
-0.00002 to 0.00002 kg m^{-2} s^{-1}, indicating relatively limited temporal variability. Areas 2 and 6 show the largest amplitudes, reaching approximately -0.00004 to 0.00004 kg m^{-2} s^{-1} during the most variable periods. Area 4 generally exhibits intermediate and relatively regular amplitudes, although isolated positive and negative anomalies occur. Areas 1 and 3 show intermediate variability, with periods of reduced amplitude around 2006-2008 followed by renewed increases in subsequent years.

An increase in the amplitude of the seasonal water budget signal is particularly evident in Areas 2 and 6 during the later part of the record. This indicates that the difference between positive and negative seasonal water budget conditions became larger in these regions, rather than representing a uniform change in the mean water budget. Conversely, Area 5 maintained the most stable temporal behaviour throughout the study period.

The regional comparison therefore indicates a common seasonal forcing superimposed on substantially different magnitudes of interannual variability. The strongest variability occurs in Areas 2 and 6, whereas Area 5 is characterised by the most stable water budget regime. These differences provide the basis for interpreting the contrasting behaviour of the four derived indices presented below.

The correlation coefficient between each time series and the average value for the whole of Europe is presented in Table 1. The correlation analysis shows strong temporal coherence between the regional water budget series and the European mean, with Pearson correlation coefficients ranging from 0.834 to 0.912 (Table 1). The highest coefficient was obtained for Area 3 ($r = 0.912$), followed by Area 2 ($r = 0.908$), whereas Area 1 showed the lowest value ($r = 0.834$). Thus, all six regions reproduce the dominant continental scale seasonal signal, but the strength of this common signal differs among regions.

The relatively narrow range of correlation coefficients (0.834-0.912) indicates that the principal temporal variability is shared across the analysed regions. However, these correlations should be interpreted as a measure of temporal coherence rather than as evidence that the regions do not differ hydrologically. Because the European mean includes the regional series themselves, the correlations are partly influenced by the construction of the reference series. The regional differences are therefore better evaluated using the amplitude, trend and distribution of the water-budget series and the derived indices.

The highest value was found for area 3 (0.912), and the lowest for area 1 (0.834).

The estimated long term trends are generally small relative to the magnitude of the seasonal variability (Table 2). Positive trends occur in Areas 1, 3, 4 and 5, whereas Areas 2 and 6 exhibit negative trends. The strongest positive trend occurs in Area 4 (5×10^{-9} yr^{-1}), followed by Area 1 (4×10^{-9} yr^{-1}) and Area 5 (3×10^{-9} yr^{-1}). Area 6 shows the strongest negative trend (-3×10^{-9} yr^{-1}), while the trend in Area 2 is close to zero (-5×10^{-10} yr^{-1}). Area 3 also shows only a weak positive trend (9×10^{-10} yr^{-1}).

The magnitude of the trends is substantially smaller than the seasonal fluctuations observed in Figure 5. Therefore, the results indicate that the dominant temporal characteristic of the water budget is its seasonal variability, while the long term changes are comparatively weak and spatially heterogeneous. In particular, the opposite signs of the trends in Areas 2 and 6 compared with Areas 1, 3, 4 and 5 indicate that the long-term evolution of the water budget is not spatially uniform across the six climatic regions.

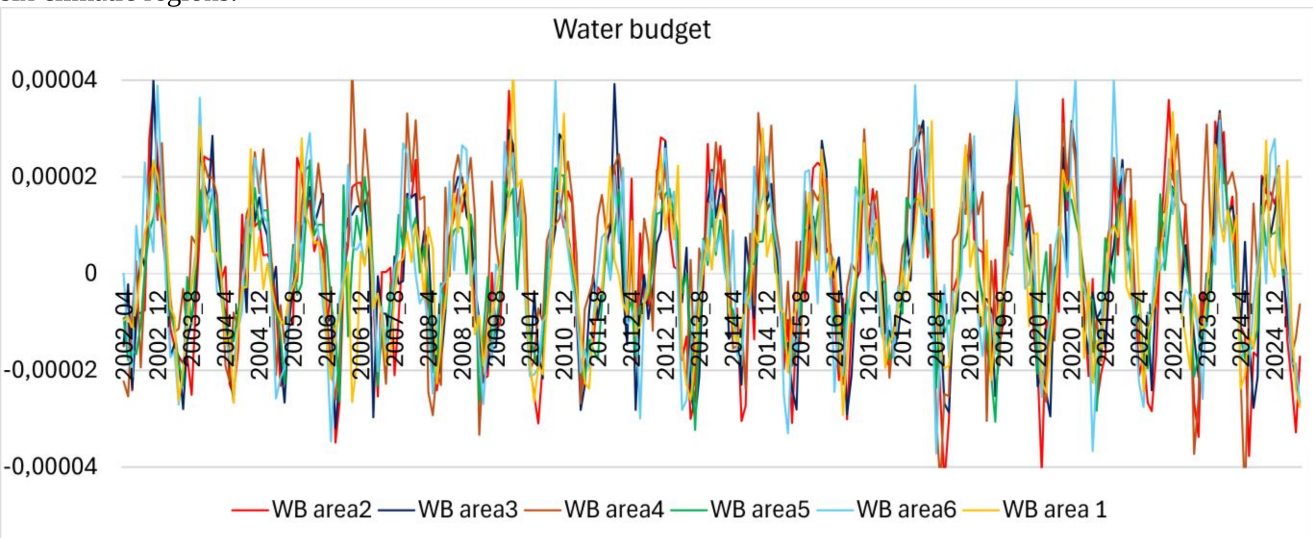

Fig. 5. Water budget time series for areas 1, 2, 3, 4, 5, and 6. All values in kg $m^{-2}s^{-1}$

Table 1. Correlation coefficient between the mean value for the whole of Europe and areas 1, 2, 3, 4, 5, and 6

	Area 1	Area 2	Area 3	Area4	Area 5	Area 6
Mean value	0.834	0.908	0.912	0.862	0.882	0.838

Table 2. Water budget trends for areas 1, 2, 3, 4, 5, and 6

	Area 1	Area 2	Area 3	Area4	Area 5	Area 6
Trend	4×10^{-9} yr^{-1}	-5×10^{-10} yr^{-1}	9×10^{-10} yr^{-1}	5×10^{-9} yr^{-1}	3×10^{-9} yr^{-1}	-3×10^{-9} yr^{-1}

3.2. RRI analysis

Having prepared the observations to determine the water budget, the Relative Retention Index was determined (Figure 6) using the formula (2). The RRI time series show substantial differences in the magnitude and variability of relative water retention among the six regions (Figure 6). Most values fall within the range of approximately 0.5-1.0, indicating that most of the analysed observations are characterised by relatively high retention in the RRI formulation. Area 4 exhibits the largest temporal variability and the lowest RRI values, occasionally reaching approximately 0.3-0.4. In contrast, Areas 1 and 6 show the highest and most stable RRI values, while Area 5 is characterised by a relatively narrow distribution.

The regional differences are also evident from the probability distributions shown in Figure 7. Area 1 is strongly concentrated toward high RRI values, whereas Area 4 has the widest distribution and the lowest lower-tail values. Areas 2 and 3 have similar distributions centred approximately around 0.85-0.90, while Area 5 shows a narrow distribution with a median of approximately 0.88. Area 6 has a distribution like Area 1, with predominantly high RRI values and relatively limited dispersion.

Overall, the results indicate that the principal difference among the regions is not the presence or absence of the seasonal RRI cycle, but its amplitude and the frequency of lower RRI conditions. Area 4 is distinguished by the greatest variability and lowest values, whereas Areas 1, 5 and 6 exhibit comparatively stable and high RRI conditions.

For the series of areas, a Kernel Density Estimation (KDE) [Weglarczyk, 2018] was performed in the form of a violin plot for better interpretation (Figure 7). Each violin plot shows whether the values are clustered or scattered (distribution shape), the median position (white dot), and the data spread (quartiles Q1 - Q3). In the case of Area 1, the distribution was observed to be clustered near the upper limit (approximately 0.9 - 1.0 kg $m^{-2}s^{-1}$), meaning high RRI values were observed most of the time (low surface runoff), but also low variability. Areas 2 and 3 were characterised by mean values in the range 0.85 - 0.9 kg/m^2/s. The most diverse distribution is in area 4, with much lower values (even ~0.3 - 0.4 kg $m^{-2}s^{-1}$, meaning most of the water runs off), but also high peaks around 0.9 kg/m^2/s (water evaporates or infiltrates). The results indicate strong seasonal fluctuations. Area 5 has a rather narrow, yet high distribution (0.8 - 0.9 kg $m^{-2}s^{-1}$). The median is close to 0.88 kg$m^{-2}s^{-1}$, indicating a stable level. Area 6 has a distribution very similar to area 1 (but also a similar climate), meaning high and stable values, and a small dispersion, which indicates the repeatability of the results.

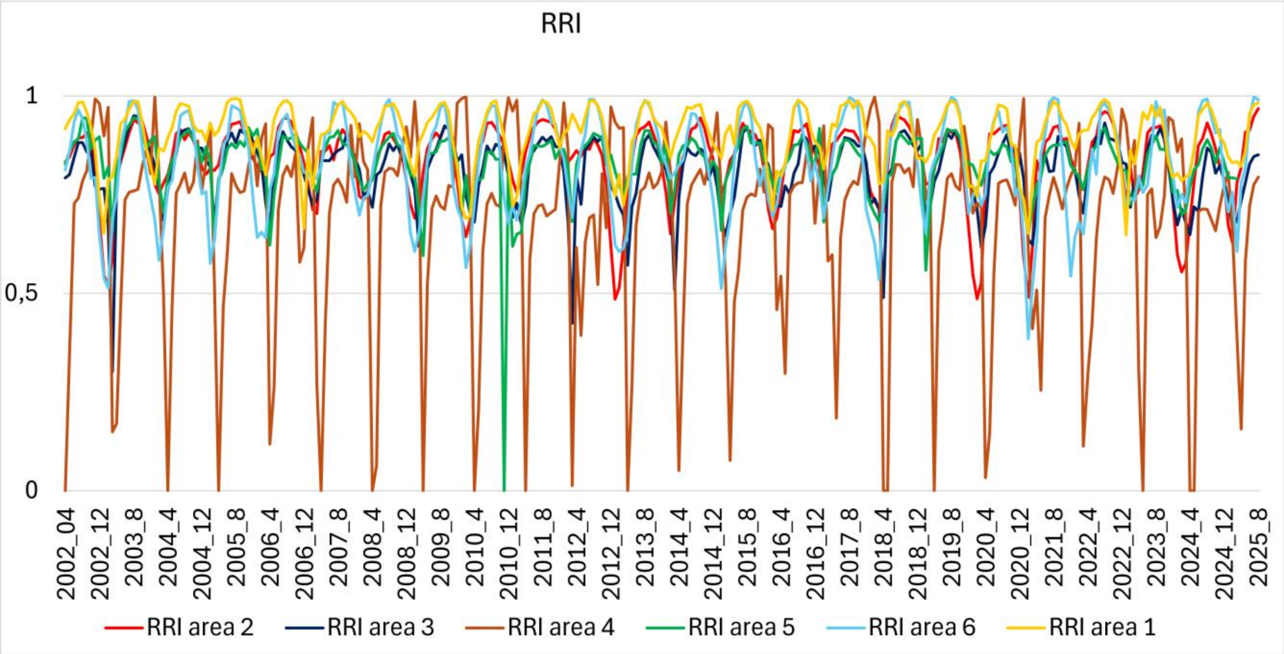

Fig. 6. Relative Retention Index time series for areas 1, 2, 3, 4, 5, and 6. All values in kg $m^{-2}s^{-1}$

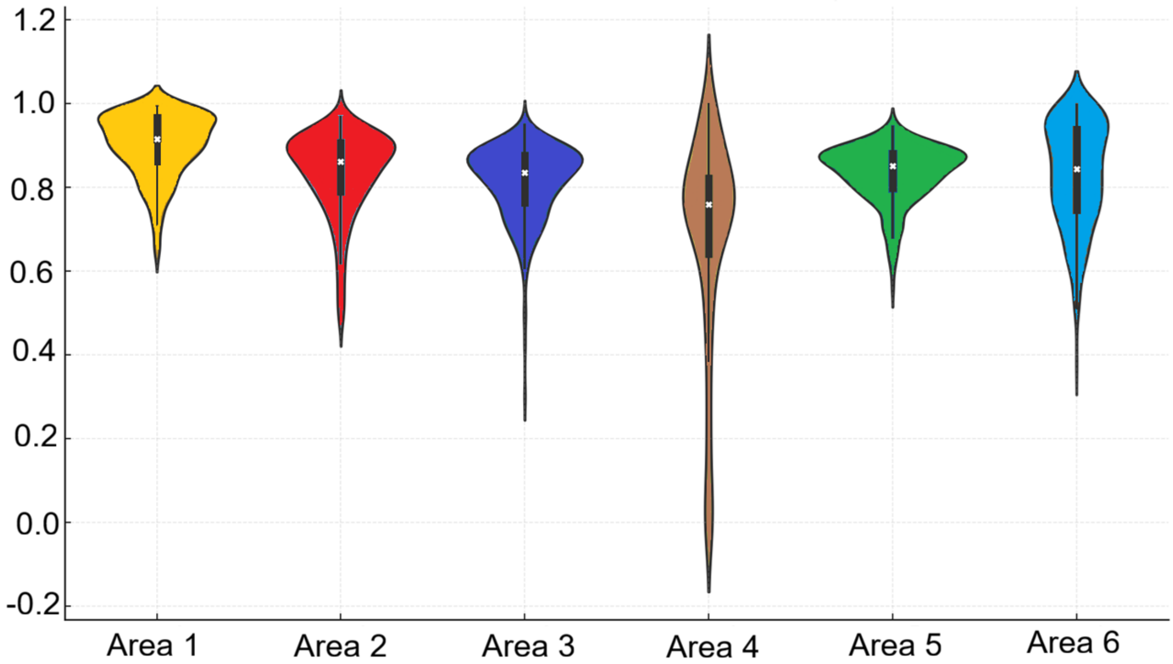

Fig. 7. Violin plot of the Relative Retention Index time series for areas 1, 2, 3, 4, 5, and 6

3.3. SCI analysis

The SCI calculated according to Equation (3) provides a normalised indication of the net water availability after accounting for evapotranspiration and surface runoff. The index exhibits a pronounced seasonal pattern, with generally higher values during winter and spring and lower values during summer. These variations reflect the seasonal relationship between precipitation and the represented water losses. Higher SCI values indicate periods in which precipitation exceeds the combined evapotranspiration and surface runoff components, whereas low or negative values indicate periods of potential water deficit within the simplified climatic water-budget formulation.

The SCI shows a pronounced seasonal cycle across all six regions (Figure 8), with generally higher values during winter and spring and lower values during summer. The seasonal minimum is more pronounced in the southern regions, particularly Areas 1 and 6, whereas Area 4 reaches the highest positive values and shows the largest seasonal contrast.

The regional distributions differ primarily in the magnitude and frequency of negative or near-zero SCI values. Areas 2 and 3 show the lowest SCI values, including periods below zero, whereas Area 4 reaches values close to 1. Areas 1 and 6 also exhibit pronounced seasonal reductions in SCI during summer. The results therefore indicate stronger seasonal contrasts in the regions characterised by higher summer water deficits.

The temporal evolution also suggests a change in the lower tail of the SCI distribution after approximately 2015, with lower minima occurring more frequently in several regions. This pattern indicates an increase in the magnitude of negative waterbudget conditions during selected periods rather than a uniform shift of the entire SCI time series. The strongest regional differences are therefore associated with the occurrence and magnitude of low SCI episodes, particularly during the warm season.

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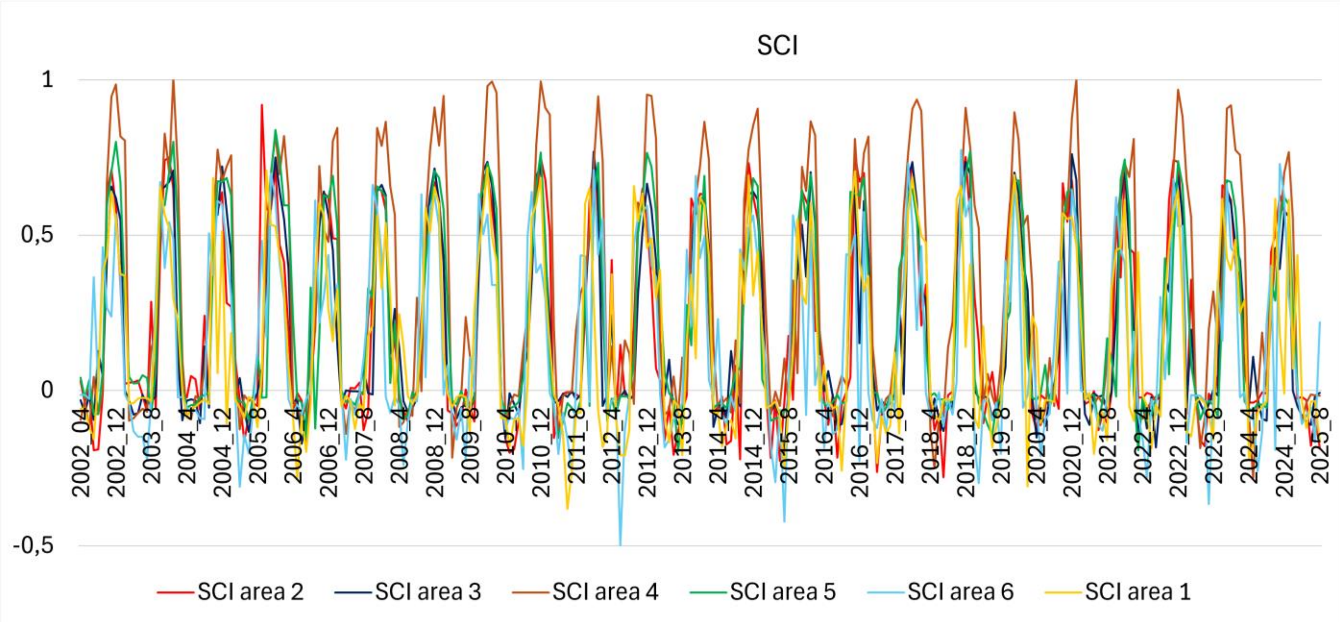

Fig. 8. Storage Change Index time series for regions 1, 2, 3, 4, 5, and 6. All values in kg $m^{-2}s^{-1}$

3.4. WSP analysis

The WSP exhibits the strongest seasonal variability among the analysed indices, with systematically higher values during summer and lower values during winter and early spring (Figure 9). The seasonal pattern is consistent across all six regions, but its magnitude differs substantially. The highest WSP values, reaching approximately 4-6, occur in Area 6, whereas Area 4 shows the lowest and most stable values, generally remaining below approximately 2. Area 1 also exhibits a relatively large seasonal amplitude, while Areas 2, 3 and 5 show intermediate variability.

The regional comparison indicates that the main distinction is the magnitude of the summer increase rather than the timing of the seasonal maximum. Area 6 combines high summer WSP values with a pronounced seasonal amplitude, whereas Area 4 exhibits a substantially smaller response. The average WSP values across the regions remain within approximately 1-2, but the regional distributions demonstrate that this continental-scale average masks considerable differences in seasonal water stress signals.

Higher WSP values become more frequent in several regions after approximately 2015, particularly in Areas 1 and 6. This temporal change is consistent with the lower SCI values observed during selected periods after 2015 and indicates a strengthening of the seasonal contrast between water availability and atmospheric water demand. Because WSP is interpreted here as a continuous index, these results describe changes in the magnitude of the relative water stress signal rather than exceedance of a predefined drought threshold.

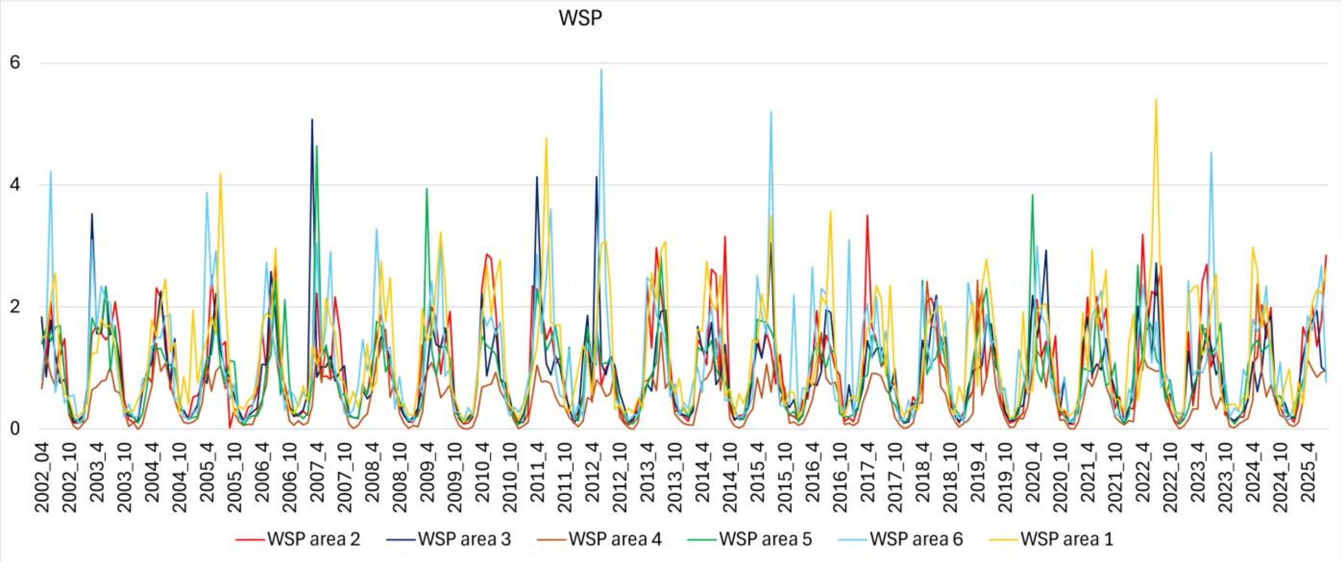

Fig. 9. Water Stress Proxy time series for regions 1, 2, 3, 4, 5, and 6. All values in kg $m^{-2}s^{-1}$

3.5. MMR analysis

The MRR shows pronounced seasonal variability in all six regions, with higher values generally occurring during periods of increased precipitation and lower values during drier periods (Figure 10). Most observations fall between 0 and 1, although values exceeding 1 occur intermittently. The highest temporal variability is observed in the regions characterised by stronger seasonal contrasts in the water budget, whereas Areas 3 and 5 exhibit comparatively stable MRR behaviour.

The occurrence of MRR values above 1 should be interpreted as a feature of the modified index formulation rather than as direct evidence of additional water inputs. Because MRR incorporates evapotranspiration and other components of the simplified water-budget formulation, values exceeding 1 may arise when the denominator becomes relatively small. This behaviour highlights the importance of considering the mathematical properties of MRR when interpreting extreme values.

A tendency toward larger MRR amplitudes after approximately 2015 is visible in several regions. However, this pattern is superimposed on strong seasonality, and the magnitude of the change differs among the climatic regions. The results therefore indicate changes in the variability of runoff response rather than a uniform long-term shift across Europe.

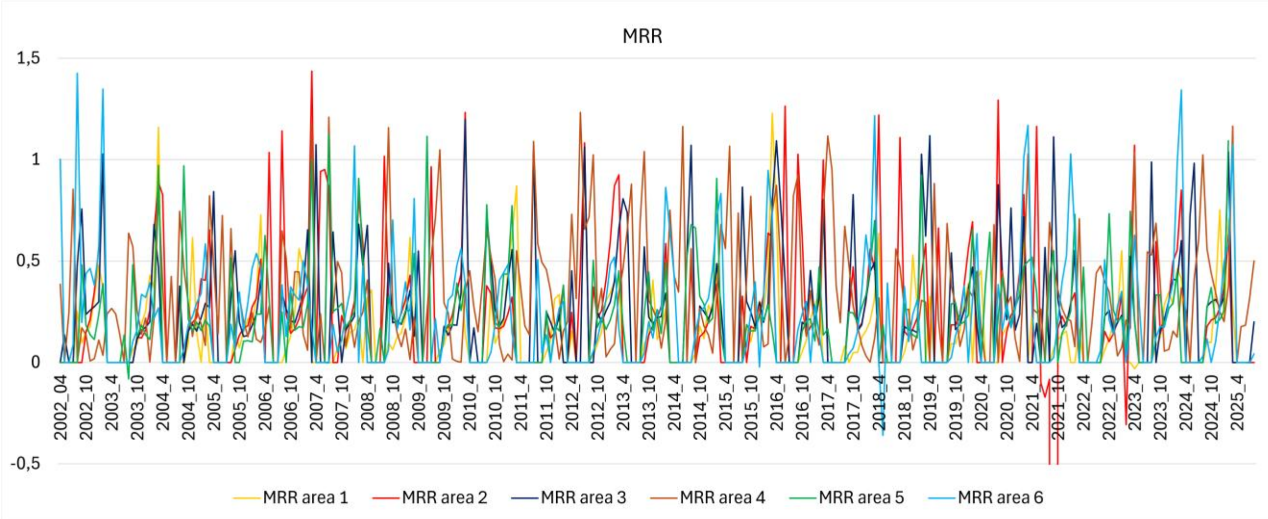

Fig. 10. Modified Runoff Ratio with EV correction time series for regions 1, 2, 3, 4, 5, and 6. All values in kg $m^{-2}s^{-1}$

3.6. Trend analysis

To distinguish long-term changes from the pronounced seasonal variability observed in the analysed time series, non-parametric trend analysis was applied to the water budget and the four derived indicators (RRI, SCI, WSP and MRR). The Mann–Kendall test was used to determine the direction and statistical significance of monotonic trends, while Sen's slope estimator was used to quantify their magnitude. The non-parametric approach was selected because the analysed hydrological and climatic variables may deviate from a normal distribution and may contain extreme observations.

Because the monthly time series exhibit pronounced annual seasonality, two complementary analyses were performed. First, annual mean values were calculated for each climatic region and indicator, and the Mann-Kendall test and Sen's slope estimator were applied to the complete calendar years 2003-2024. The use of complete calendar years avoided introducing a bias associated with the incomplete first and last years of the available record. Second, a Seasonal Mann-Kendall analysis was applied directly to the monthly time series for April 2002-August 2025, with calendar months treated as separate seasons. This approach allowed the assessment of monotonic changes while accounting for the recurring annual seasonal structure.

The long-term trend analysis did not reveal statistically significant changes in the annual mean water budget in any of the six climatic regions during 2003-2024 (Table 3). The estimated Sen's slopes ranged from -1.0×10^{-8} to 6.0×10^{-8} kg m^{-2} s^{-1} yr^{-1}, while all corresponding p-values exceeded 0.05. The largest positive slope was observed in Area 6 (4.0×10^{-8} kg m^{-2} s^{-1} yr^{-1}), whereas Area 4 showed a small negative slope (-1.0×10^{-8} kg m^{-2} s^{-1} yr^{-1}). However, neither trend was statistically significant.

In contrast, significant long-term changes were identified for selected derived indicators. RRI showed a statistically significant decreasing trend in Area 5 (Sen's slope = -1.495×10^{-3} yr^{-1}, $p = 0.008$), indicating a gradual reduction in the relative retention signal in this region. SCI also exhibited a significant decreasing trend in Area 5 (Sen's slope = -3.244×10^{-3} yr^{-1}, $p = 0.015$). No statistically significant annual trends were detected for WSP or MRR in any of the analysed regions.

The results therefore indicate that the pronounced temporal variability observed in the water-budget series does not correspond to a statistically significant long-term trend in the annual mean water budget. Instead, the clearest long-term signals occur in selected derived indicators and are spatially limited, particularly to Area 5. This distinction is important because the strong seasonal cycle observed in the monthly series can produce apparent changes in individual periods without necessarily indicating a persistent long term trend.

Table 3. Long term trends

Indicator	Area	Sen’s slope	Z	p value
WB	1	$6.00 \times 10v^{8}$	0.677	0.499
	2	1.00×10^{-8}	0.113	0.910
	3	6.00×10^{-8}	1.072	0.284
	4	-1.00×10^{-8}	-0.169	0.866
	5	-2.00×10^{-8}	-0.226	0.822
	6	4.00×10^{-8}	0.677	0.499
RRI	1	-9.158×10^{-4}	-1.015	0.310
	2	-1.064×10^{-3}	-1.072	0.284
	3	-1.363×10^{-3}	-1.466	0.143
	4	3.562×10^{-5}	0.000	1.000
	5	-1.495×10^{-3}	-2.651	0.008
	6	5.721×10^{-4}	0.620	0.535
SCI	1	-4.148×10^{-4}	-0.226	0.822
	2	-9.705×10^{-4}	-0.959	0.338
	3	-8.020×10^{-4}	-0.790	0.430
	4	4.168×10^{-4}	0.451	0.652
	5	-3.244×10^{-3}	-2.425	0.015
	6	-2.015×10^{-3}	-1.410	0.159

WSP	1	4.675×10^{-3}	0.846	0.398
	2	1.741×10^{-3}	0.226	0.822
	3	-3.155×10^{-3}	-0.846	0.398
	4	2.237×10^{-3}	1.184	0.236
	5	1.320×10^{-3}	0.226	0.822
	6	-2.516×10^{-3}	-0.677	0.499
MRR	1	3.500×10^{-7}	0.000	1.000
	2	-3.540×10^{-3}	-1.015	0.310
	3	4.788×10^{-3}	1.297	0.195
	4	2.472×10^{-3}	0.790	0.430
	5	6.166×10^{-4}	0.226	0.822
	6	1.647×10^{-3}	0.733	0.463
Statistically significant trend at $p < 0.05$. Positive and negative Sen's slope values indicate increasing and decreasing trends, respectively.				

Because the analysed monthly time series exhibit a pronounced seasonal cycle, the Seasonal Mann-Kendall (SMK) test was additionally applied to distinguish monotonic long term changes from the recurring intra-annual variability. In the SMK procedure, observations were grouped according to calendar month, and the Mann-Kendall statistic was calculated across years within each month. The seasonal statistics were then combined to obtain an overall test statistic for the complete time series. This approach allows the detection of a monotonic trend while accounting for the systematic seasonal structure of the data. Sen's slope was used as a complementary estimator of the magnitude and direction of the trend. The SMK analysis was applied to the monthly series available for April 2002-August 2025. A significance level of $\alpha = 0.05$ was adopted. The Seasonal Mann-Kendall analysis was used to assess whether the observed monthly variability was associated with a persistent monotonic trend after accounting for the pronounced seasonal cycle. For the water budget (WB), no statistically significant seasonal trend was detected in any of the six climatic regions ($p > 0.05$). The p-values ranged from 0.619 in Area 1 to 0.964 in Area 3, indicating that the strong seasonal variability observed in the monthly water-budget series does not correspond to a statistically significant monotonic long-term change.

The derived indicators showed more regionally differentiated responses. RRI exhibited statistically significant decreasing trends in Areas 1, 3, 4 and 5, with p-values of 0.036, 0.002, 0.024 and <0.001, respectively. In contrast, Area 6 showed a statistically significant increasing RRI trend (p =

0.021), while no significant trend was detected in Area 2. For SCI, a statistically significant decreasing trend was identified only in Area 5 ($p = 0.002$); the trends in the remaining regions were not statistically significant. No statistically significant seasonal trends were detected for WSP in any of the six regions.

The SMK results therefore confirm that the pronounced seasonal cycle of the water-budget series should not be interpreted as evidence of a long-term trend. The absence of a significant water budgrt trend across all regions indicates that the dominant temporal structure of the water budget is seasonal rather than a persistent monotonic change. At the same time, the significant trends detected for selected derived indicators suggest that changes in the relative relationships between precipitation, evapotranspiration and surface runoff may occur even when the aggregate water budget signal does not exhibit a significant long-term trend.

Additionally, the annual amplitude was checked (annual amplitude = annual maximum - annual minimum). For WB, no region has a significant amplitude trend (Table 4). Periods of increased variability after approximately 2015, but this pattern is not supported by a statistically significant monotonic trend in annual water-budget amplitude.

Table 4. Annual amplitude

Area	Sen's slope of annual WB amplitude	p
1	$+2.7 \times 10^{-7}$	0.413
2	$+4.6 \times 10^{-7}$	0.078
3	-1.7×10^{-7}	0.568
4	$+2.3 \times 10^{-7}$	0.333
5	-1.1×10^{-7}	0.568
6	-1.9×10^{-7}	0.637

4. DISCUSSION

4.1. Continental-scale water-budget variability

The results demonstrate that the European water budget is characterised by a strong and spatially coherent seasonal cycle, but that the magnitude of this cycle and the associated interannual variability differ substantially among climatic regions. This finding is consistent with recent European hydroclimatic studies showing that water availability is controlled not only by precipitation variability but also by the combined effects of evapotranspiration, runoff generation and changes in terrestrial water storage. Recent assessments indicate that Europe is experiencing increasing pressure on freshwater resources, with drought and water scarcity becoming particularly important in southern and western Europe, while northern regions retain a comparatively wetter hydroclimatic regime [Bakke et al., 2023].Although seasonal variability dominates all time series, the most noticeable long-term change concerns the increasing amplitude of seasonal oscillations after approximately 2015 rather than a shift in seasonal timing.

This apparent increase in seasonal amplitude is not accompanied by a statistically significant monotonic trend in the annual mean water budget or its annual amplitude. This distinction is important because visual increases in the magnitude of individual seasonal fluctuations do not necessarily indicate a persistent long-term change. Similar complexity has been reported in European drought studies. Bakke et al. [2023] showed that recent European drying is strongly influenced by changes in large-scale atmospheric circulation and that the temporal evolution of drought cannot be reduced to a simple linear trend. Thus, the lack of a significant monotonic trend in the aggregate water budget in the present study does not imply the absence of hydroclimatic change; rather, it indicates that changes are expressed primarily through variability, seasonality and individual water-budget components rather than through a uniform shift in the annual mean.

This distinction is particularly relevant because European hydrological change is spatially heterogeneous. Recent climate-impact studies show that runoff responses differ substantially across Europe even under the same forcing scenario. Deman and Boé [2025], for example, identified contrasting runoff responses in western and central Europe, with approximately half of the analysed climate-model clusters projecting decreasing annual runoff and the remainder showing little change or slight increases. Importantly, these differences could not be explained by precipitation alone, because changes in evapotranspiration and atmospheric circulation also contributed to the projected runoff response. This finding supports the interpretation of the present study that the water budget should be considered as the combined response of precipitation, evapotranspiration and runoff rather than as a direct proxy for precipitation variability alone.

The strong seasonality identified in all six regions is therefore not an indication of a uniform European water regime. Instead, the common seasonal signal is modulated by regional differences in the magnitude of evapotranspiration, runoff generation, snow storage and the timing of water release. The relatively high correlations between the regional water budget series and the European mean further indicate a common continental-scale forcing, but the substantial differences in amplitude demonstrate that this common forcing is expressed differently among the climatic regions.

4.2. Role of evapotranspiration in European water availability

The role of evapotranspiration is particularly important when interpreting the observed water budget variability. Earlier European studies demonstrated that deficits in runoff during drought periods can be considerably larger than expected from precipitation deficits alone because atmospheric evaporative demand increases during dry and warm conditions. Massari et al. [2022], using more than 200 European basins, showed that enhanced evaporation can amplify runoff deficits during multi-year droughts. Their results indicate that reduced precipitation is therefore only one part of the mechanism responsible for hydrological drought; increased atmospheric demand for water can further deplete available terrestrial water.

This mechanism is consistent with the seasonal behaviour identified in the present study. The strongest negative water-budget conditions and highest WSP values occur during the warm season, when evapotranspiration demand is highest. Conversely, positive water budget conditions are more common during autumn and winter, when atmospheric evaporative demand is lower. The results therefore suggest that the seasonal water deficit observed in several regions reflects not simply reduced precipitation but the interaction between precipitation availability and enhanced atmospheric water demand.

Recent research further supports the importance of evapotranspiration as a changing component of the terrestrial water cycle. Yang et al. [2023] reported a widespread increase in evapotranspiration during recent decades, with particularly strong increases at northern high latitudes associated with vegetation greening, while changes in precipitation and atmospheric demand also contributed to regional variability. Zhang et al. [2024] additionally demonstrated that the controls exerted by water availability and atmospheric evaporative demand on evapotranspiration are themselves changing, particularly in water limited environments. These findings provide a physical explanation for why changes in evapotranspiration may alter the water-budget response even when precipitation trends are weak or spatially inconsistent.

Consequently, the absence of a significant long-term trend in the aggregate water budget in several regions should not be interpreted as evidence that the individual components of the hydrological cycle are stationary. Compensating changes in precipitation, evapotranspiration and runoff can result in a relatively stable aggregate water-budget signal while the internal partitioning of water changes. This interpretation is particularly relevant to the significant trends detected for selected derived indices, including RRI and SCI.

4.3. Northern Europe: snow storage and seasonal runoff generation

The behaviour of Area 4 requires particular attention because it differs from the other regions in both the magnitude and variability of the RRI and water budget signals. The seasonal pattern observed in this region should be interpreted in the context of snow accumulation, soil freeze thaw processes and delayed seasonal water release rather than solely through precipitation and evapotranspiration.

In snow-dominated northern environments, precipitation falling during winter is temporarily stored as snow and therefore does not immediately contribute to infiltration or runoff in the same way as rainfall. The subsequent release of stored water during spring snowmelt can generate a pronounced seasonal runoff response. Recent research confirms that snow processes are critical for predicting runoff in northern Europe because the spatial distribution and timing of snow accumulation strongly affect the magnitude and timing of spring. More broadly, Gottlieb and Mankin [2024] demonstrated that anthropogenic warming has already caused substantial Northern Hemisphere snow loss, with particularly important implications for basins whose water availability depends on seasonal snow storage.

This mechanism provides a plausible explanation for the pronounced spring behaviour observed in Area 4. When the ground remains frozen, infiltration can be temporarily limited, and precipitation or snowmelt can contribute disproportionately to surface runoff. As the soil thaws, infiltration and subsurface storage become increasingly important. The result is a strong seasonal contrast that may appear in a simplified water-budget framework as a large change in the relative contribution of runoff.

However, this interpretation also highlights an important limitation of the present analysis. The simplified water-budget formulation does not explicitly separate rainfall, snowfall, snow accumulation, snowmelt, soil freezing or subsurface storage. Therefore, the low RRI values observed in Area 4 should not be interpreted as direct evidence that precipitation is physically unable to infiltrate. Rather, they indicate a stronger runoff-dominated response within the formulation used in this study. Explicit snow and soil-freeze information would be required to quantify the contribution of each process separately.

This distinction is important because recent European hydrological projections indicate that warming is likely to modify not only the amount of snow stored during winter but also the timing of runoff generation. For example, projections for northern Iberian Mountain basins show a substantial reduction in snowmelt contribution and changes in seasonal streamflow, illustrating how warming can shift water availability from spring toward earlier or winter runoff. Similar mechanisms are expected to be particularly relevant in northern European environments where a substantial fraction of annual water storage is seasonally controlled by snow.

4.4. Southern Europe and Mediterranean water stress

The behaviour of Areas 1 and 6 provides a contrasting example. These regions exhibit stronger summer increases in WSP and more pronounced seasonal reductions in SCI, indicating that water availability becomes increasingly constrained during the warm season. This behaviour is consistent with the hydroclimatic characteristics of Mediterranean and southern European regions, where high temperatures and strong atmospheric evaporative demand coincide with the seasonal precipitation minimum.

Recent European drought studies demonstrate that Mediterranean droughts are becoming increasingly important because warming can amplify the effects of precipitation deficits through enhanced evapotranspiration and soil-moisture depletion. Bakke et al. [2023] identified recent European drying as a combination of precipitation variability and large-scale atmospheric circulation, while recent Mediterranean studies have shown that drought severity is strongly related to the combined behaviour of precipitation and evapotranspiration. For example, studies based on SPEI and actual evapotranspiration have demonstrated that Mediterranean ecosystems are particularly vulnerable to increasing water stress because high temperatures increase atmospheric demand during periods when precipitation is already limited.

The present results are consistent with this mechanism. The simultaneous occurrence of high WSP and low SCI during the warm season suggests that the regions with the strongest seasonal atmospheric demand also experience the greatest reduction in the net water budget signal. This provides a process-based interpretation of the regional differences observed in the results: the contrast between northern and southern Europe is not simply a difference in precipitation totals, but reflects different seasonal relationships between water supply and atmospheric demand.

The persistence of this seasonal contrast is particularly important because Mediterranean water stress can develop even when annual precipitation does not show a strong negative trend. A redistribution of precipitation toward the cooler season, combined with increasing summer evaporative demand, can reduce effective summer water availability without necessarily producing a large change in annual precipitation totals. This mechanism is consistent with recent assessments of Mediterranean drought, which identify prolonged warm conditions and high evaporative demand as important amplifiers of precipitation deficits.

4.5. Runoff response and continental hydrological variability

The regional behaviour of the runoff-related indicators also agrees with evidence that European runoff is changing in a spatially heterogeneous manner. Continental-scale discharge analyses have shown substantial year-to-year variability and pronounced regional differences in river-flow conditions. In 2022, for example, European river discharge was markedly below the long-term average across a large part of the continent, illustrating how atmospheric drought can propagate into hydrological systems. More recent modelling work confirms that future runoff changes across Europe are highly uncertain and strongly dependent on the relative changes in precipitation and evapotranspiration.

The present results should nevertheless be distinguished from catchment-scale runoff studies. The runoff component analysed here represents a spatially aggregated surface-runoff signal rather than observed discharge at a river outlet. Therefore, it cannot directly reproduce the effects of river routing, groundwater contributions, reservoir regulation or basin storage. Instead, it provides information about the regional partitioning of precipitation into the components represented by the MERRA-2 land-surface framework.

This distinction is important when interpreting the MRR and RRI results. Differences among the six regions reflect not only climatic forcing but also the response of the land-surface model to soil, vegetation and surface characteristics. Consequently, the indices should be interpreted as indicators of relative water-budget behaviour rather than as direct substitutes for observed river discharge or groundwater storage.

4.6. Interpretation of the derived indices

The four derived indices provide complementary information about the same underlying water-budget components, but they should not be interpreted as statistically independent measures. Their value lies in highlighting different aspects of water partitioning and temporal variability. RRI emphasises the relative importance of runoff within the water-budget formulation, SCI captures changes in the net storage-related signal, WSP emphasises the balance between water availability and atmospheric demand, and MRR characterises the relative runoff response.

The regional comparison demonstrates why these complementary indicators can be informative even when the aggregate water budget remains statistically stable. For example, the absence of a significant long-term trend in WB does not preclude significant trends in RRI or SCI. This indicates that changes in the partitioning among water-budget components may occur without producing an equally strong trend in their aggregate balance. Such behaviour is consistent with the broader hydrological literature, which increasingly emphasises the importance of analysing individual water-cycle components rather than relying exclusively on precipitation or runoff trends.

The indices should, however, be interpreted as relative indicators within the common MERRA-2 framework. In particular, the categorical thresholds previously used for SCI and WSP have been removed from the interpretation because they were not derived from an established literature-based classification or independently calibrated. The continuous values of the indices are therefore more appropriate for quantitative comparison and trend analysis. This approach avoids assigning universal hydrological meaning to numerical thresholds that have not been independently validated.

4.7. Implications for European water security assessment

Taken together, the results indicate that European water availability is characterised by a combination of continental-scale coherence and strong regional differentiation. Northern regions are influenced by snow storage, freeze–thaw processes and seasonal runoff generation, whereas southern regions are more strongly affected by high evaporative demand and summer water limitation. Central regions occupy an intermediate position but can nevertheless experience substantial interannual variability.

This spatial differentiation has important implications for water-security assessment. A single European mean or country-level average can conceal contrasting seasonal mechanisms operating in different climatic regions. The six-region framework used here therefore provides a physically interpretable intermediate scale between individual catchments and the whole continent. It captures broad climatic contrasts while retaining regional differences in the seasonal partitioning of precipitation, evapotranspiration and runoff.

The results also suggest that water-security assessments should consider variability and seasonal redistribution in addition to long-term mean trends. The lack of statistically significant trends in the annual water budget across the six regions does not imply stable water-security conditions. In particular, increasing warm-season atmospheric demand, changes in snow storage and more pronounced seasonal contrasts can increase the vulnerability of water resources even when annual averages remain relatively unchanged. This interpretation is consistent with recent European assessments identifying drought, water scarcity and increasing hydroclimatic variability as major challenges for future water management.

4.8. Limitations

The simplified water-budget formulation constitutes one of the main limitations of this study. Although it adequately characterises climatic water availability over continental-scale regions, it does not resolve internal hydrological processes or storage dynamics.

Groundwater exchange, soil-moisture dynamics, snow accumulation and melt, freeze thaw processes, interception and river routing are not explicitly represented. Consequently, the water budget components and derived indices should be interpreted as regional-scale signals rather than as direct estimates of basin-scale hydrological fluxes.

A further limitation concerns the use of MERRA-2 as a single reanalysis source. Although this approach ensures internal consistency among the input variables, the estimates remain dependent on the forcing, parameterisations and land-surface representation of the reanalysis product. Differences among reanalysis products may be particularly important for evapotranspiration and surface runoff.

Finally, the derived indices are interpreted as continuous relative indicators and have not been independently calibrated against observed streamflow, groundwater storage or soil-moisture measurements. Their main purpose is therefore comparative, allowing regional differences in water-budget behaviour to be identified rather than providing independently validated estimates of hydrological stress or storage.

5. CONCLUSIONS

The presented study analyses the water budget of the European area, divided into climatic zones. In order to extend the analysis, additional indicators were used for interpretation: Relative Retention Index (RRI), Storage Change Index (SCI), Water Stress Proxy (WSP), and Modified Runoff Ratio with EV correction (MRR). Based on the research, it was concluded:

- The highest precipitation was observed for area 4 (Scandinavia), with the highest seasonality. Area 4 generally has the best water conditions and a stable water balance.
- Areas 6 and 1 are the most vulnerable to the effects of a changing climate and are characterised by the poorest water conditions.
- WSP and SCI are strongly complementary: where SCI decreases (less retention), WSP increases (more water stress).
- The water budget analysis showed that all the studied areas respond to the same climatic factors, and that small differences occurring locally are related to additional factors, such as soils, relief, and land use.
- SCI provided a normalised proxy of temporal variations in climatic water availability and effectively highlighted the seasonal alternation between periods of positive water availability and potential water deficit.

- The European climate regions analysed in the presented paper experience a distinctly seasonal and dynamic water budget, with retention dominating dry periods and runoff being intense and short-lived during wet periods. The statistical trend analysis indicates that the observed temporal variability does not correspond to a statistically significant long term trend in the annual mean water budget across the six analysed climatic regions. Periods of enhanced variability, including those observed after approximately 2015, should therefore be interpreted as episodes of increased seasonal or interannual variability rather than as evidence of a persistent monotonic change.

The results demonstrate that a continental scale water budget alone may not fully capture regional differences in hydroclimatic conditions. Although the six climatic regions show a common seasonal water budget signal, the derived indices reveal substantial differences in runoff response, storage-related variability and seasonal water stress. This indicates that analysing water budget components through complementary indicators can provide additional information on the spatial differentiation of hydroclimatic processes that is not apparent from the aggregate water budget signal alone. The results also demonstrate that statistically stable annual water budget conditions may coexist with significant changes in selected components or derived indicators. This highlights the importance of considering seasonal variability and water partitioning when assessing changes in European water availability.

The proposed framework can be used as a regional scale screening tool for identifying areas and seasons characterised by contrasting water-budget behaviour. In particular, the combined analysis of the water budget, RRI, SCI, WSP and MRR can support the identification of regions with stronger seasonal water deficits, enhanced runoff responses or changes in the relative partitioning of available water. Such information may be useful for regional water-resource assessment, drought-risk screening and the identification of areas requiring more detailed hydrological investigation. Because the approach uses spatially consistent MERRA-2 data, it can also be applied to regions where observations are spatially sparse or heterogeneous.

Several limitations should be considered when interpreting the results. The simplified water budget formulation constitutes one of the main limitations of this study. Although it adequately characterises climatic water availability over continental-scale regions, it does not resolve internal hydrological processes or storage dynamics. Its formulation does not explicitly represent groundwater exchange, soil-moisture dynamics, snow accumulation and melt, freeze thaw processes, interception or river routing. The derived indices therefore describe relative regional hydroclimatic behaviour rather than directly measured hydrological fluxes. In addition, the analysis is based on MERRA-2, and the results may depend on the parameterisations and land-surface representation of this reanalysis product. The SCI and WSP are interpreted as continuous relative indicators, and their numerical values have not been independently calibrated against observations or established drought thresholds. Finally, the six climatic regions represent spatial aggregates and therefore cannot resolve within region heterogeneity or basin-scale processes.

Future research should validate the proposed indices against independent observations, including streamflow, soil moisture, groundwater storage and GRACE/GRACE-FO terrestrial water storage anomalies. A multi dataset approach using additional reanalysis products and observational datasets would allow the robustness of the identified regional patterns to be assessed. Further work should also explicitly incorporate snow accumulation and melt, soil freezing and thawing, groundwater storage and soil-moisture dynamics, particularly for northern European regions. Finally, extending the analysis using higher-resolution datasets and climate projections would allow the proposed framework to be applied to future water security assessments and to evaluate whether the regional differences identified in this study are likely to intensify under continued climate change.

REFERENCES

1. Akl, M, Thomas, BF 2024. Challenges in applying water budget framework for estimating groundwater storage changes from GRACE observations, Journal of Hydrology **639**, 131600, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2024.131600
2. Avanzi, F, Rungee, J, Maurer, T, Bales, R, Ma, Q, Glaser, S and Conklin, M 2020. Climate elasticity of evapotranspiration shifts the water balance of Mediterranean climates during multi-year drought. Hydrology and Earth System Sciences **24**, Issue 4, 4317–4337, https://doi.org/10.5194/hess-24-4317-2020.
3. Baffaut, C, Baker, JM, Biederman, JA, Bosch, DD, Brooks, ES, Buda, AR, Demaria, EM, Elias, EH, Flerchinger, GN, Goodrich, DC, Hamilton, SK, Hardegree, SP, Harmel, RD, Hoover, DL, King, KW, Kleinman, PJ, Liebig, MA, McCarty, GW, Moglen, GE, Moorman, TB. Moriasi, DN, Okalebo, J, Pierson, FB, Russell, ES, Saliendra, NZ, Saha, AK, Smith, DR, Yasarer, LMW 2020. Comparative analysis of water budgets across the U.S. long-term agroecosystem research network. Journal of Hydrology **588**, 125021, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2020.125021
4. Bakke, SJ, Ionita, M, Tallaksen, LM 2023. Recent European drying and its link to prevailing large-scale atmospheric patterns. Scientific Reports **13**, 21921. https://doi.org/10.1038/s41598-023-48861-4
5. Birylo, M, Rzepecka, Z 2023. Remote Sensing-Based Hydro-Extremes Assessment Techniques for Small Area Case Study (The Case Study of Poland). Remote Sensing **15**, 5226. https://doi.org/10.3390/rs15215226
6. Birylo, M, Rzepecka, Z, Nastula, J 2018. Assessment of the Water Budget from GLDAS Model. Baltic Geodetic Congress (BGC Geomatics), Olsztyn, Poland. pp. 86-90. DOI: 10.1109/BGC-Geomatics.2018.00022
7. Birylo, M 2026a. Multi-Indicator Assessment of Hydrological Change Across Europe Using Satellite Observations. Water **18**(8). DOI10.3390/w18080986
8. Birylo, M 2026b. Satellite-based determination and analysis of groundwater drought index time series in Europe. Civil And Environmental Engineering Reports **36**(1), pp. 0159-0178. DOI: 10.59440/ceer/220434
9. Birylo, M 2026c. Drought Assessment and Forecasting according to the Köppen-Geiger Climate Classification Using GRACE and MERRA Observations. Geomatics And Environmental Engineering **20**(3), pp. 105-133. DOI: 10.7494/geom.2026.20.3.105
10. Błaszczak-Bąk, W, Birylo, M, Biłozor, A, Cieślak, I and Janicka, J 2025. The Impact of Urbanization and Infrastructure Development on Local Flood Risk in Tomaszkowo: Hydrological Analysis and Spatial Planning. Applied Sciences **15** (20): 10863. https://doi.org/10.3390/app152010863
11. Chen, Y, Liu, X, Zheng, C, Ma, Y, Gao, He, WJ, Hao, L, Liu, Z, Shi, C, Cao, Q 2024. Estimation of water budget components and its driving factors analysis in arid grassland. Science of The Total Environment **906**, 167654, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2023.167654
12. Deman, J and Boe, J 2025. Future changes in runoff over western and central Europe: disentangling the hydrological behavior of CMIP6 models. Earth System Dynamics **16** (5), pp. 1409–1426. https://doi.org/10.5194/esd-16-1409-2025
13. Droppers, B, Rakovec, O, Avila, L, Azimi, S, Cortés-Torres, N, De León Pérez, D, Imhoff, R, Francés, F, Kollet, S, Rigon, R, Weerts, A, Samaniego, L 2024. Multi-model hydrological reference dataset over continental Europe and an African basin. Scientific Data **11** (1). https://doi.org/10.1038/s41597-024-03825-9

14. Gokmen, M, Oltan, Vekerdy, Z, Lubczyński, MW, Timmermans J, Batelaan, O and Verhoef, W 2013. Assessing Groundwater Storage Changes Using Remote Sensing–Based Evapotranspiration and Precipitation at a Large Semiarid Basin Scale. Journal of Hydrometeorology **14**. DOI: 10.1175/JHM-D-12-0156.1
15. Gottlieb, AR and Mankin, JS 2024. Evidence of human influence on Northern Hemisphere snow loss. Nature **625**, pp. 293-300. https://doi.org/10.1038/s41586-023-06794-y
16. Hamal, K, Sharma, S, Khadka, N, Baniya, B, Ali, M, Shrestha, MS, Xu, T, Shrestha, D, Dawadi, B 2020. Evaluation of MERRA-2 Precipitation Products Using Gauge Observation in Nepal. Hydrology **7**, 40. https://doi.org/10.3390/hydrology7030040
17. Healy, RW, Winter, TC, LaBaugh, JW, Franke, OL 2007. Water budgets: Foundations for effective water-resources and environmental management. U.S. Geological Survey Circular **1308**, 90.
18. Houborg, R, Rodell, M, Li, B, Reichle, R and Zaitchik, F 2012. Drought indicators based on model-assimilated Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage observations. Water Resources Research **48**, W07525. DOI:10.1029/2011WR011291
19. Kansoh, R, Abd-El-Mooty, M and Abd-El-Bak, R 2020. Computing the Water Budget Components for Lakes by Using Meteorological Data. Civil Engineering Journal **6** (7). http://dx.doi.org/10.28991/cej-2020-03091545
20. Li, B, Rodell, M, Kumar, S, Beaudoing, HK, Getirana, A, Zaitchik, BF, de Goncalves, LG, Cossetin, C, Bhanja, S, Mukherjee, A, Tian, S, Tangdamrongsub, N, Long, D, Nanteza, J, Lee, J, Policelli, F, Goni, IB, Daira, D, Bila, M, de Lannoy, G, Mocko, D, Steele-Dunne, SC, Save, H, Bettadpur, S 2019. Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges. Water Resources Research **55**, pp. 7564–7586. https://doi.org/10.1029/2018WR024618
21. Martínez-Retureta, R, Aguayo, M, Abreu, NJ, Urrutia, R, Echeverría, C, Lagos, O, Rodríguez-López, L, Duran-Llacer, I, Barra, RO 2022. Influence of Climate and Land Cover/Use Change on Water Balance: An Approach to Individual and Combined Effects. Water **14**, 2304. https://doi.org/10.3390/w14152304
22. Massari, C, Avanzi, F, Bruno, G, Gabellani, S, Penna, D, Camici, S 2022. Evaporation enhancement drives the European water-budget deficit during multi-year droughts. Hydrology and Earth System Science **26**, pp. 1527–1543. https://doi.org/10.5194/hess-26-1527-2022
23. Milly, PCD 1994. Climate, soil water storage, and the average annual water balance. Water Resources Research **30**(7), pp. 2143–2156. DOI:10.1029/94WR00586
24. Moyers, K, Sabie, R, Waring, E, Preciado, J, Naughton, CC, Harmon, T, Safeeq, M, Torres-Rua, A, Fernald, A, Viers, JH 2023. A Decade of Data-Driven Water Budgets: Synthesis and Bibliometric Review. Water Resources Research **59** (11). https://doi.org/10.1029/2022WR034310
25. Nagler PL, Glenn EP, Kim H, Emmerich W, Scott RL, Huxman TE, Huete AR 2007. Relationship between evapotranspiration and precipitation pulses in a semiarid rangeland estimated by moisture flux towers and MODIS vegetation indices. Journal of Arid Environments **70**. DOI: 10.1016/j.jaridenv
26. Olden, JD, Poff, NL 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Appliations **19**, pp. 101-121. https://doi.org/10.1002/rra.700
27. Pappalardo, V, La Rosa, D, Campisano, A, La Greca, P 2017. The potential of green infrastructure application in urban runoff control for land use planning: A preliminary evaluation from a southern Italy case study. Ecosystem Services, Elsevier **26** (Part B), pp. 345-354. DOI: 10.1016/j.ecoser.2017.04.015
28. Rienecker, MM, Suarez, MJ, Gelaro, R, Todling, R, Bacmeister, J, Liu, E, Bosilovich, MG, Schubert, SD, Takacs, L, Kim, GK 2011. MERRA: NASA's modern-era retrospective analysis for

research and applications. Journal of Climate **24** (14), pp. 3624–3648. https://doi.org/10.1175/JCLI-D-11-00015.1
29. Rolf, H, Reichle, C, Draper, S, Liu, Q, Girotto, M, Mahanama, SPP, Koster, RD, De Lannoy, GJM 2017. Assessment of MERRA-2 Land Surface Hydrology Estimates. Journal of Climate **30** (8), pp. 2937–2960. https://doi.org/10.1175/JCLI-D-16-0720.1
30. Shao, R, Zhang B, He, X, Su T, Li, Y, Long, B, Wang, X, Yang, W, He, C 2021. Historical Water Storage Changes over China's Loess Plateau. Water Research Resources **57** (3). https://doi.org/10.1029/2020WR028661
31. Tardif, S, St-Hilaire, A, Roy, R, Bernier, M, Payette, S 2015. Water budget analysis of small forested boreal watersheds: comparison of Sphagnum bog, patterned fen and lake dominated downstream areas in the La Grande River region, Québec. Hydrology Research **46** (1), pp. 106–120. https://doi.org/10.2166/nh.2014.219
32. Teuling, AJ, Van Loon, AF, Seneviratne, SI, Lehner, I, Aubinet, M, Heinesch, B, Bernhofer, C, Grünwald, T, Prasse, H, Spank, U 2013. Evapotranspiration amplifies European summer drought. Geophysical Research Letters **40**, pp. 2071–2075. DOI: 10.1002/grl.50495
33. Unnisa, Z, Govind, A, Lasserre, B, Marchetti, M 2023. Water Balance Trends along Climatic Variations in the Mediterranean Basin over the Past Decades. Water **15** (1889). https://doi.org/10.3390/w15101889
34. Yang, Y, Roderick, ML, Guo, H, Miralles, DG, Zhang, L, Fatichi, S, Luo, X, Zhang, Y, McVicar, TR, Tu, Z, Keenan, TF, Fisher, JB, Gan, R, Zhang, X, Piao, S, Zhang, B, Yang, D 2023. Evapotranspiration on a greening Earth. Nature Reviews Earth and Environment **4**, pp. 626–641. https://doi.org/10.1038/s43017-023-00464-3
35. Weatherl, RK, Henao, Salgado, MJ, Ramgraber, M, Moeck, C and Schirmer, M 2021. Estimating surface runoff and groundwater recharge in an urban catchment using a water balance approach. Hydrogeology Journal **29**, pp. 2411–2428. https://doi.org/10.1007/s10040-021-02385-1
36. Weglarczyk, S 2018. Kernel density estimation and its application. ITM Web of Conferences **23**(2):00037. DOI: 10.1051/itmconf/20182300037
37. Zhang, Y, Liu, X, Wang, K, Zhang, D, Liu, W 2024. Widespread increasing control of water supply on evapotranspiration. Water Resources Research **60**, e2024WR038353. https://doi.org/10.1029/2024WR038353

Appendix 1

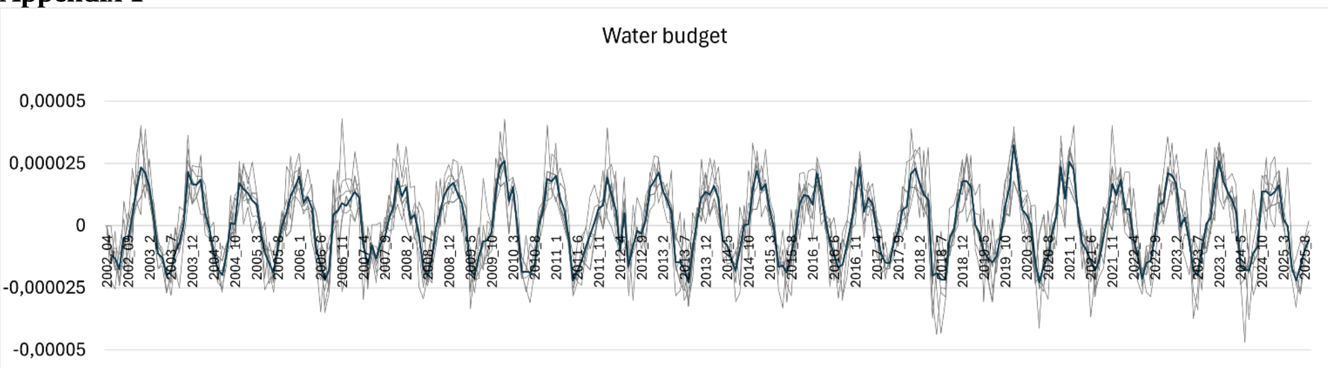

Fig. 11. Water budget time series for regions 1, 2, 3, 4, 5, and 6 – grey line versus average value of the water budget in the whole of Europe – dark blue line. All values in kg $m^{-2}s^{-1}$